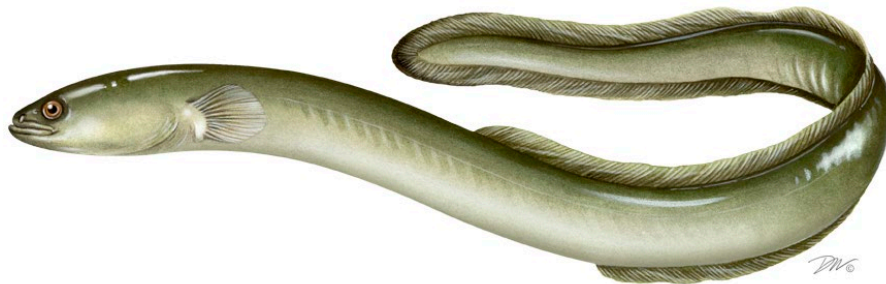


Atlantic States Marine Fisheries Commission

American Eel Benchmark Stock Assessment and Peer Review Report



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by the American Eel Management Board
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Sustainable and Cooperative Management of Atlantic Coastal Fisheries

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ASMFC American Eel Stock Assessment Subcommittee

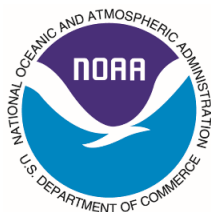
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PREFACE

The American Eel Benchmark Stock Assessment and Peer Review Report is divided into three sections:

Section A – American Eel Benchmark Stock Assessment Peer Review

PDF pages 5-28

This section provides a summary of the American Eel Benchmark Stock Assessment results supported by the Peer Review Panel. The Terms of Reference Report provides a detailed evaluation of how each Term of Reference was addressed by the Stock Assessment Subcommittee and provides recommendations from the Panel for further improvement of the model in the future.

Section B – American Eel Supplemental Report: Responses to Board and Peer Review Requests

PDF pages 29-68

This section describes additional information and analysis requested by the American Eel Management Board to address questions raised by the Board and Peer Review Panel.

Section C - American Eel Benchmark Stock Assessment

PDF pages 69-341

This section is the American Eel Benchmark Stock Assessment report that describes the background information, data used, and analysis for the assessment submitted to the Peer Review Panel. This report begins with a Term of Reference Report which describes how the Stock Assessment Subcommittee addressed each Term of Reference followed by the more detailed assessment report.

Atlantic States Marine Fisheries Commission

American Eel Benchmark Stock Assessment Peer Review



Conducted November 28 – December 5, 2022

Prepared by the
American Eel Benchmark Stock Assessment Peer Review Panel

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Sustainable and Cooperative Management of Atlantic Coastal Fisheries

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The Review Panel thanks members of the American Eel Stock Assessment Subcommittee and Technical Committee, as well as staff of the Atlantic States Marine Fisheries Commission, particularly Patrick Campfield, for support and coordination of activities during the review process

EXECUTIVE SUMMARY

Primary findings of the Review Panel:

1. The Review Panel endorses and supports the I_{TARGET} approach for the formulation of reference points for the fishery. The magnitude of the catch recommendation is contingent on the characteristics of the input data but also, importantly, determined by how the analysis is constructed. The Review Panel concludes work is still needed to establish the proposed threshold reference point and recommends a formal robustness test of the index-based method using a simulation approach (with MSE methods). With the additional analysis, I_{TARGET} can be used for developing threshold reference points for the stock.
2. The Review Panel believes it is more appropriate to consider the American eel stock to be in a “depleted” rather than “overfished” state. The Review Panel is uncomfortable with the overfished terminology because of uncertainty in the assessment methods and does not believe a reliable status determination can be defined at this time. More model development is needed to confidently provide a status determination, but the modeling approaches (e.g., MARSS) are appropriate. The time series of abundance indicates the stock, and perhaps recruitment, has decreased. However, there is little evidence that a reduction in fishing effort would result in a population response. Indications of recruitment overfishing necessitate management actions to reduce mortality on the spawning stock.
3. The SAS presented a suite of analytical methods that provide convergent results, indicating the stock has decreased over the monitored time series. Although the Review Panel recognizes the value of these analyses for providing context, select methods should be discontinued to decrease assessment team workload. We recommend the assessment team focus on methods that directly result in catch recommendations. Specifically, index-based methods and stage-based delay-difference modeling are the most promising for management and should be further explored and refined.
4. Habitat modeling for eel shows promise for helping managers understand the changes in carrying capacity and other spatial dynamics of the stock. Preliminary habitat work during the assessment should be further explored, documented, and reported in future

assessments. This type of approach has recently been used in other parts of the world for other eel species and delivered promising results (i.e., New Zealand; ICES 2021).

INTRODUCTION

The American eel *Anguilla rostrata* is one of 15 species in the family Anguillidae (Tsukamoto and Aoyama 1998). The taxa are characterized by great adaptability to a wide range of aquatic ecosystems, and consequently are found around the globe. All reproduce at sea and are at least facultatively catadromous, meaning they use inland habitats (Tesch 2003). Their complex life history is a challenge to managers and creates difficulty for “traditional” stock assessment approaches (Drouineau et al. 2016; Mateo et al. 2017). One example is that the American eel, from its northern limit in Greenland down to its southern limit in French Guiana, is considered one population (Jacoby et al. 2015).

American eels were formerly extremely abundant in inland waters of eastern North America, occupying lakes, rivers, streams, and estuaries (Prosek 2010). American eels were also an important food fish in the US, but today are mainly sold as bait or exported to Asia, where demand continues to be high (Kaifu et al. 2019). Declines in European and Asian eel abundance drive the export fishery. In particular, the export market for glass eels has commanded prices over \$2,300/lb in the past (Kaifu et al. 2019), although price and demand has declined in recent years. Decline in demand in both fisheries has been due to increasing aquaculture in Europe and effects of the global market from the COVID-19 pandemic.

There is substantial evidence that the American eel stock is reduced from historic levels. The cause for the reduction is a combination of habitat impacts and fishing pressure. In the last half of the 20th century, a suite of stressors including habitat loss from dams or urbanization, turbine mortality, the nonnative swim-bladder parasite *Anguillicola*, toxic pollutants, non-native fish species, and climate change are all factors that act in concert with fishing mortality on American eel (Castonguay et al. 1994; Jacoby et al. 2015; Drouineau et al. 2018). The American eel does not have a federal US protected status. It has been on the IUCN’s endangered list since 2013 (Jacoby et al. 2017).

Through a series of data analyses and modeling, the American Eel Stock Assessment Subcommittee (SAS) has sought to assess the current status of American eel. The unique characteristics of American eel’s distribution and life history make the species difficult to assess. The SAS has made a thorough and scientifically appropriate attempt to do so. The following Peer Review Report discusses the SAS stock assessment findings, comments on strengths and weaknesses, and makes recommendations for additional data needs and future assessments.

TERMS OF REFERENCE

1. Evaluate the definition of stock structure used in the assessment.

The Review Panel agrees with assessing eel at a coast wide scale because it is a panmictic species (Pujolar 2013). The distribution area extends further north and south than the United States. Ideally, a stock assessment should be carried out at an even larger scale - though the Review Panel realizes the challenges associated with such an undertaking. The Review Panel recommends expanding data and analysis to Canadian, Gulf of Mexico, and Caribbean regions, recognizing jurisdictional responsibilities for managing American eel. The SAS has already collected data on commercial fisheries in those regions, although in select regions landings are not comprehensive.

The majority of data originate from coastal areas where most of the commercial fishery takes place, however, the species occupies many other areas and habitats. While recognizing the current constraints in data availability and that habitat impediments restrict occurrences in upstream habitats, the Review Panel encourages future data collection and analysis of American eel in freshwater habitats. Moreover, the Review Panel supports the recent effort to develop a habitat-based model that may provide new insights on habitat use and stock productivity.

The American eel has a complex life-cycle with four unique life stages during its continental phase (glass eels, elvers, yellow eels, silver eels). The Review Panel notes the yellow eel stage is well monitored, with more fishery and survey data than other life stages.

2. Evaluate the thoroughness of data collection and the presentation and treatment of fishery dependent and fishery-independent data in the assessment, including the following but not limited to:

- a. **Presentation of data source variance (e.g., standard errors).**
- b. **Justification for inclusion or elimination of available data sources.**
- c. **Consideration of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, ageing accuracy, sample size).**
- d. **Calculation and/or standardization of abundance indices.**

The large distribution of the species across latitudes, but also inside river basins, makes it difficult to collect representative data of relative abundance for the American eel. The Review Panel considers the data collection achieved by the SAS as comprehensive, generally well presented, and thorough metadata with descriptions by data source were provided. Despite some coverage limitations (see TOR1), the Review Panel concludes the collected data sets are appropriate for the stock assessment. All potential data sources for American eel were requested and used where appropriate.

Fishery-Dependent Data

The SAS collected and described traditional fishery-dependent data. Commercial landings per life-stages and fishing gears were reported. Estimated recreational landings and associated

fishing effort were also collected. Several caveats were mentioned, especially with respect to recreational landings data. In order to better visualize the relative importance of recreational and commercial fisheries, the Review Panel suggests adding a figure showing their relative landings through time.

Because market demand is known to influence commercial landings, the Review Panel also suggests that, if available, a time series of yellow eel price (or a proxy) be presented. We believe such information would be useful for better understanding the dynamics of demand.

The Review Panel notes that no data were provided regarding commercial fishing effort. However, given the variety in fishing gears and fishing areas, the analysis of fishing effort would not be straightforward. Moreover, data on fishing effort is not critical for subsequent assessment analysis. Fishery-dependent indices, as calculated by state partners, were included as an appendix.

a. Presentation of data source variance (e.g., standard errors).

The uncertainty around commercial landings was not quantified, but this is typical of most stock assessments. Uncertainty was presented for recreational data, indicating broad confidence intervals due to limited directed fishing effort targeting the species.

b. Justification for inclusion or elimination of available data sources.

The Review Panel agrees in general with the criteria for use or exclusion of each data source. Data from the recreational fishery was not used further in the analysis, both because of its limited weight compared to the commercial fishery, and because of the caveats around these data. It might be possible to use recreational fishery data to derive abundance indices (e.g., Kahn 2019), but given the caveats and large uncertainty surrounding the data and the amount of fishery-independent data sources, the Review Panel does not necessarily see this as a main priority.

c. Consideration of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, aging accuracy, sample size).

The Review Panel observes that the fishery mainly targets yellow eels, mostly in coastal habitats. As such, fishery-dependent data does not cover the entire distribution of the species. The Review Panel also highlights a notable shift in landings coincident with a change in reporting requirements in 1998 and considers that additional explanations would be valuable (Figure 16, and Table 7, Commercial Yellow Eel Landings).

Fishery-Independent Data

The Review Panel acknowledges and appreciates the substantial amount of work in gathering, vetting, and selecting fishery-independent data sources. The data set is as comprehensive as possible.

a. Presentation of data source variance (e.g., standard errors).

Each time series is adequately described in the report: text summarizes key features (the survey design, environmental and environmental sampling, trends), boxplots display the length composition per year, and standardized indices with the associated confidence intervals are also presented.

b. Justification for inclusion or elimination of available data sources.

The methods are clearly presented and the Review Panel agrees with criteria for inclusion/exclusion decisions: a time series of at least 10 years of data, appropriate and time-consistent survey design, appropriate gear, relevant temporal and spatial coverage. The reasons for excluding specific time series are clearly stated in a dedicated table.

c. Consideration of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, aging accuracy, sample size).

The Review Panel acknowledges that the numerous available fishery-independent data sets offer good spatial coverage, with time-consistent protocols that provide both biological data and associated environmental conditions. Unfortunately, most time series began in the early 2000s when abundance was already at a low level, so that few time series cover the historical period of higher abundance and the decline.

The Review Panel notes the time series are collected using a large variety of gears, methods, and carried out in diverse monitoring seasons. Depending on the question, this might impair or at least make comparisons more difficult. Nevertheless, the Review Panel believes the differences do not impair the comparison of resulting trends of abundance.

d. Calculation and/or standardization of abundance indices.

The Review Panel agrees with the standardization approaches. The standardization is based on the fitting of a Generalized Linear Model (GLM) per time series, predicting the number of recorded eels for each fishing operation, depending on year, timing of the fishing operations, and other environmental factors. Different family distributions and sets of explanatory variables are compared to select the best model for each time series.

The Review Panel suggests to detail a bit further the systematic framework used by the SAS, perhaps by making the R standardization code available. More importantly, the Review Panel recommends adding a table that clearly summarizes the final model used (e.g., explanatory variables, distribution) for each time series, though this information can be inferred by scrutinizing the main text. This is critical for repeating standardization in future assessments, especially if an index-based approach will be used. Moreover, since the models are fitted on fishing operations, the Review Panel thinks it might be useful to include autocorrelation in the model, for example, by using the R package nlme or glmmTMB. However, the Panel suspects it would probably not drastically change the results and is partially addressed by the frequent inclusion of julian day as an explanatory variable.

The Review Panel was surprised by some trends (e.g., figure 32 “Standardized index of relative YOY abundance from New Hampshire’s Lamprey River Survey” or figure 45 “Standardized index of relative YOY abundance from Rhode Island’s Gilbert Stuart Dam Survey”) with periods of very low values alternating with periods of high values. In the future, the Review Panel proposes to add a boxplot for each time series that would display the distribution of the raw number of recorded eels per fishing operation for each year. This would allow checking the consistency between the standardized index and the raw data and visualizing the amount of eels on which the index is based.

3. Evaluate the methods and models used to estimate population parameters (e.g., biomass, abundance) and biological reference points:

a. Evaluate the choice and justification of the preferred model(s). Was the most appropriate model (or model averaging approach) chosen given available data and life history of the species?

The SAS carried out a comprehensive review of biological parameters for American eel that were used in the analysis. The Review Panel concludes the SAS used the best scientific knowledge available for the assessment. The SAS focused on four types of parameters:

Ageing: Ageing of American eels is generally carried out through otolith reading and is known to be a complex task (ICES 2020), especially given the large spatial heterogeneity in growth rates. To improve the consistency in methods across the area, several intercalibration workshops have been carried out since 2001. The latest workshop took place in 2018. It pointed out several issues and discrepancies but participants found an agreement to promote the most reliable techniques. The Review Panel concludes the ageing data are consistent. Age data were collected in various states (routine sample collection in Delaware, New Jersey, and Maryland, and a single sampling event from Georgia). Samples were primarily from the commercial fishery in coastal habitats. It might be useful in the future to complement the data collection with samples collected in freshwater habitats. The caveats with age sample reading impair the development of common age-structured stock assessment models.

Growth: Growth of eels varies substantially across latitudes and habitat types (Vélez-Espino and Koops 2009; Patey et al. 2018; Cairns et al. 2022). Given the variability, the SAS carried out an extensive meta-analysis to compile length-weight, sex, and age data. The large amount of data allowed detecting statistical differences in length-weight and length-age relationships among regions. The Review Panel acknowledges these analyses are conducted with well described state-of-the-art methods. Despite the variability in length-age relationship among regions, the subsequent models used by the SAS required the use of a single von Bertalanffy growth curve. To address the variability issue, the SAS used a bootstrap technique to estimate a single curve. The Review Panel concludes the method is indeed relevant to estimate both a mean growth curve and associated uncertainty. However, the Review Panel observes that to do so, the SAS used eels ranging from 0 to 21 years old, while ages from commercial landings were mostly 2 to 6 years old. Given the large variability in growth rates in the species, including too many older eels is likely to give too much weight to slow-growing eels that take a long time to grow to maturity, while eels that grow faster leave continental habitats at younger ages, and as such are

underrepresented in the bootstrap. This would in turn lead to an underestimated average growth curve. This might explain the small estimated asymptotic length (a length close to the minimum length of female silver eels) and whether it might be relevant to test the bootstrap on a more restricted age range. The Review Panel also notes that spatial heterogeneity in growth rates gives reason to pursue development of spatial assessment tools in the future.

Natural mortality: Natural mortality is a key parameter in population dynamics but it is known to be difficult to estimate (Jørgensen and Holt 2013). This is even more complex for eels since, as for other parameters, natural mortality is known to vary across regions and habitats, but also is thought to be density-dependent (Bevacqua et al. 2011). The SAS underwent a large literature review on the natural mortality of American eel that provided qualitative insights. Given the lack of precise quantitative data, the natural mortality was included in the sensitivity analysis by the SAS in two latter modeling approaches (egg-per-recruit, delay difference). The Review Panel observes that natural mortality was parameterized differently in those two exercises. While it is not a major issue since the two models are not used to make final recommendations, it may be worth improving the consistency. It might be also worthwhile to explore the effect of density-dependent mortality in any sensitivity analysis. The Review Panel acknowledges this is far from straightforward, given the absence of quantitative relationships for the species and since the degree of density-dependent mortality is likely to vary depending on local conditions, while modeling exercises are carried out at a coastwide scale.

Reproduction: The American eel has an environmentally driven sex-determination that occurs rather late during the growth phase (Davey and Jellyman 2005). Males and females are thought to display different life-history strategies, resulting in males having a smaller and relatively stable length-at-maturity, while females are thought to optimize a trade-off between higher fecundity but lower survival when length-at-maturity increases (Helfman et al. 1987). Sex data are not extensively used later in the assessment and as such, are not largely detailed here, and appear to arise mostly from histological observations. The Review Panel notes a recent method has been developed for an earlier sex-determination of the European eel (Geffroy et al. 2016) that might be relevant for the American eel in the future, especially if more complex sex-structured stock assessment methods are considered. Fecundity-at-length relationships from the literature were also reported and used later in the assessment (egg-per-recruit analysis).

The SAS tested several stock assessment methods, both updating formerly used tools and testing new approaches. The pros and cons of each approach were appropriately described. They include:

Mann-Kendall Trend Tests on individual time series of abundance: The approach tests whether a monotonic trend can be detected in each time series. This non-parametric test is appropriate for an exploratory analysis of a large set of time series. While conflicting signals among time series were detected with no obvious spatial pattern, results showed that significant negative trends were more frequent than positive trends, while a majority of time series did not display trends at all. An original power analysis was carried out to quantify the ability of each time series to detect a linear or exponential trend. While the results were not used in subsequent

analyses, for example for weighting time series, the Review Panel finds the analysis interesting and informative for managers, in order to prioritize their monitoring activities.

Estimation of aggregated abundance indices per life stages using MARSS and Conn: In order to derive aggregated abundance indices per life stage from the whole sets of individual time series, two different state-space models were used. The approach is well suited for this kind of time series analysis, allowing to model both process and observations errors and to account for temporal autocorrelation. The rationales are clearly explained, though the Review Panel thinks it might be worthwhile to specify a bit more the settings of the methods to facilitate repeatability (e.g., to specify the set of constraints of the MARSS matrices, the scaling and transformation of the time-series).

Two regime-shifts analyses (STARS and regression trees) were carried out on aggregate index analyses, consistently indicating that current abundance is lower compared to the beginning of the assessment period. The objective of building aggregated abundance indices is consistent with a panmictic stock and a coastwide assessment. However, the Review Panel suggests that, given the heterogeneity of signals among time series, an analysis such as a Dynamic Factor Analysis (Zuur et al. 2003b, 2003a) would highlight similarities among trends, and potentially facilitate the detection of spatial regions with consistent dynamics. This might open the door to spatial models.

The Review Panel also notes that all time series were given similar a priori weights in the analysis. It can be interesting to explore the use of river basins' weights accounting for their relative importance in the overall population dynamics, for example by using proxies for basins' carrying capacity or productivity. However, the Review Panel also observes there is currently no information on the origin of eels effectively contributing to reproduction and that given the heterogeneities in sex-ratio, fecundity, and distance to the spawning ground among basins, such weighting should be done with caution. The Review Panel recommends adding a plot of the MARSS aggregated index per life stage alongside the associated credibility intervals on back transformed/non-log scale. New figures could replace current Figures 147-149.

Traffic Light Approach: This approach was used by the SAS in a previous assessment. It consists of displaying with a color scheme the status of different indicators such as stock status and exploitation levels. Two options are explored: either comparing the indicators to the mean and quantiles across time periods, or comparing to a reference period. The latter option was presented in the assessment report. However, as acknowledged by the SAS, the ecological complexity of the species and its exploitation impairs the interpretations of classical fisheries indicators (e.g., landings, mean length). Therefore, the set of indicators is limited to the abundance indices arising from Conn and MARSS, and to the mean commercial length. The Review Panel concludes the value of the TLA is limited compared to the other assessment methods.

Egg-Per-Recruit model: This was used to compare the effects of two management options - modification of either glass eel or yellow fishery intensities. The model is clearly described and

its weaknesses identified by the SAS. The most important is the uncertainty in several key parameters such as natural mortality, maturation, and growth, especially given the spatial variability of eel life history traits. An appropriate uncertainty analysis based on MCMC simulations is used to address this issue. The results highlight that, given the likely high natural mortality affecting glass eels, a theoretical increase of the glass eel fishing mortality has less impact than an increase of the same magnitude for the yellow eel fishery. While it is possible to derive reference points based on such a model, the Review Panel considers the exercise rather theoretical. Indeed, it does not account for the diversity of fishing activity with different selection patterns, nor treat the yellow eel fishery and glass eel fishery independently. The Review Panel concludes that outputs are informative for local managers, while recognizing the limited occurrence of glass eel fisheries. Moreover, given their different behaviors, caution should be taken when comparing fishing mortality levels between the two stages. Yellow eel are sedentary while glass eel are migratory and more vulnerable to the fishery, which can achieve very high harvest rates (e.g., Briand et al. 2003, Aranburu et al. 2016).

Surplus production model: This type of model was tested by the SAS in a previous assessment. Two new versions of surplus production models were used that allow for variations in intrinsic growth rate (TVr) or non-equilibrium models (ASPIC). The SAS emphasized that American eel violates almost all assumptions of a surplus production model, and concluded the outputs cannot be used for fishery management advice. The Review Panel endorses this conclusion and notes that a recent ICES assessment gave the same conclusion for European eel (ICES 2021).

Habitat-based modeling: Habitat modeling consists of using GIS analyses to derive statistical relationships between eel abundance and habitat descriptors of the river network. This type of approach has recently been used in other parts of the world for similar species and delivered promising results (Beentjes et al. 2016; Hoyle 2016; ICES 2021; Briand et al. 2022; Mateo et al. 2022). The American eel work supported by the SAS is still in progress and currently consists of a pilot study in the data-rich Chesapeake region. Therefore, it is not possible to draw definitive conclusions on the relevance of results and on transferability of the approach to data-poor regions. It will likely depend on the availability and interoperability of both fish data and habitat data. The Review Panel considers habitat modeling an interesting option to explore in future assessments.

Delay-difference model: This kind of model is an intermediate between a simple production model and a more complex age-structured model. By not requiring complex age-structured data but allowing a finer description of biological processes (growth, natural mortality, reproduction) than a surplus production model, delay-difference models appear relevant to eel. The approach and data used by the SAS is clearly described. Given the large variability in delay-difference model implementation, even within the package used by the SAS, the Review Panel suggests that explicitly writing the dynamic equations underlying the final model would be worthwhile to facilitate understanding and reproducibility. As acknowledged by the SAS, the current model suffers from some weaknesses. For the Review Panel, the most important is the stock-recruitment relationship that (1) does not allow for process errors and (2) does not take into account that a large part of the spawning stock lies outside the US coast (e.g., Canada,

Caribbean Sea). Moreover, catches are assumed to be known without errors. Finally, given the large variability in life history traits, the SAS was required to carry out the exercise using an ‘average eel’ from the Chesapeake region. While the approach was able to estimate reference points and concluded the stock was overfished but overfishing was not occurring, the SAS and the Review Panel conclude the results cannot be used as the basis for management at the coastwide scale. However, the Review Panel finds the delay-difference model to be a promising way forward to model the stock. It would be possible to use a state-space formulation of the model to relax the assumption on the stock-recruitment relationship and on catches. Moreover, it might be possible to develop a Bayesian hierarchical version of the model to account for regional differences in life-history traits and transfer information from data-rich to data-poor areas. This would be somewhat similar to the spatial stage-based model recently promoted by ICES for the European eel (ICES 2021).

Index-Based Method: This is a data-limited approach that can be useful in situations, such as for American eel, where an age-structured population assessment can become problematic (NEFSC 2020). The SAS evaluated a variety of data-limited methods and focused on exploring four, based on data availability and assumptions: PlanB, I_{SLOPE} , I_{TARGET} , and Skate. Of these, the I_{TARGET} method was selected to be the best for American eel given the depleted nature of the stock and flexibility in determining reference years, and productivity characteristics of the modeled stock. The Review Panel agrees with the use of I_{TARGET} as a threshold reference point, the I_{TARGET} approach requires a selection of a reference period for stock status and a value for I_{TARGET} ‘mult’ parameter, representing the relationship of the reference period to the biomass target. The parameter can range from 1, indicating the average index over the reference period represented the biomass target for the population, to 1.5, indicating the average index value during the reference period represented one-half the biomass target. The Review Panel agreed with the SAS’ rationale and selection of 1974-1988 as a reference period and 1.25 as the I_{TARGET} MULT, representing a population that has reduced carrying capacity due to habitat impacts and has previously experienced fishing pressure. The Review Panel believes the I_{TARGET} method is promising for management and should continue to be explored and refined. The Review Panel concludes that work is still needed to test the robustness of the assessment method to establish the proposed threshold reference point (e.g., sensitivity analysis, MSE, stakeholder input). Further discussion of the I_{TARGET} method can be found in TOR5.

- b. Evaluate model parameterization and specification (e.g., choice of CVs, effective sample sizes, likelihood weighting schemes, calculation/specification of M, stock-recruitment relationship, choice of time-varying parameters, plus group treatment).**

See previous section 3a.

- c. Recommend best estimates of stock biomass, abundance, and exploitation from the assessment for use in management, if possible, or specify alternative estimation methods.**

The Review Panel concludes the aggregated indices per life stage from MARSS are currently the best available coastwide aggregated indices and can be used to indicate stock abundance

variations over time. The ratio of landings and MARSS indices can be used as a proxy of exploitation rate trends. The Panel agrees with the SAS about potential problems of standardization with the Conn approach due to inconsistent time-coverage of the time series, and therefore prefers the MARSS indices.

The Panel also highlights that all time-series in the MARSS indicators have the same weight. As a consequence, a time series collected in a zone with low abundance has the same weight as a time series collected in a zone of higher abundance, and regions with more time-series have more weights than data poor regions. In the future, habitat modeling might provide a better way to weight the regions and time series based on their importance in contributing to total biomass.

d. If multiple models were considered, evaluate the analysts' explanation of any differences in results.

The Conn and MARSS methods used to derive abundance indices provide very consistent results, confirming the robustness of trends.

4. Evaluate the methods used to characterize uncertainty in estimated parameters. Ensure the implications of uncertainty in technical conclusions are clearly stated.

The models evaluated by the SAS that can be used to determine fishery and stock reference points were the surplus production, egg-per-recruit, and delay-difference models. Each of these modeling approaches, for reasons of poor or lack of fit, were not able to provide reliable or useful results. The 'estimated parameters' in this context are the estimated reference points, which were not developed.

- Due to the issues stated by the SAS and the previous TOR, the surplus production model was not suitable for use.
- As discussed in the previous TOR, the egg-per-recruit model has weaknesses identified by the SAS. MCMC simulations were used to account for uncertainty in key life history parameters. While it is possible to derive reference points based on such a model that can have some value on local scales where yellow and glass eel fisheries co-exist, the Panel considers the exercise theoretical and caution should be used when interpreting results.
- Although the delay-difference model shows promise, and is the only non-index-based model the SAS indicated they will be moving forward with for management advice (and the Review Panel agrees), the model is not suitable at this time. As stated in the previous TOR, the method needs more development to account for the variability and uncertainty in American eel life history characteristics across range.

- 5. Evaluate the diagnostic analyses performed, including but not limited to:**
- a. Sensitivity analyses to determine model stability and potential consequences of major model assumptions.**
 - b. Retrospective analysis.**

The model chosen by the SAS for determining stock status and associated catch recommendations was the index-based I_{TARGET} method. In the report and during the review meeting the Review Panel was presented with two types of evaluation of uncertainty. The first was the systematic varying of the I_{TARGET} 'mult' parameter from 1.0, 1.25, and 1.5. This value represents the relationship of the reference period to the biomass target. The second method of uncertainty was a simulation analysis requested by the Review Panel. This analysis focused on understanding how catch advice using I_{TARGET} varied when values of the input abundance index were altered. The intention was to account for additional uncertainty within the I_{TARGET} method.

The SAS bootstrapped predicted confidence intervals of the MARSS time series and then used the resulting time series within the I_{TARGET} method. This bootstrapping approach is not the ideal approach, as it ignores autocorrelation in the data, but is adequate given the time-constraints of the assessment. Future assessments should further explore alternative methods to better describe uncertainty. The Review Panel very much appreciated both of these investigations.

Retrospective analysis is not used in the index-based modeling approach. However, the Review Panel advises future simulations that alter some of the temporal characteristics in the model.

Adoption of the I_{TARGET} method for determining catch advice will necessitate a complete and full simulation analysis for American eel. The Review Panel recommends the following:

- 1) Simulation of the input time series should be explored further. The Panel recommends exploring more fully the input data comprising the yellow eel index of abundance. We recommend the MARSS index be iteratively derived in a simulation approach by subsampling the indices, developing the coastwide aggregate time series, and then using this in the simulation. The benefit would be to allow a complete understanding of those time series having the most impact on the model, in the I_{TARGET} context. This is characterized to a certain extent by the correlation analysis presented in the assessment report. However, the Review Panel thinks it is a sensitivity and exploration approach worth pursuing because many of the indices are not positively correlated with one another. The simulation would give decision-makers insight into the probability of abundance index increases that might be expected for a given catch recommendation.
- 2) The decision to establish the reference period was in part made by using information from Rodionov's STARS algorithm. The Review Panel thinks it was reasonable. The second, and we believe impactful exploration of the I_{TARGET} model that could be explored, would be systematic or stochastic changes to what constitutes the reference

period. Because the reference period is based on the analysis from the STARS algorithm, it would be informative, while pursuing #1 above, to also evaluate the robustness of the choice of reference period. The Panel recommends for each time series using the best fitting STARS predicted abundance index to determine the timing of 'regime shift'.

- 3) One of the penalties of using an index-based approach, and especially one in that uses the information from so many different time series, will be the frequency of availability of each input to build the coast wide index of abundance. Although the nature of smoothing in deriving the MARSS-based index of abundance likely reduces the deviations one might expect, it presents challenges in terms of implementation of the harvest control rule. This aspect of the I_{TARGET} -based control rule should be explored in simulation. It is likely that operational frequency of assessment – in this case index standardization and development of the coastwide index – will be at frequencies that exceed one or even two years. Given the amount of work and coordination required to do these analyses, a three-year gap is likely between each modeling event. The Review Panel recommends simulation be used to evaluate the magnitude of bias that might be expected when the catch advice is only available every two to three years. Given the large amount of process error, the ability to detect a significant change in the abundance index could be reduced if evaluated infrequently.
- 4) Although mentioned above, the documentation of the characteristics and structure of the models used for individual time series' standardization will need to be consistent moving forward. To accomplish this, each standardization algorithm will need full and complete documentation.

To address the above points and those presented in TOR 6, the Review Panel recommends the development of an MSE to test the robustness of the assessment method (index method, schedule of assessment) and harvest control rules (setting of catch limits based on assessment results). This would require the development of:

- An operation model: a simulation model that can be used to simulate plausible "virtual" trajectories of population according to different scenarios – e.g., assumptions about what happens outside the US, assumptions about the relative importance of coastal versus freshwater fractions of populations, stock recruitment relationship – and catch levels. The operation model is typically a complex model able to simulate various kinds of uncertainty, with many parameters that cannot be properly estimated, and do not aim to hindcast nor to forecast series of fishing mortalities or SSB. It purely aims at simulating plausible trajectories. An example is the Multi-Sed model (Lambert 2011) for the European eel.
- Testing the index-based assessment method at considered frequency – e.g., every 3 years of data – to assess the status of the population.

- Use the assessment result to set the management measures (e.g., catch limits) according to the harvest control rules. These catch limits are then used to simulate the next time steps with the operating model.

The Review Panel acknowledges MSE is a time-consuming task, especially the development of the simulation model. Therefore, such an MSE is probably not suited to be part of the recurring stock assessments, and may be more suited to a co-constructed research project.

6. Evaluate stock status determination and reference points used by the assessment.

a. Recommend stock status determination from the assessment, or, if appropriate, specify alternative methods/measures.

The primary model used in the assessment, the I_{TARGET} approach, does not allow the determination of stock or fishery status with respect to traditional MSY-based biological reference points. The evaluation of the coastwide index, presented by the SAS, does indicate the stock has declined. The Review Panel concludes that the term ‘depleted’ is appropriate to describe the stock biomass for the yellow eel life stage. This is a qualitative term used only as a descriptor and not as a determination of status.

b. Evaluate the choice of reference points and the methods used to estimate them.

The characterization of the fish stock being depleted was developed by the SAS using a suite of modeling approaches, each based on the coastwide index of abundance (e.g., Rodionov’s STARS and the I_{TARGET} model). The Review Panel encourages the SAS to do a full simulation to test the robustness of catch advice. Given the catch advice from I_{TARGET} , an evaluation should be performed to understand if following the catch advice will result in increases in stock biomass. It is important to test the robustness of the index approach to uncertainty, and the ability of this or an alternative index to move the population trajectory in a positive direction. This can be accomplished by simulating plausible population dynamics for American eel with a simulation modeling exercise (see TOR 5).

Given the process error associated with the complex life history of the stock, the fact that a significant portion of the stock resides outside of the assessed area, anthropogenic impacts other than fishing affect the stock, the focus on yellow eel in the I_{TARGET} approach, the exclusion of other life stages, and the error associated with landings data, it is necessary to evaluate the robustness of the catch advice developed from I_{TARGET} .

7. Evaluate the incorporation of new information or attempts at novel approaches to assess the stock.

Overall, the SAS did an excellent job incorporating new information and approaches in the assessment. This is important for species like American eel where there are limited data for certain aspects of biology and population status that restrict the use of traditional, age-structured stock assessment approaches.

American eel ageing has been a problematic issue for past assessments. This issue was addressed during a coastwide age sample exchange (2017) and a workshop (2018) to compare

ageing methods and results. Techniques to produce less biased age estimates were used to improve the quality of data available to the assessment.

The assessment makes use of a large number of indices sourced from various state, academic, international, and other entities across the range of American eel. The SAS has done an excellent job collecting the indices, updating them, and documenting changes in the surveys that affect their use in assessments.

MARSS is a relatively new aggregate time series analysis developed since the completion of the previous eel stock assessment. This method, and the similar Conn method, were used to analyze the large amount of index data in the assessment. These methods are powerful tools for detecting and determining trends in multiple indices. The Review Panel approves of the use of these models and of the SAS' preference for MARSS over the Conn approach. The MARSS model should be further developed in future assessments, incorporating aspects such as covariates and Dynamic Factor Analysis (DFA), to improve fit, and better explore uncertainty and the potential cause of conflicting trends among indices.

The delay-difference model was used to estimate biomass, abundance indices, and fishing mortality over time. While the model is well established, the SAS took into account recommendations from the 2020 American shad stock assessment and used the SAMtool and DLMtool packages that allowed greater model flexibility and outputs. The delay-difference model is a valuable approach for American eel and it is important to take advantage of lessons from other assessments, updated data, and new modeling developments.

The Review Panel approves of the use of index-based methods developed by the SAS. These approaches have advanced significantly since the last assessment and are useful for data-limited species. The SAS evaluated a variety of different index-based approaches and selected I_{TARGET} using sound reasoning. Future assessments should build on what was done here and continue to update the approach as the data and methodology improves.

8. Review the research, data collection, and assessment methodology recommendations provided by the Technical Committee and make any additional recommendations warranted. Clearly prioritize the activities needed to inform and maintain the current assessment, and provide recommendations to improve the reliability of future assessments.

To save time and effort in future assessments, the surplus production model and TLA assessment approaches should be discontinued. Given the issues with American eel life history and the fishery, and the assumptions of surplus production models, this approach is not useful for the assessment. It is not entirely clear why the surplus production model was repeated from previous assessments, given the same assumption problems likely existed. The TLA may have some utility for the species, but needs more development to be usable. Due to the characteristics of the TLA approach, this might be a better management approach for the species as opposed to an assessment approach.

The Review Panel recommends that more effort be placed on methods with the most potential in the future, including the index-based methods and stage-based delay-difference models. These hold the most promise for providing management advice and should continue to be explored and refined. The I_{TARGET} method is useful for developing a threshold reference point for the stock. The Panel concludes that work is still needed to establish the proposed threshold reference point (sensitivity analysis, MSE, stakeholder input) and harvest control rules.

Habitat modeling for eel shows promise for helping managers understand the changes in carrying capacity and other spatial dynamics of the stock, and should be explored in future assessments. This type of approach has recently been used in other parts of the world for similar species and has delivered promising results (i.e., New Zealand, ICES 2021).

The Panel agrees with the SAS and TC recommendation that the biological sampling requirement for YOY surveys be made optional. This is based on the lack of trends in pigment, length, and weight within and among sites. As stated, if states continue to voluntarily collect biological data, the data can be re-evaluated during the next stock assessment, or as needed, and biological sampling can be mandated again in the future. Annual YOY surveys should continue in order to monitor eels and collect associated environmental data, since abundance indices are such a key component of the assessment.

9. Recommend timing of the next benchmark assessment and updates, if necessary, relative to the life history and current management of the species.

The Review Panel recommends conducting the next benchmark assessment after additional data are collected and progress is achieved in addressing the Panel's analytical recommendations. This would be at a minimum of 5 years from the current benchmark. It is also in keeping with the long generation time for eel (3-5 years in the south, 10-20 years in the north).

Effort should be made to conduct an international assessment, including Canadian, Caribbean, and Gulf of Mexico (GOM) input. The Review Panel applauds the inclusion of Canadian and GOM data in this assessment. Future efforts may benefit from more participation from these areas.

ADVISORY SECTION

Status of Stocks: Current and Projected

The Review Panel believes the American eel population is depleted in US waters. The Panel is uncomfortable with overfished terminology because of uncertainty in the assessment methods and did not believe a reliable status determination could be defined at this time. More model development is needed to confidently provide a status determination, but the modeling approaches (e.g., MARSS) are appropriate. The time series of abundance indicates the stock, and possibly recruitment, has decreased. Indications of recruitment overfishing necessitate management actions to reduce mortality on the spawning stock. However, the overfishing and

overfished status in relation to biomass and fishing mortality reference points cannot be stated with confidence.

Factors affecting stock status include a combination of historical overfishing, habitat loss due to damming mainstems and tributaries of rivers, mortality from passing through hydroelectric turbines, pollution, possibly parasites and disease, climate change, and other unexplained factors at sea.

An important consideration with American eel stock status is that habitat impacts and fishing pressure are not the same across the stock range. This is shown by the magnitude of historic landings by state and region. The amount and types of habitat impacts likely vary as well, based on region, with some areas being fully developed and others relatively untouched. This implies a certain proportion of the adult stock has a level of protection from human impact.

The North Atlantic region has already experienced significant cumulative climate-related changes in oceanographic conditions (Ramírez et al. 2017; Greenan et al. 2018) and substantial changes in regional fisheries production (Pershing et al. 2015; Britten et al. 2016). This observation, combined with the regime shift evidence presented in the assessment, could suggest there are ocean-level environmental drivers for American eel stock status. Given the broad distribution of American eel, the center of the species range does not align with the assessed range. Therefore, climate-induced range shifts or contractions may not be fully observable by the indices used in the assessment.

Stock Identification and Distribution

The American eel is a panmictic species. A single, genetically homogeneous population. This is due to having a single spawning region in the Sargasso Sea. After hatch, American eel leptocephali (larvae) drift with currents in a generally westward direction, encountering both the North and South American continents. Consequently, the distribution of American eel ranges from northern South America, into the Gulf of Mexico, and along the North American east coast as far as Labrador and Greenland. There is overlap on the spawning grounds with the European eel, *Anguilla anguilla*, and a hybrid zone is found in Iceland (Albert et al. 2006).

Although panmictic, there are distinct, habitat-related trends in size and sex ratio in anguillid eels (e.g., Oliveira 1999, Davey and Jellyman 2006). Sex determination is environmentally determined and appears to be a function of density and growth rate, with males arising at higher local population densities. These differences appear to produce females that are larger and therefore more fecund, and take longer to mature, while males mature as quickly as possible (Davey and Jellyman 2006). Therefore, loss of larger, older females in the female-dominated Laurentian Great Lakes drainage, and possibly other areas where females are produced, is cause for concern.

Management Unit

As noted in previous stock assessment peer reviews (ASMFC 2006; ASMFC 2012), because of the broad range (over 50 degrees of latitude) and geographic biological differences in this

panmictic species, management of eels in US waters must also consider status of eels beyond the US territory. The inclusion of Canadian data was welcome in the assessment, but Caribbean coordination is also necessary. The Review Panel recommends future stock assessments be carried out at the population scale and encourages internationally coordinated assessments, as achieved for the European eel.

Landings

Earliest US federal records of eel fishing date from the late 19th century. Eel fishing has been documented back to the 17th century. Gear ranges from traditional spears to pots, pound nets, and weirs. During the 20th century, heaviest fishing pressure occurred in response to demand from Asia beginning in the 1960s, and decline began to occur in the early 1980s. Harvests have been more or less constant since the late 1990s. Recent harvests dropped due to declining demand resulting from increased competition from aquaculture and COVID-19 pandemic downturns. A coastwide cap on yellow eel landings and a glass eel quota for Maine have been in place since 2014 and have not been exceeded through 2020.

A glass eel fishery arose in the 1970s in response to demand from Japan. High prices for glass eels periodically drove up effort in this fishery and demand peaked in 2012 due to a shortage of Japanese eels in the wake of the 2011 tsunami and its impacts. During several years from 2011-2019 average price/lb was approximately \$2,000, but the COVID impacted market in 2020 saw a 10-year low of \$525/lb. The glass eel fishery is legal only in the states of Maine and South Carolina, while high market prices could result in illegal poaching.

Landings have been restricted coastwide in recent years for both the glass and yellow eel fisheries. This can limit the usefulness of recent landings indicator data, such as in the TLA.

Data and Assessment

Data sets were canvassed from as many sources as possible and trends examined. Fishery-dependent data were examined and used in several aspects of the assessment, including the surplus-production, delay-difference, and I_{TARGET} methods. Fishery-independent data sets were standardized with generalized linear models (GLMs), then analyzed using a variety of methods to evaluate different aspects of the data. Methods included: index correlation; the ability to detect trends (power analysis); monotonic trends (Mann-Kendall tests); evidence of regime change (STARS); coherence of trends over space (via meta-analysis); long-term population change (MARSS, CONN); and general temporal and geographic trends (Traffic Light Analysis). The results indicated variable responses, but most of the data sets indicated declining or stable populations.

Biological Reference Points

Index-based methods and stage-based delay difference modeling are the most promising for management advice and should be further explored and refined. I_{TARGET} is useful for developing a threshold reference point for the stock. The Review Panel considers that work is still needed to establish the proposed threshold reference point (e.g., sensitivity analysis, MSE, stakeholder input).

A TLA was used by grouping different data sets within geographic regions and years, categorizing them as ‘good’, ‘intermediate’, and ‘bad’ in terms of percentiles of ranges. The results were complex and difficult to interpret. The Panel felt the TLA approach was not a priority for future stock assessments. However, TLA could be a useful tool if developed in conjunction with managers and refined to include an optimized set of indices – including environmental and habitat indices – related to American eel population dynamics.

Fishing Mortality

While trends in fishing mortality (F) can be discerned from the model, estimates from recent years are somewhat uncertain, as they depend on the assumed level of current depletion. However, the trends in F have been relatively stable over the past 20 years and were known to decline as a result of COVID and market effects at the end of the time series. The catch limits put in place in 2014 have also likely moderated or reduced the trends in F seen earlier in the time series.

An important aspect of the American eel fishery is the targeting of two different life stages (glass and yellow). Throughout the assessment, most effort in F estimation and stock status are focused on the yellow eel stage. While the landings of glass eel are relatively small and, according to the EPR analysis in the assessment, not as important of a component to spawning production, it is worthwhile to point out that this stage was not included in the assessment’s index-based catch recommendations.

Recruitment

Trends in recruitment were primarily monitored through the YOY surveys. While it is important to have the surveys, the spatial variability and lack of correlation among surveys was concerning. While states should continue the surveys, some effort should be made to prioritize surveys that are the most informative, with higher encounter rates and longer time-series. Efforts should also be made to gain more insight into the factors driving variability in the surveys, including, but not limited to geography, environmental conditions, ocean currents, etc.

Spawning Stock Biomass

The magnitude of spawning stock biomass (SSB), both current and historical, is difficult to assess due to uncertainties in abundance estimates, variable growth rates, and population productivity. An unknown fraction of the spawning stock is outside of U.S waters.

The Review Panel reminds that available SSB indices are a proxy based on silver eel abundance indices, the later continental stages, but there is no evidence that silver eels effectively contribute to spawning. Moreover, the stock extends beyond American Atlantic waters and the indices cover only a portion of the total potential SSB.

Bycatch

Eel bycatch is not considered to be a major problem. Eels are caught incidentally by recreational fishers. The Marine Recreational Information Program (MRIP) lists eel as a bycatch species.

Other Comments

In general, the Panel was satisfied with the progress made by the SAS and encourages the continuation of work on new approaches developed for the stock assessment. Given the unique life history and biology of anguillid eels, which defy national boundaries, it is important to account for the contributions of and threats to the portion of the American eel population outside of the US.

LITERATURE CITED

- Albert, V., B. Jónsson, and L. Bernatchez. 2006. Natural hybrids in Atlantic eels (*Anguilla anguilla*, *A. rostrata*): evidence for successful reproduction and fluctuating abundance in space and time. *Molecular ecology* 15(7): 1903-1916.
- Aranburu, A., E. Diaz, C. and Briand. 2016. Glass eel recruitment and exploitation in a South European estuary (Oria Bay of Biscay). *ICES Journal of Marine Science*, 73: 111–121.
- ASMFC (Atlantic States Marine Fisheries Commission). 2006. Update of the American eel stock assessment report. ASMFC, Washington, D.C. 51 pp.
- _____. American Eel Benchmark Stock Assessment. Stock Assessment Report 12- 01 of the Atlantic States Marine Fisheries Commission. 342 pp.
- Beentjes, M.P., J. Sykes, S. and Crow. 2016. GIS mapping of the longfin eel commercial fishery throughout New Zealand, and estimates of longfin habitat and proportion fished. *New Zealand Fisheries Assessment Report 2016/32*, New Zealand Fisheries Assessment Report 2016/32.
- Bevacqua, D., P. Melià, G.A. de Leo, and M. Gatto. 2011. Intra-specific scaling of natural mortality in fish: The paradigmatic case of the European eel. *Oecologia* 165: 333–339.
- Briand, C., D. Fatin, G. Fontenelle, and E. Feunteun. 2003. Estuarine and fluvial recruitment of the European glass eel, *Anguilla anguilla*, in an exploited Atlantic estuary. *Fisheries Management and Ecology*, 10: 377–384.
- _____, M. Maria, H. Drouineau, K. Maria, D. Estibaliz, and B. Laurent. 2022. Eel Density Analysis (EDA 2.3). Escapement of silver eels (*Anguilla anguilla*) from French, Spanish and Portuguese rivers. GT4 - deliverable E4.1.1. HAL CCSD. https://hal.archives-ouvertes.fr/hal-03590458/file/Briand_et_al_2022_EDA_SUDOANG_report.pdf (Accessed 28 October 2022).
- Britten, G.L., M. Dowd, and B. Worm. 2016. Changing recruitment capacity in global fish stocks. *Proceedings of the National Academy of Sciences* 113: 134–139.
- Cairns, D.K., J. Benchetrit, L. Bernatchez, V. Bornarel, J. M. Casselman, M. Castonguay, A.R. Charsley, et al. 2022. Thirteen novel ideas and underutilised resources to support progress towards a range-wide American eel stock assessment. *Fisheries Management and Ecology* 29: 516–541.
- Castonguay, M., P.V. Hodson, C.M. Couillard, M.J. Eckersley, J.D. Dutil, and G. Verreault. 1994. Why is recruitment of the American eel, *Anguilla rostrata*, declining in the St. Lawrence River and Gulf? *Canadian Journal of Fisheries and Aquatic Sciences* 51: 479–488.

- Davey, A., and D. Jellyman. 2005. Sex determination in freshwater eels and management options for manipulation of sex. *Reviews in Fish Biology and Fisheries* 15: 37–52.
- Drouineau, H., L. Beaulaton, P. Lambert, and C. Briand. 2016. GEREM (Glass-Eel Recruitment Estimation Model): a model to estimate glass-eel recruitment at different spatial scales. *Fisheries Research* 174: 68–80.
- _____, C. Durif, M. Castonguay, M. Mateo, E. Rochard, G. Verreault, K. Yokouchi, et al. 2018. Freshwater eels: a symbol of the effects of global change. *Fish and Fisheries* 19: 903–930.
- Geffroy, B., F. Guilbaud, E. Amilhat, L. Beaulaton, M. Vignon, E. Huchet, J. Rives, et al. 2016. Sexually dimorphic gene expressions in eels: useful markers for early sex assessment in a conservation context. *Scientific Reports* 6.
<http://www.ncbi.nlm.nih.gov/pmc/articles/PMC5034313/> (Accessed 3 November 2016).
- Greenan, B.J.W., T.S. James, J.W. Loder, P. Pepin, K. Azetsu-Scott, D. Ianson, R.C. Hamme, D. Gilbert, J.E. Tremblay, X. Wang, and W. Perrie. 2018. Changes in oceans surrounding Canada. *Canada's Changing Climate Report*, eds E. Bush and DS Lemmen (Ottawa, ON: Government of Canada), pp.343-423.
- Helfman, G., D.E. Facey, L. Stanton Hales Jr., and E.L. Bozeman Jr. 1987. Reproductive ecology of the American eel. *American Fisheries Society Symposium*, 1: 42–56.
- Hoyle, S.D. 2016. Feasibility of longfin eel stock assessment. *New Zealand Fisheries Assessment Report 2016/29*, New Zealand Fisheries Assessment Report 2016/29.
- ICES (International Council for the Exploration of the Sea). 2020. Third workshop on age reading of European and American eel (WKAREA3). VOLUME 2, ISSUE 84.
- _____. 2021. Workshop on the Future of Eel Advice (WKFEA). VOLUME 3, ISSUE 13.
- Jacoby, D., J.M. Casselman, M. DeLucia, G.A. Hammerson, and M. Gollock. 2017. *Anguilla rostrata* (amended version of 2014 assessment). In *The IUCN Red List of Threatened Species 2017*: e.T191108A121739077. <http://www.iucnredlist.org>.
- _____, J.M. Casselman, V. Crook, M.B. DeLucia, H. Ahn, K. Kaifu, T. Kurwie, et al. 2015. Synergistic patterns of threat and the challenges facing global anguillid eel conservation. *Global Ecology and Conservation* 4: 321–333.
- Jørgensen, C., and R.E. Holt. 2013. Natural mortality: Its ecology, how it shapes fish life histories, and why it may be increased by fishing. *Journal of Sea Research* 75: 8–18.
- Kahn, D.M. 2019. Trends in abundance and fishing mortality of American eels. *Fisheries* 44: 129–136.
- Kaifu, K., F. Stein, W. Dekker, N. Walker, C. Dolloff, K. Steele, A.A. Aguirre, et al. 2019. Global exploitation of freshwater eels (genus *Anguilla*): fisheries, stock status and illegal trade. In *Eels. Biology, monitoring, management, culture and exploitation. Proceedings of the first international eel science symposium*, pp. 377–422. Ed. by A. Don and P. Coulson. 5m Publishing, Sheffield.
- Lambert, P. 2011. Développement d'outils de modélisation de la population d'anguille

- européenne prenant en compte la diversité des paramètres de dynamique par grande fraction d'aire de répartition continentale de l'espèce : Rapport final 2011. Partenariat Irstea Onema 2011 – Domaine: Espèces aquatiques continentales - Action n°11.1, Partenariat Irstea Onema 2011–Domaine: Espèces aquatiques continentales-Action n°11.1.
- Mateo, M., P. Lambert, S. Tétard, and H. Drouineau. 2017. Impacts that cause the highest direct mortality of individuals do not necessarily have the greatest influence on temperate eel escapement. *Fisheries Research* 193: 51–59.
- _____, E. Díaz, L. Beaulaton, H. Drouineau, C. Antunes, E. Amilhat, A. Bardonnnet, et al. 2022. Evaluating Silver Eel Escapement at a Large Scale Using Eel Density Analysis (EDA). In *Biology and Life Sciences Forum*. <https://hal.archives-ouvertes.fr/hal-03699085> (Accessed 24 June 2022).
- NEFSC (Northeast Fisheries Science Center). 2020. Research Track Assessment for Index-Based Methods and Control Rules. Woods Hole, MA. 59 pp.
- Oliveira, K. 1999. Life history characteristics and strategies of the American eel, *Anguilla rostrata*. *Canadian Journal of Fisheries and Aquatic Sciences* 56: 795–802.
- Patey, G., C.M. Couillard, H. Drouineau, G. Verreault, F. Pierron, P. Lambert, M. Baudrimont, et al. 2018. Early back-calculated size-at-age of Atlantic yellow eels sampled along ecological gradients in the Gironde and St. Lawrence hydrographical systems. *Canadian Journal of Fisheries and Aquatic Sciences* 75: 1270–1279.
- Pershing, A.J., M.A. Alexander, C.M. Hernandez, L.A. Kerr, A. Le Bris, K.E. Mills, J.A. Nye, et al. 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science* 350: 809–812.
- Prosek, J. 2010. *Eels: An exploration, from New Zealand to the Sargasso, of the world's most mysterious fish*. Harper Collins.
- Pujolar, J.M. 2013. Conclusive evidence for panmixia in the American eel. *Molecular Ecology* 22: 1761–1762.
- Ramírez, F., I. Afán, L.S. Davis, and A. Chiaradia 2017. Climate impacts on global hot spots of marine biodiversity. *Science Advances* 3: e1601198.
- Tesch, F.W. 2003. *The Eel*. Blackwell Publishing, Oxford, UK. 408 pp.
- Tsukamoto, K., and J. Aoyama. 1998. Evolution of freshwater eels of the genus *Anguilla*: a probable scenario. *Environmental Biology of Fishes* 52: 139–148.
- Vélez-Espino, L.A., and M.A. Koops. 2009. A synthesis of the ecological processes influencing variation in life history and movement patterns of American eel: towards a global assessment. *Reviews in Fish Biology and Fisheries* 20: 163–186.
- Zuur, A.F., R.J. Fryer, I.T. Jolliffe, R. Dekker, and J.J. Beukema. 2003b. Estimating common trends in multivariate time series using dynamic factor analysis. *Environmetrics* 14: 665–685.

_____, I.D. Tuck, and N. Bailey. 2003a. Dynamic factor analysis to estimate common trends in fisheries time series. *Canadian Journal of Fisheries and Aquatic Sciences* 60: 542–552.

Atlantic States Marine Fisheries Commission

American Eel Supplemental Report: Responses to Board and Peer Review Requests



Prepared by the
ASMFC American Eel Stock Assessment Subcommittee

and

Approved by the
ASMFC American Eel Technical Committee
June 27, 2023



Sustainable and Cooperative Management of Atlantic Coastal Fisheries

EXECUTIVE SUMMARY

This report outlines the follow-up work the Stock Assessment Subcommittee (SAS) was tasked with after the 2023 American Eel Benchmark Stock Assessment and Peer Review Reports were presented to the American Eel Management Board (Board) in February 2023. The Peer Review Panel concluded that additional work is needed to establish threshold reference points in the management tool proposed (I_{TARGET}) and that work should be done using a simulation approach with management strategy evaluation (MSE) methods. The Panel also stated that it is more appropriate to consider American eel depleted rather than overfished and likely experiencing overfishing as the SAS suggested. The SAS disagreed with the Panel on these two points. Consistent with the Commission's Technical Support Group Guidance and Benchmark Stock Assessment Process, the Board tasked the SAS with providing justification for deviating from the advice from the peer review advice. In addition to providing justification, the Board also asked the SAS to provide additional analyses to show the influence of individual surveys on the resulting coastwide yellow eel index, consider other reference periods and configurations for I_{TARGET} , and discuss how the habitat model may help assess eel in the future.

To address this task, the SAS completed additional simulation work on the Multivariate Auto-Regressive State-Space (MARSS) index and explored a dynamic factor analysis (DFA) as recommended by the Peer Review Panel. A leave-one-out analysis was completed to evaluate the influence of single surveys on the coastwide trends and each of the resulting indices were analyzed using a regime shift analysis, the basis for determining a reference period for I_{TARGET} . Several I_{TARGET} configurations explored the threshold value used in that analysis in addition to changing the reference period and the multiplier used within the tool, as well as including a survey from South Carolina that was mistakenly omitted during the benchmark. A response was provided for why the I_{TARGET} method can be used without an MSE and how the habitat model will help assessments in the future. Finally, the SAS defined stock status, gave examples of management responses to each stock status, and ultimately conceded that depleted is likely the most appropriate status for American eel.

The conclusions of this report are:

- The simulated MARSS model fits were very similar to the MARSS model fit in the 2023 stock assessment report.
- Overall, omitting a single survey from the MARSS index had little effect on the general coastwide abundance pattern, resulting regimes identified, or the choice of the reference period for I_{TARGET} .
- Omitting all three Hudson River surveys, which is not recommended, shortens the time series and results in the largest change to the MARSS index and identified regimes.
- The application of DFA on the current suite of indices is not ideal due to their differing time series lengths and missing data, but may be promising in the next benchmark.

- Changing the threshold value in I_{TARGET} results in recommended catches from 202,453 – 518,281 lbs, and the choice of configuration should be determined by a Plan Development Team through a management document to reflect the goals of the fishery. Other configurations were explored for the multiplier and reference period, but changing those from the base run is not recommended by the SAS.
- If the assessment and I_{TARGET} are accepted for management, the South Carolina Department of Natural Resources Electrofishing Survey should be included in the analysis.
- Population projections are not possible using the index-based method, I_{TARGET} .
- Data limitations restrict the development of a coastwide habitat model, but advances in modeling may help in the future.
- An MSE could be considered during the next benchmark, but in the meantime the I_{TARGET} tool can be used for management because it was designed for when an assessment model fails.
- Based on the definitions of depleted, overfishing, and overfished, the American eel stock is depleted and coastwide yellow eel catch should be decreased. If reference points are established through the use of I_{TARGET} , overfishing and overfished statuses could be determined.

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1 INTRODUCTION

In February 2023, the American Eel Management Board (Board) was presented the 2023 American Eel Benchmark Stock Assessment and Peer Review Reports (ASMFC 2023). As part of the assessment, a management tool was developed for setting the coastwide catch limit for yellow eels and for determining stock status (I_{TARGET}). The Peer Review Panel found that the stock assessment sufficiently addressed all terms of reference, but recommended additional work to test the robustness of the I_{TARGET} method for setting catch limits using a simulation approach within a management strategy evaluation (MSE) framework before it is used for management.

At the Board meeting, the Stock Assessment Subcommittee (SAS) argued that the simulation work within an MSE framework, as recommended by the Peer Review Panel, may not be a productive exercise for eel. The inability to estimate life history parameters throughout the species' range remains a challenge and data limitations would constrain the usefulness of the MSE exercise. Additionally, the SAS believes that a simulation within an MSE to explore the I_{TARGET} approach is unnecessary since I_{TARGET} has already been simulation-tested and peer-reviewed as part of NEFSC 2020. The methods in NEFSC 2020 are specifically designed for when an assessment model fails, as the delay-difference model has for American eel in its current form (ASMFC 2023). In addition to the disagreement about the usefulness of an MSE, the SAS and Peer Review Panel also provided differing advice on stock status. Consistent with the Commission's Technical Support Group Guidance and Benchmark Stock Assessment Process, the Board tasked the SAS with providing justification for deviating from the advice from the Peer Review Panel the peer review advice and completing some follow-up work to address several of the Peer Review Panel and Board comments.

This report responds to the MSE exercise (Section 10) and the difference in stock status between the SAS and Peer Review Panel (Section 9.4). As requested by the Board, this report also defines a stock status of depleted versus overfished (Section 9), describes how the habitat model could assist in future stock assessments (Section 8), and discusses why the management tool proposed will not be able to make predictions on biomass or abundance increases in response to harvest reductions (Section 6.2).

In addition to those responses, the SAS has completed work to address questions and follow-up tasks from the Peer Review Panel and the Board. For example, the Peer Review Panel suggested iteratively deriving the Multivariate Auto-Regressive State-Space (MARSS) index by subsampling the indices, and the Board expressed concerns about the influence of the Hudson River indices on the overall trend of the coastwide yellow eel index. To address these issues, the SAS conducted simulations to determine how uncertainty in annual indices of abundance influence the final MARSS yellow eel index (Section 2). Additionally, a leave-one-out sensitivity analysis was done where each 1 of the 14 yellow eel indices was dropped and the MARSS index was recalculated (Section 3). The same approach was applied to exclude entire regions like the Hudson River or the Chesapeake Bay indices. Together these analyses show if an individual index or group of indices influences the trends seen in the coastwide yellow eel index. The

results of those sensitivities around the MARSS index were then inputted into the regime shift analysis to determine if changes in the indices resulted in changes in the regimes, and thus the choice of reference period in I_{TARGET} (Section 4), which was another concern the Board expressed during the February meeting. The SAS also expanded a dynamic factor analysis that was initiated during the Peer Review workshop (Section 5). Finally, the SAS explored different threshold values for I_{TARGET} to address the Peer Review comment that more work is needed on the threshold and to give the Board more options (Section 6). Different reference periods and multipliers for I_{TARGET} were also provided as sensitivity runs, as was the inclusion of an additional South Carolina abundance index that was mistakenly left out of the benchmark (Section 7 and Appendix A).

2 MARSS RESAMPLING

The yellow eel fishery-independent surveys have uncertainty associated with their annual indices of abundance. This uncertainty was not included in the MARSS model fitting and the MARSS model was fit to annual point estimates. To explore the effects of this uncertainty on the final MARSS model results, simulations were conducted to determine how uncertainty in annual indices of abundance may influence the final fitted MARSS model and how this may then influence recommended harvest by the I_{TARGET} method.

MARSS simulations were conducted by randomly drawing a value for each fishery-independent survey for each year the survey was conducted from a normal distribution. The mean of the distribution was equal to the point estimate of the survey and the standard deviation was equal to the standard deviation of the point estimate. These randomly chosen values were then \ln transformed prior to fitting the MARSS model. In cases where a randomly chosen value was ≤ 0 , a value of $\ln(0.01)$ was substituted. Fitting of the simulated MARSS models was conducted in the same manner as in the 2023 stock assessment report assuming American eels are one panmictic species with a single underlying population growth rate across all surveys (U model = equal) and similar process errors across all surveys (Q model = diagonal and equal), but unequal observation errors (R model = diagonal and unequal).

Each simulated MARSS model fit was used to calculate a recommended catch of American eels according to the same methods used in the 2023 stock assessment report. The reference period for the MARSS index was 1974 – 1987 with reference period average annual landings equal to 2,747,352 pounds of eel. The target index (I_{TARGET}) was set to 1.25 times the average simulated MARSS index value over the reference period. Finally, the $I_{THRESHOLD}$ value was set to 0.8 time the I_{TARGET} value.

The resulting distribution of simulated MARSS model fits was very similar to the MARSS model fit in the 2023 stock assessment report (Figure 1). There was a high period of abundance from 1974 – 1987 followed by a steep decline in abundance through the early-1990s and another decline after 2010 through the terminal year of 2020.

The corresponding recommended catch from the application of the I_{TARGET} method to the simulated MARSS model fits was also similar to that in the 2023 stock assessment report (Figure

2). Throughout the simulated time series, the recommended catch would have been substantially less than the observed catch except in 2020 when observed catches were at their lowest point, likely as a result of the COVID-19 pandemic. The median simulated recommended catch in the terminal year was 255,285 pounds (95th percentile range: 190,411 – 337,171 pounds).

These simulation results suggest that conclusions about trends in the coastwide population of yellow eels based on the MARSS model and recommended catch of based on the I_{TARGET} method are robust to uncertainty in individual point estimates of relative abundance from fishery-independent surveys.

3 LEAVE-ONE-OUT SENSITIVITY ANALYSIS

It was evident in the 2023 stock assessment report that the trends in the coastwide yellow eel abundance index based on a fitted MARRS model were influenced by the longest time series of fishery-independent surveys. The longest time series came from the Hudson River with the Hudson River Estuary (HRE) monitoring survey being the one that extended furthest back in time (1974). To see plots of the individual yellow eel surveys compared to the resulting MARSS index trend, see ASMFC 2023 Figures 150-163. To further explore the influence of any one survey on the final MARSS model index, a sensitivity analysis was conducted in which each individual survey was omitted from the data one at a time and the MARSS model fit to the remaining surveys. Additional model fits were conducted where the time series was truncated to begin in 1980, omitting all Hudson River surveys, and omitting all Chesapeake Bay surveys. Finally, a MARSS model fit was made to a dataset including only a single survey from each of the geographical regions for American eels defined in the 2012 stock assessment report.

Overall, omitting a single survey had little effect on the general pattern of the MARSS model index (Figure 3 and Figure 4). In all cases except one, the MARSS model index showed the same decline from the mid-1980s through the early 1990s. The exception was the case where all Hudson River surveys were omitted, which showed a dramatic decrease during the 1980s followed by a sharp increase through the 1990s, and then another decrease (Figure 3). With the omission of all Hudson River surveys, the next longest time series was the Delaware River Trawl survey and the early portion of the MARSS model index thus followed patterns in this survey. A commonality among all of these sensitivity analyses was that they all showed a decline near the end of the time period examined (2010 – 2020) with the lowest abundance in the terminal year.

Since there are several indices available in some areas but not others along the Atlantic coast, a sensitivity run was completed where only one index from each region was used. If there were multiple indices in a region, the longest time series was used. The longest time series in each region were: the MA Rainbow Smelt survey (Gulf of Maine), Farmill River Electrofishing survey (Southern New England), HRE Trawl (Hudson), Delaware River Trawl (Delaware Bay/Mid-Atlantic), VIMS Seine (Chesapeake Bay), and SC Rediversion Canal survey (South Atlantic). When a MARSS model was fit to only these six surveys, the large decline in abundance from the mid-1980s through the early-1990s was still evident (Figure 5). However, the lowest abundance

occurred in the early 2000s followed by an increase to the late-2000s and a slight decline from 2010 – 2020.

These sensitivity analyses showed that the MARSS model abundance index can be influenced by the suite of surveys included, and the length of their time series. However, no single survey completely drives the trends in the final abundance index time series. There was concern that the Hudson River surveys were driving the final MARSS model abundance index and the choice of 1974 – 1986 as a reference period with relatively high abundance. The Hudson River is a large system representing a significant portion of the coastwide stock, and to completely exclude the Hudson River from the analysis seems inappropriate. Also, the three independent surveys from the Hudson River showed similar trends in the early portion of the time series suggesting that these trends are not an artifact of observation error in any single survey. The results of this sensitivity analysis suggest that the final MARSS model abundance index is robust to deviations due to any single survey and it appears to be the best index of coastwide abundance of the species along the US Atlantic coast. It is noted in ASMFC 2023 that American eel is regarded as a single, panmictic population and the current assessment is not range wide, i.e., does not include data from Canada, Gulf of Mexico, Caribbean, or elsewhere. Completing a range wide assessment remains as a research recommendation and in the meantime, the data used in ASMFC 2023 represent the best data available for US Atlantic coast management.

4 REGIME SHIFT SENSITIVITY ANALYSIS

A regime shift analysis was completed for each of the yellow eel MARSS indices produced as part of the sensitivity runs in Section 3. Sequential t-test Analysis of Regime Shifts (STARS) was used to identify change points in the time series using the same methods as ASMFC 2023. Briefly, a regime cut-off length of ten years was used, although regimes shorter than ten years may still be detected by the analysis. Huber’s $h=2$ was used for down-weighting outliers and a significance value of $P=0.05$ was used to determine significance. As a reminder, in ASMFC 2023, this analysis determined that the yellow eel abundance index was in a high regime from 1974-1987 (ASMFC 2023 reports the first regime as 1974-1988, but that is an error and it should be 1974-1987), a low regime in 1988-1999, and an even lower regime in 2000-2020. The reference period for I_{TARGET} was 1974-1987 based on this analysis as well as the fact those years seemed to be a stable, if variable, point for both landings and index.

Overall, omitting a single survey had little effect on the general pattern of the MARSS model index (Section 3; Figure 3-Figure 4) and therefore little effect on the regimes identified by STARS (Table 2). Of the 18 sensitivity runs, 13 resulted in the same regimes as the base or different by only one year. Excluding the VIMS Seine Survey, NY HRE, or all the indices from the Chesapeake Bay resulted in regimes that were different from the base by more than one year around the cutoff points, but generally still had similar patterns in the regimes, i.e., a high regime at the beginning of the time series, a lower regime in the middle, and the lowest regime through the terminal year. The two notable differences in the results were when all the indices from the Hudson River were excluded from the MARSS index and for the sensitivity run “Regional Longest Surveys” where the MARSS index was comprised of the longest survey from each region (Section 3; Figure 5). When all the Hudson River indices were dropped, the time

series was shorter (1980-2020) because the indices from that river are the only sources of data before 1980. Without the Hudson River indices, the regimes flipped with 1980-1994 being a low regime and 1995-2020 being a high regime. When the MARSS index is built using only the longest index available from each region, the results indicate four regimes. Like the many of the other sensitivities, the first regime in the beginning of the time series is high and is followed by a low regime, then an even lower regime, but then the last regime increases but is still considered low.

The intent of the sensitivity runs for MARSS was to show the effects each survey had on the resulting abundance index trend for coastwide yellow eel and thus the choice of reference period in I_{TARGET} based on the regime shift analysis. The Board expressed concern that the Hudson River indices were having an undue influence on the resulting coastwide index and were not representative of trends seen outside of the region (e.g., Maryland and Delaware) and therefore it may not be appropriate to use the 1974-1987 high regime as a reference period. As discussed in the leave-one-out analysis (Section 3), these sensitivity runs show that no one index is driving the trends in the coastwide yellow eel index nor the regimes identified by the STARS analysis. Dropping one Hudson River index does not result in a significantly different answer. Dropping all three Hudson River indices results in the largest difference observed in the sensitivity analyses wherein the first regime is considered a low regime (1980-1994) followed by a high regime (1995-2020; Table 2). The only indices available for American eel before 1980 come from the Hudson River and those indices influence the early part of the time series. And yet, the Hudson River is a large system representing a significant portion of the coastwide stock and it is an important source of historical data for the stock. The SAS reiterates that to completely exclude the Hudson River from the analysis is inappropriate for a panmictic population.

5 DYNAMIC FACTOR ANALYSIS

The Peer Review Panel concluded that the index from MARSS (Figure 1) is currently the best available coastwide aggregated index and can be used to indicate stock abundance variations over time, but they also suggested that Dynamic Factor Analysis (DFA) could be used to explore the potential cause of conflicting trends among indices. Dynamic factor analysis is a multivariate time series analysis that can be used to detect common trends in time series (Zuur et al. 2003).

The SAS explored both the full time series (1974-2020) and an abbreviated time series (2006-2019) in the DFA using the 14 yellow eel indices (Table 1). DFA had convergence issues with the full time series and problems fitting the data. The lack of convergence is likely due to the numerous missing values (Holmes et al. 2021) since most indices do not go back to the start year of 1974. There are only 3 years when all 14 surveys are operating: 2010-2012 and 2014. Therefore, an abbreviated time series without missing years of data is not possible. The years of 2006-2019 were selected for the abbreviated time series because most surveys are operating during this time, although there are still several years of missing data.

Both time series (full and abbreviated) identified one trend in the yellow eel abundance data and for both time series, the DFA model converged for one trend and one trend had the lowest AIC value. Therefore, the DFA model indicates there is one trend in the yellow eel data, or conversely, no trend. With that said, both time series lengths tested had a lot of missing data for several years which is not ideal for applying DFA. Using DFA on the yellow eel indices may not be an appropriate application of this method given the amount of data missing from the various yellow eel surveys. The analysis in its current form does not elucidate the influence of the Hudson River surveys on the coastwide MARSS index. If future assessments want to develop the DFA, indices should be developed specifically with that in mind (e.g., indices of the same length with no missing data). The indices developed for the current assessment were to support a coastwide index and modeling approaches used in the assessment which can handle missing data and series of varying lengths.

6 I_{TARGET} CONFIGURATIONS

6.1 Sensitivity Runs

Within the I_{TARGET} method (NEFSC 2020), there are a few values that need to be specified such as a reference period, multiplier, and threshold. The I_{TARGET} value is defined as the average index over the reference period times a multiplier which indicates a level of abundance that management is striving for. The threshold is a portion of the I_{TARGET} value that depends on the goals of the fishery. Inputs into the analysis are the time series of yellow eel catch and the MARSS index of yellow eel abundance. The base run of I_{TARGET} in ASMFC 2023 used a reference period of 1974-1987, a multiplier of 1.25, and a threshold of 0.8. The SAS explored several sensitivities for each of the values that are specified in I_{TARGET} which are described in the following sections.

6.1.1 Threshold Sensitivity Runs

The threshold value in the base run of I_{TARGET} was set at 0.8 in ASMFC 2023 based on NEFSC 2020. Within I_{TARGET} , suggested landings are adjusted up or down depending on how far above or below the three-year average index is from the I_{TARGET} value (I_{TARGET} is the average index from the reference period*1.25 in the base run for eel). If the three-year average index is below the threshold value (e.g., $0.8 * I_{TARGET}$), even larger reductions in catch are suggested. The SAS explored threshold values of 0.5-0.8, in 0.1 intervals, since the overfished threshold of half (0.5) of the target is appropriate in many fisheries (Carruthers et al. 2016) and 0.8 is used by NEFSC 2020. Depending on the threshold used and using the base multiplier of 1.25, the catch advice for 2020 would have varied from 202,453 lbs (threshold= $0.8 * I_{TARGET}$) to 518,281 lbs (threshold= $0.5 * I_{TARGET}$; Table 3; Figure 6). Of the three values to be specified in this method (i.e., reference period, threshold, and multiplier), the SAS suggests that the threshold could be set by the Board to reflect the goals of the fishery, where 0.8 would be more conservative and 0.5 would be less conservative, although still consistent with how other fisheries are managed.

6.1.2 Multiplier Sensitivity Runs

NEFSC (2020) used a multiplier equal to 1.5, indicating that the biomass target should be higher than the average index value during the reference period. Another option is to set the multiplier lower, at 1.0 for example, indicating that the average index over the reference period represented the biomass target for the population. Setting the multiplier to 1.5 is more conservative, while setting it at 1.0 would be less conservative. In the ASMFC 2023 base run, the SAS used a value of 1.25 since the reference period covers a time when the carrying capacity of the stock has declined due to habitat loss; however, this was balanced by the knowledge that fishing, exploitation, and stock depletion have been occurring well before the reference period. Both 1.0 and 1.5 were included as sensitivity runs in ASMFC 2023 and are expanded here to 1.0-1.5 in 0.1 increments. Depending on the multiplier used and using the base threshold value of 0.8, recommended catch in 2020 varied from 140,593 lbs to 316,334 lbs (Table 3; Figure 7). The SAS reiterates that the choice of 1.25 is justified and was supported by the Peer Review Panel.

6.1.3 Reference Period Sensitivity Runs

The reference period should represent a stable or desirable period of abundance within the available time series. The base configuration of I_{TARGET} uses a reference period of 1974-1987, the high abundance period based on the results of the regime analysis. ASMFC 2023 used 1974-1988, which was an error and has been corrected in this report. The SAS and peer review panel both agreed that using the high regime as the reference period is appropriate, although the Board requested sensitivity runs that explored other options. The SAS decided to test the second regime, 1988-1999, as the reference period to eliminate the influence of the Hudson River indices early in the time series and to represent a time when more coastwide surveys were in operation. As a reminder, only indices from the Hudson River are available from 1974-1980 and the region represents three of the four indices available from 1980-1989 (Table 1). Since 1988-1999 is a low regime, the SAS believed that setting the multiplier to 1.5 instead of 1.25 would be justified, so both were tested in addition to setting it the multiplier to 1.0, although that is not recommended. Based on the change in reference period and multiplier, the recommended catch in 2020 ranged from 199,133 lbs to 448,049 lbs (Table 3; Figure 8). When the low regime (1988-1999) is used and the multiplier is adjusted to 1.5, the results are very similar to the base run using the high regime (1974-1987) and a multiplier of 1.25. The reference period should be set at the high regime (1974-1987) since that is the period of more desirable abundance in the time series.

6.1.4 Conclusions

Ultimately, the choice of the I_{TARGET} configuration for the threshold, multiplier, and reference period should be discussed by a Plan Development Team if the Board accepts the 2023 stock assessment for American eel and initiates a management document. The sensitivity analyses included in this report explore several options. The majority of the SAS continue to support a reference period of 1974-1987 and justification has been given for a 1.25 multiplier (ASMFC 2023), but ultimately the choices in configuration should reflect the management goals of the Board for this fishery, particularly for the threshold value (0.5-0.8).

6.2 Can I_{TARGET} make predictions on abundance increases in response to harvest reductions?

Survey or index-based methods have very limited or no ability to provide population-wide projections of either biomass or abundance. Surveys or indices only track a population's abundance and biomass across time, and index-based methods only compare those points in time with historical values. These methods generally do not include important population parameters, such as recruitment, intrinsic growth, mortality, or individual growth. While this allows them to be very useful in data-limited situations, they cannot be generally used to provide forecasts or projections under differing harvest scenarios. In contrast, model-based approaches can and do often provide such projections and allow for harvest scenario testing but require much more data and information than is currently available for American eels.

7 SOUTH CAROLINA INDEX INCLUSION

After reviewing a draft of the 2023 American Eel Benchmark Stock Assessment and Peer Review Report (ASMFC 2023) in the February 2023 meeting materials, South Carolina Department of Natural Resources (SC DNR) contacted ASMFC staff in April to inquire about the omission of the SC DNR Electrofishing Survey as an index of relative yellow eel abundance. After investigating this issue, it appears that this survey data was provided for consideration to the SAS but got deleted from the state folder on the data sharing site, thus it was not considered by the index group during the assessment. SC DNR noted that it met the criteria developed by the SAS in ASMFC 2023 for fishery-independent indices. Therefore, to correct this error, the SAS evaluated the SC DNR Electrofishing Survey data, calculated a standardized index from the survey, and then re-ran the MARSS index, regime shift analysis, and I_{TARGET} base run to include SC DNR Electrofishing Survey in addition to the 14 yellow eel surveys already used. The recommended harvest when SC DNR Electrofishing Survey was included was similar throughout the time series to the original base run. The sensitivity runs that included SC DNR Electrofishing Survey were reviewed and the TC and SAS agree that if the assessment is accepted for management use and options for I_{TARGET} are developed by a Plan Development Team, the SC DNR Electrofishing Survey should be included as an index of relative abundance.

For details about the SC DNR Electrofishing Survey, the index standardization, and results of the sensitivity runs, see Appendix A.

8 HABITAT MODEL

From the Peer Review Report:

Habitat-based modeling: Habitat modeling consists of using GIS analyses to derive statistical relationships between eel abundance and habitat descriptors of the river network. This type of approach has recently been used in other parts of the world for similar species and delivered promising results (Beentjes et al. 2016; Hoyle 2016; ICES 2021; Briand et al. 2022; Mateo et al. 2022). The American eel work supported by the SAS is still in progress and currently consists of a pilot study in the data-rich Chesapeake region. Therefore, it is not possible to draw definitive conclusions on the relevance of results and on transferability of the approach to data-poor regions. It will likely depend on the availability and interoperability of both fish data and habitat

data. The Review Panel considers habitat modeling an interesting option to explore in future assessments.

The peer reviewers reference a desire to see more exploration of a habitat-based approach for informing the American eel stock assessment, and rightly cite work that has been conducted on eel congeners in other parts of the world (New Zealand: Beentjes et al. 2016, Hoyle 2016; France and Europe: Briand et al. 2022, Mateo 2022). In the US, several studies have been conducted on American eel habitat relationships (Smogor 1995; Geer 2003; Wiley et al. 2004; Woods and McGarvey 2018), and while local-scale factors are yet to be definitive on habitat requirements for eel, restrictions on access to habitats, particularly fragmentation of river systems by dams is well established as is the re-occupation of habitats after dam removal (Hitt et al. 2012). Ocean connectivity was also seen to be of primary importance for predicting occupancy in US river systems in a pilot analysis conducted by Young in parallel to the 2023 American eel benchmark stock assessment in the Chesapeake Bay region (*unpublished*). Recent efforts on American shad (Zydlewski et al. 2021) point the way for coupling habitat area and habitat fragmentation to a population model to estimate current and historic stocks by river system. While this analysis is promising, estimating habitat size and availability in the much larger area occupied by American eel, as well as the difficulty in estimating population parameters for all life phases of this panmictic catadromous species, is daunting and is highly reliant on the availability of georeferenced fishery-independent and -dependent biological response data in inland rivers, lakes, estuaries, and oceanic habitats. However, recent advances in geospatial predictor datasets may allow better quantification of river, stream, and lake habitat area, volume, and connectivity over broad areas using national-scale hydrography data sets (McManamay et al. 2018; McManamay and DeRolph 2019; King et al. 2021). Application of egg-per-recruit models as in Sweka et al. (2014) may allow for successfully linking escapement of inland habitats past dams to reproductive output. Continued development of these approaches is of interest to research and management partners in Canada and is being further developed as part of the ICES Workgroup on American eel (ICES 2023).

9 STOCK STATUS

9.1 Stock Status Definitions

The ASMFC uses the following definitions for stock status determinations:

Depleted - Reflects low levels of biomass or abundance, though it is uncertain if fishing mortality or other factors such as habitat loss or environmental changes are the primary cause for reduced stock size.

Overfished - Occurs when stock biomass or abundance falls below the threshold established by the Fishery Management Plan (FMP), impacting the stock's reproductive capacity to replace fish removed through harvest, and that decline is driven primarily by fishing mortality.

Overfishing – Occurs when the rate of fishing (i.e., exploitation or fishing mortality) exceeds the threshold established in the FMP, negatively impacting the stock’s reproductive capacity to replace fish removed through harvest.

Determining stock status means estimating one or more biological characteristics of a fishery (e.g., abundance or biomass) and comparing the estimated values to reference values that reflect a desirable condition. To do so typically requires the development of a statistical model or method to estimate biomass, fishing mortality, and biologically-based indicators or reference values. When a stock is found to be overfished or experiencing overfishing, action should be taken to reduce fishing pressure and/or increase biomass. A “depleted” stock status is often used by the ASMFC when a statistical model and reference points cannot be developed due to data limitations but trend analyses or other data-poor methods indicate that the stock is below historic levels. Within the ASMFC framework, the response to a stock status determination is typically outlined in the species’ FMP and action is subsequently taken by the Board. The ASMFC is not subject to the Magnuson-Stevens Fishery Conservation and Management Act (MSA), which governs marine fisheries management in US *federal* waters and requires a rebuilding plan when a fishery is found to be overfished.

9.2 Examples of ASMFC Management Response to an Overfished and/or Overfishing Status

The 2018 benchmark stock assessment for striped bass indicated the stock was overfished and experiencing overfishing relative to the reference points defined in the assessment. To address the overfished status, the Management Board approved an Amendment to the striped bass FMP to rebuild the spawning stock biomass to the target level in a timeframe not to exceed 10 years, no later than 2029 (ASMFC 2022). Based on the 2021 management track stock assessment for bluefish conducted by the Northeast Fisheries Science Center, the stock was overfished, but not experiencing overfishing. In response, the Management Board approved an Amendment to the bluefish FMP that initiated a seven-year rebuilding plan while revising its allocation and other FMP objectives (ASMFC 2021a). The 2017 assessment for tautog found that three of the four regional stocks were overfished and overfishing was occurring in two of the four regions. In response, an Amendment to the tautog FMP required the two regions that were overfished and experiencing overfishing to reduce catch by a specific percentage (which varied by region) and adjusted regulations in the remaining two regions (ASMFC 2017a).

9.3 Examples of ASMFC Management Responses to a Depleted Status

Unlike the clear definitions and expected response to an overfished or overfishing determination, a depleted stock status determination does not come with a clear path forward for managing the stock. The ASMFC has responded differently to depleted stock statuses in the past. For example, the northern shrimp stock is considered depleted relative to a stable period and a moratorium has been in place since the 2014 season (ASMFC 2021b). Similarly, Atlantic sturgeon was found to be depleted compared to historical levels when it was assessed in 2017 (ASMFC 2017b) and the moratorium implemented in 1998 was maintained. Recognizing the depleted status of river herring in many rivers along the Atlantic coast, management responded by requiring states with fisheries to develop sustainable fishery management plans (SFMPs),

which are reviewed by the Technical Committee and approved by the Board, in order to maintain commercial and recreational fisheries (ASMFC 2009). States or jurisdictions without SFMPs are required to prohibit commercial and recreational harvest. The same management response was implemented for American shad when the 2007 stock assessment found many populations along the coast to be near all-time lows (ASMFC 2010).

American eel was found to be depleted and at or near historically low levels in 2012. In response, management established stricter measures for the commercial and recreational fisheries, implemented monitoring requirements, and set a coastwide yellow eel quota, which was an average of 1998-2010 landings (907,671 lbs; ASMFC 2013). At that time, the American Eel TC recommended a coastwide cap on yellow eel landings with a 12% reduction in the catch (798,750 lbs; ASMFC 2013). In 2018, the Board increased the cap to 916,473 lbs to account for revised landings values during the 1998-2010 years (ASMFC 2018) even as the 2017 stock assessment update found the stock to be at lower levels than the 2012 benchmark and the TC recommended no increases in landings at any stage.

9.4 SAS Justification of Stock Status

In the assessment report (ASMFC 2023), the SAS determined that the American eel stock was overfished and has likely been experiencing overfishing in the last few decades based on the results of the index-based method used. While this method does not lend itself well to defining exploitation-based reference points, the results of I_{TARGET} and other analyses in the assessment indicated a decline in the stock. Therefore, the SAS was comfortable with a determination of overfished and made the recommendation that yellow eel catch should be lower.

The Peer Review Panel stated in their report (ASFMC 2023) that while the modeling approaches used in the assessment were appropriate, they were uncomfortable using the overfished terminology because of the uncertainty in the methods. The Panel stated that the analyses in the assessment all showed a decline in the stock and concluded that the qualitative term 'depleted' is more appropriate.

Recognizing that the SAS did not use a traditional method to determine an overfished status and that factors other than fishing likely contribute to the decline in the stock, the SAS acknowledges that a stock status of depleted is appropriate. And yet, with each stock assessment (ASMFC 2012, 2017, 2023), the methods used indicate lower and lower coastwide yellow eel abundance despite the coastwide catch having been maintained at roughly the same level, on average, since the mid-1990s with the exception of the COVID years. Therefore, the SAS believes fishing is having an effect on the trends and that yellow eel fishing should be decreased coastwide, but concedes that the status of the stock is likely influenced by a myriad of factors other than fishing. If the Board accepts the 2023 stock assessment and management tool and initiates a management document using I_{TARGET} , reference points would be established and the stock could be considered using overfished and overfishing definitions in the future.

10 RESPONSE TO MSE

During the review, several Panel members expressed interest in using management strategy evaluation (MSE) to help provide insights and to test the robustness of the I_{TARGET} methods for eels. As outlined by the Panel, a simulation could be constructed as was done for the European eel (Lambert 2011) using plausible virtual population trajectories. Simulation testing could then be conducted to examine sensitivities around assumptions of removals outside the US, the relative importance of coastal versus freshwater fractions of populations, stock-recruitment relationship, catch levels, and other factors. While such an examination is possible, it is likely unfeasible, given the timeframe and resources available currently.

Building a plausible simulation requires underlying knowledge of important population parameters such as recruitment, natural mortality, or intrinsic growth. While rough approximations could be made based on the assumed life history of the American eel, experience has shown that simulations and their results tend to be very sensitive to those assumed parameters. A model-based rather than index-based approach would have been more fruitful if the SAS had this level of information. Building such a simulation, choosing the appropriate parameters and sensitivities, and examining the output would require extensive analysis and vetting through a new peer review. Additionally, stakeholder involvement could both enhance and slow this process considerably. While the suggestion to conduct an MSE may be appropriate as a long-term research and modeling objective, such an endeavor would require years of work and more resources than the SAS currently has available.

It should also be noted that extensive simulation testing across various life-history strategies has already been conducted for the I_{TARGET} and other index-based methods; both worldwide (Carruthers 2015) and in the Northeast (NEFSC 2020). While eels may have a different life history from the small pelagic or groundfish species tested in NEFSC 2020, those differences are the very same issues that make building a plausible simulation so challenging.

Given the above reasons, the SAS recommends that a full or partial MSE be considered as a future research objective, perhaps during the next benchmark peer review. In the intermediate time frame, the SAS will incorporate some of the Panel's suggestions to help illustrate the potential uncertainties inherent in the I_{TARGET} approach.

11 CONCLUSIONS

At the February 2023 meeting, the Board tasked the SAS with completing some additional sensitivity analyses and simulation work around the yellow eel indices, providing more options within the proposed management tool, determining stock status in response to the Peer Review Panel's report, and explaining why an MSE is not necessary for using I_{TARGET} for management and how the habitat model could help assessments in the future. The follow-up work exploring the yellow eel indices indicated that no single survey was driving the trends in the final yellow eel abundance index (Section 3 and 4). The three indices from the Hudson River did influence the beginning of the time series since those surveys are the longest time series available for eel and are the only surveys available prior to 1980 and represent three of the four surveys available prior to 1989 (Table 1). The SAS does not think it is appropriate to drop the

entire region from the analysis since the Hudson River is a large system representing a significant portion of the coastwide stock, and likely a large portion of the available biomass. The results of the index simulations (Section 2) and leave-one-out sensitivity analyses (Section 3) show that the coastwide yellow eel MARSS index is robust to deviations due to any single survey and is the best index of coastwide abundance currently.

Several additional options were explored in this report for the proposed management tool, I_{TARGET} (Section 6.1). The resulting recommended harvest varies depending on the specifications made to three values in the tool: the reference period, threshold, and multiplier. The decisions made for each of these values should be based on the goals of the fishery. Throughout the sensitivity runs, the SAS reiterates the choice of 1974-1987 as the reference period and 1.25 as the multiplier, although other options were presented in Section 6.1. The choice of the threshold value between 0.5 and 0.8 should be chosen to reflect the goals of the fishery where 0.8 is more conservative and 0.5 is less conservative but still justifiable for managing fisheries. And finally, in Section 6.2, the SAS provided a discussion on why the index-based method cannot make predictions on abundance in response to harvest reductions.

In ASMFC 2023, the SAS concluded that the American eel stock is overfished, likely experiencing overfishing. The Peer Review Panel stated that a stock status of depleted is more appropriate for eel. To address this disagreement, the SAS provided definitions of each of those statuses in Section 9.1. Given that American eel is likely in a depleted state due to factors such as habitat loss, low water quality in many river systems, the swim bladder parasite, limited upstream and downstream passage, and other environmental factors, the SAS agrees with the Peer Review Panel that the stock is depleted. The majority of the SAS thinks that continued fishing pressure on a depleted stock is likely contributing to the continued decline in abundance seen over several assessments (ASMFC 2012, 2017, 2023). Additionally, the management response to a depleted status for American eel was compared to other depleted species such as northern shrimp, Atlantic sturgeon, and river herring in Section 9.3.

The SAS recommends that a full or partial MSE be considered as a future research objective, but it is not necessary at this time for using I_{TARGET} to manage the fishery (Section 10). I_{TARGET} has already been simulation tested for various life-history strategies (Carruthers 2015; NEFSC 2020) and it is currently a tool for managing a fishery when the stock assessment model has failed, as it has for American eel. To address some of the Peer Review comments, some simulation work was done for the yellow eel index in Section 2. To develop a plausible full simulation model for American eel, knowledge of parameters such as recruitment, natural mortality, or growth would be needed and those are not available for coastwide American eel at this time. While the suggestion to conduct an MSE may be appropriate as a long-term research and modeling objective, such an endeavor would require years of work and more resources than the SAS has available currently.

In Section 7 (and Appendix A), the SAS noted that a survey from South Carolina was mistakenly not considered during the benchmark. Once this error was pointed out in April, the SAS reconsidered the data, developed an index of relative yellow eel abundance, and re-ran the

MARSS, regime shift analysis, and I_{TARGET} to include it. The SAS and TC are recommending that if the assessment and I_{TARGET} are used for management, the additional South Carolina index should be included since it represents the best available data.

In Section 8, the SAS described the application of habitat models in other parts of the world and a similar application in the US for American shad. At this time, the data is limited for developing a comprehensive habitat model to couple with a population model for American eel but modeling advances in the future may make it possible.

In conclusion, the simulation and sensitivity analyses show that the coastwide yellow eel index is robust to the inclusion or exclusion of individual indices. Future research should consider both habitat models and an MSE. In the meantime, the Board can consider using I_{TARGET} to set a coastwide catch. The choice of the I_{TARGET} configuration for the threshold, multiplier, and reference period should be discussed by a Plan Development Team if the Board accepts the 2023 stock assessment for American eel and initiates a management document. The sensitivity analyses done in this report explore several options. The majority of the SAS continues to support a reference period of 1974-1987 and justification has been given for a 1.25 multiplier (ASMFC 2023), but ultimately the choices in configuration should reflect the management goals of the Board for this fishery, particularly for the threshold value (0.5-0.8). It is this threshold value which is most uncertain in the opinion of the SAS, and thus the best parameter to vary when examining trade-offs and risk. The stock is at or near historically low levels due to a combination of historical overfishing, habitat loss, food web alterations, predation, turbine mortality, environmental changes, toxins and contaminants, disease, and potentially continued fishing pressure. American eel's stock status was depleted in the 2012 benchmark stock assessment and each subsequent re-assessment (ASMFC 2017, 2023) has found yellow eel abundance levels to be lower than the previous assessment. The American eel stock remains depleted and in need of management action.

12 REFERENCES

- ASMFC (Atlantic States Marine Fisheries Commission). 2009. Amendment 2 to the Interstate Fishery Management Plan for Shad and River Herring. Arlington, VA.
- ASMFC. 2010. Amendment 3 to the Interstate Fishery Management Plan for Shad and River Herring. Arlington, VA.
- ASMFC. 2013. Addendum III to the Fishery Management Plan for American eel. Arlington VA.
- ASMFC. 2017a. Tautog Amendment 1. Arlington VA.
- ASMFC. 2017b. Atlantic Sturgeon Benchmark Stock Assessment and Peer Review Report. Arlington, VA.
- ASMFC. 2018. Addendum V to the Fishery Management Plan for American eel. Arlington VA.
- ASMFC. 2021a. Amendment 2 to the Interstate FMP for Bluefish. Arlington VA.
- ASMFC. 2021b. Northern Shrimp Stock Assessment Update. Arlington VA.
- ASMFC. 2022. Amendment 7 to the Interstate FMP for Atlantic Striped Bass. Arlington, VA.
- ASMFC. 2023. American Eel Benchmark Stock Assessment and Peer Review Reports. Arlington, VA.
- Beentjes, M.P., J. Sykes, and S. Crow. 2016. GIS mapping of the longfin eel commercial fishery throughout New Zealand, and estimates of longfin habitat and proportion fished. New Zealand Fisheries Assessment Report 2016/32, New Zealand Fisheries Assessment Report 2016/32.
- Briand, C., M. Maria, H. Drouineau, K. Maria, D. Estibaliz, and B. Laurent. 2022. Eel Density Analysis (EDA 2.3). Escapement of silver eels (*Anguilla anguilla*) from French, Spanish and Portuguese rivers. GT4 - deliverable E4.1.1. HAL CCSD. https://hal.archives-ouvertes.fr/hal-03590458/file/Briand_et_al_2022_EDA_SUDOANG_report.pdf
- Geer, P.J. 2003. Distribution, relative abundance, and habitat use of American eel *Anguilla rostrata* in the Virginia portion of the Chesapeake Bay. *American Fisheries Society Symposium* 2003(33):101-115.
- Hitt, N.P., S. Eyler, and J.E.B Wofford. 2012. Dam removal increases American eel abundance in distant headwater streams. *Transactions of the American Fisheries Society*, 141(5), 1171–1179. <https://doi.org/10.1080/00028487.2012.675918>
- Holmes, E.E., M.D. Scheuerell, and E.J. Ward. 2021. Applied time series analysis for fisheries and environmental data. Northwest Fisheries Science Center, NOAA, Seattle, WA, USA.
- Hoyle, S.D. 2016. Feasibility of longfin eel stock assessment. New Zealand Fisheries Assessment Report 2016/29, New Zealand Fisheries Assessment Report 2016/29.
- ICES. 2023. Working Group on American Eel (WGAMEEL; outputs from 2022 meeting). ICES Scientific Reports. 5:29. 44 pp. <https://doi.org/10.17895/ices.pub.21762842>
- King, K.B.S., Q. Wang, L.K. Rodriguez, and K.S. Cheruvellil. 2021. Lake networks and connectivity metrics for the conterminous U.S. (LAGOS-US NETWORKS v1). *Limnology And Oceanography Letters* 6(5): 293–307. <https://doi.org/10.1002/lol2.10204>
- Mateo, M., E. Díaz, L. Beaulaton, H. Drouineau, C. Antunes, E. Amilhat, A. Bardonnnet, et al. 2022. Evaluating Silver Eel Escapement at a Large-Scale Using Eel Density Analysis (EDA). In *Biology and Life Sciences Forum*. <https://hal.archives-ouvertes.fr/hal-03699085> (Accessed 24 June 2022).
- McManamay, R.A., M.J. Troia, C.R. DeRolph, A.O. Sheldon, A.R. Barnett, S.C. Kao, and M.G. Anderson. 2018. A stream classification system to explore the physical habitat diversity

- and anthropogenic impacts in riverscapes of the eastern United States. PLoS ONE 13(6).
<https://doi.org/10.1371/journal.pone.0198439>
- McManamay, R.A., and C.R. Derolph. 2019. Data descriptor: A stream classification system for the conterminous United States. Scientific Data 6.
<https://doi.org/10.1038/sdata.2019.17>
- NEFSC (Northeast Fisheries Science Center). 2020. Research Track Assessment for Index-Based Methods and Control Rules. Woods Hole, MA. 59 p.
- Smogor, R.A., P.L. Angermeier, and C.K. Gaylord. 1995. Distribution and abundance of American eels in Virginia streams: Tests of null models across spatial scales. Transactions of the American Fisheries Society, 124(6):789–803.
- Sweka, J.A., S. Eyler, and M.J. Millard. 2014. An Egg-Per-Recruit Model to Evaluate the Effects of Upstream Transport and Downstream Passage Mortality of American Eel in the Susquehanna River. North American Journal of Fisheries Management 34(4): 764–773.
<https://doi.org/10.1080/02755947.2014.910578>
- Wiley, D.J., R.P. Morgan, R.H. Hilderbrand, R.L. Raesly, and D.L. Shumway. 2004. Relations between Physical Habitat and American Eel Abundance in Five River Basins in Maryland. Transactions of the American Fisheries Society 133(3): 515–526.
<https://doi.org/10.1577/T02-162.1>
- Woods, T., and D.J. Mcgarvey. 2018. Assessing the relative influences of abiotic and biotic factors on American eel *Anguilla rostrata* distribution using hydrologic, physical habitat, and functional trait data. Ecography, 41(12): 2067–2079.
<https://doi.org/10.1111/ecog.03782>
- Zuur, A.F., I.D. Tuck, and N. Bailey. 2003. Dynamic factor analysis to estimate common trends in fisheries time series. Canadian journal of fisheries and aquatic sciences, 60(5), 542-552.
- Zydlewski, J., D.S. Stich, S. Roy, M. Bailey, T. Sheehan, and K. Sprankle. 2021. What Have We Lost? Modeling Dam Impacts on American Shad Populations Through Their Native Range. Frontiers in Marine Science 8. <https://doi.org/10.3389/fmars.2021.734213>

13 TABLES

Table 1. The 14 yellow eel indices used in the coastwide MARSS index. Trends are the results from the Mann-Kendall test indicating the direction of the trend (P -value $< \alpha$; $\alpha = 0.05$). NS = not significant.

| State | Site | Gear | Model | Years of Survey | Trend |
|-------|-------------------------------|--------------------------------|---|----------------------------|-------|
| NH | Rainbow Smelt Fyke Net Survey | Fyke Net | NB GLM year+temp+river | 2010-2020 | NS |
| MA | Rainbow Smelt Fyke Net Survey | Fyke Net | NB GLM year+temp+offset(effort) | 2004-2019 | NS |
| CT | Farmill River | Electrofishing | Population estimate | 2001-2012, 2014 | NS |
| CT | Eightmile River | Electrofishing | Population estimate | 2001-2003, 2005-2017, 2019 | NS |
| NY | HRE Monitoring | Epibenthic sled & tucker trawl | Quasi-poisson GLM year+temp+river mile+water volume | 1974-2017 | ↓ |
| NY | Hudson Juvenile Alosine | Beach Seine | NB GLM year+station+temp | 1985-2019 | ↓ |
| NY | Hudson Juv Striped Bass | Beach Seine | NB GLM year+station+temp | 1980-2019 | ↓ |
| NJ | Delaware River Seine | Seine | NB GLM year+station+temp | 1998-2019 | NS |
| DE | Delaware Juvenile Trawl | Trawl | Nominal index with delta distribution | 1980-2019 | NS |
| PA | Delaware River Area 6 | Electrofishing | Nominal | 2005-2020 | ↓ |
| MD | Sassafras River | Pot | Nominal | 2006-2019 | ↑ |
| VA | VIMS Trawl Survey | Trawl | NB GLM year+salinity+offset(effort) | 1996-2019 | NS |
| VA | VIMS Seine Survey | Seine | NB GLM year+salinity | 1989-2019 | ↑ |
| SC | Rediversion canal | Aluminum ladder | Quasi-poisson GLM year+temp+gear condition | 2003, 2005-2007, 2009-2020 | NS |

Table 2. Regimes identified from the leave-one-out sensitivity analysis on the MARSS yellow eel index. Regimes were identified as high (green), middle (yellow), low (red), or very low (dark red) by the analysis. Sensitivity runs with the same regimes as the base run are indicated in the table, as are sensitivity runs with regimes similar to the base run (plus or minus one year).

| Sensitivity Run | Regimes | Same as Base | Same or Similar to Base +/- one year |
|---|--|--------------|--------------------------------------|
| Base | 1974-1987, 1988-1999, 2000-2020 | X | X |
| 1980 Cutoff | 1980-1986, 1987-1998, 1999-2020 | | X |
| Drop MD Sassafras | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop VIMS Seine | 1974-1987, 1988-1996, 1997-2020 | | |
| Drop VIMS Trawl | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop PA Area 6 | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop NJ Delaware River Seine | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop DE Trawl | 1974-1988, 1989-2020 | | X* |
| Drop MA Rainbow Smelt | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop NH Rainbow Smelt | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop HRE | 1980-1985, 1986-2000, 2001-2020 | | |
| Drop Hudson River Alosine | 1974-1986, 1987-1998, 1999-2020 | | X |
| Drop Hudson Striped Bass Seine | 1974-1986, 1987-1998, 1999-2020 | | X |
| Drop CT Eightmile | 1974-1987, 1988-2000, 2001-2020 | | X |
| Drop CT Farmill | 1974-1986, 1987-1998, 1999-2020 | | X |
| Drop SC Redivision | 1974-1987, 1988-1999, 2000-2020 | X | X |
| Drop All Hudson Indices | 1980-1994, 1995-2020 | | |
| Drop All CB Indices | 1974-1987, 1988-1996, 1997-2020 | | |
| Include Longest Survey from Each Region | 1974-1985, 1986-1997, 1998-2007, 2008-2020 | | |

*collapses last two regimes into one

Table 3. Resulting recommended catch for 2020 based on the sensitivity analysis around the threshold and multiplier values for the I_{TARGET} method as well as the reference period. Values used in the base run of I_{TARGET} in ASMFC 2023 are indicated in the table.

| Reference Period | Multiplier Value | Threshold Value | Recommended 2020 Catch (lbs) |
|-------------------------|-------------------------|------------------------|-------------------------------------|
| 1974-1987 (Base) | 1.25 (Base) | 0.5 | 518,281 |
| 1974-1987 (Base) | 1.25 (Base) | 0.6 | 359,917 |
| 1974-1987 (Base) | 1.25 (Base) | 0.7 | 264,429 |
| 1974-1987 (Base) | 1.25 (Base) | 0.8 (Base) | 202,453 |
| 1974-1987 (Base) | 1.00 | 0.8 (Base) | 316,334 |
| 1974-1987 (Base) | 1.10 | 0.8 (Base) | 261,433 |
| 1974-1987 (Base) | 1.20 | 0.8 (Base) | 219,676 |
| 1974-1987 (Base) | 1.30 | 0.8 (Base) | 187,180 |
| 1974-1987 (Base) | 1.40 | 0.8 (Base) | 161,395 |
| 1974-1987 (Base) | 1.50 | 0.8 (Base) | 140,593 |
| 1988-1999 | 1.00 | 0.8 (Base) | 448,049 |
| 1988-1999 | 1.25 (Base) | 0.8 (Base) | 286,751 |
| 1988-1999 | 1.50 | 0.8 (Base) | 199,133 |

14 FIGURES

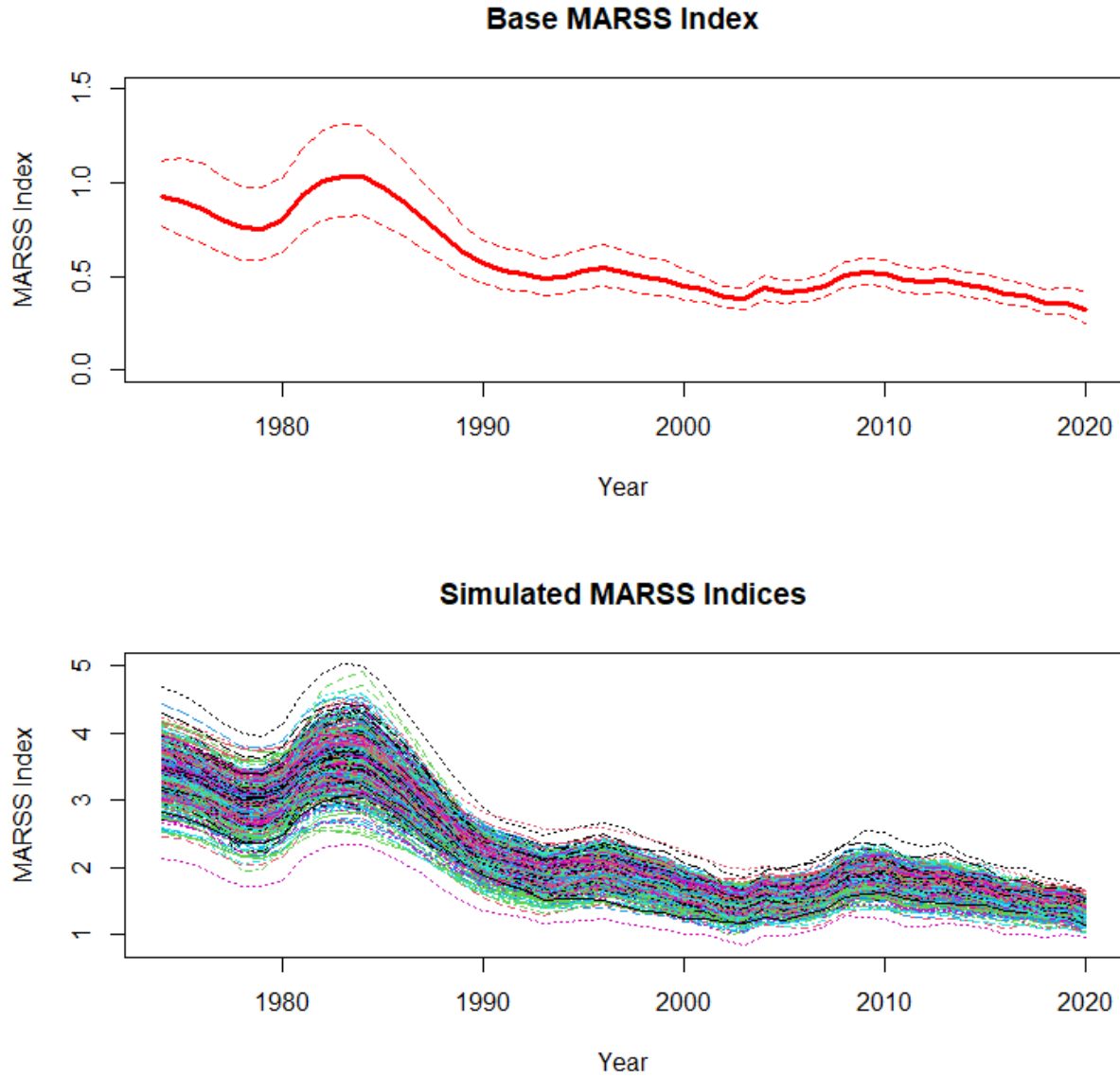


Figure 1. Base MARSS model abundance index (top) and simulated MARSS model abundance index (bottom) showing the results of 500 simulations. Scales on the y-axis differ simply because of the order of individual surveys input to the MARSS model fit. (The MARSS package scales the resulting index to the first survey entered into the model.)

Observed catch versus Recommended Catch

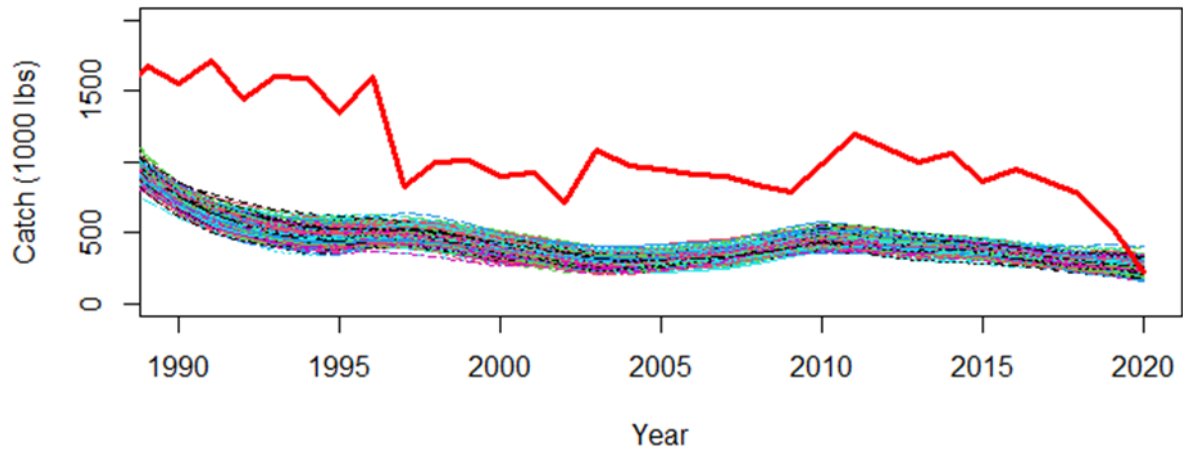


Figure 2. Comparison of 500 simulations of the recommended catch of American eels from the base run of the I_{TARGET} method to the observed landings. The median recommended catch in 2020 was 255,285 lbs (95th percentile range: 190,411 – 337,171 lbs).

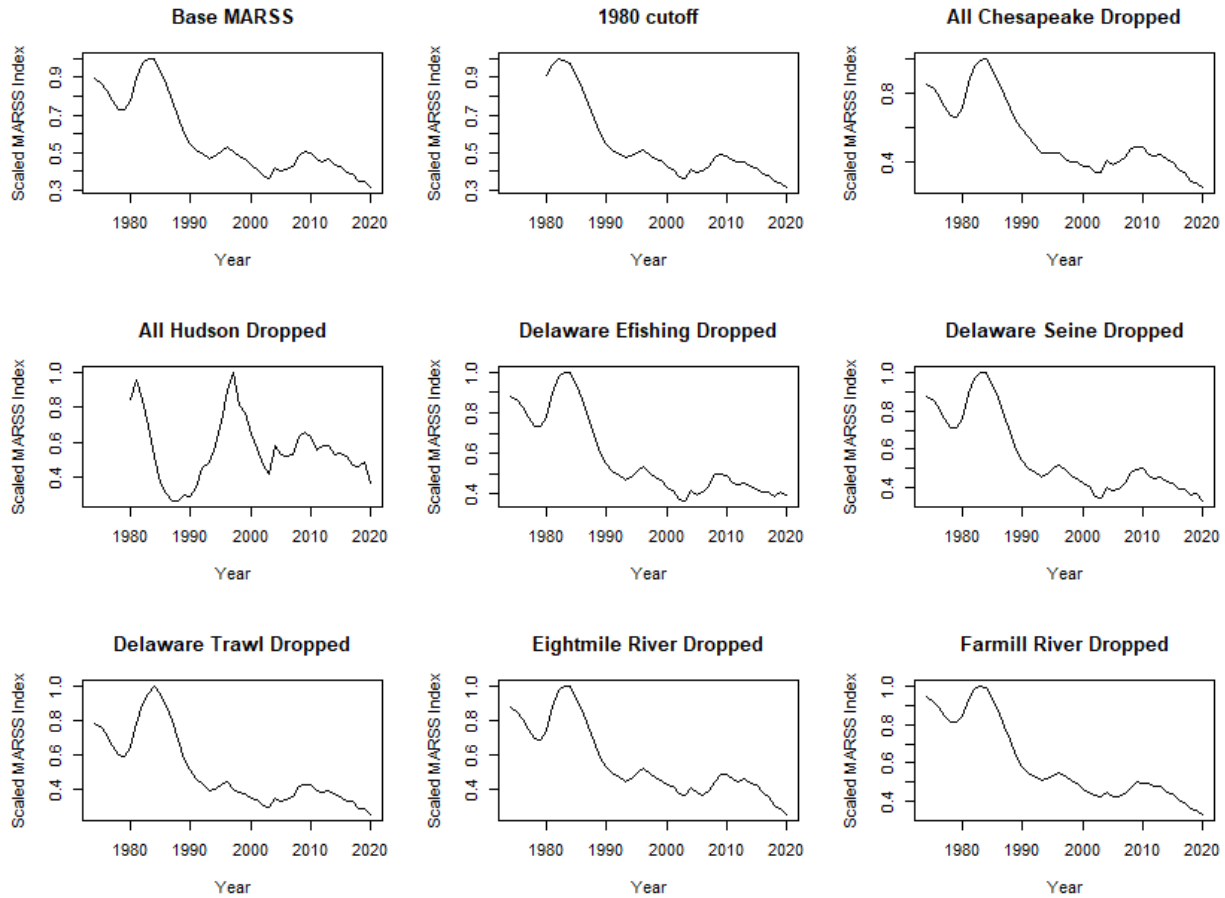


Figure 3. Results of the leave-one-out sensitivity analysis. The upper left panel shows the base MARSS model abundance index with all 14 yellow eel surveys included. Other panels indicate which survey was omitted from the model fit. Indices have been scaled to a maximum of 1.0 to facilitate comparisons.

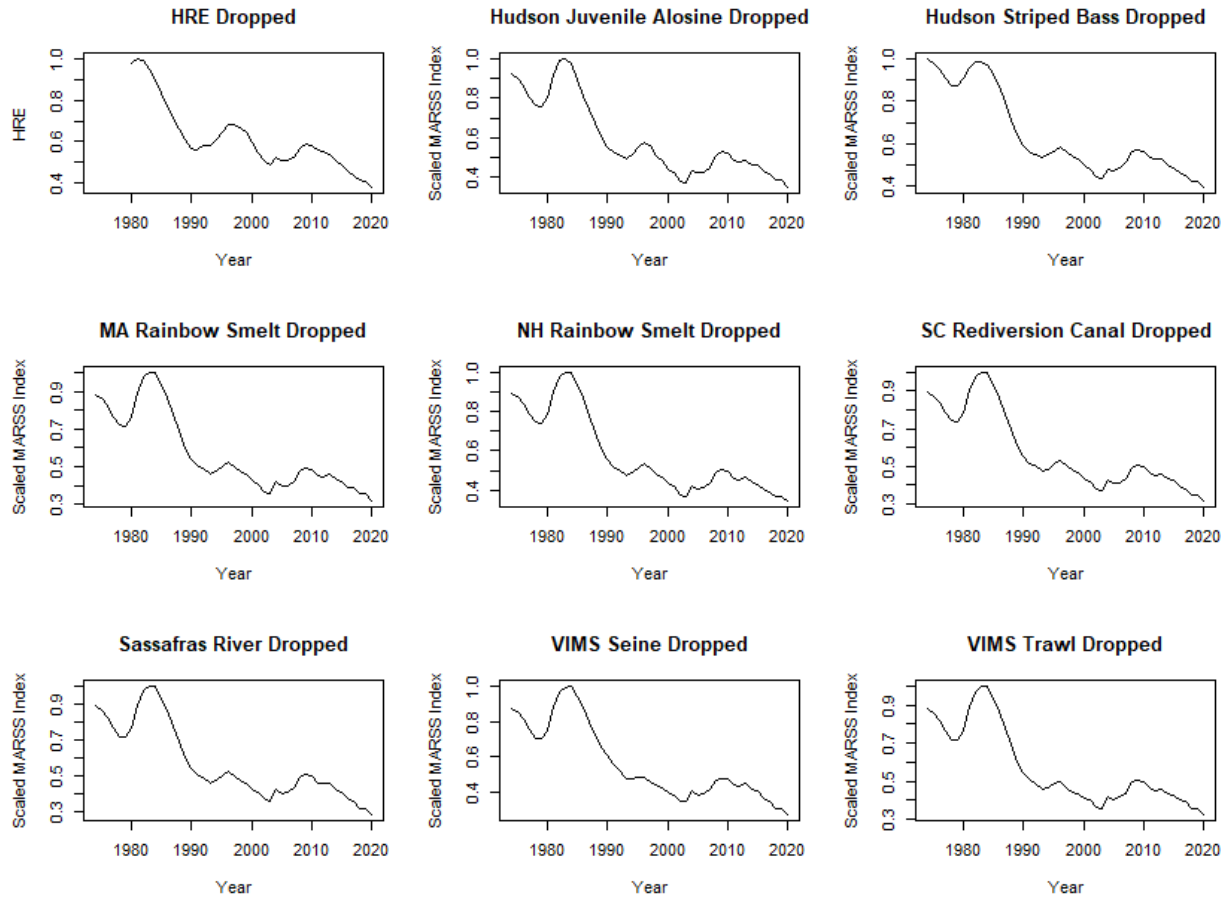


Figure 4. Results of the leave-one-out sensitivity analysis. Panels indicate which survey was omitted from the model fit. These can be compared to the upper left panel in Figure 3 showing the base MARSS model abundance index with all 14 yellow eel surveys included. Indices have been scaled to a maximum of 1.0 to facilitate comparisons.

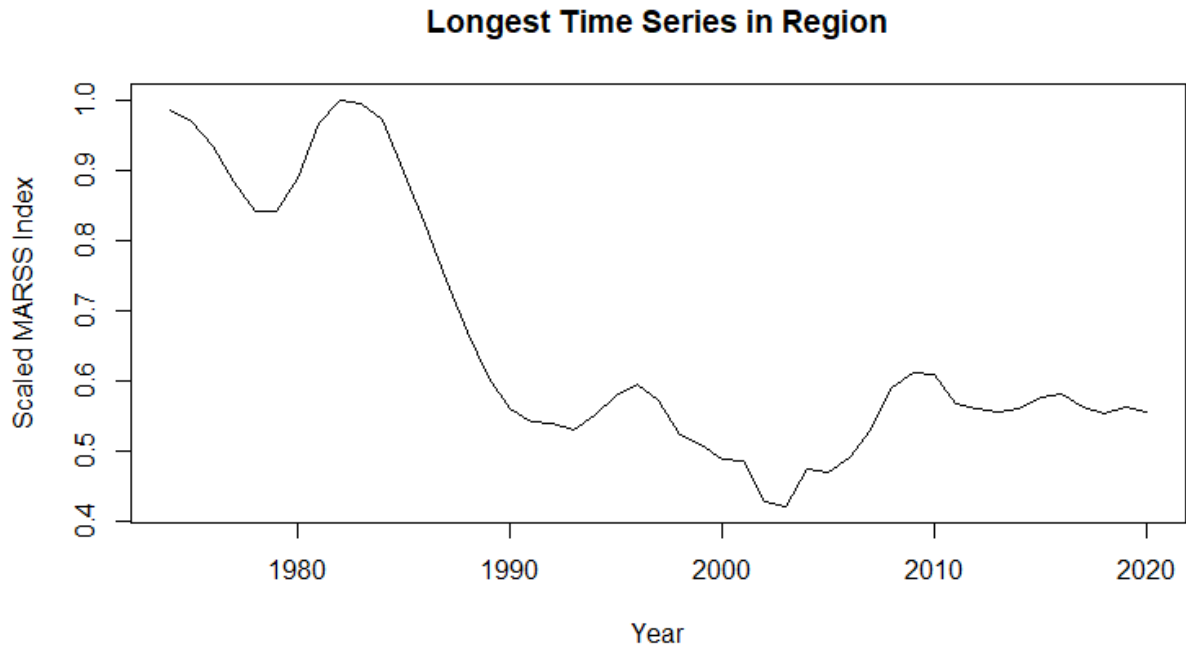


Figure 5. MARSS model abundance index when including the longest time series from each geographical region of the Atlantic coast as defined in the 2012 American eel stock assessment report. These surveys included: MA Rainbow Smelt survey (Gulf of Maine), Farmill River Electrofishing survey (Southern New England), HRE Trawl (Hudson), Delaware River Trawl (Delaware Bay/Mid-Atlantic), VIMS Seine (Chesapeake Bay), and SC Rediversion Canal survey (South Atlantic). The index was scaled to a maximum of 1.0 to facilitate comparisons with other scenarios.

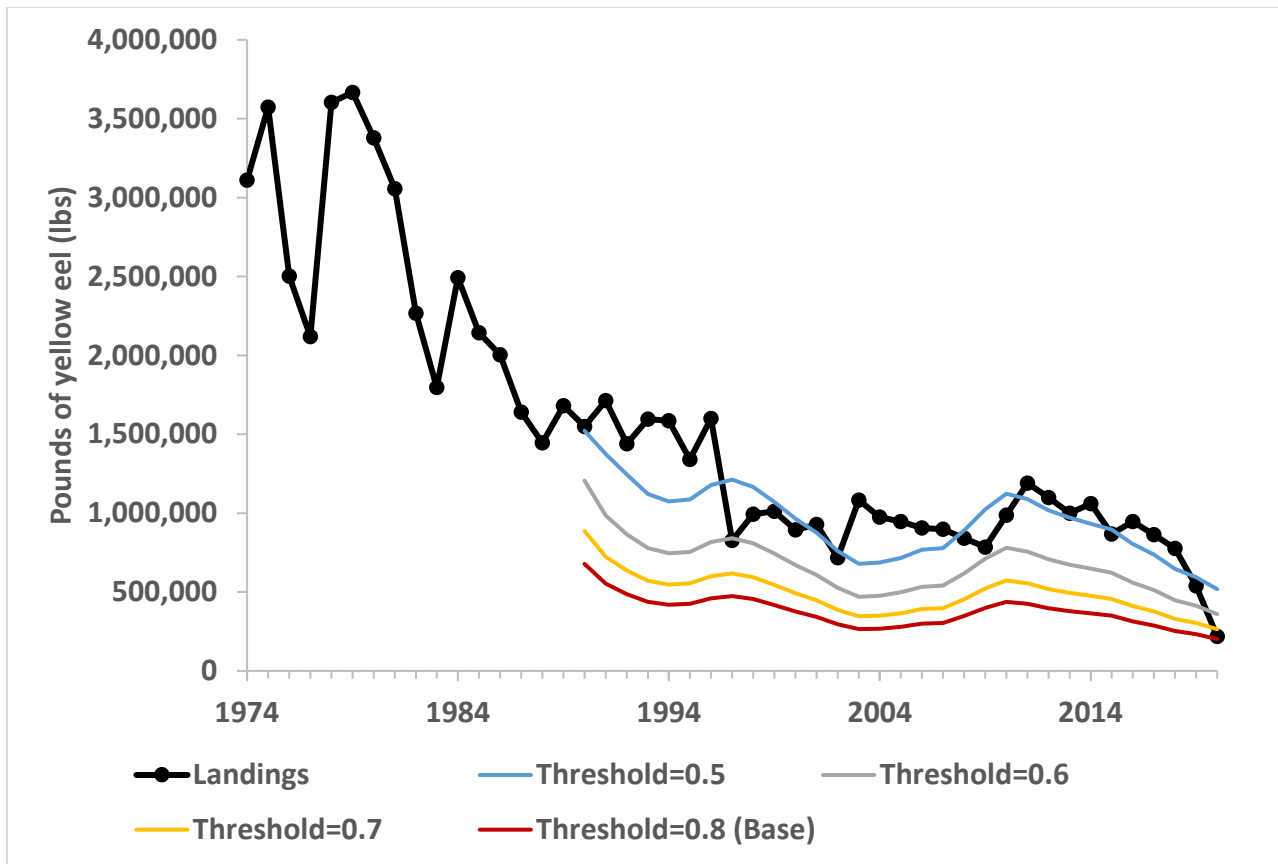


Figure 6. Coastwide landings (black line) and recommended removals (colored lines) from I_{TARGET} when the threshold value is varied. The threshold sensitivities tested were $0.5 \cdot I_{TARGET}$ through $0.8 \cdot I_{TARGET}$ in 0.1 increments. For these sensitivity runs, the reference period was 1974-1987 and the multiplier was held constant at 1.25.

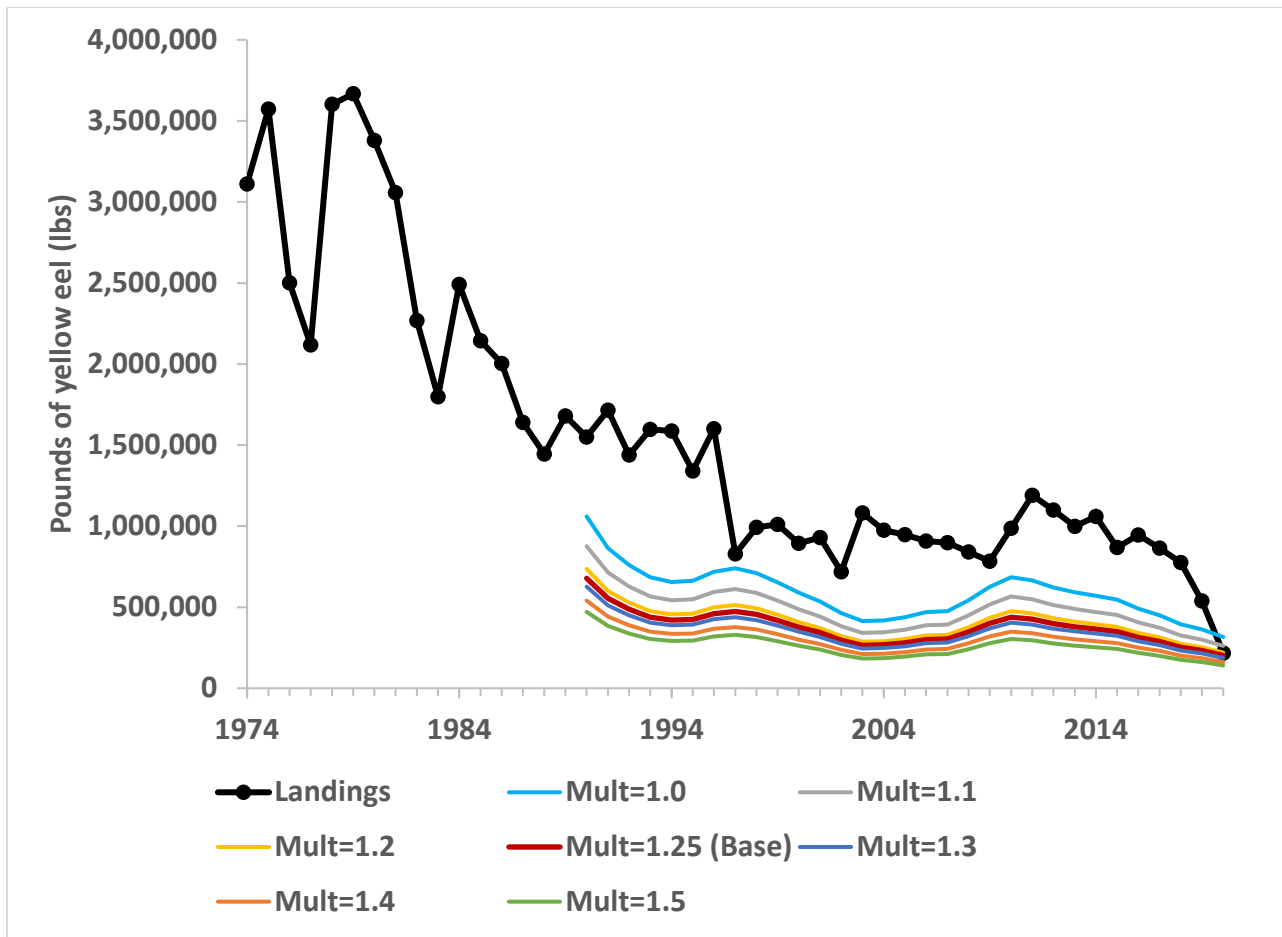


Figure 7. Coastwide landings (black line) and recommended removals (colored lines) from I_{TARGET} when the multiplier value is varied from 1.0-1.5 in 0.1 increments. The base run used a multiplier of 1.25 as indicated in the figure. For these sensitivity runs, the reference period was 1974-1987 and the threshold value was held constant at $0.8 * I_{TARGET}$.

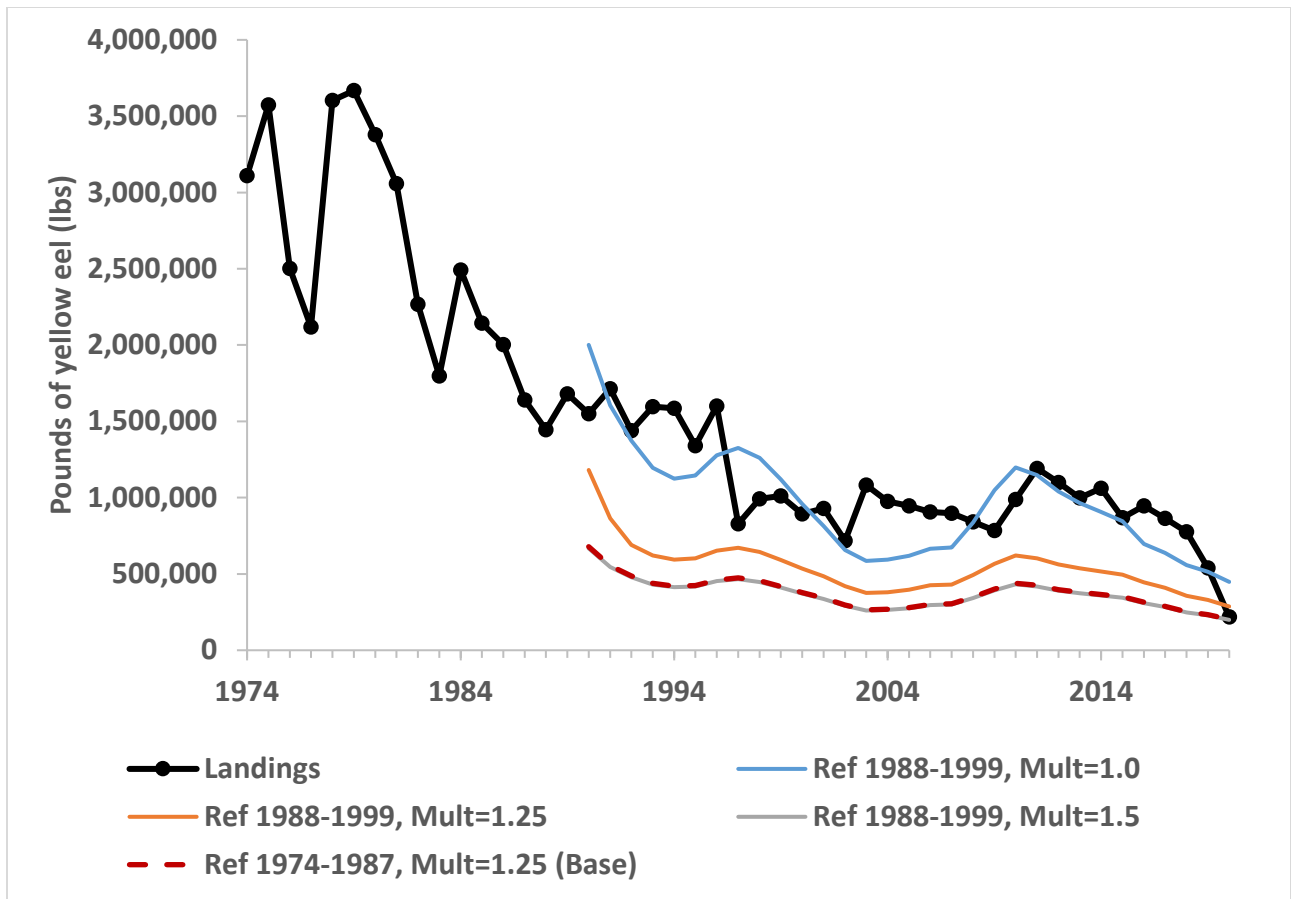


Figure 8. Coastwide landings (black line) and recommended removals (colored lines) from I_{TARGET} when the reference period is changed to 1988-1999 and the multiplier was varied from 1.0 to 1.5. The base run used a 1974-1987 reference period and a 1.25 multiplier as indicated in the figure. For these sensitivity runs, the threshold value was held constant at $0.8 * I_{TARGET}$.

15 APPENDIX A: SC DNR ELECTROFISHING SURVEY

Survey Design and Methods

The SC DNR Electrofishing Survey operates within the oligohaline portions of the Combahee, South Edisto, Ashley, Cooper, and Waccamaw/Sampit/Winyah Bay Rivers (Figure A1). The survey has a stratified random design where five strata are identified (one for each river) with fixed station locations identified for each river system. The survey has been in operation since 2001 and occurs monthly where five to six stations per strata per month are sampled. Catch is identified by species and a subsample is collected for biological sampling, including age and length. Due to COVID, the survey did not operate from the end of March through May in 2020.

Biological and Environmental Sampling

Depth, salinity, dissolved oxygen, temperature, tidal stage, sampling duration, and location are recorded during this survey. Lengths are consistently recorded throughout the time series and some age, weight, sex, and maturity data is also available.

Evaluation of Survey Data

Mean length was consistent across years (Figure A2) and averaged 376.0 mm \pm 138.5 mm (\pm SD). The data was subset to the areas that most reliably encountered eel which were the ACE Basin, Charleston Harbor, and Winyah Bay. While the survey encountered eel in all months, the index was subset to April – November when catches were the highest. Available covariates for the GLM framework included year, depth, salinity, dissolved oxygen, temperature, tidal stage, sampling duration, stratum, and location. Duration was used as an offset in the GLM. The best-fitting model assumed a negative binomial distribution and included year, stratum, and the offset for effort. While the SC DNR staff advised that 2020 data could be used, the index was calculated with and without it. Ultimately, 2020 was dropped from the index to be consistent with how missing data due to COVID was handled in other data sets used the 2022 assessment.

Abundance Index Trends

While the index for 2001-2020 was calculated and provided (Figure A3), the index was recalculated to omit 2020 data since it represented a year with decreased sampling during some of the months in the index. For 2001-2019, the index increased from 2001 to a peak in 2003 followed by a steady decline through the terminal year (Figure A4). While there was a slight increase in abundance in 2016-2017, 2019 was the lowest value in the time series. The 2001-2019 time series was used in the sensitivity runs for MARSS, the regime shift analysis, and I_{TARGET} in the following sections.

MARSS Index

Two sensitivity runs were done to test the choice of SC indices on the resulting MARSS coastwide yellow eel index. First, the MARSS index was recalculated by dropping the SC Rediversion Survey and including the SC DNR Electrofishing Survey. Second, a MARSS index was

calculated that included both SC indices, in addition to the other 12 yellow eel indices previously used. In both cases, the resulting index and confidence intervals were similar to the original MARSS index, although both sensitivity runs were more similar to each other than to the original MARSS (Figure A5).

Regime Shift Analysis

The two recalculated MARSS indices (MARSS with SC DNR Electrofishing Survey substituted for SC Rediversion and MARSS including both SC indices) were analyzed to identify regimes in the time series using the same methods as ASMFC 2023. The regimes were slightly different from the previous regime shift analysis. Using the original MARSS index, the regimes were 1974-1987 (high), 1988-1999 (low), and 2000-2020 (lower). Using either of the recalculated MARSS indices, the regimes identified were 1974-1986 (high), 1987-1997 (low), and 1998-2020 (lower; Figure A6). While the overall pattern was very similar, the change points identified were slightly different by 1-2 years. This would change the reference period in I_{TARGET} from 1974-1987 to 1974-1986.

I_{TARGET}

The proposed management tool, I_{TARGET} , was rerun with the revised reference period of 1974-1986 and the two recalculated MARSS indices (MARSS with SC DNR Electrofishing Survey substituted for SC Rediversion and MARSS including both SC indices). All other configurations in I_{TARGET} remained the same as the base run (e.g., multiplier=1.25, threshold=0.8). With the revised MARSS indices, the recommended harvest in the terminal year was 187,729 lbs (for MARSS with SC DNR Electrofishing) or 187,920 lbs (for MARSS with both SC indices) compared to the 202,453 lbs from the original base run. While the point values are marginally different, the recommended harvest between the revised and original base run are fairly consistent (Figure 7A).

Conclusions

The SC DNR Electrofishing Survey reliably encounters American eel and would have been included as an abundance index had it been considered during the assessment. Due to miscommunication, this data was not included and the TC and SAS agree that this error should be corrected if the assessment is used for management since it represents the best available science. The substitution of the SC DNR Electrofishing Survey for the SC Rediversion Survey or the inclusion of both SC yellow eel indices resulted in slightly different management advice but overall the results are consistent with the previous trends and conclusions. The TC and SAS recommend including both SC indices. Additionally, the SAS and TC recommend that the Assessment Science Committee (ASC) develop guidelines for how to handle survey issues like this in stock assessments since similar questions have arisen in other assessments.

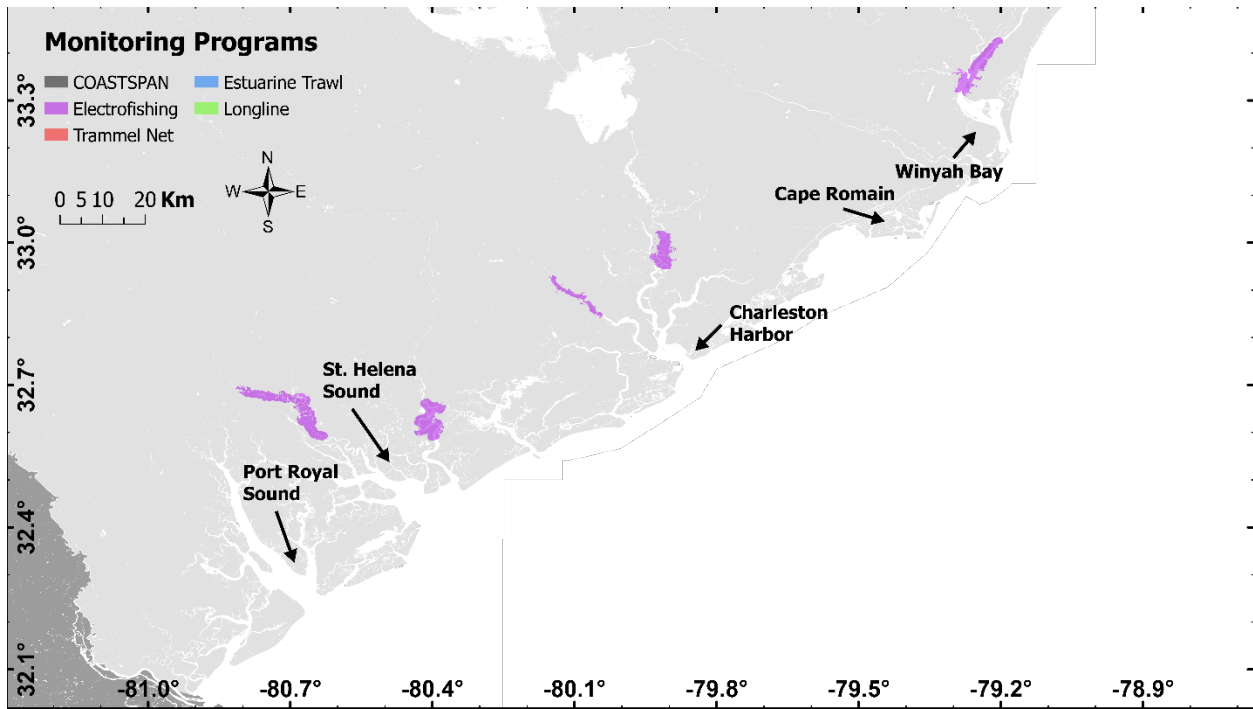


Figure A1. Map of the South Carolina Department of Natural Resources Electrofishing Survey.

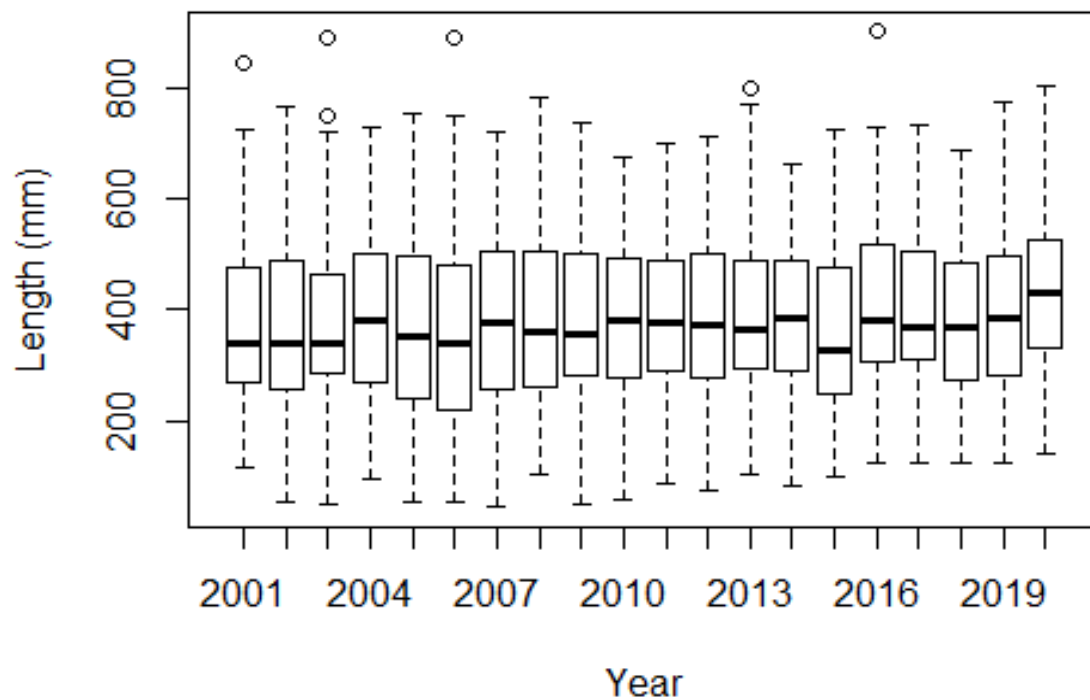


Figure A2. Boxplot of American eel lengths recorded in the South Carolina Electrofishing Survey.

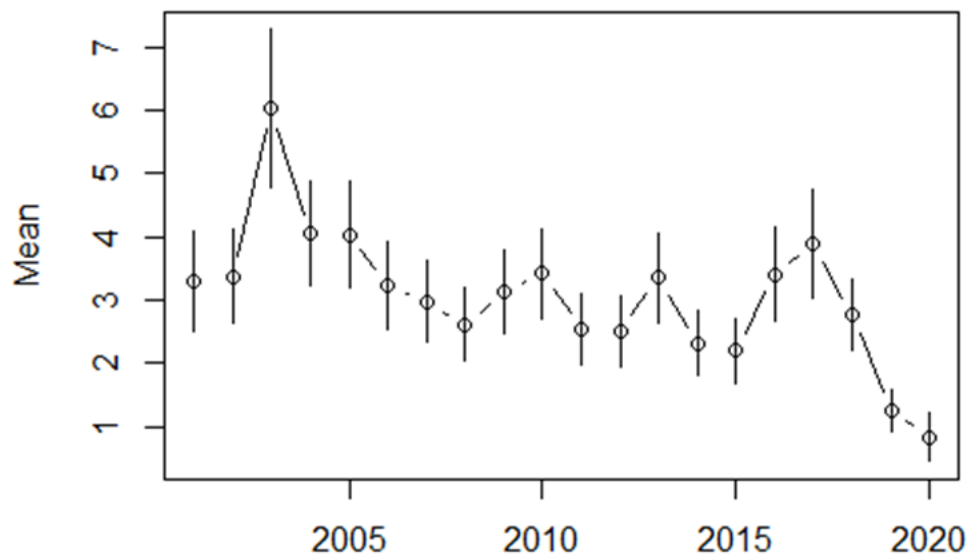


Figure A3. Standardized index of relative yellow eel abundance developed from the South Carolina Department of Natural Resources Electrofishing Survey, 2001-2020. The survey did not operate in March-May in 2020 due to COVID.

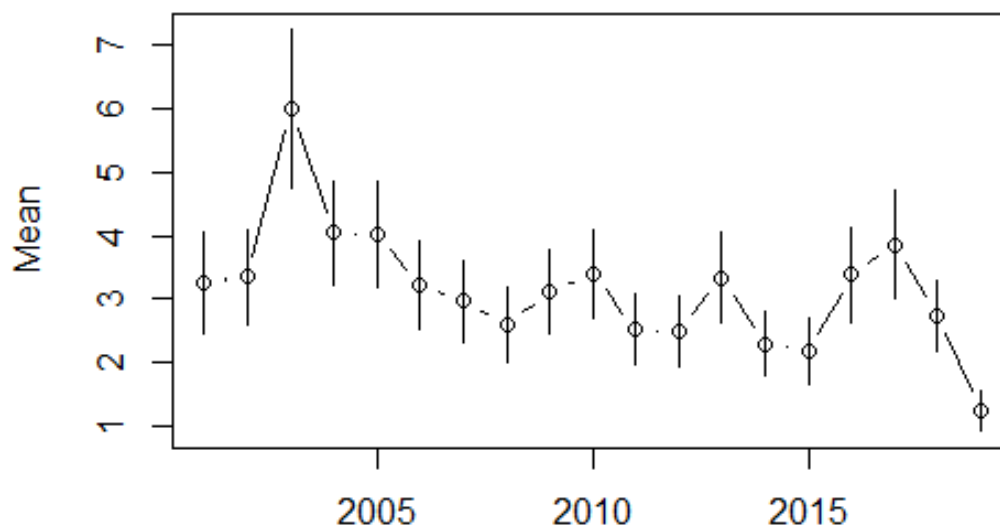


Figure A4. Standardized index of relative yellow eel abundance developed from the South Carolina Department of Natural Resources Electrofishing Survey, 2001-2019.

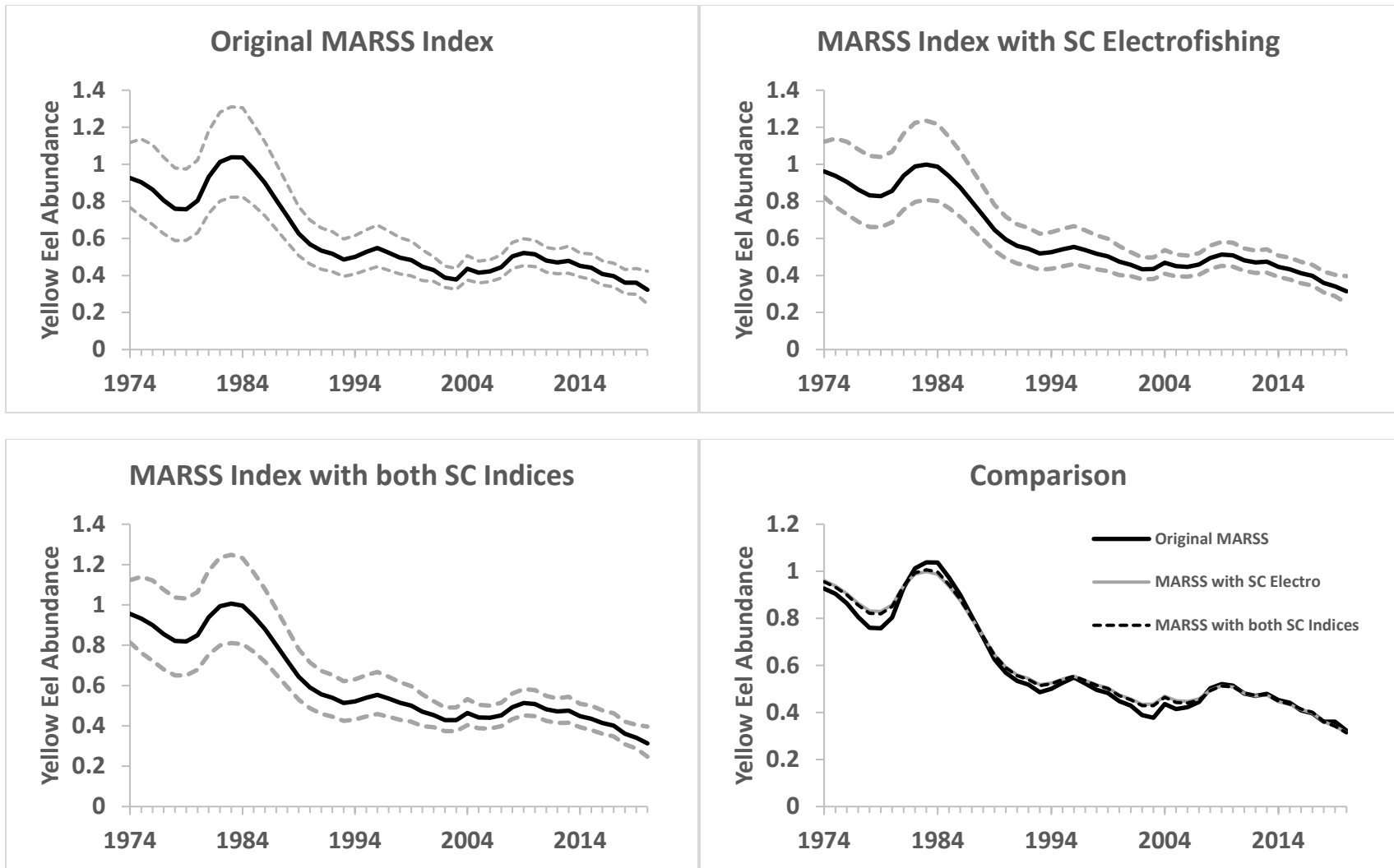


Figure A5. Comparison between the original MARSS index and the recalculated MARSS indices where SC DNR Electrofishing was substituted for SC Rediversion or where both SC indices were included.

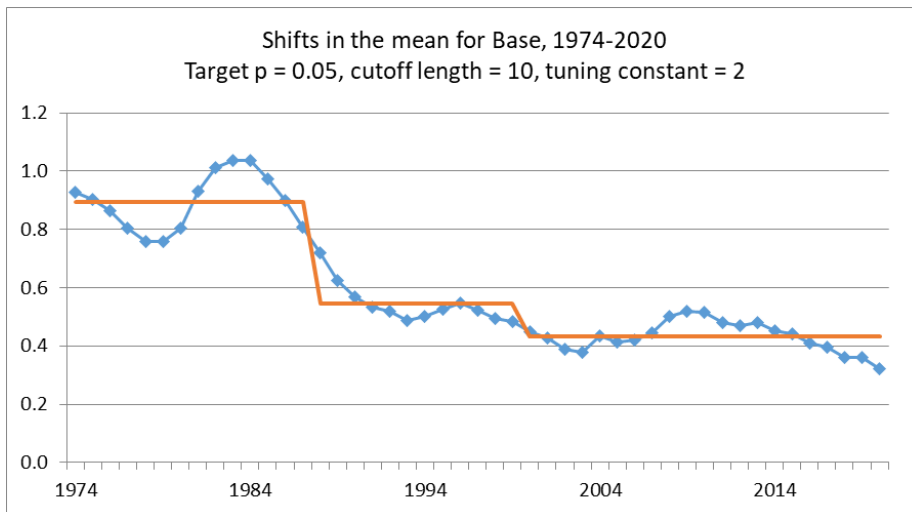
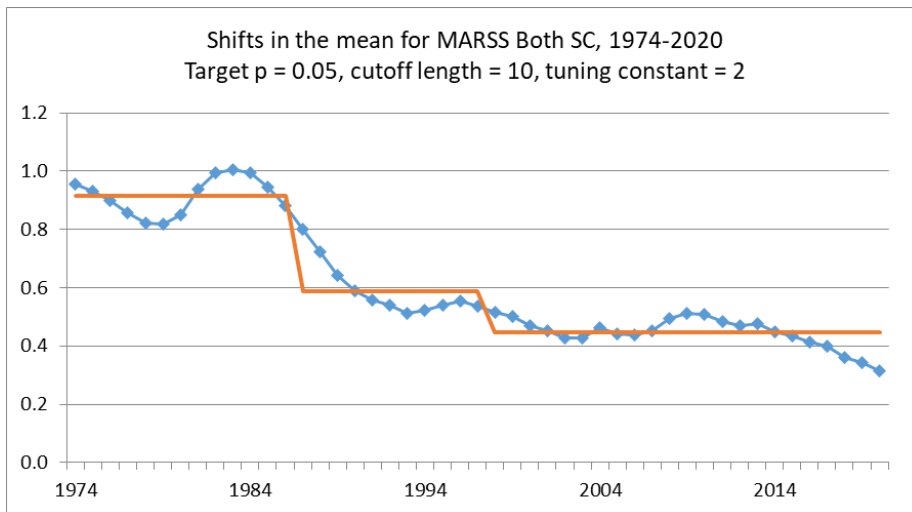
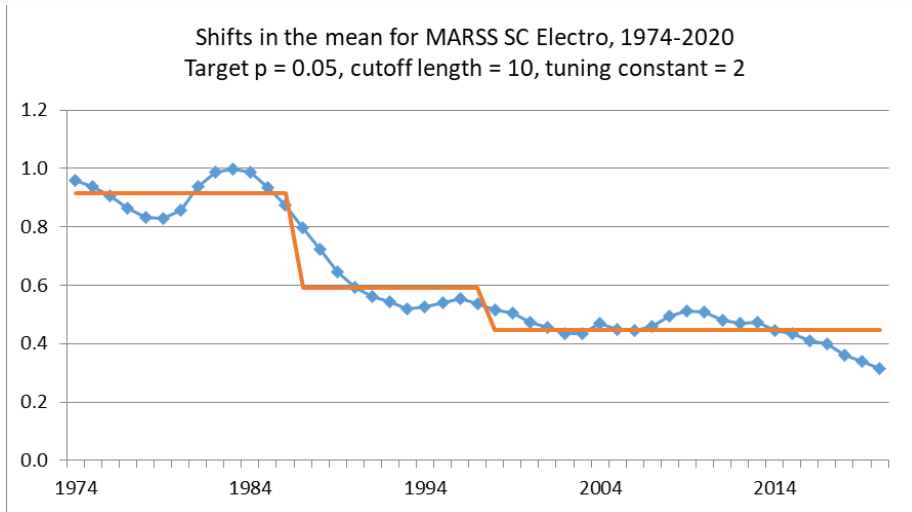


Figure A6. Comparison between the regimes for the recalculated (top, middle) and original MARSS indices (bottom).

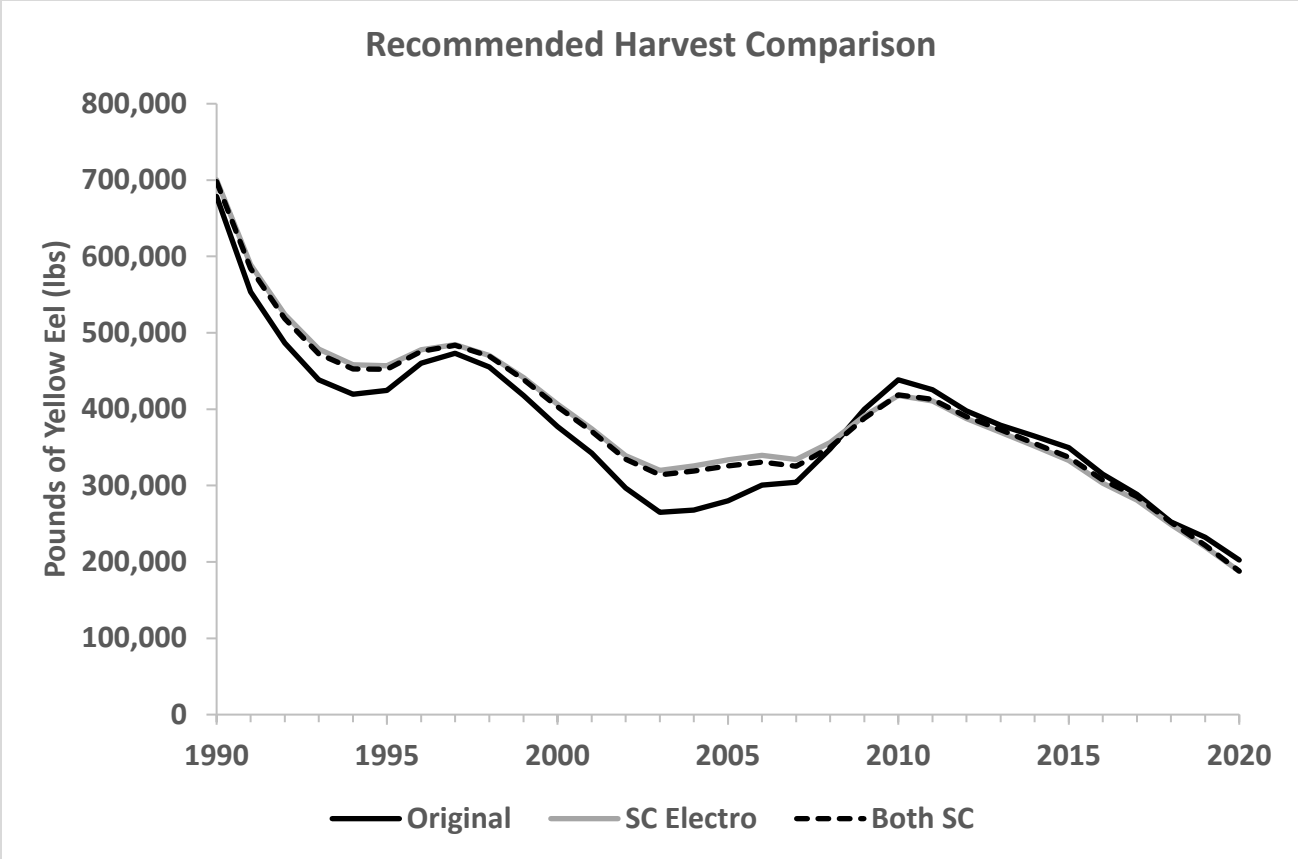


Figure A7. Comparison between the original and revised recommended catch from the I_{TARGET} method.

Atlantic States Marine Fisheries Commission

American Eel Benchmark Stock Assessment



Prepared by the
ASMFC American Eel Stock Assessment Subcommittee

In Collaboration with
John Young, US Geological Survey
David Cairns, Fisheries and Oceans Canada

And

Approved by the
ASMFC American Eel Technical Committee
August 9, 2023



Sustainable and Cooperative Management of Atlantic Coastal Fisheries

EXECUTIVE SUMMARY

The purpose of this assessment was to evaluate the current status of American eels along the US Atlantic coast.

Landings

Along the US Atlantic coast, all life stages are subject to fishing pressure and the degree of fishing varies. Glass eel fisheries are permitted in Maine and South Carolina. Yellow eel fisheries exist in all Atlantic Coast states and jurisdictions with the exception of Pennsylvania and the District of Columbia. American eels are harvested for food, bait, and export markets. From 1950 to 2020, American eel landings ranged from over 3 million pounds in the 1970s to early 1980s to around 1 million pounds or less since the late 1990s. In 2020, landings were at a time series low of approximately 218,000 pounds, likely due to fishing restrictions associated with the COVID-19 pandemic. There has been a coastwide cap on yellow eel landings and a glass eel quota for Maine since 2014.

Recreational harvest and release data for American eel is collected by the Marine Recreational Information Program (MRIP), formerly the Marine Recreational Fishery Statistics Survey. There is very high error and low precision associated with the estimates due to the limited number of American eels that have been encountered during the survey. Available information indicates that few recreational anglers directly target American eel.

Indices of Relative Abundance

The abundance indices developed and used in this assessment are more robust and better defined than previous assessments. State-mandated young-of-year (YOY) surveys have been in operation for twenty years or more in some cases. From Maine to Florida, 25 surveys from were developed into individual indices of relative abundance and then combined into a coastwide YOY index using a multivariate auto-regressive state-space (MARSS) model. There was a declining trend in coastwide YOY abundance from 1987-2020.

There were 10 elver indices developed from multiple surveys from Maine to Virginia that were combined into a coastwide index using the MARSS model. The coastwide index indicated no trend in elvers from 1999-2020.

There were 14 yellow eel indices developed from multiple surveys from New Hampshire to South Carolina that were combined into a coastwide index using the MARSS model. There was a declining trend in coastwide YOY abundance from 1974-2020.

In addition to developing YOY indices from the state-mandated surveys, the stock assessment investigated the biological data (e.g., pigment stage, length, weight) for trends within a site or between sites. There was a trend in length where average lengths increased with latitude, but the differences in sampling gear used among the surveys may have confounded the results. Otherwise, there was a lack of trends in the biological data within and among sites and the stock assessment recommends not requiring YOY biological data collection going forward.

Modeling Approaches

This stock assessment tried several new approaches for American eel that were suggested in past stock assessments including a delay-difference model, further exploring a traffic light analysis or a surplus production model, and developing an egg-per-recruit model. Several additional trend analysis approaches were included in the report. Additionally, the US Geological Survey conducted a pilot assessment of the ability to use a GIS-based habitat analysis to inform eel stock assessments. The stock assessment subcommittee also explored several index-based methods for determining stock status and providing catch advice.

Stock Status

From a biological perspective, much is still unknown about the species. Information is limited about their abundance, status at all life stages, and habitat requirements. No overfishing determination has been made based on the analyses performed during any of the previous stock assessments. Widely varying life history traits along the coast and between freshwater and ocean habitats and American eel's large distribution from Brazil to Canada have complicated attempts to quantitatively model and assess this species over several stock assessments. This stock assessment has not resolved these issues despite investigating several new tools and methods.

For this assessment, a delay-difference model was explored and associated reference points were developed, but ultimately the stock assessment subcommittee did not find the model appropriate for management use. Instead, the SAS used an index-based method to determine stock status and develop catch advice. Based on the index-based method used in this assessment, American eels are overfished and have likely been experiencing overfishing in the last few decades and the coastwide cap should be significantly lowered from the current cap of 916,473 pounds to 200,000-300,000 pounds.

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TERMS OF REFERENCE

For the 2022 ASMFC American Eel Benchmark Stock Assessment
Board Approved June 2020

Terms of Reference for the American Eel Benchmark Stock Assessment

TOR1. Define population structure based on available data. If alternative population structures are used in the models (e.g., coastwide, regional, sub-regional or estuary-specific), justify the use of each population structure.

American eels are a panmictic species with a single spawning stock based on genetic research (Section 2.1). American eels in this assessment include the portion of the stock from Maine to the Atlantic coast of Florida with no regional substructure.

TOR2. Characterize precision and accuracy of fishery-dependent and fishery-independent data used in the assessment, including the following but not limited to:

- a. Provide descriptions of each data source (e.g., geographic location, sampling methodology, potential explanation for outlying or anomalous data).
- b. Describe calculation and potential standardization of abundance indices. Consider the consequences of environmental factors on the estimates of abundance or relative indices derived from surveys.
- c. Discuss trends and associated estimates of uncertainty (e.g., standard errors).
- d. Justify inclusion or elimination of available data sources.

Fishery-dependent data for American eel are available for the commercial yellow (Section 4.1) and glass eel fisheries (Section 4.2). There is also data available to characterize the recreational fishery (Section 4.3), although this data is likely not comprehensive and estimates have large associated errors. The assessment also describes available landings data from Canada, the Gulf of Mexico, Mexico, Dominican Republic, and Cuba as well as eels exported from the US annually (Sections 4.4-4.7). For each fishery, a description of the fishery, data collection program, landings, and potential data limitations have been provided.

Over 80 fishery-independent surveys were reviewed by the stock assessment subcommittee (SAS) for the development of young-of-year (YOY), elver, or yellow eel relative abundance indices. Surveys that met the criteria developed by the SAS for evaluating available data were developed into indices of relative abundance for American eel (Section 5.1). All surveys were standardized using a variety of statistical models and environmental covariates. Individual survey designs and methods, biological and environmental sampling description, statistical model used, and abundance index trends are described for each survey used in the assessment (Sections 5.2). Coastwide indices by stage were developed using two different methods: a Multivariate Auto-Regressive State-Space (MARSS) model (Section 6.1) and Conn (2010; Section 6.2). While the trends were consistent between the two methods, the SAS preferred the MARSS

model and that was used for the majority of modeling approaches. The Conn was maintained in the report for methods that needed a longer time series.

TOR3. Develop models used to estimate population parameters (e.g., F , biomass, abundance) and biological reference points, and analyze model performance.

- a. Briefly describe history of model usage, its theory and framework, and document associated peer-reviewed literature. If using a new model, test using simulated data.
- b. Describe stability of model (e.g., ability to find a stable solution, invert Hessian)
- c. Clearly and thoroughly explain model strengths and limitations.
- d. Justify choice of CVs, effective sample sizes, or likelihood weighting schemes.
- e. If multiple models were considered, justify the choice of preferred model and the explanation of any differences in results among models.

Several methods were developed for this assessment from simple trend analyses to statistical models. For analyzing the fishery-independent indices of relative abundance for trends, a Multivariate Auto-Regressive State-Space model (MARSS; Section 6.1), the methods of Conn (2010; Section 6.2), a power analysis (Section 6.3), Mann-Kendall tests (Section 6.4), a regime shift analyses (Section 6.5), and a traffic light analysis (Section 6.6) were explored. Index-based methods were also developed in order to provide managers catch advice for setting the coastwide harvest cap for yellow eels (Section 6.10). For models that can produce population parameters and biological references points, an egg-per-recruit model (Section 6.7), two surplus production models (Section 6.8), and a delay-difference model (Section 6.9) were explored. For each model and method discussed, a background of the analysis, configuration, and results are provided in the stock assessment report. The stock status and conclusions sections of the report (Sections 7 and 8) discuss the differences between the results and justification for the recommended management tool for American eel, the index-based method I_{TARGET} .

TOR4. Characterize uncertainty of model estimates and biological or empirical reference points.

Ultimately this stock assessment was not able to produce population estimates or reference points based on the statistical models developed (e.g., surplus production, delay-difference model). Uncertainty was examined in the results of the various approaches by considering each data source during model development and performing sensitivity runs when possible.

TOR5. Perform sensitivity and retrospective analyses.

- a. Perform sensitivity analyses for starting parameter values, priors, etc. and conduct other model diagnostics as necessary.
- b. Assess magnitude and direction of retrospective patterns detected, and discuss implications of any observed retrospective pattern for uncertainty in population parameters (e.g., F , SSB), reference points, and/or management measures.

Each model developed explored a range of starting values and data sources when possible. The final tool used in the assessment for giving management advice explored several alternative scenarios to evaluate the uncertainty in the advice (Section 6.10). A retrospective analysis was not done for any of the models, but the index-based method recommended for giving catch advice did compare the advice the method would have given each year to the landings.

TOR6. Recommend stock status as related to reference points (if available). For example:

- a. Is the stock below the biomass threshold?**
- b. Is F above the threshold?**

The SAS developed reference points for the delay-difference model in order to determine stock status (Section 6.9.4) but is not recommending this approach because of multiple concerns with the application of that model. Instead of using the delay-difference model, the SAS proposes that the index-based method I_{TARGET} method should be used to both determine stock status and provide catch advice for American eels. Using this methodology, the target biomass would be set at the three-year average of the MARSS index associated with I_{TARGET} and which corresponds to a B_{TARGET} . The threshold would be set at the three-year average of the MARSS index associated with the $I_{THRESHOLD}$ using the base case for both the reference period and the $I_{TARG MULT}$ (Section 6.10).

Based on the results of the I_{TARGET} method, the stock would be considered overfished since the current three-year average of the MARSS index (0.348) is below the $I_{THRESHOLD}$ (0.882). This result is in line with other methods (e.g., Conn index, MARSS index, regime shift analysis, delay-difference model, Mann-Kendall Test) that also show the stock as depleted or experiencing downward trends in the abundance data. While the American eel stock is overfished, the SAS was unable to determine if overfishing was occurring. However, it can be inferred that the stock is experiencing overfishing since the catches have been well above the recommended removals. Therefore, the SAS suggests that American eels likely have been experiencing overfishing in the last few decades based on the I_{TARGET} method and supported by additional methods explored in this assessment.

TOR7. Other potential scientific issues:

- a. If traditional assessment models cannot be used due to data limitations, consider other novel approaches to assess the stock and provide advice to managers such as habitat modeling, data limited models, or trend analyses.**
- b. Evaluate new information on life history such as characterizing length, weight, age, and sex structure, distribution, spawning, or maturation. Explore possible impacts of environmental change on life history characteristics.**

The challenges of using traditional stock assessment models for American eel was documented in the previous stock assessments (ASMFC 2012, 2017) and this stock assessment. The Introduction (Section 1) outlines the challenges of modeling and assessing eel, both in the US and internationally. Several modeling approaches from trend analyses to assessment models were attempted for this report (Section 6). Ultimately the SAS is recommending an index-based

approach, I_{TARGET} , for determining stock status and for setting catch advice (Section 6.10 and 7) which is a novel approach developed by the Northeast Fisheries Science Center for data-poor situations (NEFSC 2020).

Another novel approach investigated during this stock assessment was a habitat model developed in collaboration with scientists from the US Geological Survey (USGS; Section 3.1). For the assessment, USGS conducted a pilot assessment of the capability to employ geographic information systems (GIS) –based habitat analysis to potentially inform American eel stock assessments. Like other methods in the assessment, data quantity and quality posed a challenge for this modeling effort.

The life history section of the assessment was updated to incorporate and describe new research since the last assessment (Section 2). Additionally, a growth meta-analysis and a bootstrapping approach for estimating growth parameters was developed from all available data (Section 2.5). Environmental covariates were used in index standardization when that data was available (Section 5). Additionally, the habitat description (Section 3) describes several new studies about the influence of the Gulf Stream on American eel recruitment and the effects of dam removal throughout its range.

TOR8. Develop detailed short and long-term prioritized lists of recommendations for future research, data collection, and assessment methodology. Highlight improvements to be made by next benchmark review.

Research recommendations from ASMFC 2012 and 2017 remain important, but the SAS compiled a list of research recommendations for this assessment that are specific to what could improve the next stock assessment (Section 9). Research recommendations are broken down into future research and data collection and assessment methodology.

TOR9. Recommend timing of next benchmark assessment and intermediate updates, if necessary relative to biology and current management of the species.

The SAS recommends an update be considered in five years and a new benchmark be considered in ten years. This is the assessment schedule that American eel has been on in recent years and should be maintained.

TOR10. If a minority report has been filed, explain majority reasoning against adopting approach suggested in that report. The minority report should explain reasoning against adopting approach suggested by the majority.

No minority report was filed.

Terms of Reference for the American Eel Peer Review

- TOR1.** Evaluate the definition of the stock structure used in the assessment.
- TOR2.** Evaluate the thoroughness of data collection and the presentation and treatment of fishery-dependent and fishery-independent data in the assessment, including the following but not limited to:
- a. Presentation of data source variance (e.g., standard errors).
 - b. Justification for inclusion or elimination of available data sources.
 - c. Consideration of data strengths and weaknesses (e.g., temporal and spatial scale, gear selectivities, aging accuracy, sample size).
 - d. Calculation and/or standardization of abundance indices.
- TOR3.** Evaluate the methods and models used to estimate population parameters (e.g., F , biomass, abundance) and biological reference points, including but not limited to:
- a. Evaluate the choice and justification of the preferred model(s). Was the most appropriate model (or model averaging approach) chosen given available data and life history of the species?
 - b. Evaluate model parameterization and specification (e.g., choice of CVs, effective sample sizes, likelihood weighting schemes, calculation/specification of M , stock-recruitment relationship, choice of time-varying parameters, plus group treatment).
 - c. Recommend best estimates of stock biomass, abundance, and exploitation from the assessment for use in management, if possible, or specify alternative estimation methods.
 - d. If multiple models were considered, evaluate the analysts' explanation of any differences in results.
- TOR4.** Evaluate the methods used to characterize uncertainty in estimated parameters. Ensure that the implications of uncertainty in technical conclusions are clearly stated.
- TOR5.** Evaluate the diagnostic analyses performed, including but not limited to:
- a. Sensitivity analyses to determine model stability and potential consequences of major model assumptions.
 - b. Retrospective analysis.
- TOR6.** Evaluate stock status determination and reference points used by the assessment.
- a. Recommend stock status determination from the assessment, or, if appropriate, specify alternative methods/measures.
 - b. Evaluate the choice of reference points and the methods used to estimate them.
- TOR7.** Evaluate the incorporation of new information stock or attempts at novel approaches to assess the stock.

- TOR8. Review the research, data collection, and assessment methodology recommendations provided by the TC and make any additional recommendations warranted. Clearly prioritize the activities needed to inform and maintain the current assessment, and provide recommendations to improve the reliability of future assessments.**
- TOR9. Recommend timing of the next benchmark assessment and updates, if necessary, relative to the life history and current management of the species.**
- TOR10. If a minority report has been filed, review minority opinion and any associated analyses. If possible, make recommendation on current or future use of alternative assessment approach presented in minority report.**
- TOR11. Prepare a peer review panel terms of reference and advisory report summarizing the panel's evaluation of the stock assessment and addressing each peer review term of reference. Develop a list of tasks to be completed following the workshop. Complete and submit the report within 4 weeks of workshop conclusion.**

1 INTRODUCTION

American eels *Anguilla rostrata* are a challenging species to conserve, assess, and manage for a number of reasons. During its lifespan, American eels navigate through and reside in a wide range of habitats, from the oceanic waters of the Sargasso Sea to the brackish waters of coastal estuaries and the inland freshwater river systems. Throughout this journey, American eels inhabit areas under a myriad of management authorities, from international to multiple federal, state, and local governments. Life history characteristics such as late age of maturity and a tendency to aggregate during certain life stages further confound conservation efforts. These life history traits along with their large distribution from Brazil to Canada have complicated attempts to quantitatively model and assess this species over several stock assessments (ASMFC 2006a, 2006b, 2012, 2017a). This stock assessment has not resolved these issues despite investigating several new tools and methods. A delay-difference model was explored and associated reference points were developed, but ultimately the Stock Assessment Subcommittee (SAS) did not find the model appropriate for management use. Modelling and producing reference points for this species is not currently possible, nor will it be in the foreseeable future. Instead, the SAS used an index-based method to determine stock status and develop catch advice. Based on that approach, the SAS finds that the American eel stock is overfished and likely experiencing overfishing. A data-poor management tool is offered in this stock assessment for setting future harvest levels.

The challenges of assessing and managing eels are not unique to the Atlantic states' portion of the stock. Issues with comprehensive data collection, spatially variable life history parameters, habitat fragmentation due to dams, large geographic range, climate change, parasites, and inability to find an appropriate model for producing reference points are universally acknowledged by other countries that have eel populations, e.g., Japanese eels *Anguilla japonica* (Kaifu 2019), European eels *A. anguilla* (ICES 2013), and the longfin eels *A. dieffenbachii* and shortfin eels *A. australis* in New Zealand (Hoyle 2016). Several of these other countries or international bodies have come to similar conclusions as this SAS. Recently, New Zealand abandoned an analytical stock assessment for their stocks and suggested proceeding with habitat-oriented assessments which will not produce stock parameters (Cairns et al. 2022). An International Council for the Exploration of the Sea (ICES) Working Group on Eels (WGEEL) conducts stock assessments for European eels and their most recent report also outlines many of the same challenges as the US and acknowledges that their reliance on recruitment indices does not define which direction or action needs to be taken to recover the stock (ICES 2021a). Additionally, an ICES workshop focused on the future of eel advice, reviewing assessment options, provided a recommendation that focused on habitat consideration similar to New Zealand's recent work (ICES 2021b). Fisheries and Oceans Canada (DFO) attempted to use quantitative methods to determine stock status but could not, instead relying on trend analyses like the US assessments (Cornic et al. 2021).

This stock assessment tried several new approaches for American eel that were suggested in past stock assessments including a delay-difference model (Section 6.9), further exploring a traffic light analysis or a surplus production model (Section 6.6 and 6.8), and developing an egg-per-recruit model (Section 6.7). Additionally, USGS conducted a pilot assessment of the ability

to use a GIS-based habitat analysis to inform eel stock assessments (Section 3.1). The SAS took a critical look at the abundance indices used for American eel and made some revisions, including using two new methods for developing composite indices (Conn 2010; Holmes et al. 2018). The abundance indices developed and used in this assessment are more robust and better defined than previous assessments.

In order to provide the American Eel Management Board (Board) with a tool for setting an annual coastwide cap for yellow American eel harvest, the SAS is offering an index-based assessment method. Index-based methods were recently tested as management tools using an operating model (NEFSC 2020). The SAS evaluated several of these methods for use in setting a harvest control rule for American eels using a time series of landings and the available abundance indices (Section 6.10). Reference points were also developed for the delay-difference model to help inform stock status (Section 7), but ultimately the SAS did not recommend using these for management. The SAS evaluated the nearly 20 years of state-mandated young-of-the-year (YOY) surveys and made recommendations about their usefulness and where effort could be reduced (Section 5.4). The SAS, in collaboration with the Technical Committee (TC), made several research recommendations. The next benchmark should be initiated if some of these recommendations are accomplished or if there is a promise of a new management or modeling tool for American eels. In the meantime, the abundance indices and index-based methods can help guide the Board in setting appropriate harvest levels for the species.

1.1 Management Unit Definition

American eels are a catadromous species that historically occurred in all major rivers from Canada through Brazil. The management unit for American eels under the jurisdiction of ASMFC includes that portion of the population occurring in the territorial seas and inland waters along the Atlantic coast from Maine to Florida.

1.2 Regulatory History

The Board first convened in November 1995 and finalized the Fishery Management Plan (FMP) for American Eel in November 1999 (ASMFC 2000a). The goal of the FMP is to conserve and protect the American eel resource to ensure ecological stability while providing for sustainable fisheries. The FMP requires all states and jurisdictions to implement an annual YOY abundance survey to monitor the annual recruitment of each year's cohort (ASMFC 2000a, 2000b). In addition, the FMP requires a minimum recreational size and possession limit and a state license for recreational fishermen to sell American eels. The FMP requires that states and jurisdictions maintain existing or more conservative American eel commercial fishery regulations for all life stages, including minimum size limits. Each state is responsible for implementing management measures within its jurisdiction to ensure the sustainability of its American eel population.

In August 2005, the Board directed the American Eel Plan Development Team (PDT) to initiate an addendum to establish a mandatory catch and effort monitoring program for American eels. The Board approved Addendum I at the February 2006 Board meeting.

In January 2007, the Board initiated a draft addendum to increase the escapement of silver American eels to the spawning grounds. In October 2008, the Management Board approved Addendum II, which placed increased emphasis on improving the upstream and downstream passage of American eels. The Board chose to delay action on management measures in order to incorporate the results of the 2012 stock assessment.

In August 2012, the Management Board initiated Draft Addendum III with the goal of reducing mortality on all life stages of American eels. The addendum was initiated in response to the findings of the 2012 benchmark stock assessment, which declared the American eel stock along the US East Coast as depleted. The Board approved Addendum III in August 2013.

Addendum III requires states to reduce the yellow American eel recreational possession limit to 25 eel/person/day with the option to allow an exception of 50 eel/person/day for party/charter employees for bait purposes. The recreational and commercial size limit increased to a minimum of 9". Eel pots are required to be constructed with a minimum of ½" by ½" mesh size. The glass American eel fishery is required to implement a maximum tolerance of 25 pigmented American eels per pound of glass American eel catch. The silver American eel fishery is prohibited in all states from September 1st to December 31st from any gear type other than baited traps/pots or spears. The addendum also set minimum monitoring standards for states and required dealer and harvester reporting in the commercial fishery.

In October 2014, the Board approved Addendum IV. The addendum was also initiated in response to the 2012 American Eel Benchmark Stock Assessment and the need to reduce mortality on all life stages. The Addendum established a coast-wide cap of 907,671 pounds of yellow American eels, reduced Maine's glass American eel quota to 9,688 pounds (2014 landings) and allowed for the continuation of New York's silver American eel weir fishery in the Delaware River. For yellow American eel fisheries, the coast-wide cap was implemented starting in the 2015 fishing year and established two management triggers: (1) if the cap is exceeded by more than 10% in a given year, or (2) the coast-wide quota is exceeded for two consecutive years regardless of the percent overage. If either one of the triggers are met, then states would implement state-specific allocation based on average landings from 1998–2010 with allocation percentages derived from 2011–2013.

In August 2018, the Board approved Addendum V. The Addendum increased the yellow American eel coastwide cap starting in 2019 to 916,473 pounds to reflect a correction in the historical harvest data. Further, the Addendum adjusted the method (management trigger) to reduce total landings to the coastwide cap when the cap has been exceeded and removed the implementation of state-by-state allocations if the management trigger is met. Management action is initiated if the yellow American eel coastwide cap is exceeded by 10% in two consecutive years. If the management trigger is exceeded, only those states accounting for more than 1% of the total yellow American eel landings will be responsible for adjusting their measures. Additionally, the Addendum maintains Maine's glass American eel quota of 9,688 pounds. The Board also slightly modified the glass American eel aquaculture provisions, maintaining the 200-pound limit for glass American eel harvest but adjusting the criteria for

evaluating the proposed harvest area's contribution to the overall population consistent with the recommendations of the Technical Committee.

1.3 Petitions for ESA Listing

In response to the extreme declines in American eel abundance in the Saint Lawrence River-Lake Ontario portion of the species' range, the ASMFC requested that the US Fish and Wildlife Service (USFWS) and the National Marine Fisheries Service (NMFS) conduct a status review of American eels in 2004. The ASMFC also requested an evaluation of a Distinct Population Segment (DPS) listing under the Endangered Species Act (ESA) for the Saint Lawrence River/Lake Ontario and Lake Champlain/Richelieu River portion of the species range, as well as an evaluation of the entire Atlantic coast American eel population. A preliminary status review conducted by USFWS determined that American eels were not likely to meet the requirements of DPS determinations; however, the USFWS initiated a coastwide status review of the American eel in coordination with the NMFS and ASMFC. At this same time, two private citizens submitted a petition to the USFWS and NMFS to list American eels under the ESA.

In February 2007, the USFWS announced the completion of a Status Review for American eel (USFWS 2007). The report concluded that protecting American eels as an endangered or threatened species was not warranted. The USFWS did note that while the species' overall population was not in danger of extinction or likely to become so in the foreseeable future, the American eel population has "been extirpated from some portions of its historical freshwater habitat over the last 100 years... [and the species abundance has declined] likely as a result of harvest or turbine mortality, or a combination of factors."

In 2010, the Center for Environmental Science Accuracy and Reliability filed a petition to the USFWS to consider placing the American eel on the endangered species list. The proposal was based on new information that had become available since the last status review. In September 2011, the USFWS published a positive 90-Day Finding, which stated that the petition contained enough information to warrant conducting a status review (USFWS 2011).

In 2015, the USFWS announced that the American eel population is stable and protection under ESA was not warranted although the agency did recommend continuing efforts to maintain healthy habitats, monitor harvest levels, and improve river passage (USFWS 2015). Conversely, the International Union for the Conservation of Nature (IUCN) listed the American eel as "Endangered" on the Red List in 2014 (Jacoby et al. 2014). While this has no legal implications, it is an important metric and the ASMFC remains committed to closely monitoring this species and making management adjustments as necessary.

1.4 Assessment History

1.4.1 Previous stock assessments

In 2005, a stock assessment for American eels was conducted by the ASMFC and reviewed by a panel of independent experts (ASMFC 2005). The Peer Review Panel recognized sufficient

shortcomings with the assessment to warrant additional action prior to its use for future technical and management purposes (ASMFC 2006a). The 2005 stock assessment was not accepted by the Board; therefore, the stock status of American eels was deemed unknown by the ASMFC.

Following the rejected stock assessment, the American Eel SAS and TC were tasked with reviewing the recommendations from the peer review advisory report and recommending a follow-up plan. Subsequently, a report was issued in October of 2006 containing updated datasets and the short-term analyses suggested by the review panel (ASMFC 2006b).

The 2012 benchmark stock assessment represented the most recent work performed by the ASMFC to ascertain stock status since 2006 (ASMFC 2012). Analyses and results indicated that the American eel stock had declined and that there were significant downward trends in multiple surveys across the coast. It was determined that the stock was depleted but no overfishing determination could be made based on the analyses performed. The 2012 benchmark was updated in 2017 and maintained the depleted status (ASMFC 2017a).

1.4.2 Summary of previous assessment models

Several modeling approaches were explored in the 2012 benchmark including a suite of models used by ICES (Study Leading to Informed Management of Eels or SLIME), surplus production models (both age-structured and catch-free), traffic light analysis (TLA), and depletion-based stock reduction analysis (DB-SRA). The SLIME model was deemed inappropriate to the needs of the ASMFC for managing American eels since it was designed to meet northeast Atlantic-specific management requirements (i.e., provide estimates of escapement). Several trend analyses were done including a power, Mann-Kendall, and Manly analyses as well as autoregressive integrated moving average models (ARIMA).

1.4.3 Previous peer review comments

The surplus production models did not find stable solutions and the TLA produced results that were difficult to interpret. Therefore, surplus production models and the TLA were not endorsed for management use by the Peer Review Panel in 2012, although the Panel did suggest that the TLA be explored in the next assessment to incorporate more data. The Panel noted that ARIMA is sensitive to the first data point in the time series and they suggested that trends be interpreted with caution. ARIMA was not used for developing reference points for American eel management but was one of the trend analyses used to draw general conclusions about the status of the stock. The Peer Review Panel endorsed the DB-SRA model for assessing American eels but had a number of concerns about the model and ultimately was not comfortable using it to develop reference points or determine stock status without further refinements. Specifically, the Peer Review Panel's criticisms of the DB-SRA were that the underlying production function may not be appropriate for the species, there was no consideration of stock dynamics in the marine stage or full range of American eels, it assumed there was negligible error in catch data, and that there was uncertainty in the input parameters and the magnitude of resulting biomass and fishing mortality estimates.

1.4.4 Previous stock status

The data evaluated in the 2012 assessment provided evidence of a neutral or declining abundance of American eels in the US in recent decades. All three trend analysis methods (Mann-Kendall, Manly, and ARIMA) detected significant declining trends in some indices over the time period examined. The Mann-Kendall test detected a significant declining trend in 6 of the 22 YOY indices, 5 of the 15 yellow eel indices, 3 of the 9 regional trends, and the coastwide yellow-phase abundance index. No overfishing determination could be made based on the analyses performed. Trend analyses and DB-SRA results indicated that the American eel stock declined in recent decades and the prevalence of significant downward trends in multiple surveys across the coast is cause for concern. Therefore, the stock status was determined to be depleted.

The trend analysis results in the 2017 update were consistent with the ASMFC 2012 results, with few exceptions. Compared to ASMFC 2012, there were more significantly downward trends in indices as indicated by the Mann-Kendall test and similar results for the ARIMA. This trend analysis and stable low landings support the updated conclusion that the American eel population in the assessment range remained depleted.

2 LIFE HISTORY

American eels are found from the southern tip of Greenland, Labrador, and the northern Gulf of St. Lawrence in the north, south along the Atlantic and Gulf coasts of North America and eastern Central America to the northeast coast of South America, and into the inland areas of the Mississippi and Great Lakes drainages (Tesch 1977). The American eel is regarded as a single, panmictic breeding population. American eels are found in a variety of habitats throughout their life cycle, including the open ocean, large coastal tributaries, small freshwater streams, and lakes and ponds. They are opportunistic feeders that will eat, depending on their life stage, phytoplankton, zooplankton, insects, crustaceans, and fish. Individuals grow in freshwater or estuarine environments for anywhere from 3 to 30 or more years before maturing and returning to the ocean as adults to spawn and die.

American eels are confronted with many environmental and human-induced stressors which affect all life stages and may reduce survival. Since all anthropogenic eel mortality is pre-spawning, reproduction can be reduced by these cumulative pressures. Commercial harvest occurs at all American eel life stages (glass, elver, yellow, and silver). Blockages and obstructions that limit upstream migration of American eels have reduced habitat availability and limited the range of the species. Dams may also limit or delay downstream movements of spawning adults. Additionally, downstream mortality may be caused by hydroelectric facilities by impingement or turbine passage. Freshwater habitat degradation resulting in reduced food productivity increases mortality of the freshwater life stages. Predation by fish, birds, and mammals can impact eel populations during all life stages. The non-native swim bladder parasite, *Anguillicoloides crassus*, can decrease swimming ability and reduce the silver American eel's ability to reach the spawning grounds. Contaminants also may reduce the reproductive success of American eels because they have a high contaminant bioaccumulation

rate (Couillard et al. 1997). Oceanographic changes influencing larval drift and migration may reduce year-class success. American eel, as a panmictic species, could be particularly vulnerable to drastic oceanic variations. An understanding of the requirements of the American eel's different life stages is needed to protect and manage this species.

2.1 Stock Definitions

The American eel is a panmictic species, with a single spawning stock that reproduces in the Sargasso Sea. American eel larvae (leptocephali) are broadly dispersed by ocean currents along the Atlantic coasts of northern South, Central, and North America. Genetic research indicates that there is no reproductive isolation of American eels migrating from the Atlantic Coast (Avisé et al. 1986; Wirth and Bernatchez 2003; Cote et al. 2013; Bonvechio et al. 2018). Further, any genetic differentiation is a result of natural selection upon a particular cohort within a geographic area rather than actual genetic differences within the species (Pavey et al. 2015).

2.2 Migration Patterns

American eels may travel thousands of miles in their lifetime. They are a catadromous fish that spawn in the Sargasso Sea, and the larvae drift on ocean currents until they reach the eastern seaboard of North America. Young American eels actively swim upstream to reach estuarine and freshwater habitats, sometimes hundreds of miles upriver. The young American eels spend between 3 and 30 or more years in estuarine or freshwater habitats before maturing and migrating back downstream and to the Sargasso Sea to spawn. Since the 2012 assessment, oceanic tracking of silver American eels from Canada has been conducted, suggesting that migration to the Sargasso Sea occurs along the edge of the Continental Shelf and then through deeper waters from Canada directly to the spawning grounds (Beguer-Pon et al. 2015; Beguer-Pon et al. 2017).

2.3 Life Cycle

American eels undergo six distinct life stages. The life cycle begins when the eggs hatch and leptocephali (larvae) are carried by ocean currents from the spawning grounds in the Sargasso Sea. The prevailing currents along coastal areas disperse the leptocephali, which metamorphose into glass eels on the continental shelf. Glass eels move toward inland areas and become pigmented elvers before or during their entry into coastal estuaries. Elvers and yellow American eels settle in habitats ranging from estuaries to far upstream freshwater reaches. American eels reach the silver stage at maturity and return to the Sargasso Sea, where they spawn and die.

2.4 Age

2.4.1 Ageing Workshops and Recommendations

A workshop on ageing and sexing American eels was held by the ASMFC in 2001 (ASMFC 2001). The workshop's goals were to present current knowledge to the TC on techniques for ageing

and sexing that could be used by states to collect data for future stock assessments. The workshop concluded that acceptable methods for sexing American eel are gonad squash and histology. For ageing, embedding and sectioning or grinding and polishing were preferred techniques for processing and reading otoliths. These methods became accepted by the ASMFC and are described by Liew (1974), Chisnall and Kalish (1993), and Oliveira (1996). At that time, neither a sample exchange was performed nor was there any calculation of ageing bias or precision between agencies and laboratories ageing the species.

Age data were available for the 2012 assessment from otolith samples from Delaware Division of Fish and Wildlife and Maryland Department of Natural Resources, as well as some research studies (see Appendix 3 Table 1 in ASMFC 2012). Concerns raised from both the Workshop on Ageing and Sexing American Eel (2001) and the benchmark stock assessment (2012) regarding the ages of American eels were that analyses indicated age is a poor predictor of length, age samples from estuarine populations may not be representative of freshwater populations, current biological sampling may not provide sufficient spatial coverage, and there is the possibility that during metamorphosis the otolith reabsorbs material and causes discrepancies for ageing (McCleave 2008). As more age data are collected by agencies and labs along the Atlantic coast and efforts are being made to collect data to eventually support an age-based model, the TC recommended organizing a sample exchange for American eel agers.

An exchange of American eel otoliths from various states along the Atlantic coast was completed in May 2017 (ASMFC 2017b). The exchange had participation and samples from Maine to Florida and included whole (both (1) loose whole otoliths and (2) mounted and polished whole otoliths) and sectioned otoliths, many as paired samples. Analysis from the exchange indicated systematic bias and a lack of precision in age readings as well as low agreement between readers both within lab and between states. Varying levels of experience, lack of familiarity reading whole otoliths, identifying the first and last annulus, and knowing when to round ages based on annulus count, catch date, and margin codes were all identified as potential reasons for the low agreement. The agers requested an in-person workshop to compare methods, establish a preferred method and ageing protocol, and discuss an ageing timeline for American eels.

In January 2018, American eel agers met for an in-person workshop to compare protocols, make age determinations as a group, establish a preferred method for processing and ageing American eel otoliths, and discuss an ageing timeline. The participants of the workshop agreed that loose whole otoliths should not be used for ageing American eels; rather, only whole otoliths that have been mounted and polished or sectioned otoliths should be used. Adding a drop of water to sectioned or whole otoliths did improve readability for some samples and may be used. Staining or dyeing the sectioned otoliths with Toluidine Blue did not significantly increase readability despite it being the historical standard for processing sectioned otoliths (Oliveira 1996). Readers concluded that given the extra processing time it required, it did not offer a large enough benefit to continue using it. Additionally, it seemed to hamper the reading of the historical samples and may require them to be reprocessed and re-stained in order to make them readable. The most agreement in ages occurred when workshop participants

examined the paired section and whole (mounted and polished) otoliths together. Recognizing that is not a feasible way to do production ageing, it should be considered at least for training purposes for new readers.

There were several issues the participants identified that led to age reading discrepancies. Double banding or splitting of annuli did not occur in all samples, but it did appear on many samples and readers should be conscious of not over-counting. Following a complete annuli around the otolith can help determine if it is a single or split annuli. Over-sanding or sectioning samples too thin also resulted in over-counting and should be avoided. Participants also noted that for older aged samples (>7 years), sometimes annuli on the edge were lost on whole mounted samples as compared to the paired section. Properly sanding the mounted otolith did improve readability, but readers may want to consider an age cutoff for when whole otolith reading may not be appropriate and samples should be sectioned for age determination.

The ageing timeline for American eel developed by the Gulf and Atlantic States Marine Fisheries Commissions ageing manual was reviewed by the agers at the workshop (Figure 1). After evaluating samples from along the coast during this workshop, readers suspected that the time of annulus deposition varied latitudinally and that there was not enough information coastwide to establish this in a comprehensive way.

2.4.2 Age Data

Age data were supplied for this assessment from the commercial pot fisheries in New Jersey, Delaware, Maryland, and Georgia (Table 1). Maryland also supplied some ages collected from a fishery-independent survey. Sample sizes varied from state to state and most ages were supplied by Maryland, where whole otoliths are used for ageing rather than sectioned otoliths like other states. Most ages were between 2–6 years old (Figure 2).

2.4.3 South Carolina Ageing Project

Following ASMFC 2017, South Carolina Department of Natural Resources (SC DNR) noted that both the YOY and yellow American eel surveys in their state had significant downward trends in relative abundance. In response to these findings, biologists in the state reviewed the research recommendations in the assessments and noted that one of the most critical data needs was to “conduct intensive age and growth studies at regional index sites to support the development of reference points and estimates of exploitation.” To begin to address this data gap in their waters, SC DNR obtained a grant to complete a project to collect and process histological and otolith samples. From 2012–2018, SC DNR processed 1,141 gonad histological samples to determine sex and maturity stage and 1,081 paired whole and sectioned otolith samples to determine age. Life history information was also summarized to characterize American eels in South Carolina waters including length, weight, life stage, *A. crassus* infection, maturity stage, and age. The project’s final report was provided to the SAS (SC DNR 2020).

The SC DNR group found no ageing bias for sectioned otoliths but did find bias for whole otolith readings. Similarly, there was precision and reproducibility of age estimates using sections but

not for whole otolith samples. When comparing the samples to each other, the two methods were not comparable. SC DNR found the sectioned otoliths to be the superior hard part for age determination and developed an ageing method translation table to convert whole otolith ages into sectioned otolith ages.

2.5 Growth

Growth rates are highly variable for American eels across their range and within the same watershed. American eels tend to grow more quickly in the southern portion of their range compared to the north, and females tend to grow more quickly than males (Jessop 2010). Male maximum size is the same throughout their distribution (Jessop 2010); however, female American eels reach a larger maximum size in the northern portion of their range compared to the south (Jessop 2010). American eel length varies widely for a given age and sex for individuals in the same watershed, so length-at-age relationships for American eels are unreliable (ASMFC 2017).

2.5.1 Growth Meta-Analysis

2.5.1.1 Methods

Biological data for American eels was compiled from a number of past and ongoing research programs along the Atlantic coast and classified into one of the six geographic regions used in the assessment. These data, updated through 2020, were used to model both the length-weight and age-length relationship for American eel. The relation of length in millimeters to weight in grams was modeled using the allometric length-weight function. Length-weight parameters were estimated by region, sex, and for all data pooled together. The analysis of the residual sum of squares (ARSS) method was performed to compare the length-weight curves among regions and between sexes (Chen et al. 1992; Haddon 2001). The ARSS method provided a procedure for testing whether two or more nonlinear curves are coincident (i.e., not statistically different). Values were considered statistically significant at $\alpha < 0.05$.

Linear regression was used to model the relation of age in years to length in millimeters by region, sex, and for all data pooled together. A test for coincident regressions was applied to test for differences in the regressions among regions and between sexes (Zar 1999). Values were considered statistically significant at $\alpha < 0.05$. The age-length relationship for American eels was also described through the von Bertalanffy model, which is given by:

$$L_t = L_\infty [1 - e^{-K(t-t_0)}]$$

where L_t is length-at-age t , L_∞ is the theoretical asymptotic average length (if $K > 0$), K is growth rate at which the asymptote is approached, and t_0 is the hypothetical age at which length is zero. Model fits were first evaluated based on convergence status; models that did not successfully converge were removed from consideration for the associated dataset.

2.5.1.2 Results

The length-weight analysis consisted of 81,830 American eels across all six geographic regions, 7,249 identified by sex. The length-age analysis included 20,577 samples across all regions, including 6,507 identified by sex. The Chesapeake Bay and Delaware Bay/Mid-Atlantic Coastal Bays regions were the source of more than 73% and 76% of the length-weight and length-age biological samples, respectively. The length-weight model successfully converged and parameters estimated for each of the six regions, by sex, and for all data pooled (Table 2; Figure 3). The results of the ARSS indicated that there were statistically significant differences in the length-weight relationship between at least two regions ($F_{10, 81,816}$, $P < 0.001$). Parameter estimates were very similar in five of the six regions with the exception of Southern New England; however, length-weight data from this region consisted solely of samples from Marine Recreational Fisheries Statistics Survey (MRFSS). Due to weights being estimated in the MRFSS survey and an extremely small sample size ($N=166$), length-weight parameters in the Southern New England region should be evaluated with extreme caution. Except for Southern New England, American eels from the South Atlantic exhibited slightly higher weights at length compared to the remaining regions. The results of the ARSS indicated sex-specific significance between estimated length-weight parameters ($F_{2, 7,245}$, $P = 0.027$; Table 2). These results were somewhat expected due to the drastically different growth history strategies for male and female American eels.

The parameters estimated from the linear regression of length on age for the various dataset configurations are presented in Table 3. There are statistically significant differences in the age-length relation among regions based on the results of the test for coincident regressions ($F_{10, 20,565}$, $P < 0.0001$). The final parameter estimates suggested distinct differences in growth patterns between the northernmost regions (Hudson River, Southern New England, Gulf of Maine) and the southernmost regions (Del Bay/Mid-Atlantic Coastal Bays, Chesapeake Bay, South Atlantic; Table 3; Figure 4). All three southernmost regions exhibited extremely similar growth patterns based on the linear regression. Growth estimates by region largely followed a latitudinal pattern, where the greatest lengths at age were estimated for the South Atlantic and the slowest lengths at age were estimated for the Gulf of Maine. The test for coincident regressions also detected significant differences in the age-length regressions between sexes ($F_{2, 6,503}$, $P < 0.0001$). The results suggested the rate of growth in length with age is faster in females than in males (Table 3; Figure 5).

Parameters were estimated from the von Bertalanffy model to further examine the age-length relationship of American eels by region and by sex (Table 4; Figure 6). The model failed to converge for the Southern New England region and for males. Although differences in growth estimates between the northernmost and southernmost regions were not as apparent with the von Bertalanffy model compared to the linear regression analysis, there were clear latitudinal differences in estimated length at age by region. Estimates of length at age were the greatest among all regions for the South Atlantic from ages 2–11 years and the Chesapeake Bay from ages 12–18 years. Estimates of length-at-age were the smallest for the Gulf of Maine ages 2–16 years.

Significant variation in length at age and a broad overlap in lengths across multiple age groups were observed in the data even within a regional analysis (Figure 7–Figure 13). Pooled data for all regions amplified these variations in length at age. These analyses confirm the relationship between age and length for American eels is not well defined and that age is a poor predictor of length for American eels. Ageing error and uncertainty around ageing estimates may also play an additional role in the weak relationship between length and age.

2.5.2 Bootstrap Estimation of von Bertalanffy Age-Length Growth Parameters

Because the results of the growth meta-analysis indicated that there was significant variation in length at age, the SAS struggled with what values to use in the modeling approaches, specifically the coastwide delay-difference model. Growth model parameters are needed for the delay-difference model, which is coded for von Bertalanffy growth parameters but could potentially be expanded to accommodate a different growth model if needed. The growth data was explored and ultimately the SAS recommended setting up a bootstrapping routine to take a specified number of samples at each age regardless of where the data were collected geographically. The SAS noted that there was some sex data available, but the delay-difference model was developed for both sexes and therefore the bootstrapping estimation of von Bertalanffy growth parameters was not done by sex.

2.5.2.1 Method

Parameters from the von Bertalanffy age-length growth model were estimated using standard bootstrapping techniques (Efron and Tibshirani 1993). Ages in the available age-length data ranged from age 0 (primarily from the YOY data) to age 37 and the number of lengths available at each age was variable (Table 5). The working group decided to only include in the bootstrap analysis those ages that had a minimum of 30 lengths. This excluded ages older than 21 years.

Bootstrapping was used to construct 1,000 bootstrap replicates of the data by randomly sampling the data with replacement at each age. The von Bertalanffy age-length growth model was fit to each bootstrap sample to estimate L_{∞} , K , and t_0 . The median value for each parameter was computed over all bootstrap estimates. The analysis was performed in R (version 4.1.1, R Core Team 2021).

2.5.2.2 Results

The median values of the bootstrap parameter estimates were L_{∞} equal to 452.7 mm, K equal to 0.4864, and t_0 equal to -0.3349 (Figure 14). These values are used in the delay-difference model (Section 6.9).

2.6 Reproduction

The sex of American eels can be determined by gross morphological examination. Differentiation between sexes occurs in the yellow eel stage of American eels and maturity at length varies by sex and latitude and males mature at a smaller size and younger age (Jessop 2010). Sex ratios by location are also variable with males found more commonly in downriver

sites and females more common in upriver sites, but the mechanism for sex determination has not been established. Field studies suggest that sex determination may either be driven by density dependence or that females more typically migrate upstream (Roncarati et al. 1997; Krueger and Oliveira 1999; Davey and Jellyman 2005; Cote et al. 2015). Oliveira and McCleave (2000) found that yellow eels >400 mm and silver eels >425 mm were exclusively female. The fecundity of female American eels is directly related to size (Jessop 2018). American eels are thought to spawn in the Sargasso Sea during late winter through spring, but spawning has never been observed. Several silver American eels have been tracked from Canada to the Sargasso Sea and arrival at the spawning grounds occurred in January and February for American eels that were tagged and released in October (Beguer-Pon et al. 2017). It is unknown if American eels have paired or group spawning. Because no spent American eel has ever been documented, it is assumed that American eels are semelparous.

2.7 Natural Mortality

Very little is known about the natural mortality of American eels. Since American eels are highly fecund, natural mortality is likely very high, particularly during the early life stages. American eel survival is likely impacted by changes in oceanographic conditions, predation, and the spread of the non-native swim bladder nematode *Anguillicoloides crassus*. Estimates of natural mortality are often obtained through indirect measures, such as estimating total mortality and subtracting fishing mortality to obtain natural mortality estimates or linking natural mortality to life history characteristics (e.g., Lorenzen 1996; Hewitt and Hoenig 2005). For European eel, Bevacqua et al. (2011) developed a relationship between eel body mass, water temperature, stock density, and sex from 15 European populations to estimate natural mortality and such models may help provide estimates of natural mortality for American eels. Generalized depletion models have also been used to provide estimates of natural mortality for American eel elvers in Nova Scotia (Lin and Jessop 2020).

American eel early life stages are likely highly impacted by changes in oceanographic conditions that affect both survival and transportation to the coast of North America (ASMFC 2012; Miller et al. 2015; ASMFC 2017). Jessop (2020) found that the elver fishery in Nova Scotia has occurred earlier in recent years suggesting that warming sea surface temperatures and a northward shift in the Gulf Stream may result in shorter migration periods and earlier arrival in continental waters.

Predation on American eels is a source of natural mortality (ASMFC 2012; ASMFC 2017). Several studies examined the diet of blue catfish *Ictalurus furcatus* in the Chesapeake Bay and have shown a relatively small percentage of stomachs contained American eels (Schmitt et al. 2017; Schmitt et al. 2019a, 2019b); however, the large population size of blue catfish in Chesapeake Bay Rivers could result in considerable numbers of American eels being consumed each year. Additional predation by flathead catfish *Pylodictis olivaris* has also been documented (Schmitt et al. 2017).

Given their life history, American eels are likely to have a high rate of predation, particularly at young ages and smaller sizes. Glass eels, elvers, and even smaller yellow American eels are

likely preyed upon by estuarine and freshwater fishes, birds, and other organisms. Despite this, few sources of diet data contain records of American eels in the stomachs of predators. The NEFSC (Northeast Fisheries Science Center) food habits database contains only six individuals found in the stomachs of smooth dogfish *Mustelus canis*, spiny dogfish *Squalus acanthias*, haddock *Melanogrammus aeglefinus*, and goosefish *Lophius americanus* for 1973–2020. While this is unsurprising given that the food habits database is collected during the off-shore NEFSC bottom trawl survey, Nelson et al. (2003) reported no American eels in the stomachs of striped bass *Morone saxatilis* during their research. Likewise, investigations during the menhaden ecological reference points project (SEDAR 2020) found little evidence of American eel consumption after surveying multiple studies on striped bass, bluefish *Pomatomus saltatrix*, spiny dogfish, and weakfish *Cynoscion regalis* diet data; however, Walter and Austin (2003) suggested that American eels composed 3% by weight of the diets of striped bass in the mesohaline portions of Chesapeake Bay for large striped bass (>710 mm) and low (1%–2%) but detectable amounts in other areas of the Bay for other sizes. This suggests that current diet studies in more coastal or lower estuarine habitats may be missing the low but consistent contribution of American eels to the diet of predators. Further research on the importance of American eels to the diet of upper estuarine systems and lower freshwater habitats is suggested.

The non-native swim bladder nematode, *A. crassus*, may be reducing American eel survival during the yellow and silver eel life stages (see ASMFC 2012, 2017). Location is observed to be a key factor influencing nematode prevalence. In American eels collected from Hannacroix Creek, a tributary of the Hudson River, New York in 2009, *A. crassus* infections were present in all size classes with an infestation rate of 49.7% (Waladt et al. 2013). Large American eels had a significantly higher incidence of parasite infection than medium or small eels, and the highest incidence of empty stomachs was observed in American eels with the highest incidence of parasite infestation (Waladt et al. 2013). In Canada, nematode prevalence levels were 7.9% in New Brunswick and 0.7% in Nova Scotia in 2008–2009 (Campbell et al. 2013); however, a different study reported an overall prevalence of 46% in 2009 to 2010 from Nova Scotia (Denny et al. 2013). Prevalence of *A. crassus* in American eels in the St. Lawrence River watershed has been reported to increase since 2014 to approximately 30% in recent years (Pratt et al. 2019). Two American eel samplings at Conowingo Dam, Maryland in 2012 estimated nematode prevalence to be 32% and 46% (Minkinen and Park 2014). Later studies have found a higher prevalence at Conowingo Dam on the Susquehanna River ranging from 54 to 62.5% (Normandeau Associates 2018, 2021). From 2011–2013, parasite prevalence in South Carolina ranged from 29% to 58%. (Hein et al. 2014, 2016) with season significantly impacting only larval prevalence (Hein et al. 2014). In different regions of Florida, 0%–78% of American eels were infected with the swim bladder parasite from 2014 to 2016 (Bonvechio et al. 2018). In contrast to the high prevalence seen in many areas, Kwak et al. (2019) did not find any of the 120 American eels they examined in the Caribbean Island of Puerto Rico during 2015–2016 to be parasitized by *A. crassus*.

Warshafsky et al. (2019) quantified nematode prevalence, abundance, intensity, and swim bladder damage in various life stages of the American eel in the lower Chesapeake Bay in 2015

in relation to season of capture, river system, and total length. They found glass eels had a much lower infection prevalence (3.2%), mean abundance per eel (0.047 ± 0.009), and mean infection intensity (1.46 ± 0.195) as compared to elvers and yellow eels (prevalence was 59.2%, mean abundance per eel was 1.51 ± 0.061 , and mean intensity per infected eel was 2.44 ± 0.072). A weak positive correlation was observed between nematode abundance and swim bladder damage. Also, the survival probability of disease-positive eels was estimated to be lower (0.76) compared with disease-negative eels.

2.8 Incidental Mortality

Incidental mortality, caused by anthropogenic activities other than harvest, can be attributed to habitat alterations and restrictions as well as mechanical and chemical injuries. Inland habitat alterations and restrictions come primarily in the form of barriers to upstream migration for American eels. These can either be physical (dams) or chemical (areas of poor water quality) factors that limit habitat use by American eels. This compression of range through habitat restrictions may increase the level of predation mortality or contribute to density-dependent effects on growth or reproductive success. Mechanical and chemical injuries and mortality can occur during migration through or at hydroelectric turbines, navigation locks, industrial and municipal water intakes, chemical barriers, and contaminants. Impingement, entrainment, and turbine operation, such as at dams, locks, and power plants, can result in high rates of mortality. Poor water quality, such as low dissolved oxygen, drastic salinity changes, chemical spills, point source releases, and non-point source releases can cause incidental mortality and reduced reproductive success of American eels. These issues are described in more detail in the 2012 and 2017 assessment documents (ASMFC 2012, 2017).

Recent studies have further documented that providing upstream passage or removing dams can increase American eel populations in rivers (Turner et al. 2018) but those benefits can be negated by migratory delays and mortality caused by turbines in rivers with hydroelectric projects (Eyler et al. 2016; Mensinger et al. 2021). Sweka et al. (2014) found that the upstream passage of American eels had to consider the cumulative survival of downstream migrating adults in systems where turbine mortality can occur to provide any benefits to the population. If the downstream passage did not meet a certain “break-even threshold”, then upstream passage negatively impacts the population versus no passage at all.

2.9 Bycatch

Little data exist to document the bycatch of American eels in other fisheries. Only two individuals were recorded in the NEFOP (Northeast Fisheries Observer Program) as bycatch over the entire program since 2003 (Micah Dean, MA DMF, personal communication). This is unsurprising, as the focus of the NEFOP data collection program tends to be off-shore fisheries in federal waters, whereas American eels tend to be more abundant in coastal estuarine and freshwaters. Fisheries in state waters, particularly pots and gill nets, are more likely candidates for having American eel bycatch; however, without a comprehensive database combining various at-sea monitoring programs run by the individual states, investigations into this possibility were not feasible during the timeframe of this assessment.

3 HABITAT DESCRIPTION

A detailed review of American eel habitat requirements can be found in the Atlantic Coast Diadromous Fish Habitat document (Greene et al. 2009). Habitat needs are summarized in ASMFC's [habitat factsheet](#) for American eels and descriptions by life history stage can be found in Section 3 of ASMFC 2012.

Briefly, American eels exhibit a highly complex catadromous life cycle and are found in marine, brackish, and freshwater habitats (Adams and Hankinson 1928; Facey and LaBar 1981; Helfman et al. 1984; Facey and Van Den Avyle 1987). Habitat types used by different phases of American eels include open ocean, estuaries, rivers, streams, lakes (including land-locked lakes), and ponds (Facey and Van Den Avyle 1987). American eel habitat associations and requirements vary by life stage. After hatching in winter and spring in the Sargasso Sea, larval American eels passively migrate to the continental shelf along the east coast of North America where they metamorphose into glass eels (Greene et al. 2009). After developing pigment (becoming elvers), some American eels start migrating upstream into freshwater while others remain in coastal rivers and estuaries. Upstream migration may continue throughout the yellow phase as well and yellow eels are known to migrate between fresh and brackish habitats. During maturation, silver American eels migrate downstream to the ocean and return to the Sargasso Sea to spawn before dying (Haro and Krueger 1991).

Whereas several factors have likely contributed to the decline of American eels across their range, barriers such as dams have been a major factor in habitat fragmentation that restricted American eel's access to various habitats. There have been many efforts to remove dams to improve passage over the last few decades. The effects of dams and the benefits of removals on American eels are well documented, but studies since the last stock assessments (ASMFC 2012, 2017) continue to describe the effects of the dams on impeding movements of American eels and document population increases or expanding habitat use following a dam's removal. A recent study in New York's Bronx River showed that upstream areas had decreased abundance of American eel compared to downstream sites, with abundance decreasing rapidly above the first dam on the river (Camhi et al. 2021). Following the removal of the Embrey Dam on the Rappahannock River in Virginia, American eel abundance significantly increased in headwater streams (Hitt et al. 2012). Similarly, yellow American eel abundance increased in the Mill River in Massachusetts following barrier removal (Turner et al. 2018). Further, Hitt et al. (2012) documented that dams can influence American eel abundance up to 150 river kilometers upstream from the dam. For the dams that remain in place, such as hydroelectric, American eels are sometimes able to move above dams but then can experience injuries and mortality when they migrate downstream. Sweka et al. (2014) evaluated if passing American eels upstream of dams leads to reduced reproductive output from a river with hydroelectric facilities. Using an egg-per-recruit (EPR) model applied to the Susquehanna River, Sweka et al. (2014) found that if American eels were passed upstream of multiple dams then a minimum cumulative downstream passage survival had to be achieved for the upstream passage to be beneficial. Without achieving that level of survival, upstream passage results in a lower EPR when compared to no passage.

Since the publication of the last stock assessments for American eel (ASMFC 2012, 2017), there have been a couple of publications about the influence of the Gulf Stream on American eel recruitment. Rypina et al. (2014, 2016) used models to show how ocean circulation can affect how American eel larvae reach the coastal nursery habitats. The success of larvae reaching nursery habitats is significantly affected by the Gulf Stream since it is an obstacle that needs to be crossed in order to reach coastal habitats. Typically, the Gulf Stream flows from Florida northward to Cape Hatteras where it separates from the coast and moves toward the open ocean, although in some years it separates north of Cape Hatteras, in what is called “overshoot” events. Eddies often break off from the Gulf Stream near the separation point and flow toward the coastline, helping to carry larvae to nursery grounds. Rypina et al. (2014, 2016) found that American eel larval success rates were higher when the Gulf Stream had an overshoot event and that eddies played a large role.

3.1 USGS Habitat Analysis

At the request of and in partnership with the ASMFC, the USGS conducted a pilot assessment of the capability to employ geographic information systems (GIS) -based habitat analysis to potentially inform American eel stock assessment analyses. While initially limited to the relatively data-rich Chesapeake Bay and Delaware River watersheds, the pilot project reviewed previous habitat assessment studies on American eels and closely related eel congeners in other parts of the world, assembled tidal and non-tidal occurrence and abundance records for the study region, assessed occurrence records for modeling suitability, gathered appropriate GIS-based environmental predictor datasets, and tested statistical modeling of occurrence and abundance based on GIS predictors. The USGS identified 10,286 inland and 63,812 tidal eel records suitable for spatial distribution modeling. Additionally, useful predictor GIS datasets, including river network fragmentation from dams, connectedness to the ocean, stream temperature and substrate, watershed land use and pollution sources, and other spatial data were identified and assembled from available sources for modeling. Results demonstrate that using these data, reliable spatial models of American eel occurrence, particularly for the period from 1995–2019, can be constructed from existing data, and dependent on data availability, models of abundance can also be reliably produced in a fashion that considers zero-inflated survey data. As with many previous studies, the major factors influencing American eel distribution continue to be large-scale network fragmentation from dams; however, due to the limited availability of historical data of sufficient quantity and quality, it is difficult to assess the historical restriction on habitat availability and use from past dam construction. Instead, models are largely limited to assessing current habitat use, but moving forward it may be possible to inform American eel population restoration efforts from fishway construction and dam removal. A full description of the data and analysis explored will be available as a USGS Open File Report (OFR) series in fall 2022.

4 FISHERY-DEPENDENT DATA SOURCES

4.1 Commercial Yellow Eel Fishery

4.1.1 Description of Fishery

The yellow life stage of the American eel has been the primary target of US eel fisheries in both historical and modern periods. Yellow eels are harvested for use as bait in other fisheries and for food both domestically and internationally as part of an export market (Section 4.5). The use of harvested American eels for bait in other fisheries is not well described, although it does not appear to have been common before the 20th century nor had the relative importance of food markets. In recent years, American eels have been used as bait in the recreational fisheries for striped bass, cobia, and catfish.

The dominant gear for targeting yellow American eels in the US has been baited pots (Figure 15). The use of in-river weirs and fykes to capture spring movements of yellow American eels has not been a widespread practice but has provided important local fisheries in some regions. The contributions of both spear and other non-pot fisheries have been minor relative to overall US American eel harvests and are incidental in contemporary fisheries.

American eels currently support commercial fisheries throughout their range in North America, with significant fisheries occurring in the US Mid-Atlantic region and Canada. These fisheries are executed in riverine, estuarine, and ocean waters. In the US, commercial fisheries for glass eel/elvers exist in Maine and South Carolina and a silver eel weir fishery exists in New York's Delaware River, whereas yellow eel fisheries exist in all states and jurisdictions with the exception of Pennsylvania and the District of Columbia.

4.1.2 Data Collection

The earliest detailed account of US eel fisheries was provided by Goode (1884) for the period of 1877 to 1880. Historical commercial landings data from 1888 to 1940 were transcribed from online US Fish and Fisheries Commission Annual reports. Since 1950, most landings information on the East Coast has been collected by NOAA Fisheries through dealer and/or fisherman reporting under a state-federal cooperative program. All historical NOAA Fisheries data are now housed at Atlantic Coastal Cooperative Statistics Program (ACCSP) data warehouse.

The most reliable landings for American eels are from 1998 through the present. Commercial yellow American eel landings for each state were validated through ACCSP for 1998–2020. Inconsistencies between landings in the ACCSP data warehouse and annual compliance reports were resolved as part of the validation process. The data from 2020 are considered preliminary.

4.1.3 Data Caveats

NOAA Fisheries data collection is focused on species that are managed exclusively or jointly at the federal level, although information is also collected on species that are managed at the state level. Other caveats associated with these data are discussed at the following website:

<https://www.fisheries.noaa.gov/commercial-landing-data-caveats>. Because American eels are managed by the states and are not a target species for the NOAA Fisheries, landings may be underreported in the historical record (pre-1998). In addition, at least a portion of commercial American eel landings typically come from non-marine water bodies. Even in states with mandatory reporting, these requirements may not extend outside the marine district, resulting in a potential underestimate of total landings. Despite concern about the level of under-reporting, the committee felt that reported landings were indicative of the trend in total landings over time.

In both federal and state landings reports there may be misreporting of other eel species (e.g., conger eel) as American eels either due to data entry mistakes or lack of species-specific reporting requirements. The committee has vetted the data where possible to eliminate known cases of misreporting by species; however, an unknown amount of American eel landings used in this assessment may actually be other species of eel; therefore, marine landings of American eels in some areas and years may be over-reported.

4.1.4 Yellow Eel Landings

Commercial yellow eel landings for the 1900s through 1950 should be used with caution since there are several data caveats associated with the historical records (Section 4.1.3). While the 1950–1998 yellow eel landings record is more comprehensive than pre-1950 landings, there are still many caveats with their use and they should also be used with caution. Again, historical landings (pre-1998) cannot be validated. State-by-state landings from 1998–2020 were validated through ACCSP and state partners (Table 6), although some states have confidential landings due to the rule of three, e.g., there are not more than three harvesters within a state.

Beginning in 1950, landings were at two million pounds and began to decline through the 1960s to almost half a million pounds (Table 7; Figure 16). Landings began to increase again through the 1960s to the time series highs in the 1970s and 1980s of over 3.5 million pounds, although those landings cannot be validated. Beginning in the early 1980s, commercial yellow eel landings began a steady decline through the terminal year. In 2020, all states saw their landings decline and 2020 was the lowest coastwide landings since 1950. The Advisory Panel (AP) met and provided feedback that the decline in landings for 2020 was primarily market demand; demand for wild-caught American eels from the US for European food markets has decreased in recent years due to increased aquaculture in Europe. Additionally, demand for domestic bait decreased from 2019 to 2020 due in part to COVID-19 restrictions. A smaller proportion of landings traditionally goes to the domestic bait market, and the AP indicated that it does not anticipate landings to increase significantly from current levels in the near future.

4.1.5 Commercial Catch-per-Unit-Effort

Commercial yellow eel catch-per-unit-effort (CPUE) was available in some states but following a review of these data they were not considered indicative of trends in the stock as a whole. Fishery-dependent CPUE is almost exclusively composed of positive trips only. Trip reports with zero eels caught are rare because most agencies do not require reports of zero catches. Several

states did provide a commercial CPUE in their data submission and those are included in this assessment in Appendix A but were not used in any analyses.

4.2 Commercial Glass Eel Fishery

4.2.1 Description of Fishery

Glass eel fisheries along the Atlantic coast are prohibited in all states except Maine and South Carolina. In recent years, there has been an increase in the demand for glass eel due to the high value and concerns over population levels of European and Japanese eels, as well as tighter restrictions on the export of European eel. Harvest by dip net or fyke net has increased as the average market price has risen to over \$1,000 per pound since 2012, with peaks exceeding \$2,000 per pound (Figure 17). Since the implementation of Addendum IV (ASMFC 2014), Maine's glass eel quota has been set at 9,688 pounds (a 17.5% reduction from the 2014 quota). In 2020, preliminary landings indicate that 9,652 pounds of glass eels were sold for a value of \$5.1 million (\$525 per pound).

4.2.2 Data Collection

Maine has a daily dealer report/swipe card program. There is a tribal permit system in place for some Native American groups. In South Carolina, only fyke and dip nets are permitted for the glass eel fishery. Dealer/harvester reports are made monthly on trip tickets.

4.2.3 Glass Eel Landings

South Carolina's glass eel landings are confidential because of the rule of three but are reported annually in the FMP Reviews as being less than 750 pounds since 2015. Maine's glass eel landings have fluctuated through time from just over 1,000 pounds in 2004 to over 20,000 pounds in 2012 (Figure 17). Since the 2015 fishing season, Maine has had a glass eel quota of 9,688 pounds that has not been exceeded.

4.3 Recreational Fisheries

4.3.1 Description of Fishery

Studies and reports that summarize US American eel fisheries provide little information on targeted recreational American eel fisheries (Bigelow and Schroeder 1953; Fahay 1978; Lane 1978; and Van Den Avyle 1984). The practice of spearing or gigging American eels buried in the mud during winter is an eel fishing method that was developed for subsistence fishing but came to have both commercial and sportfishing appeal in the 19th century until recently. American eels are encountered over much of their US range by recreational anglers as bycatch. Van Den Avyle (1984) reported that no major sport fishery for American eels occurred in coastal rivers of the South Atlantic Bight, but incidental catches were made by anglers in estuaries and rivers. Despite the incidental nature of eel hook-and-line catches, the Marine Recreational Information Program (MRIP) does encounter enough observations to generate catch estimates that indicate widespread and common presence as a bycatch species.

4.3.2 Data Collection

The MRIP is designed to provide annual and bi-monthly estimates of marine recreational fisheries catch and effort data. Information on commercial fisheries has long been collected by the National Marine Fisheries Service (NMFS); however, data on marine recreational fisheries were not collected in a systematic manner by NMFS until implementation of the Marine Recreational Fishery Statistics Survey (MRFSS) in 1979. The purpose of the MRFSS was to provide regional estimates of effort and catch from the recreational sector. Importantly, the National Research Council (NRC) identified under-coverage, inefficiency, and bias issues within the MRFSS survey and estimation methodologies (NRC 2006). These deficiencies spurred the development of the MRIP as an alternative data collection program to the MRFSS. The MRIP is a national program that uses several component surveys to obtain timely and accurate estimates of marine recreational fisheries catch and effort and provides reliable data to support stock assessment and fisheries management decisions. The program is reviewed periodically and undergoes modifications as needed to address changing management needs. A detailed overview of the program can be found online at <https://www.fisheries.noaa.gov/topic/recreational-fishing-data>.

The MRIP uses three complementary surveys: (1) the Fishing Effort Survey (FES), a mail survey of households to obtain trip information from the private boat and shore-based anglers; (2) the For-Hire Telephone Effort Survey (FHTES) to obtain trip information from charter boat operators; and (3) the Access Point Angler Intercept Survey (APAIS), a survey of anglers at fishing access sites to obtain catch rates and species composition from all modes of fishing. The data from these surveys are combined to provide estimates of the total number of fish caught, released, and harvested, the weight of the harvest, the total number of trips, and the number of people participating in marine recreational fishing. In 2005, the MRIP began at-sea sampling of headboat (party boat) fishing trips.

The APAIS component was improved in 2013 to sample throughout the day (24-hour coverage) and remove any potential bias by controlling the movement of field staff to alternative sampling sites. The MRFSS allowed samplers to move from their assigned site to more active fishing locations but could not statistically account for this movement when calculating estimates. The MRIP implemented the FES in 2018 to replace the Coastal Household Telephone Survey (CHTS) due to concerns of under-coverage of the angling public, the declining number of households using landline telephones, reduced response rates, and memory recall issues.

Creel clerks collect intercept data year-round (in two-month waves) by interviewing anglers completing fishing trips in one of four fishing modes (man-made structures, beaches, private boats, and for-hire vessels). Intercept sampling is separated by wave, mode, and area fished. Sites are chosen for interviewing by randomly selecting from access sites that are weighted by estimates of expected fishing activity. The intent of the weighting procedure is to sample in a manner such that each angler trip has a representative probability of inclusion in the sample. Sampling is distributed among weekdays, weekends, and holidays.

The FES mail survey employs a dual-frame design with non-overlapping frames (1) state residents are sampled from the United States Postal Service computerized delivery sequence file (CDS) and (2) non-residents are individuals who are licensed to fish in one of the target states but live in a different state and are sampled from state-specific lists of licensed saltwater anglers. Sampling from the CDS uses a stratified design in which households with licensed anglers are identified prior to data collection. The address frame for each state is stratified into coastal and non-coastal strata defined by geographic proximity to the coast. For each wave and stratum, a simple random sample of addresses is selected from the CDS and matched to the addresses of anglers who are licensed to fish within their state of residence. Non-resident anglers are sampled directly from state license databases. The sample frame for each of the targeted states consists of unique household addresses that are not in the targeted state but have at least one person with a license to fish in the targeted state during the wave.

The FES mail survey collects fishing effort data for all household residents, including the number of saltwater fishing trips by fishing mode (shore and private boat). The FES is a self-administered mail survey, administered for six two-month reference waves annually. The initial survey mailing is sent one week prior to the end of the reference wave so that materials are received right at the end of that wave. This initial mailing is delivered by regular, first-class mail and includes a cover letter stating the purpose of the survey, a survey questionnaire, a post-paid return envelope, and a \$2 cash incentive. One week after the initial mailing, a follow-up thank you and reminder postcard is mailed via regular first-class mail to all sampled addresses. For addresses that could be matched to a landline telephone number, an automated voice message is also delivered as a reminder to complete and return the questionnaire. Three weeks after the initial survey mailing, a final mailing is delivered to all addresses that have not yet responded to the survey.

Fish that are available during APAIS interviews for identification, enumeration, weighing, and measuring by the interviewers are called landings or Type A catch. Fish not brought ashore in whole form but used as bait, filleted, discarded dead, or are otherwise unavailable for inspection are called Type B1 catch. Finally, fish released alive are called Type B2 catch. Type A and Type B1 together comprise harvest, while all three types (A, B1, and B2) represent total catch. The APAIS interviewers routinely sample fish of Type A catch that are encountered. Fish discarded during the at-sea headboat survey are also sampled. The headboat survey is the only source of biological data characterizing discarded catch that are collected by the MRIP; however, this number has been negligible (eight American eels from headboat discards between 2005 and 2019). The sampled fish are weighed to the nearest five one-hundredth (0.05) of a kilogram or the nearest tenth (0.10) of a kilogram (depending on the scale used) and measured to centerline length.

4.3.3 Data Caveats

The low precision associated with the recreational fishery statistics is due to the limited numbers of American eels that have been encountered during surveys of recreational anglers along the Atlantic coast. These limited numbers are partly due to the design of the

MRFSS/MRIP survey, which does not include the areas and gears assumed to be responsible for the majority of recreational fishing for American eels. As such, the recreational fishery statistics for American eels provided by MRIP should be interpreted with caution.

4.3.4 Recreational Harvest and Discards

Annual recreational harvest (Type A + B1) of American eels have exhibited high inter-annual variability in terms of both numbers and weight from 1981 through 2019, averaging around 136,000 American eels per year (Table 8; Figure 18). The estimates of recreational harvest for American eels are associated with high uncertainty as PSE values for both numbers and weight typically exceeds 50% (Table 8). Estimates of live releases (Type B2) have been less variable and more precise, averaging around 223,000 American eels per year from 1981 to 2019 (Table 8; Figure 18).

The high uncertainty associated with the estimates of recreational harvest for American eels is partly due to the rarity with which they are encountered during APAIS interviews. Between 1981 and 2019, there were over three million intercepts conducted along the Atlantic coast and, in the time period, less than one-half of one percent encountered American eels (Table 9).

4.3.5 Recreational Catch-per-Unit-Effort

An index of relative abundance for American eels was developed using MRIP data by Kahn (2019). The SAS decided not to adopt this index or expand this work for the benchmark due to many of the caveats listed in Section 4.3.3. First, the low number of American eels encountered by MRIP and the low precision make it inappropriate as an abundance index. Second, MRIP is designed to characterize recreational fisheries, such as striped bass *Morone saxatilis*, bluefish *Pomatomus saltatrix*, and weakfish *Cynoscion regalis*, as noted by Kahn (2019). The gears and areas where the survey operates are not consistent with those that encounter American eels. For instance, MRIP does not sample in freshwater where a large proportion of the population occurs. Additionally, MRIP targets rod and reel fisheries which are not typically used to capture American eels. A third concern relates to the fisheries-dependent nature of the index. Most stock assessment models assume that the population index is proportional to abundance. In order for this to be true, effort must be random with respect to the distribution of the population and catchability must be constant over space and time. Fishery-dependent CPUE indices are notoriously biased partly due to the non-random distribution of fisheries activity over time and space. Finally, several multi-species fisheries-independent surveys operate along the Atlantic coast that reliably encounter American eels and can be used to characterize the population. A fisheries-independent index of abundance that catches fewer than 0.014 American eels per trip, as Kahn's index does, would not be considered for use in any modeling approach (see section 5.1 for criteria).

4.4 Gulf of Mexico

A small portion of US landings are attributed to the Gulf of Mexico. Landings records in this region were historically collected by the NOAA Fisheries but have been administered by the

Gulf States Marine Fisheries Commission since 1985 (D. Bellais, GSMFC, personal communication). Between 1950 and 1999, landings in the Gulf of Mexico ranged between approximately 200 pounds in 1994 and 28,000 pounds in 1985 (Figure 19). Landings reported since 1999 have been negligible and are confidential (R. Maxwell, LA DWF, personal communication; Fisheries Information Network <https://data.gsmfc.org/apex/public>). Fahay (1978) reported total US landings of American eels during 1955–1973 with minor landings registered from the US Gulf of Mexico region during about half of those years but never exceeded 1% of total US landings. Note that the Gulf States (including western Florida) are under the jurisdiction of the Gulf States Marine Fisheries Commission and are not subject to ASMFC-led interstate fisheries management.

4.5 Export Data

Domestic imports and exports of live American eels from the US are tracked by the US Fish and Wildlife Service in the Law Enforcement Management Information System (LEMIS). The database contains import and export data from 1998 to present. Exports of live American eels from the Atlantic coast ranged from 2,447 to 605,273 pounds (1,110 to 274,547 kilograms) per year from 2000 through 2018 and the majority of exports in recent years have been of US origin (Figure 20). Life stage and number of American eels are not reported in this database and some portion of the exports consist of glass eels. Because of the wide range of American eel weights, depending on life stage, it is not possible to compare US exports to commercial landings for either yellow or glass eels (Thomas Leuteriz, LEMIS, personal communication).

4.6 Canada

4.6.1 Range

In historic times, American eels likely occupied all coastal and freshwater draining into the Atlantic coast of Canada, to the limit of drainage basins or impassible natural barriers (Cairns et al. 2013; Cairns 2020). This is termed the plausible historic range (Figure 21). Major barriers preventing upstream eel passage are Muskrat Falls on the Churchill River in Labrador, Caron Falls on the Saguenay River and Shawinigan Falls on the Saint-Maurice River, Quebec, and Niagara Falls on the Niagara River. The northern limit of known eel distribution is about 55°N on the coast of Labrador (Cairns 2020). A substantial fraction of the American eel's plausible range in the St. Lawrence Basin is in New York State, Pennsylvania, and Vermont (Figure 21). The upper St. Lawrence Basin includes the two largest lakes in the species' range: Lake Ontario (between Canada and the US) and Lake Champlain (between New York and Vermont). These lakes formerly supported abundant American eel populations, which persisted for 70 and 140 years, respectively, after the first damming of their outlet rivers (Morin and Leclerc 1998; Verdon et al. 2003; Busch and Braun 2014; Cairns et al. 2022).

The current range has diminished from the plausible historic range due to artificial barriers to migration and decreased recruitment to the upper St. Lawrence system. The shrinkage of Ontario's habitat occupied by eels has been documented from historic records and indigenous

and community knowledge (Mathers and Pratt 2011). Elsewhere in Canada, fine-scale habitat occupancy is generally less well documented.

The northern part of Maine drains to the Bay of Fundy through the Saint John River, which runs through New Brunswick (Figure 21). Water exiting northern Maine passes over Grand Falls (Grand Sault), a major waterfall on the Saint John in northwestern New Brunswick. NatureServe maps northern Maine as part of the eel range, although the supporting text does not cite data sources (Cairns et al. 2013).

4.6.2 Governance

American eel fisheries in Canada are governed by asymmetrical federalism. In the Atlantic Provinces (Newfoundland and Labrador, Nova Scotia, New Brunswick, Prince Edward Island), the federal Department of Fisheries and Oceans (DFO) manages fisheries through a regional structure consisting of the Maritimes Region (the Atlantic and Bay of Fundy drainages of New Brunswick and Nova Scotia), Gulf Region (Prince Edward Island and the Gulf of St. Lawrence drainages of New Brunswick and Nova Scotia), and Newfoundland and Labrador Region. In Ontario and Quebec, fisheries management authority is held by provincial governments. Both federal and provincial governments have regulatory oversight over habitat and general environmental matters.

4.6.3 Fisheries

Fisheries landing data have been consistently gathered in Canada since the 1870s. Figure 22 (A) plots reported landings beginning in 1875. Three major humps in reported landings are evident: the late 1800s, the inter-war period of the 20th century, and the 1970s and 1980s. Landings from the St. Lawrence Basin are strong or dominant through all these humps. The largest component of St. Lawrence landings are out-migrating silver eels caught in large traps in the estuary of the river. Since the early 1990s, total reported landings for the study area have decreased sharply, with St. Lawrence landings declining faster than landings from other regions. The last reported landings from New York State occurred in 1997 and Ontario closed its American eel fishery in 2004. American eel landings in Quebec have steeply declined, in part because of commercial license buy-back programs.

In recent years, the southern Gulf of St. Lawrence, especially eastern New Brunswick and Prince Edward Island, have become the dominant contributors to Canadian American eel landings. Fisheries for glass eels/elvers are highly lucrative but contribute little to landings by weight. Glass eel/elver fisheries occur primarily on the Atlantic coast of Nova Scotia and to a lesser extent on the Bay of Fundy coast of New Brunswick. There is also a small glass eel/elver fishery with undocumented landings on the south coast of Newfoundland.

Figure 22 (B) plots range-wide reported landings for the American eels. Reported landings were highest at the end of the 19th century and the beginning of the 20th; however, it is difficult to gauge the accuracy of these early reports. Nearly all reported landings are from Canada or US Atlantic states, with a minor contribution from the Gulf of Mexico and the Caribbean. Nearly all

landings in the St. Lawrence Basin were made in Canada and are therefore registered in Canadian statistics; however, a substantial fraction of American eels caught in Canada likely had spent time in US portions of the St. Lawrence system.

4.6.4 Status Evaluation

The main instrument that DFO Science Branch uses to formulate advice on the management of aquatic resources is the Canadian Science Advisory Secretariat (CSAS). Findings of CSAS workshops are web-posted as Research Documents and Science Advisory Reports. A second instrument, the Species at Risk Act (SARA), works through a body called the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). COSEWIC commissions status reviews of candidate species (or populations) at risk. Endangerment categories available to COSEWIC are Endangered, Threatened, and Special Concern. COSEWIC assessments are transmitted to the responsible department (DFO for aquatic species), and then to the federal cabinet for a decision on official listing. The decision may be to officially list the species as assessed by COSEWIC, reject the assessment, or send the file back for further study. The government may also postpone a decision indefinitely. If the species is officially listed, certain automatic provisions of SARA come into effect, depending on the endangerment category.

COSEWIC assessed the status of American eels in Canada as a Special Concern in 2006 (COSEWIC 2006) and Threatened in 2012 (COSEWIC 2012). The Government of Canada has not decided on either assessment, which means that the species is not officially listed.

In 2009, a CSAS workshop reviewed progress toward achieving the management goal of reducing the mortality on American eels (DFO 2010). In 2013, a CSAS workshop examined the potential of American eel populations to recover. This produced an advisory report (DFO 2013) and detailed accounts of life history and status indicators (Cairns et al. 2013), mitigation options (Chaput et al. 2014a), threats (Chaput et al. 2014b), and habitat (Pratt et al. 2014). In 2019, CSAS workshops examined the quality of abundance indicators (Cairns 2020) and calculated standardized abundance indicators for series which met an adequate quality standard (Cornic et al. 2021). Most of these series measure yellow eel abundance. One of them is glass eels/elvers (East River Chester, Nova Scotia; Figure 21). Only one watercourse (the St. Lawrence River) possesses a series that measure the abundance of outgoing silver eels.

A further report from the 2019 workshops reviewed methods and options to support American eel population analysis (Cairns et al. 2021). Cairns et al. (2022), arising in part from the 2019 CSAS workshops, examines novel ideals and underused resources which may aid progress toward a range-wide American eel assessment.

Broadly speaking, the reports cited above review general issues of biology and conservation, including distribution, threats, demographic parameters, fisheries harvest, habitat, passage, and abundance indicators. Most reports concentrate on Canadian data, although Cairns (2020) and Cairns et al. (2021, 2022) attempt species-wide coverage. All abundance series sites are located within Canada; however, 6 of the 16 sites shown in Figure 22 are at locations in the St. Lawrence Basin where a substantial fraction of the American eels encountered would have

occupied or passed through US waters. This means that these series should be considered international indicators, inferring abundance in waters of both Canada and the US.

No quantitative stock assessment has been attempted for the full Canadian segment of the American eel range; however, for the Maritimes Region (Atlantic and Fundy drainages of New Brunswick and Nova Scotia), spawner-per-recruit analysis has been used to generate biological reference points for elver fishing and turbine mortality (DFO 2019).

4.7 Eel Fisheries Outside the US and Canada

Because of the panmictic status of American eels, fisheries outside the jurisdiction of the United States are relevant to ASMFC management efforts, although they are not subject to management regulations implemented through the ASMFC. Brief descriptions of American fisheries at locations south of the United States are provided below for perspective on the activity at the southern end of the American eel's range. Information on commercial American eel landings from south of the US were queried from the Fisheries Department of the Food and Agriculture Organization (FAO) of the United Nations website.

4.7.1 Mexico, Dominican Republic, and Cuba

Studies and reports that summarize the US American eel fisheries provide no information on commercial eel fisheries in Mexico or the Caribbean Islands other than mentioning that the American eel's range does extend to these regions (Bigelow and Schroeder 1953; Fahay 1978; Lane 1978; Van Den Avyle 1984). Annual landings between 1950 and 2019 are available by country and major fishing area from the Food and Agriculture Organization (FAO) of the United Nations Fishery Global Statistics Program of the Fisheries Data, Information, and Statistics Unit (FIDI) via online tables. Mexico, the Dominican Republic, and Cuba reported a small amount of landings (primarily from in-river fisheries) from 1975–2010, although there are several missing values or years of no landings (Figure 23). There was an increase in landings, or reported landings, for 2011–2012 from Mexico and the Dominican Republic. From 2013–2017, landings remained relatively high for the Dominican Republic but not Mexico. It is unknown whether these reports are comprehensive.

5 FISHERY-INDEPENDENT DATA SOURCES

5.1 Stock Assessment Subcommittee Criteria

The SAS established the following set of criteria for evaluating data sets and developing indices of relative abundance for American eels:

Time series: Ideally, the time series should be at least 10 years long.

Survey design: Surveys with statistical designs are preferred, such as surveys with random stratified sampling.

Gear: Surveys should operate with gear that is capable of catching American eel and to which American eel are available.

Temporal and spatial coverage: Only surveys that operate during a time and place where American eels are available for capture should be considered. Examining the precision or proportion of zero catches of American eels in a survey can be tools for evaluating this.

Methodology: Survey methodology should be consistent throughout the time series or changes should be able to be accounted for in the standardization process.

The SAS evaluated over 80 data sets for developing indices of abundance for American eels. After some preliminary analysis, several were rejected for various reasons as indicated in Table 10, and abundance indices were developed from the remaining surveys. Indices of abundance were developed by stage: YOY (Table 11), elver (Table 12), or yellow eel (Table 13). All surveys were standardized by the SAS using R code developed by SAS member Laura Lee to consider a variety of statistical models, including generalized linear models (GLM), as well as zero-inflated models and nominal indices. Maps of the surveys were included when they were supplied by the data provider. The SAS discussed variables that should be included in the GLM standardization of YOY indices and decided to consider adding day of the year and day of the year squared as variables in the analysis in order to capture variables that influence the YOY run in addition to other variables (e.g., temperature, water level).

5.2 Surveys

5.2.1 Maine West Harbor Pond Survey

5.2.1.1 Survey Design and Methods

West Harbor Pond is the site of Maine's state-mandated YOY survey which has been in operation since 2001. The survey uses an Irish elver ramp and typically samples April through June depending on the run. During the run, gear is left to soak for 6–24 hours and checked 3–5 times a week.

5.2.1.2 Biological and Environmental Sampling

Biological sampling for YOY eel length, weight, and pigmentation of 60 samples is done once or twice a week. Water temperature, level, and discharge are collected as part of the survey.

5.2.1.3 Evaluation of Survey Data

West Harbor Pond Survey has 91% positive tows for American eels. GLMs were attempted for the West Harbor Pond data but the models had convergence issues. A nominal index was developed as was done for the 2012 benchmark. Length and pigment data were collected in the West Harbor Pond YOY survey. Mean length was consistent across years (Figure 24) and averaged 60.6 ± 3.6 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 25).

5.2.1.4 Abundance Index Trends

The index of YOY abundance at West Harbor Pond has varied throughout the time series with many lows and highs (Figure 26). In 2017, the survey experienced its highest YOY abundance in the time series, but the last few years have seen higher numbers similar to the first few years of the survey.

5.2.2 Maine Juvenile Finfish Beach Survey

5.2.2.1 Survey Design and Methods

This beach seine survey was initiated in 1979 on the Kennebec River between Augusta and Waterville at 14 sites and on the Androscoggin River at 6 sites (Figure 27). Deployment method changed in the years before 2000. The survey was designed to target alosines and striped bass, but it also encounters and records American eels. Sampling is conducted every other week from July to October at the permanent sampling sites. All fish are counted and the total length of ten of each non-target species is measured.

5.2.2.2 Biological and Environmental Sampling

No environmental data were collected as part of this survey. Length data on American eels were collected.

5.2.2.3 Evaluation of Survey Data

The survey was subset to the months of July–September when American eels are encountered. On average, American eels were caught in this survey with 18% positive seine hauls. Due to method changes in the early years of the survey, the time series was limited to 2000–2019. Additionally, the six JAB-SB sites were eliminated from the analysis since those sites rarely encountered American eels. A full model that predicted catch as a function of year, month, site, and day of the year was compared with nested submodels using AIC. The model including year, site, day of the year, and day of year squared with a negative binomial error structure was selected. Length data indicated that this survey catches mostly elvers (Figure 28).

5.2.2.4 Abundance Index Trends

The index was relatively stable through the early 2000s until it reached a peak of abundance in 2008 (Figure 29). The abundance of elvers was relatively low but stable in the early 2010s but increased to a high and stable abundance for 2016-2019.

5.2.3 New Hampshire Lamprey River

5.2.3.1 Survey Design and Methods

The Lamprey River YOY survey site is located near the fish ladder in Newmarket, New Hampshire, and has been monitored since 2001. A biologist from New Hampshire Fish and

Game sets up the monitoring station each year in mid-April when the fish ladder is being opened for the river herring run and sampling for American eels occurs for approximately ten weeks. Attractant water flows from the freshwater above the dam down a hose to the elver ramp. American eels ascend the ramp by going through Enkamat and drop into a bucket. Sampling stations are monitored four times a week by department biologists.

5.2.3.2 Biological and Environmental Sampling

During sampling, water temperature, water level, discharge, gear condition, and moon phase are recorded. A subsample for pigmentation stage, length, and weight of 60 American eels is taken twice a week.

5.2.3.3 Evaluation of Survey Data

Length and pigment data were collected in the Lamprey River YOY survey. Mean length was consistent across years (Figure 30) and averaged 65.6 ± 15.4 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 31). A full model that predicted YOY catch as a function of year, water level, discharge, gear condition, day of the year, and day of the year squared was compared with nested submodels using AIC. The model including year, day of the year, and day of year squared with an offset for effort and a negative binomial error structure was selected.

5.2.3.4 Abundance Index Trends

The index was variable for several years in the 2000s with high values and others with nearly zero (Figure 32). YOY catch peaked in 2013 and has been variable since with a slight uptick in abundance in the terminal year of 2020.

5.2.4 New Hampshire Fish and Game Rainbow Smelt Fyke Survey

5.2.4.1 Survey Design and Methods

The New Hampshire Fish and Game Rainbow Smelt Fyke Survey began operating in the Squamscott and Winnicut Rivers in 2008 and in the Oyster River in 2010 (Figure 33). The survey is conducted in March and April and is a fixed-station design using fyke nets that are set below the head of the tide at the three rivers. The sites are sampled three times a week beginning at “ice-out,” when the fyke nets can be placed in the river (usually early March) and lasts until the third week in April.

5.2.4.2 Biological and Environmental Sampling

During sampling, the catch is sorted by species. Rainbow smelt are counted and length, sex, and age are recorded. For bycatch, which includes American eels, species are counted and 25 lengths are recorded per species per sampling day. Water temperature, pH, specific conductivity, dissolved oxygen, and turbidity are recorded in addition to fyke net soak time (effort).

5.2.4.3 Evaluation of Survey Data

A spring (March–April) index of yellow eel abundance was developed from this survey. The index began in 2010 when all three sites were sampled and environmental data began to be collected. On average, American eels were caught in this survey with 26% positive tows. A full model that predicted catch as a linear function of year, month, water temperature, pH, turbidity, salinity, dissolved oxygen, and the river was compared with nested submodels using AIC. Nominal indices were also explored. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year, temperature, and river with an offset for effort. Length data indicated that this survey catches yellow eel (Figure 34).

5.2.4.4 Abundance Index Trends

The survey of relative abundance of yellow eel in New Hampshire showed relatively stable abundance throughout the time series (Figure 35). Abundance bounced around in recent years and was on the decline in the terminal year of 2020.

5.2.5 Massachusetts Jones River

5.2.5.1 Survey Design and Methods

The Jones River YOY survey site is located in Kingston, Massachusetts, and has been monitored since 2001. The survey uses a Sheldon trap and the sampling season targets ten weeks from the last week of March to the first week of June. The trap is set on a Monday and hauled Tuesday–Friday for four hauls each week.

5.2.5.2 Biological and Environmental Sampling

The survey records water temperature, water flow, moon phase, gear condition, and tidal amplitude. A subsample for pigmentation stage, length, and weight of 60 American eels is taken 2–3 times a week.

5.2.5.3 Evaluation of Survey Data

Length and pigment data were collected in the Jones River YOY survey. Mean length was consistent across years (Figure 36) and averaged 59.6 ± 4.0 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 37). A full model that predicted YOY catch as a function of year, water temperature, water flow, moon phase, gear condition, tidal amplitude, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year and water flow with an offset for effort and a negative binomial error structure was selected.

5.2.5.4 Abundance Index Trends

The index of relative abundance was variable in the early part of the time series and peaked in 2001, 2003, and 2005 (Figure 38). The index declined through the late 2000s and has been stable and low through the terminal year of 2019 which was the lowest value in the time series.

5.2.6 Massachusetts Wankinco River Ramp Survey

5.2.6.1 Survey Design and Methods

The Wankinco River in Wareham, Massachusetts has been sampled for American eel since 2009 via a piped, gravity-flow eel ramp in April and May each year. The ramp is located in tidal waters below the dam and passes YOY eels with very few age-1+ eels.

5.2.6.2 Biological and Environmental Sampling

The survey records water temperature, air temperature, flood tide, moon phase, discharge, and gear condition. Lengths were collected but not provided for this assessment. Summary data were submitted and indicated that American eels caught in the survey are predominantly YOY.

5.2.6.3 Evaluation of Survey Data

GLMs were attempted for the Wankinco River Ramp Survey data but the models had convergence issues. A nominal index was developed for an index of relative abundance.

5.2.6.4 Abundance Index Trends

The relative index of YOY eel abundance began as low in the survey from the first year of 2009 through the 2010s (Figure 39). The index increased in 2018 to a time series high and decreased slightly in the terminal year of 2019.

5.2.7 Massachusetts Saugus River Ramp Survey

5.2.7.1 Survey Design and Methods

An eel ramp was installed on the first dam upstream of the Saugus Iron Works at 9.4 km in the spring of 2007. Stream flow exits the head pond through a bottom opening sluice gate in the dam that is impassable for eels. The ramp tank catches of American eels were monitored by the Saugus River Watershed Council and the Lynn Water and Sewer Commission and represent a census of American eels passing over the dam. In most years of the time series, catches have been elver eels in the size range of 7 to <20 cm.

5.2.7.2 Biological and Environmental Sampling

The survey records water temperature, air temperature, flood tide, moon phase, discharge, and gear condition. Lengths were collected but not provided for this assessment. Summary data

were submitted and indicated that American eels caught in the survey are predominantly elvers.

5.2.7.3 Evaluation of Survey Data

The data were subset to April–June when the survey most reliably caught American eels. During those months, the survey encountered elvers in 86% of sampling events. A full model that predicted catch as a linear function of year, month, water temperature, air temperature, flood tide, moon phase, discharge, and gear condition was compared with nested submodels using AIC. Nominal indices were also explored. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year and temperature with an offset for effort.

5.2.7.4 Abundance Index Trends

Relative abundance of elver eels in the Saugus River was variable in the beginning years of the survey (Figure 40). The index peaked in 2013 but then steadily declined to stable but low abundance through the terminal year.

5.2.8 Massachusetts Rainbow Smelt Fyke Net Survey

5.2.8.1 Survey Design and Methods

The Massachusetts Division of Marine Fisheries began monitoring anadromous rainbow smelt *Osmerus mordax* populations in 2004 using fyke nets at four coastal rivers and four additional rivers have been added since 2005. The spring fyke net monitoring occurs when resident yellow eels become active and are susceptible to capture as non-target bycatch. The fyke nets are set at mid-channel three nights a week from early March to the third week of May. The fyke net opening is a 4' x 4' box frame with 4' x 4' wings on both sides and the net mesh is ¼ inch delta.

5.2.8.2 Biological and Environmental Sampling

Diadromous fish are counted, measured, and released. Date, soak time, flood tide, tidal amplitude, moon phase, river discharge, water temperature, and air temperature are available from this survey.

5.2.8.3 Evaluation of Survey Data

Massachusetts Division of Marine Fisheries confirmed that the eels caught in this survey were yellow American eels although the biological data were not submitted. This survey was also used in the 2012 benchmark as a yellow eel survey. The data were subset to April–May when the survey most reliably caught American eels. On average, American eels were caught in this survey with 46% positive tows. A full model that predicted catch as a linear function of year, month, water temperature, river discharge, moon phase, and river was compared with nested submodels using AIC. Nominal indices were also explored. Based on several diagnostics (AIC,

dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year and temperature with an offset for effort.

5.2.8.4 Abundance Index Trends

Relative yellow eel abundance began low in 2004 and 2005, increased through the late 2000s and early 2010s, and then decreased to one of the lowest abundances in 2014 (Figure 41). The index did increase in 2017 but then declined again except for a slight uptick in the 2019 terminal year.

5.2.9 Rhode Island Gilbert Stuart Dam Survey

5.2.9.1 Survey Design and Methods

Young-of-the-year American eels have been sampled at Gilbert Stuart since 2000 (Figure 42). This survey uses modified Irish elver ramps made of marine plywood and lined with filamentous plastic (Enkamat). The ramp at Gilbert Stuart is ten feet in length and is secured to the dam parallel to the existing fish ladder. The ramp allows juvenile eels to pass up and over a 53-inch high dam and into a collecting bucket. A steady stream of water is fed down the ramp using an electrical pump and spray bar. Gear is typically monitored for YOY eels from April–June.

5.2.9.2 Biological and Environmental Sampling

American eels collected at the site were counted, measured, and released above the dams. If daily collection exceeded 60 fish, measurements of individual lengths and weights were taken bi-weekly. Length was measured to the nearest 1 mm and weight to the nearest 0.01 g. The following physical data were recorded each time the gear was checked: dissolved oxygen, soak time, moon phase, water level, and temperature. The time of day and condition of gear were also noted.

5.2.9.3 Evaluation of Survey Data

Length and pigment data were collected in the Gilbert Stuart Dam YOY survey. Mean length was variable across years (Figure 43) and averaged 62.4 ± 16.4 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 44). For index standardization, one large tow (10,000 YOY eel) was eliminated due to convergence problems with the model. A full model that predicted YOY catch as a function of year, water temperature, water level, moon phase, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year and temperature with an offset for effort and a negative binomial error structure was selected.

5.2.9.4 Abundance Index Trends

The relative abundance of YOY eel in the Rhode Island Gilbert Stuart Dam Survey was high in 2000, 2002, and 2011 but otherwise was low and stable (Figure 45).

5.2.10 Rhode Island Hamilton Fish Ladder Survey

5.2.10.1 Survey Design and Methods

Young-of-the-year American eels have been sampled at the Hamilton Fish Ladder in the Annaquatucket River since 2004 (Figure 46). This survey uses modified Irish elver ramp that is four feet in length and positioned at the base of the Hamilton dam next to the existing fish ladder. The ramp is gravity fed using stopper boards and PVC piping, thus does not need a power supply. Gear is typically monitored for YOY eels from April through late June or early July.

5.2.10.2 Biological and Environmental Sampling

American eels collected at the site stations were counted, measured, and released above the dams. If daily collection exceeded 60 fish, measurements of individual lengths and weights were taken bi-weekly. Length was measured to the nearest 1 mm and weight to the nearest 0.01 g. The following physical data were recorded each time the gear was checked: dissolved oxygen, soak time, moon phase, water level, and temperature. The time of day and condition of gear were also noted.

5.2.10.3 Evaluation of Survey Data

Length and pigment data were collected in the Hamilton Fish Ladder YOY survey. Mean length was variable across years (Figure 47) and averaged 56.5 ± 7.3 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 48). A full model that predicted YOY catch as a function of year, water temperature, water level, moon phase, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year, day of the year, and day of the year squared with an offset for effort and a negative binomial error structure was selected.

5.2.10.4 Abundance Index Trends

The relative abundance of YOY eel in the Rhode Island Hamilton Fish Ladder has been variable throughout its time series with notable highs in 2013-2014 and 2018 and lows in 2006, 2012, and 2016 (Figure 49). The terminal year of 2019 was the lowest abundance in the time series.

5.2.11 Connecticut Ingham Hill Survey

Connecticut Department of Energy and Environmental Protection (CT DEEP) began sampling for YOY eel using an Irish Elver Ramp at the Ingham Hill site, sometimes called Fishing Brook Eel Ramp, in 2007. The site is located 14 meters upstream of the head of tide and 3.6 river km upstream of the Long Island Sound (Figure 50).

5.2.11.1 Survey Design and Methods

The survey operates annually from about March 25th through July 4th. When operating, the survey gear is checked Monday through Friday except for holidays. The daily catch is sorted by size and weighed.

5.2.11.2 Biological and Environmental Sampling

Weekly, a total of 60 YOY eels are sampled for total length, weight, and pigment stage.

5.2.11.3 Evaluation of Survey Data

Length and pigment data were collected in the Ingham Hill YOY survey. Mean length was fairly stable across years (Figure 51) and averaged 57.5 ± 3.3 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 52). A full model that predicted YOY catch as a function of year, water temperature, water level, river discharge, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year and day of the year and day of the year squared with an offset for effort and a negative binomial error structure was selected.

5.2.11.4 Abundance Index Trends

The index of relative abundance of YOY eel in the Ingham Hill site increased from 2007–2012 and then decreased (Figure 53). The index rose again slightly, remained low through the mid-2010s, and then began a large increase through the terminal year of 2019.

5.2.12 Connecticut Farmill River Electrofishing Survey

5.2.12.1 Survey Design and Methods

CT DEEP began sampling a 126 m-long section of the Farmill River in 2001. The sample site substrate is coarse sand and cobble. The Farmill River, a tributary of the Housatonic River with a 26 square mile watershed, is tidal freshwater at the sampling site in Shelton (Figure 54). There are no barriers to American eel migration between the sampling site and the ocean. This is an electrofishing survey that uses blocknets on the boundaries to prevent migration during sampling. The survey uses a three-pass depletion where each pass catch is counted and measured.

5.2.12.2 Biological and Environmental Sampling

All American eels captured are anesthetized, counted, and measured to the nearest mm, then released back into the sample site.

5.2.12.3 Evaluation of Survey Data

A population estimate is derived using maximum weighted likelihood by CT DEEP biologists and supplied to the SAS. As in previous years, raw data were not submitted for this survey and the SAS used the population estimates as supplied by CT DEEP.

5.2.12.4 Abundance Index Trends

Population estimates in the Farmill River for yellow eels varied from around 250 American eels for 2001–2012 (Figure 55). In 2015, the survey changed sites. Dramatic changes in the population estimate could be due to changes in the river’s American eel population but more likely are due to the site change so the SAS decided to only use 2001–2014 for use in this stock assessment, even with the missing 2013 data point.

5.2.13 Connecticut Eightmile River Electrofishing Survey

5.2.13.1 Survey Design and Methods

CT DEEP began this electrofishing survey in Eightmile River in 2001 (Figure 54). The survey uses blocking nets on the boundaries to prevent migration during sampling. This survey uses a three-pass depletion where each pass catch is counted and measured.

5.2.13.2 Biological and Environmental Sampling

All American eels captured are anesthetized, counted, and measured to the nearest mm, then released back into the sample site.

5.2.13.3 Evaluation of Survey Data

A population estimate is derived using maximum weighted likelihood by CT DEEP biologists and supplied to the SAS. The raw data were not submitted for this survey and the SAS used the population estimates as supplied by CT DEEP.

5.2.13.4 Abundance Index Trends

Population estimates for yellow eels in the Eightmile River were variable but averaged around 30 American eels (Figure 56). The survey did not operate in 2004 and 2018–2019.

5.2.14 New York Hudson River Estuary Monitoring Program

5.2.14.1 Survey Design and Methods

The Hudson River Estuary (HRE) Monitoring Program has been run on behalf of several utility companies with power stations in the Hudson River Estuary since 1974. The Program consists of three different surveys. Data from the HRE Ichthyoplankton Survey were available in time for this assessment. The HRE Ichthyoplankton survey was designed to sample for YOY striped bass and follows a random sampling design that consists of paired Tucker trawl (targeting surface and

channel) and epibenthic sled (targeting bottom) tows. The Hudson River is split into 13 sampling areas of equal volume and each area is divided into three strata (shoal, channel, bottom). The HRE survey is conducted primarily between March and October and collects approximately 100–200 samples per week depending on the season. The survey was discontinued in 2017 and the data are now housed by the Stony Brook University's Chen Laboratory which provided the raw data for this assessment.

5.2.14.2 Biological and Environmental Sampling

All American eels are measured and categorized by life stage (YOY vs. yearling or older). Date, water temperature, river mile, water volume, depth, day/night, and tidal stage were recorded. No raw biological data were provided for this assessment, but the stage categories were discussed with HRE biologists during the 2017 stock assessment update and were consistent with the eel designations used in the assessment. Like previous assessments, the stages were used from the data supplied.

5.2.14.3 Evaluation of Survey Data

Two indices were developed for this assessment: a YOY and a yellow eel index. For the YOY and yellow eel indices, a full model that predicted catch as a function of year, month, day of the year, and day of the year squared, river mile, water volume, water temperature, depth, and day/night was compared with nested submodels using AIC. For YOY, the model that included year, water temperature, river mile, and water volume with a quasi-Poisson error structure was selected because it produced the lowest AIC and the best model diagnostics. For yellow eel, the model that included year, water temperature, river mile, and water volume with a quasi-Poisson error structure was selected because it produced the lowest AIC and the best model diagnostics.

5.2.14.4 Abundance Index Trends

The YOY index began with relatively high abundance in 1974, decreased, and then peaked in 1980 (Figure 57). The index was at its lowest points through the 1980s and then began to increase in the 1990s. The index was mid-range and steady through the 2010s when it began to decrease again to a relatively low point in the terminal year of 2017. The yellow eel index began with high relative abundance in the 1970s, decreased until 1980, peaked in 1984, and then steadily declined through the mid-2000s (Figure 58).

5.2.15 New York Carman's River Survey

5.2.15.1 Survey Design and Methods

The New York Department of Environmental Conservation Carman's River YOY Carman's River YOY survey began in 2000. The survey site is in the tidal portion of the Carman's River that flows through the Wertheim National Wildlife Refuge into Bellport Bay (Figure 59). The tidal portion

of the river is 5.8 km. Glass eels are sampled with a fyke net that has been historically checked daily over an 8-9 week period during the spring (primarily March-April).

5.2.15.2 Biological and Environmental Sampling

The catch is sorted by species with glass eels distinguished from pigmented elvers. Environmental data collected include water and air temperature, tide stage, time of previous high tide, and the amount of the previous day's precipitation. Also, the condition of the gear during daily checks is noted, and the elapsed time between checks. A subsample of American eels is taken to a laboratory where lengths are measured and pigment stage assessed.

5.2.15.3 Evaluation of Survey Data

An index of abundance was developed for 2000-2019 for this survey. The proportion of positive catches was generally >80% throughout the time series. A negative binomial GLM was used to model catches. Although temperature data were available as a covariate, this was not included in the model because it was correlated with the year, and catches appeared to increase and then decrease as the day of the year increased. Thus the final model included day of the year and day of the year squared with an offset for effort. Effort was the time elapsed between checks of the fyke net.

The length of American eels collected in the Carman's River Survey averaged 64 ± 13 mm (\pm SD) and did not show any trend through time (Figure 60). Pigment stages of American eels showed some variation among years (Figure 61).

5.2.15.4 Abundance Index Trends

The relative abundance of YOY eels from Carman's River varied without trend from 2000-2019, but noticeable peaks in YOY occurred in 2002 and 2013 (Figure 62).

5.2.16 New York Hudson River YOY Survey

5.2.16.1 Survey Design and Methods

The NYSDEC Hudson River Estuary Program and National Estuarine Research Reserve support a citizen science American eel monitoring program within the Hudson River basin. This survey has taken place since 2008 and has expanded to include up to 15 sampling sites located on tributaries to the Hudson River (Figure 63). Fyke nets are deployed in each tributary and checked daily over approximately a six to eight-week period from February to May.

5.2.16.2 Biological and Environmental Sampling

All American eels that are caught in fyke nets are enumerated and classified as "glass eels" or "elvers." Water temperature, air temperature, weather, and tide are collected at each site every day.

5.2.16.3 Evaluation of Survey Data

The six sites with the longest time series of data were selected for evaluation as an index of abundance. These included Black Creek, Fall Kill Creek, Furnace Brook, Hannacroix Creek, Miniceongo Creek, and Saw Kill Creek. Among these sites, greater than 80% of samples had positive catches of YOY eels throughout the time series. Effort was indexed as the time between daily checks of each net. A negative binomial GLM model was used to standardize catch data and the final form of the model included site, day of the year, day of the year squared, and an offset for logged effort. The time series used in the analysis began in 2010 when all six of the aforementioned sites began to be sampled and extended through 2020.

5.2.16.4 Abundance Index Trends

The relative abundance of YOY American eels in the Hudson River YOY survey showed an exponentially increasing trend from 2010–2020 (Figure 64).

5.2.17 New York Hudson River Juvenile Alosine Survey

5.2.17.1 Survey Design and Methods

The NYSDEC Juvenile Alosine survey targets YOY American shad in the freshwater portion of the Hudson River (> RM 54). Annual sampling covers 9 weeks, from July through October. The survey gear consists of a 30.5m x 3.05m seine with 1.6 cm mesh. The survey began in 1985 with a random selection of sites but transformed into a fixed site survey by 1985.

5.2.17.2 Biological and Environmental Sampling

Although catches of eels are enumerated in the Juvenile Alosine seine survey, very few of them have biological data taken on them. Environmental data collected at the time of sampling include tidal stage, water and air temperature, salinity, and cloud cover.

5.2.17.3 Evaluation of Survey Data

An index of yellow eel abundance was developed from this survey. The index began in 1985 when there was consistency in the stations sampled each year. American eels were collected in approximately 20% of seine hauls over the time series. A negative binomial GLM with covariates of year, station id, and temperature provided the best fit to the data based upon dispersion and significance of covariates.

5.2.17.4 Abundance Index Trends

The Hudson River Juvenile Alosine survey showed a rapidly declining trend in yellow eel relative abundance from 1985 through 1996. Relative abundance increased slightly in the early 2000s, but has since shown a gradual decline through 2019 (Figure 65).

5.2.18 New York Hudson River Juvenile Striped Bass Survey

5.2.18.1 Survey Design and Methods

The NYSDEC Juvenile Striped Bass seine survey targets YOY striped bass in brackish portions of the Hudson River (RMs 22 - 39). Annual sampling covers 6 weeks, from late August through mid-November. The survey gear consists of a 61m x 3.05m seine with 1.6 cm mesh. The survey began in 1979 with a random selection of sites but transformed into a fixed site survey by 1980.

5.2.18.2 Biological and Environmental Sampling

Although catches of eels are enumerated in the Juvenile Striped Bass seine survey, few of them have biological data taken on them. Environmental data collected at the time of sampling includes tidal stage, water and air temperature, salinity, and cloud cover.

5.2.18.3 Evaluation of Survey Data

An index of yellow eel abundance was developed from this survey. The index began in 1980 when there was consistency in the stations sampled each year. American eels were collected in approximately 15 - 20% of seine hauls over the time series. A negative binomial GLM with covariates of year, station id, and temperature provided the best fit to the data based upon dispersion and significance of covariates.

5.2.18.4 Abundance Index Trends

The relative abundance of yellow eels in the Juvenile Striped Bass seine survey peaked in 1982 and has shown a general declining trend since that time with occasional spikes in relative abundance (Figure 66).

5.2.19 New Jersey Little Egg Inlet Survey

5.2.19.1 Survey Design and Methods

The Little Egg Inlet YOY survey uses an ichthyoplankton net to collect YOY American eels during the months of January – May each year since 1992.

5.2.19.2 Biological and Environmental Sampling

No biological data on YOY were provided. Environmental covariates collected during plankton net tows included: discharge, salinity, and temperature. Effort was indexed as the volume of water sampled by a plankton net tow.

5.2.19.3 Evaluation of Survey Data

An index of abundance was developed for 1992 – 2015 for this survey. The proportion of positive catches was generally 60% throughout the time series. A negative binomial GLM was used to model catches. Although temperature data was available as a covariate, this was not

included in the model because it was correlated with the year, and catches appeared to increase and then decrease as the day of the year increased. Thus the final model included day of the year, day of the year squared, salinity, and an offset for logged effort.

5.2.19.4 Abundance Index Trends

The relative abundance of YOY American eels from the Little Egg Inlet survey was variable across years, but there was an apparent overall decline (Figure 67).

5.2.20 New Jersey Patcong Creek Survey

5.2.20.1 Survey Design and Methods

The New Jersey Patcong Creek survey uses a fyke net to sample YOY American eels. The survey began in 1999 and samples YOY eels primarily during the late-winter and early-spring months (February – April).

5.2.20.2 Biological and Environmental Sampling

Length, weight, and pigment stage data are collected from a subsample of YOY eels captured by the survey. Environmental data collected at the time fyke nets are checked includes water temperature, water level, and discharge.

5.2.20.3 Evaluation of Survey Data

An index of abundance was developed for 1999 – 2020 for this survey. The proportion of positive catches was generally > 90% throughout the time series, but a low of ~ 50% occurred in 2010. A negative binomial GLM was used to model catches. Although temperature data was available as a covariate, this was not included in the model because it was correlated with the year, and catches appeared to increase and then decrease as the day of the year increased. Thus the final model included day of the year and day of the year squared.

Length, weight, and pigment data were collected in most years of the Patcong Creek YOY survey. Mean length was consistent across years (Figure 68) and averaged 58.54 ± 3.6 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 69).

5.2.20.4 Abundance Index Trends

The standardized index of relative abundance for the Patcong Creek YOY survey greatly varied across years with large increases in some years followed by abrupt decreases (Figure 70). Overall, there was no discernable trend in the time series of relative abundance.

5.2.21 New Jersey Delaware River Seine Survey

5.2.21.1 Survey Design and Methods

The Delaware River seine survey targets YOY striped bass in the summer through fall (June – October). The survey began in 1980 and uses a 100-foot long, 6-foot deep bagged beach seine with 0.25 inch mesh. The survey is conducted from rivermile 54.2 – 125.4 (Figure 71). From 1980 to 1986, stations were randomly selected each year, with a different number sampled each year. By 1987, the survey evolved into a sampling scheme that consisted of sixteen fixed stations. From 1980-1990, two hauls were performed at each station. In 1991, a sampling season from August through October was developed; using both fixed and random stations; concentrating fifty percent of the sampling effort on Region 2; and eliminating replicate samples. From 1991-1997, fixed and random stations were sampled. In 1998, 32 fixed stations were chosen to be sampled twice a month from July through October. This sampling plan has remained in effect since enacted. Sampling seasons have also varied over the years. From 1980-1987, sampling mostly occurred between August and October. Beginning in 1987, the survey began to routinely sample during the months of July through October. In 1998, the first year that sampling stations were all fixed, each station was sampled twice a month from July through October. In 2000, one round of sampling was added to the first half of November and in 2002, one round of sampling was added during the second half of June. This plan remained in effect until 2016 when November sampling was cut from the project.

5.2.21.2 Biological and Environmental Sampling

The catch is sorted by species after each haul. Non-target species are counted and minimum and maximum lengths are recorded. DO, salinity, pH, water temp, and tidal stage are collected after each haul. Air temp, wind speed and direction, and wave height are recorded daily.

5.2.21.3 Evaluation of Survey Data

Because the survey had frequent changes, only catch data collected from 1998 and onward were used to develop a standardized relative abundance index. Also, data were filtered for those stations that were consistently sampled from 1998 – 2019. Overall, only about 10% of seine hauls in each year of the time series captured yellow eels. A negative binomial GLM provided the best fit to the data based upon AIC, dispersion, and significance of predictor variables. The final model included year, sampling station, and temperature.

5.2.21.4 Abundance Index Trends

The standardized relative abundance of yellow American eels in the Delaware River seine survey varied without trend (Figure 72).

5.2.22 Delaware Millsboro Dam Survey

5.2.22.1 Survey Design and Methods

The Delaware Division of Fish and Wildlife Millsboro Dam Survey began operating in 2000, twelve miles inland from the Indian River Inlet (Figure 73). The survey is conducted from February 1, or when water temperatures exceed 3°C until the catch rate drops, usually in late March or April. The survey is a fixed station design using a fyke net set below the dam. The site is sampled Monday through Friday, then hauled out on weekends.

5.2.22.2 Biological and Environmental Sampling

During sampling, all American eels are counted volumetrically. A subsample of 60 individuals is taken twice a week and measured for length, weight, and pigment stage. Water temperature and river discharge are recorded in addition to fyke net soak time (effort).

5.2.22.3 Evaluation of Survey Data

A spring index of YOY eel abundance was developed from this survey. The index began in 2000 when sampling was started. On average, American eel were caught in this survey with 99.6% positive tows. A full model that predicated catch as a function of year, day of the year, day of the year squared, and river discharge was compared with nested submodels using AIC. Day of the year and day of the year squared were substituted for temperature in the model. Nominal indices were also explored. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year, day of the year, day of the year squared, and river discharge with an offset for effort. Length data indicated that this survey catches YOY eel (Figure 74).

5.2.22.4 Abundance Index Trends

The index of relative abundance of YOY eel in Delaware showed relatively stable abundance throughout the time series, with a substantial increase in the mid-2010s (Figure 75). Abundance bounced around in recent years and was on the decline in the terminal year of 2020.

5.2.23 Delaware Juvenile Trawl Survey

5.2.23.1 Survey Design and Methods

The Delaware Division of Fish and Wildlife (DEDFW) operates two finfish trawl surveys—one for juvenile finfish and one for adult finfish. The DEDFW's Juvenile Trawl Survey has been monitoring juvenile fish and crab abundance in Delaware's inshore waters since 1980. Sampling for the Juvenile Trawl Survey is conducted monthly from April through October at 23 fixed sites in Delaware Bay, seventeen fixed sites in the Delaware River, and 12 fixed sites in Indian River, Indian River Bay, and Rehoboth Bay (Figure 76). At each site, the 19-m R/V *First State* tows a 4.8-m semi-balloon trawl with a 1.3-cm cod-end liner. Tows are made against the current for ten minutes. The DEDFW's Adult Trawl Survey was implemented in 1966 as a long-term

fisheries-independent monitoring program to monitor the abundance of subadult and adult fish; however, the net used rarely caught eels, and the data is not included.

5.2.23.2 Biological and Environmental Sampling

For the Juvenile Trawl Survey, the catch from each tow is sorted by species, and individuals are measured and weighed. Ageing of eels captured at the Delaware River sites was begun in 2007. Water temperature, salinity, dissolved oxygen, cloud cover, and depth are recorded in addition to tow duration (effort).

5.2.23.3 Evaluation of Survey Data

An annual index of yellow eel abundance was developed from this survey. The index began in 1980 when sites were sampled and environmental data began to be collected. On average, American eel were caught in this survey with 20% positive tows. A full model that predicted catch as a linear function of year, month, water temperature, pH, turbidity, salinity, dissolved oxygen, and river was compared with nested submodels using AIC. Nominal indices were also explored. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the linear models were rejected and a nominal index with delta distribution was chosen. Length data indicated that this survey catches yellow eel (Figure 77).

5.2.23.4 Abundance Index Trends

The index declined from a peak in 1982 through the late 1980s, increased through the early 1990s, and remained stable with inter-annual variation throughout the rest of the time series (Figure 78).

5.2.24 Pennsylvania Delaware River Area 6 Survey

5.2.24.1 Survey Design and Methods

Pennsylvania Fish and Boat Commission (PFBC) conducts electrofishing surveys at four fixed sites spread over 72 km of the Delaware River. Sites are located at Yardley (RKM 258), Point Pleasant (RKM 291), Upper Black Eddy (RKM 318), and Raubsville (RKM 330) (Figure 79). Sites have been sampled once annually in July or August from 1999–2020; however, the Upper Black Eddy and Raubsville sites were not sampled in 2000. At each site, six 50-meter sections of shoreline are electrofished for a total of 300 m of shoreline. The number of “pencil eels” (elvers) is counted within each 50-meter section since 1999, with the recording of yellow eels beginning in 2005.

5.2.24.2 Biological and Environmental Sampling

A count of eels is performed, with no other biological or environmental sampling conducted.

5.2.24.3 Evaluation of Survey Data

Two separate nominal indices were developed from the survey calculated from the arithmetic mean of counts, an elver eel index and a yellow eel index. On average, American eels were caught in this survey with 88% positive samples for elvers and 64% positive samples for yellow eels.

5.2.24.4 Abundance Index Trends

The elver eel index of abundance has remained stable throughout most of the time series, with a decrease in 2016 and lower numbers persisting through 2020 (Figure 80). The terminal year of 2020 was on the increase. The yellow eel index of abundance has remained stable throughout most of the time series, with a decrease from 2006 through 2008 and 2016 through 2020 (Figure 81). The terminal year of 2020 was on the decline.

5.2.25 Maryland Turville Creek Survey

5.2.25.1 Survey Design and Methods

Glass eel relative abundance is monitored at Turville Creek, near Ocean City, Maryland. An Irish elver ramp is used to capture migrating glass eels and has been in use since 2000. The trap is typically set in March and hauled in April, though the months that are sampled vary by year. The trap is checked several times each week.

5.2.25.2 Biological and Environmental Sampling

Subsamples of glass eels were returned to the lab each week for length (Figure 82) and weight measurements and beginning in 2007 pigment stage was also recorded (Figure 83). Soak time, water and air temperature, salinity, water level, and water discharge were also recorded.

5.2.25.3 Evaluation of Survey Data

A full model that predicted YOY catch as a function of year, water temperature, salinity, gear condition, day-of-the-year, and day-of-the-year squared was compared with nested submodels using AIC. The model including year, water temperature, day-of-the-year, and day-of-year squared with an offset for effort and a negative binomial error structure was selected.

5.2.25.4 Abundance Index Trends

The index was relatively stable throughout the time series, though the highest abundance was observed in 2019 (Figure 84).

5.2.26 Maryland Susquehanna River Conowingo Dam Survey

5.2.26.1 Survey Design and Methods

The US Fish and Wildlife Service Conowingo Dam Ramp Survey began operating on the Susquehanna River in 2008. The survey was taken over by the dam operator, Constellation, starting in 2016. The dam is located on the western shore of the mainstem of the Susquehanna River at river mile 10 in Maryland. The survey is conducted in the spring and summer between late May and early September. Samples are taken an average of three times per week. If there were less than 200 mL of elvers in the collection tank, all elvers were sedated and counted; however, if there were more than 200 mL of elvers in the collection tank, then 200 mL were sedated and individually counted, while the remaining elvers were enumerated volumetrically. Up to 25 individuals were randomly selected and measured for total length.

5.2.26.2 Biological and Environmental Sampling

During sampling, American eels are counted and length is recorded from at least one hundred elvers annually. Sampling of length data began in 2007, with an additional sampling of age and weight from 2017–2019. Water temperature, lunar phase, and river discharge are recorded in addition to fishing time (effort).

5.2.26.3 Evaluation of Survey Data

An index of elver eel abundance was developed from this survey. The index began in 2008 when counts of elver eels began. On average, American eel were caught in this survey with 97% positive catches. A full model that predicted catch as a linear function of year, month, water temperature, moon phase, and river discharge was compared with nested submodels using AIC. Nominal indices were also explored. Based on several diagnostics (AIC, dispersion, percent deviance explained, and resulting CVs), the model chosen was a negative binomial that included year, temperature, and river discharge with an offset for effort. Length data indicated that this survey catches elver eels (Figure 85).

5.2.26.4 Abundance Index Trends

The survey of relative abundance of elver eel in the Susquehanna River showed relatively stable abundance over the time series with a large increase in the mid-2010's (Figure 86). Abundance bounced around in recent years and was on the increase in the terminal year of 2020.

5.2.27 Maryland Sassafras River Survey

5.2.27.1 Survey Design and Methods

The primary objective of this study is to characterize the current population segment of American eels in the Sassafras River through a fishery-independent pot survey. This area was specifically chosen because it was previously sampled through a Maryland DNR fishery-independent eel pot study from 1998–2000. The survey was reinitiated in 2006 and is currently

ongoing. This study provides the size and age structure, parasite infestation rates, and sex composition of eels in the Sassafras River, as well as a fishery-independent relative abundance index. The Sassafras River is located on the East Upper Chesapeake Bay near the head of the bay. The river is 22 miles long and the drainage encompasses approximately 97 square miles. Tides are diurnal with approximately 0.55 meters (1.8 feet) normal tide range. Salinities predominantly range from 0 to 3.

The Sassafras River eel pot study was replicated from 1998 field survey methods with slight modifications. In the current study, approximately 30 cylindrical pots with galvanized wire mesh of either 0.83 x 0.83cm (1/3" x 1/3") or 1.27 x 1.27cm (1/2" x 1/2") were set in fixed locations on individual lines at depths ranging from 3–20 feet. Sample area totaled 8.7 river miles and divided equally between an 'upper' and 'lower' pot set (Figure 87). Since 2006, sampling has occurred for 4-6 weeks from the middle of May to early June. 'Upper' and 'lower' pot sets were sampled on alternate weeks. The pots were baited with razor clams (*Tagellus plebius*) and soaked for 48 hours. In the 1998–2000 survey only 1/3" x 1/3" mesh pots were used and only a portion of the pots had a 1/2" x 1/2" escape panel installed. All 1/3" x 1/3" mesh pots used in the current study had the escape panel installed. Both menhaden (*Brevoortia tyrannus*) and horseshoe crabs (*Limulus polyphemus*) were used in addition to razor clams in the previous study. Sampling covered approximately 4.5 river miles and consisted primarily of the current study's 'upper' pot set. Sampling in 2000 only occurred on 2 days, both of which were in July.

5.2.27.2 Biological and Environmental Sampling

All captured eels were retained, euthanized by an ice slurry, clove oil, or MS 222 and measured to the nearest mm (Figure 88) and weighed to the nearest gram. Subsamples were taken for age, gonad, and swim bladder analysis.

5.2.27.3 Evaluation of Survey Data

A full model that predicted yellow eel catch (in pounds) as a function of year, water temperature, salinity, and bullheads was compared with nested submodels using AIC. The nominal model that included year was selected.

5.2.27.4 Abundance Index Trends

There is an increasing trend in the relative biomass of American eels caught in the survey over time from 2006 to 2019 (Figure 89).

5.2.28 PRFC Clark's Millpond Survey

5.2.28.1 Survey Design and Methods

Clark's Millpond (Coan River – Northumberland County) spillway is situated approximately one meter above the creek with a steady stream flow that requires a modified ramp extension to allow the eels to access the spillway. The Coan River empties into the Potomac River (Figure 90).

Irish eel ramps were used to collect eels Clark's Millpond. The ramp configuration successfully attracts and captures small eels in tidal waters of Chesapeake Bay. Ramp operation requires continuous flow of water over the climbing substrate and the collection device, and was accomplished through a gravity feed. Hoses were attached to the ramp and collection buckets with adapters to allow for quick removal for sampling. Enkamat™ erosion control material on the ramp floor provided a textured climbing surface and extended into the water below the trap. The ramps were placed on an incline (15-45°), often on land, with the ramp entrance and textured mat extending into the water. The ramp entrance was placed in shallow water (< 25 cm) to prevent submersion. The inclined ramp and an additional 4° incline of the substrate inside the ramp provided sufficient slope to create attractant flow. A hinged lid provided access for cleaning and flow adjustments. The timing and placement of gear coincided with periods of peak YOY onshore migration. The gear was deployed and fished continuously typically from early March to late June each year.

5.2.28.2 Biological and Environmental Sampling

The entire catch of YOY eels and elvers was counted from each sampling event and at least 60 glass eels (if present) were examined for length, weight, and pigmentation stage weekly. All eels were counted and placed above the impediment, with any subsample information recorded, if applicable. Specimens less than or equal to ~ 85 mm total length (TL) were classified as YOY, while those greater than 85 mm TL were considered elvers. Water temperature, air temperature, wind direction and speed, and precipitation were recorded during site visits.

5.2.28.3 Evaluation of Survey Data

The proportion of YOY eels in each pigment stage varied across years (Figure 91). A full model that predicted YOY and elver catch as a function of year, water temperature, salinity, gear condition, day-of-the-year and day-of-the-year squared was compared with nested submodels using AIC. The model including year and water temperature with an offset for effort and a negative binomial error structure was selected for glass eels and the model including year, water temperature, day-of-the-year, and day-of-year squared with an offset for effort and a negative binomial error structure was selected for elvers.

Due to changes near the spillway that included scouring and a hard clay substrate, catches of glass and elver eels dropped to zero in 2014 and sampling at this location was terminated after 2016. The years of 2014-2016 were not included in the analyses or modeling approaches in the following sections.

5.2.28.4 Abundance Index Trends

Collection of the YOY eels at Clark's Millpond was low and variable over time and decreased to zero beginning in 2014 due to changes at the spillway (Figure 92). Elver eels showed a similar pattern with a decrease in catches in 2014 (Figure 93). This site is no longer sampled with the last year of effort occurring in 2016.

5.2.29 PRFC Gardy's Millpond Survey

5.2.29.1 Survey Design and Methods

Gardy's Millpond (Yeocomico River – Northumberland County) contains a spillway that drains through four box culverts, across a riffle constructed of riprap and into a lotic area of the Yeocomico River. The Yeocomico River empties into the Potomac River (Figure 90).

Irish eel ramps were used to collect eels Gardy's Millpond. The ramp configuration successfully attracts and captures small eels in tidal waters of Chesapeake Bay. Ramp operation requires continuous flow of water over the climbing substrate and the collection device, and was accomplished through a gravity feed. Hoses were attached to the ramp and collection buckets with adapters to allow for quick removal for sampling. Enkamat™ erosion control material on the ramp floor provided a textured climbing surface and extended into the water below the trap. The ramps were placed on an incline (15-45°), often on land, with the ramp entrance and textured mat extending into the water. The ramp entrance was placed in shallow water (< 25 cm) to prevent submersion. The inclined ramp and an additional 4° incline of the substrate inside the ramp provided sufficient slope to create attractant flow. A hinged lid provided access for cleaning and flow adjustments. The timing and placement of gear coincided with periods of peak YOY onshore migration. The gear was deployed and fished continuously typically from early March to late June each year.

5.2.29.2 Biological and Environmental Sampling

The entire catch of YOY eels and elvers was counted from each sampling event and at least 60 glass eels (if present) were examined for length (Figure 94), weight, and pigmentation stage (Figure 95) weekly. All eels were counted and placed above the impediment, with any subsample information recorded, if applicable. Specimens less than or equal to ~ 85 mm total length (TL) were classified as YOY, while those greater than 85 mm TL were considered elvers. Water temperature, air temperature, wind direction and speed, and precipitation were recorded during site visits.

5.2.29.3 Evaluation of Survey Data

The proportion of YOY eels in each pigment stage varied across years (Figure 96). A full model that predicted YOY and elver catch as a function of year, water temperature, salinity, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year, water temperature, gear condition, day of the year, and day of the year squared with an offset for effort and a negative binomial error structure was selected for glass eels and the model including year, water temperature, day of the year, and day of the year squared with an offset for effort and a negative binomial error structure was selected for elvers.

5.2.29.4 Abundance Index Trends

There was a decrease in relative abundance of glass eels early in the time series and catches remained stable, but low thereafter (Figure 97). Relative abundance of elvers was low early in the time series but has risen in recent years (Figure 98).

5.2.30 Virginia Wormley Creek Survey

5.2.30.1 Survey Design and Methods

Irish eel ramps were used to collect eels at Wormley Creek. The ramp configuration successfully attracts and captures small eels in tidal waters of Chesapeake Bay. Ramp operation requires continuous flow of water over the climbing substrate and the collection device, and was accomplished through a gravity feed. Hoses were attached to the ramp and collection buckets with adapters to allow for quick removal for sampling. Enkamat™ erosion control material on the ramp floor provided a textured climbing surface and extended into the water below the trap. The ramps were placed on an incline (15–45°), often on land, with the ramp entrance and textured mat extending into the water. The ramp entrance was placed in shallow water (< 25 cm) to prevent submersion. The inclined ramp and an additional 4° incline of the substrate inside the ramp provided sufficient slope to create attractant flow. A hinged lid provided access for cleaning and flow adjustments. The timing and placement of gear coincided with periods of peak YOY onshore migration. The gear was deployed and fished continuously typically from early March to late June each year.

5.2.30.2 Biological and Environmental Sampling

The entire catch of YOY eels and elvers was counted from each sampling event and at least 60 glass eels (if present) was examined for length (Figure 99), weight, and pigmentation stage (Figure 100) weekly. All eels were counted and placed above the impediment, with any subsample information recorded, if applicable. Specimens less than or equal to ~ 85 mm total length (TL) were classified as YOY, while those greater than 85 mm TL were considered elvers. Water temperature, air temperature, wind direction and speed, and precipitation were recorded during site visits.

5.2.30.3 Evaluation of Survey Data

The proportion of YOY eels in each pigment stage was fairly stable across years with the exception of 2009 (Figure 101). A full model that predicted YOY and elver catch as a function of year, water temperature, salinity, gear condition, day-of-the-year and day-of-the-year squared was compared with nested submodels using AIC. The model including year, water temperature, gear condition, day-of-the-year, and day-of-year squared with an offset for effort and a negative binomial error structure was selected for glass eels and the model including year, water temperature, day of the year, and day of year squared with an offset for effort and a negative binomial error structure was selected for elvers.

5.2.30.4 Abundance Index Trends

YOY eel relative abundance was variable over the time series with stable, but lower estimates in recent years (Figure 102). Elver eel relative abundance has been relatively stable over the time series with a peak observed in 2007 (Figure 103).

5.2.31 Virginia Bracken's Pond Survey

5.2.31.1 Survey Design and Methods

Irish eel ramps were used to collect eels at Bracken's Pond. The ramp configuration successfully attracts and captures small eels in tidal waters of Chesapeake Bay. Ramp operation requires continuous flow of water over the climbing substrate and the collection device, and was accomplished through a gravity feed. Hoses were attached to the ramp and collection buckets with adapters to allow for quick removal for sampling. Enkamat™ erosion control material on the ramp floor provided a textured climbing surface and extended into the water below the trap. The ramps were placed on an incline (15–45°), often on land, with the ramp entrance and textured mat extending into the water. The ramp entrance was placed in shallow water (<25 cm) to prevent submersion. The inclined ramp and an additional 4° incline of the substrate inside the ramp provided sufficient slope to create attractant flow. A hinged lid provided access for cleaning and flow adjustments. The timing and placement of gear coincided with periods of peak YOY onshore migration. The gear was deployed and fished continuously typically from early March to late June each year.

5.2.31.2 Biological and Environmental Sampling

The entire catch of YOY eels and elvers was counted from each sampling event and at least 60 glass eels (if present) was examined for length, weight, and pigmentation stage weekly. All eels were counted and placed above the impediment, with any subsample information recorded, if applicable. Specimens less than or equal to ~85 mm total length (TL) were classified as YOY, while those greater than 85 mm TL were considered elvers. Only five years of pigmentation stage were available and therefore annual proportion of pigment stage was not analyzed. Water temperature, air temperature, wind direction and speed, and precipitation were recorded during site visits.

5.2.31.3 Evaluation of Survey Data

A full model that predicted YOY and elver catch as a function of year, water temperature, salinity, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year, water temperature, gear condition, day of the year, and day of year squared with an offset for effort and a negative binomial error structure was selected for glass eels and the model including year, water temperature, day of the year, and day of year squared with an offset for effort and a negative binomial error structure was selected for elvers.

5.2.31.4 Abundance Index Trends

There is a decreasing trend in relative abundance of glass eels at Bracken's Pond with zeros observed in 2016 and 2017 (Figure 104). Elver eels at Bracken's Pond were variable throughout the time series (Figure 105). The lack of glass eels at the site in 2016 and 2017 was the result of a change in habitat at the fixed location and as a result sampling was terminated at this location after 2017. The years of 2016-2017 were not included in the analyses or model approaches in the following sections.

5.2.32 Virginia Kamp's Millpond Survey

5.2.32.1 Survey Design and Methods

Irish eel ramps were used to collect eels at Kamp's Millpond. The ramp configuration successfully attracts and captures small eels in tidal waters of Chesapeake Bay. Ramp operation requires continuous flow of water over the climbing substrate and the collection device, and was accomplished through a gravity feed. Hoses were attached to the ramp and collection buckets with adapters to allow for quick removal for sampling. Enkamat™ erosion control material on the ramp floor provided a textured climbing surface and extended into the water below the trap. The ramps were placed on an incline (15–45°), often on land, with the ramp entrance and textured mat extending into the water. The ramp entrance was placed in shallow water (<25 cm) to prevent submersion. The inclined ramp and an additional 4° incline of the substrate inside the ramp provided sufficient slope to create attractant flow. A hinged lid provided access for cleaning and flow adjustments. The timing and placement of gear coincided with periods of peak YOY onshore migration. The gear was deployed and fished continuously typically from early March to late June each year.

5.2.32.2 Biological and Environmental Sampling

The entire catch of YOY eels and elvers was counted from each sampling event and at least 60 glass eels (if present) was examined for length, weight, and pigmentation stage weekly. All eels were counted and placed above the impediment, with any subsample information recorded, if applicable. Specimens less than or equal to ~85 mm total length (TL) were classified as YOY, while those greater than 85 mm TL were considered elvers. Only four years of pigmentation stage were available and therefore annual proportion of pigment stage was not analyzed. Water temperature, air temperature, wind direction and speed, and precipitation were recorded during site visits.

5.2.32.3 Evaluation of Survey Data

A full model that predicted YOY and elver catch as a function of year, water temperature, salinity, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year, water temperature, day of the year, and day of year squared with an offset for effort and a negative binomial error structure was selected independently for glass eel and elver eel indices.

5.2.32.4 Abundance Index Trends

Relative abundance of glass eels was highest from 2001 to 2005 and 2010 to 2014 and low in other years (Figure 106). Elver eel abundance was relatively stable throughout the time series with a peak in 2003 (Figure 107).

5.2.33 Virginia Wareham's Pond Survey

5.2.33.1 Survey Design and Methods

Irish eel ramps were used to collect eels at Wareham's Millpond. The ramp configuration successfully attracts and captures small eels in tidal waters of Chesapeake Bay. Ramp operation requires continuous flow of water over the climbing substrate and the collection device, and was accomplished through a gravity feed. Hoses were attached to the ramp and collection buckets with adapters to allow for quick removal for sampling. Enkamat™ erosion control material on the ramp floor provided a textured climbing surface and extended into the water below the trap. The ramps were placed on an incline (15–45°), often on land, with the ramp entrance and textured mat extending into the water. The ramp entrance was placed in shallow water (<25 cm) to prevent submersion. The inclined ramp and an additional 4° incline of the substrate inside the ramp provided sufficient slope to create attractant flow. A hinged lid provided access for cleaning and flow adjustments. The timing and placement of gear coincided with periods of peak YOY onshore migration. The gear was deployed and fished continuously typically from early March to late June each year.

5.2.33.2 Biological and Environmental Sampling

The entire catch of YOY eels and elvers was counted from each sampling event and at least 60 glass eels (if present) was examined for length, weight, and pigmentation stage weekly. All eels were counted and placed above the impediment, with any subsample information recorded, if applicable. Specimens less than or equal to ~85 mm total length (TL) were classified as YOY, while those greater than 85 mm TL were considered elvers. Only four years of pigmentation stage were available and therefore annual proportion of pigment stage was not analyzed. Water temperature, air temperature, wind direction and speed, and precipitation were recorded during site visits.

5.2.33.3 Evaluation of Survey Data

A full model that predicted YOY and elver catch as a function of year, water temperature, salinity, gear condition, day of the year and day of the year squared was compared with nested submodels using AIC. The model including year, water temperature, day of the year, and day of year squared with an offset for effort and a negative binomial error structure was selected for glass eels and day-of-the-year, and day-of-year squared with an offset for effort and a negative binomial error structure was selected for elvers.

5.2.33.4 Abundance Index Trends

Glass eel relative abundance was low in the early part of the time series and exhibited a peak in 2011. Since 2011, relative abundance has been variable (Figure 108). Elver relative abundance increased from 2003 to 2016 and has decreased since (Figure 109).

5.2.34 VIMS Trawl Survey

5.2.34.1 Survey Design and Methods

The Virginia Institute of Marine Science (VIMS) Juvenile Trawl Survey was implemented in 1955 to monitor the seasonal distribution and abundance of important finfish and invertebrate species occurring in the Chesapeake Bay and its tributaries. The main objective of this survey is to develop indices of relative abundance to track year-class strength of target species. The survey sites and sampling frequency has not been consistent throughout the history of the survey (Tuckey and Fabrizio 2010). The survey currently employs a mixed design, incorporating both stratified random sites and fixed (historical mid-channel) sites. Prior to 1996, sampling occurred at fixed stations only and these were located generally in deep, mid-channel areas of the rivers. In 1996, random stations were added to the sampling frame in the rivers and account for about 63.3% of the stations sampled in any given year after 1996. The stratification system is based on depth and latitudinal regions in the bay (random stations), or depth and longitudinal regions in the tributaries (random and fixed stations). Each bay region spans 15 latitudinal minutes and consists of six strata: western and eastern shore shallow (4–12 ft), western and eastern shoal (12–30 ft), central plain (30–42 ft), and deep channel (>42 ft). Each tributary is partitioned into four regions of approximately ten longitudinal minutes, with four depth strata in each (4–12 ft, 12–30 ft, 30–42 ft, and >42 ft). Strata are collapsed in areas where certain depths are limited. In each tributary, fixed stations are spaced at approximately 5-mile intervals from the river mouths up to the freshwater interface. Fixed sites are assigned to strata based on location and depth. The stratified random sites are selected randomly from the National American Ocean Service's Chesapeake Bay bathymetric grid, a database of depth records measured or calculated at 15-cartographic-second intervals. The trawl gear configuration has been modified a number of times but was standardized in 1979. The various gear configurations have been compared through extensive sampling in order to standardize the catch rates associated with each gear combination. Currently, a trawl net with a 5.8-m head line, 40-mm stretch-mesh body, and a 6.4-mm liner was towed along the bottom for five minutes during daylight hours.

5.2.34.2 Biological and Environmental Sampling

At the completion of each tow, all fishes were identified to species, counted, and measured to the nearest millimeter (Figure 110) and water quality measurements were taken at the surface and bottom for temperature, salinity, dissolved oxygen, and depth.

5.2.34.3 Evaluation of Survey Data

Due to low catches of American eel at many sites sampled by the trawl survey, survey data strata were restricted to sites located in the James, York, and Rappahannock rivers (strata: 37, 38, 39, 40, 58, 59, 60, 61, 62, 77, 78, 79, 80, 81). Months were also restricted to April, May, and June when most eels were observed.

A full model that predicted yellow eel catch as a function of year (1955–2019), water temperature, salinity, and depth was compared with nested submodels using AIC. The model including year with an offset for effort and a negative binomial error structure was selected for the long time series.

An additional set of models were compared for a shorter time series (1996–2019) where sampling design and gear was consistent. A full model that predicted yellow eel catch as a function of year, water temperature, salinity, dissolved oxygen, and depth was compared with nested submodels using AIC. The model including year and salinity with an offset for effort and a negative binomial error structure was selected for the short time series.

5.2.34.4 Abundance Index Trends

Yellow eel indices were high from the late 1970s to the late 1980s (Figure 111). Many changes to survey effort, gear, and site selection occurred prior to 1996 raising concerns about the utility of the full time series. As a result, a shorter time series (1996–2019) was investigated when the sampling design and gear were standardized. The short time series shows a decrease in yellow eel relative abundance from the late 1990s to today (Figure 112).

5.2.35 VIMS Seine Survey

5.2.35.1 Survey Design and Methods

The Virginia Institute of Marine Science (VIMS) initiated a juvenile striped bass seine survey in 1967, but the survey was not conducted between 1973 and 1979 due to funding cuts. Funding was restored in 1980, and the survey has been conducted in every year since.

Sampling strategy has changed multiple times over the duration of the survey, with standardized methods being adopted in 1989. Since then, 40 stations are sampled biweekly from early July through mid-September (five rounds per year) using a 100-foot (30.5 m) seine net. Stations are located in the James, York, and Rappahannock Rivers (Figure 113). Data prior to 1989 are not standardized and should therefore be considered with caution. However, data from years prior to the harvest increase observed in the 1970s are limited, making early years of the VIMS seine survey very important in characterizing the population during that time period.

5.2.35.2 Biological and Environmental Sampling

All American eels were measured for total length (Figure 114) and water temperature, salinity, depth, and Secchi depth was measured at each site.

5.2.35.3 Evaluation of Survey Data

VIMS Striped Bass Seine Survey data were subset to include months from June to September. In addition, fixed sites were restricted to stations that regularly encounter eels (stations: RA0037, RA0069, RA0065, RA0060, JA0051, JC0001, JC0003, YK0015, YK0021, YK0028, MP0052). A shorter and longer time series was investigated.

A full model that predicted yellow eel catch as a function of year (1967–2019), water temperature, salinity, and Secchi depth was compared with nested submodels using AIC. The model including year and salinity with a negative binomial error structure was selected for the long time series.

An additional set of models were compared for a shorter time series (1989–2019) where sampling design and gear was consistent. A full model that predicted yellow eel catch as a function of year, water temperature, salinity, and secchi depth was compared with nested submodels using AIC. The model including year and salinity with a negative binomial error structure was selected for the short time series.

5.2.35.4 Abundance Index Trends

Yellow eels in the VIMS Striped Bass Seine Survey full time series showed stable catches throughout the study period (Figure 115). The short time series showed a similar pattern with a peak index in 1997 and low, but stable values during the remaining years (Figure 116).

5.2.36 North Carolina Beaufort Bridgenet Ichthyoplankton Sampling Program

5.2.36.1 Survey Design and Methods

The NOAA National Ocean Service laboratory in Beaufort, North Carolina, has been conducting bridge-based plankton sampling near Beaufort, North Carolina since 1985. Ingressing glass eels are often captured in the survey, providing an index of glass eel recruitment to the estuary. The survey samples once weekly at night during flood tide from a fixed platform on Pivers Island Bridge, Beaufort, North Carolina (Figure 117). The bridge spans a 40-m wide channel 1.5 km upstream from Beaufort Inlet. Beaufort Inlet is a principal connection between the back bays of North Carolina's Outer Banks and the Atlantic Ocean in the region of Beaufort, North Carolina. The major systems near Beaufort Inlet include Bogue Sound, Core Sound, Newport River, and North River. Tidal range within the estuary is approximately 1 meter. Approximately 10% of the water entering Beaufort Inlet passes through the Radio Island—Pivers Island channel where sampling occurs.

Sampling is conducted using a 2-m² rectangular plankton net with 1-mm mesh. A flow meter is attached to the net to measure flow rates. Four replicate sets have been made at the surface (0–1m) during night time flood tides at weekly (1985 to 2001) or bi-weekly (2001 to present) intervals. Sampling is conducted from November to April in every year, with occasional sampling in May and October. Tow duration was approximately 5 minutes per tow during 1985 to 1997; since 1998 tows have been standardized to volume sampled (approximately 100 m³) rather than tow duration.

5.2.36.2 Biological and Environmental Sampling

Ichthyoplankton is sorted by species and either measured (nearest mm) or counted; no weights are collected. Environmental data are collected and a flow meter is attached to the net to measure flow rates.

5.2.36.3 Evaluation of Survey Data

Mean length was fairly consistent across years (Figure 118) and averaged 51.9 ± 3.0 mm (\pm SD). Available covariates for the GLM framework included year, day of year, and water temperature. Tow duration was used as an offset in the GLM. The best-fitting model assumed a negative binomial distribution. Year, day of year, day of year squared, and water temperature were all found to be significant (dispersion = 1.4).

5.2.36.4 Abundance Index Trends

The standardized YOY index of relative abundance derived from the Beaufort Bridgenet Ichthyoplankton Sampling Program was variable without trend throughout the available time series (Figure 119). There is a peak that occurred in 1998, the highest relative abundance observed in the time series.

5.2.37 South Carolina Goose Creek Survey

5.2.37.1 Survey Design and Methods

Goose Creek is the site of South Carolina's state-mandated YOY survey, which has been in operation since 2000 (Figure 120). The survey uses a fyke net and typically samples from mid-February through mid-April depending on the run. During the run, gear is left to soak for 24–48 hours and checked 3–5 times a week.

5.2.37.2 Biological and Environmental Sampling

Biological sampling for YOY eel length, weight, and pigmentation of 60 samples is done once or twice a week. Water temperature, water level, and gear condition are collected as part of the survey.

5.2.37.3 Evaluation of Survey Data

Mean length was fairly consistent across years (Figure 121) and averaged 54.1 ± 2.9 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 122). Available covariates for the GLM framework included year, day, water temperature, water level, and gear condition. Time was used as an offset in the GLM. Water level was removed from consideration in the GLM as it was highly correlated with at least one other variable based on the results of the variance inflation factor analysis. The best-fitting model assumed a negative binomial distribution. Year and water temperature were found to be significant (dispersion = 1.0).

5.2.37.4 Abundance Index Trends

The standardized YOY index started out relatively low then jumped to a peak in the second year of the index time series in 2001 (Figure 123). The index then declined and increased to a second peak observed in 2005 and then decreased and remained low throughout the remainder of the time series.

5.2.38 South Carolina Rediversion Canal Aluminum Ladder Survey

5.2.38.1 Survey Design and Methods

The St. Stephen Dam is located on the Rediversion Canal on the Santee River in South Carolina (Figure 124). Experimental data were collected from 2003–2005 from February to March with both fyke nets and fish ladders. Beginning in 2006, year-round sampling began on two different experimental ladders: aluminum and corrugated. No sampling was done in 2008 due to river flow issues that made sampling difficult. From 2014 on, year-round sampling continued on the permanent aluminum eel ladder so the SAS agreed to use the aluminum ladder data instead of the corrugated ladder.

5.2.38.2 Biological and Environmental Sampling

Soak time, water temperature, river discharge, and gear condition were recorded for this survey. American eel lengths were also recorded.

5.2.38.3 Evaluation of Survey Data

Mean length was fairly consistent across years (Figure 125) and averaged 94.7 ± 18.0 mm (\pm SD). Available covariates for the GLM framework included year, water temperature, discharge, and gear condition. Duration was used as an offset in the GLM. The best-fitting model assumed a quasi-Poisson distribution. Year, water temperature, and gear condition were found to be significant.

5.2.38.4 Abundance Index Trends

The American eel index developed from this survey is variable throughout the index time series (Figure 126). Peaks were observed in 2012 and 2018.

5.2.39 Georgia Altamaha Canal Survey

5.2.39.1 Survey Design and Methods

Beginning in 2001, a single, fixed-station sampling design was implemented for monitoring YOY eels in the Altamaha River. The Altamaha River is a man-made canal dug over 100 years ago (Figure 127). Sampling followed the methods provided by the ASMFC American Eel Technical Committee. The survey operated from January to March and fyke nets were staked out for the season and sampled two days a week. The survey was discontinued after 2013.

5.2.39.2 Biological and Environmental Sampling

Water temperature and gear condition were collected during sampling in addition to the required biological subsampling for lengths, weight, and pigments.

5.2.39.3 Evaluation of Survey Data

Mean length was fairly consistent across years (Figure 128) and averaged 52.4 ± 2.9 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 129). Available covariates for the GLM framework included year, day, water temperature, and gear condition. Time was used as an offset in the GLM. The best-fitting model assumed a negative binomial distribution. Year and day were found to be significant (dispersion = 1.0).

5.2.39.4 Abundance Index Trends

The relative YOY index developed from the Georgia Altamaha Canal Survey was highest in the first year of the survey and then sharply declined (Figure 130). The index remained low and without trend throughout the rest of the time series.

5.2.40 Georgia Hudson Creek Survey

5.2.40.1 Survey Design and Methods

Beginning in 2003, a single, fixed-station sampling design was implemented for monitoring YOY eels in the Hudson Creek, a small branch which feeds into the Dobby Sound system (Figure 127). Sampling followed the methods provided by the ASMFC American Eel Technical Committee. The survey operated from January to March and fyke nets were staked out for the season and sampled two days a week. The survey was discontinued after 2013.

5.2.40.2 Biological and Environmental Sampling

Water temperature and gear condition were collected during sampling in addition to the required biological subsampling for lengths, weight, and pigments.

5.2.40.3 Evaluation of Survey Data

Mean length was fairly consistent across years (Figure 131) and averaged 52.1 ± 3.6 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years (Figure 128). Available covariates for the GLM framework included year, day, water temperature, and gear condition. Time was used as an offset in the GLM. The best-fitting model assumed a negative binomial distribution. Year and water temperature were found to be significant (dispersion = 1.1).

5.2.40.4 Abundance Index Trends

Relative abundance of YOY American eel remained relatively low throughout most of the index time series with the exception of two peaks observed in 2005 and 2007 (Figure 133). A smaller peak was observed in 2003.

5.2.41 Florida Guana River Survey

5.2.41.1 Survey Design and Methods

The Guana River Dam is located in Northeast Florida (Figure 134). Sampling typically runs six to eight weeks from early January through February. The site is sampled four random nights per week with two dip net sweeps per side every 30 minutes on a night-time incoming tide.

5.2.41.2 Biological and Environmental Sampling

Water temperature, flood time, flood duration, tide height, and discharge are recorded as part of this survey in addition to biological sampling for American eel length, weight, and pigment stage.

5.2.41.3 Evaluation of Survey Data

Mean length was fairly consistent across years (Figure 135) and averaged 51.2 ± 2.9 mm (\pm SD). The proportion of YOY eels in each pigment stage varied across years but was dominated by stage zero and one (Figure 136). Available covariates for the GLM framework included year, day, water temperature, flood time, flood duration, tide height, and discharge. Soak time was used as an offset in the GLM. The best-fitting model assumed a negative binomial distribution. Year, day, and discharge were found to be significant (dispersion = 1.1).

5.2.41.4 Abundance Index Trends

The YOY American eel index peaked in the first year of the index time series and then declined and remained low through the most recent year of the survey (Figure 137).

5.3 Index Correlations

5.3.1 YOY Indices

Spearman's rank correlation coefficient, ρ , and the associated probability were calculated for all pairs of YOY indices to assess the degree of association among the indices. Indices were considered significantly correlated at $\alpha = 0.10$. Of the 300 comparisons, 38 were either significantly negatively and positively correlated (Table 14; Figure 138).

5.3.2 Elver Indices

Spearman's rank correlation coefficient, ρ , and the associated probability were calculated for all pairs of elver indices to assess the degree of association among the indices. Indices were considered significantly correlated at $\alpha = 0.10$. Of the 45 comparisons, 5 were statistically significant with 2 negatively correlated and 3 positively correlated (Table 15; Figure 139).

5.3.3 Yellow Eel Indices

Spearman's rank correlation coefficient, ρ , and the associated probability were calculated for all pairs of yellow eel indices to assess the degree of association among the indices. Indices were considered significantly correlated at $\alpha = 0.10$. Of the 91 comparisons, 17 were significantly correlated, both negatively and positively (Table 16; Figure 140). There were some significant correlations between the indices in the New York Bight and Mid-Atlantic and between Connecticut and New York indices but otherwise there were few significant correlations among yellow eel indices.

5.4 YOY Survey Analysis

Data from YOY American eel surveys (Table 11; Figure 141) were examined to determine if there were any latitudinal or temporal patterns in length measurements, pigment stages, or abundance estimates. Multiple gear types were used to collect YOY eels and include dip nets (Florida), fyke nets (Delaware, Georgia, New Jersey, New York, South Carolina), Irish elver ramps (Connecticut, Maryland, Maine, New Hampshire, Potomac River Fisheries Commission, Rhode Island, Virginia), and Sheldon traps (Massachusetts) with some jurisdictions monitoring more than one site (Table 11). Sites were located from Maine to Florida, and there were no YOY monitoring sites in the Gulf of Mexico despite the presence of American eels in the region. Biological data were not collected at all sites and some years were missed resulting in varying numbers of sites with data available for the analysis.

5.4.1 Biological Characteristics

There were 128,112 YOY eels with length, weight, and pigment stage assessments across all sites and years. There was no obvious pattern in the relationship between lengths of YOY eels and the different pigment stages (Figure 142a). There was also no pattern evident between pigment stage and weights of YOY eels (Figure 142b) or between relative condition of YOY eels and pigment stage (Figure 142c). There does appear to be an increase in length with increasing

latitude (Figure 143); however, the gear used to sample YOY eels varies across latitude and confounds some of the observations (e.g., Guana, Florida is the only site that uses dip nets to collect YOY eels and has the smallest observed sizes). It appears that sites from South Carolina (Goose Creek) and south are smaller on average and the northern two sites (West Harbor Pond, Massachusetts and Lamprey River, New Hampshire) tend to have the largest YOY eels (Figure 144). Sites ranging from Virginia (Wormley Creek and Gardy's Millpond) to Rhode Island (Gilbert Stuart Dam) have varying mean lengths with no clear pattern. Results from GAMMs with collection date as a random factor to account for the clustered nature of length observations from each site indicate a significantly smaller ($P < 0.001$) length in FL from all other sites (mean = 59.7 mm, SE = 9.6).

5.4.2 YOY Index Comparison

Young-of-the-year eel GLM-indices produced in this assessment were standardized (mean-centered) by site to allow direct comparisons since different gear were used along the coast. Sites were arranged along the x-axis by latitude (south to north) to visually assess if there were geographic patterns in recruitment (Figure 145). Overall, recruitment varies annually along the Atlantic Coast with only a few years showing localized regions where recruitment was high. Within a site (Figure 146), standardized GLM indices indicate some sites have periods of strong recruitment followed by periods of low recruitment (i.e., Jones River, Massachusetts) or the opposite with low recruitment in early years and higher recruitment in more recent years (e.g., Millsboro, Delaware); however, most sites show no clear pattern in recruitment over time. Analysis of the coastwide index of abundance for YOY American eels (calculated using the Conn Method, Section 6.2) showed no significant relationships with climatic drivers including the Atlantic Multidecadal Oscillation, North Atlantic Oscillation, or the Gulf Stream North Wall Index; however, it should be noted that there are only 20 data points for the time series and these observations occurred when the American eel stock is believed to be at a depleted level.

5.4.3 Recommendation

Given the lack of trends in pigment, length, and weight within and among sites, the SAS and TC recommend that the biological sampling requirement for YOY surveys be made optional. Additionally, no new YOY sites should be required to collect biological data as part of their compliance with the FMP. Many states indicated that they will continue to collect biological data voluntarily, but may reduce sample sizes as needed. Trends in the available biological data will be evaluated during the next stock assessment, or as needed, and biological sampling can be mandated again in the future. The FMP requirement to conduct an annual YOY survey should be maintained. States and jurisdictions should continue to annually monitor YOY eels and collect associated environmental data since abundance indices are important to continue throughout the range.

6 METHODS

6.1 MARSS

6.1.1 Background of Analysis and Model Description

A Multivariate Auto-Regressive State-Space (MARSS) model was used to analyze time series data from American eel fishery-independent surveys. The MARSS model incorporates both process and observation error using a linear combination of random walks. It can be used to determine a common long-term population growth rate among multiple time series assuming each time series represents the same population. The MARRS model can also be used to examine population structure and test hypotheses about whether multiple time series represent the same or different populations (Holmes et al. 2018).

6.1.2 Configuration

For American eels, MARSS models were fit to yellow, elver, and YOY indices using the R package MARSS. Because American eels along the east coast represent one panmictic population, a single model was fit to all surveys within a life stage. This assumes there is single underlying population growth rate across all surveys (U model = equal) and similar process errors across all surveys (Q model = diagonal and equal); however, there are likely differences in catchability across surveys due to differences in gear, physical habitat where surveys are conducted, and environmental covariates which would result unequal observation errors (R model = diagonal and unequal). The yellow MARSS model used 14 surveys; elver used 10 surveys, and YOY used 25 surveys. The yellow eel MARSS model began in 1974 with the Hudson River HRE survey being the longest survey; the elver MARSS model began in 1999 with the Delaware River Electrofishing survey having the longest time series; and the YOY MARSS model began in 1987 when both the Hudson River HRE and Beaufort surveys occurred. Abundance indices from all surveys were natural-log transformed before fitting MARSS models.

6.1.3 Results

Although MARSS model fits to yellow and YOY time series suggested a slightly declining population (Figure 147 and Figure 148), the 95% confidence intervals on population growth rate estimates overlapped 0 suggesting a stable population (Table 17). The model fit to the elver time series showed no change in population through time (Figure 149). Estimated population growth rates were -0.023 (95% CI: -0.058 – 0.012) for yellow eels, 0.007 (95% CI: -0.014 – 0.027) for elvers, and -0.010 (95% CI: -0.042 – 0.022) for YOY eels (Table 17). To compare the MARSS index of yellow eel abundance to each individual yellow eel index, the MARSS index model fit was scaled to each index and provided in Figure 150 - Figure 163.

6.2 Conn Method

6.2.1 Background of Analysis and Model Description

When several population abundance indices provide conflicting signals, hierarchical analysis can be used to estimate a single population trend. The abundance indices for American eel were

combined into a coastwide composite index using hierarchical modeling as described in Conn (2010). This method assumes each index samples a relative abundance but that the abundance is subject to sampling and process errors. It can be used on surveys with different time series, but it does assume that indices are measuring the same relative abundance.

6.2.2 Configuration

Yellow, elver, and glass eel abundance indices for American eel were standardized to their means before being combined using the methods of Conn in R and WinBUGS. Each coastwide Conn index by stage was developed using all the surveys available for all years when at least two surveys were in operation (Table 11-Table 13).

6.2.3 Results

6.2.3.1 YOY

The hierarchical index developed for the coastwide relative abundance of YOY eels from 1987–2020 predicted a variable but stable index (Table 18; Figure 164). There was a moderate increase in the terminal year although the estimate had wide confidence intervals as not all individual YOY surveys provided 2020 data.

6.2.3.2 Elver

The hierarchical index developed for the coastwide relative abundance of elvers from 2000–2019 predicted a stable index with little variation (Table 18; Figure 165).

6.2.3.3 Yellow eel

The hierarchical index developed for the coastwide relative abundance of yellow eels from 1955–2020 predicted high abundance in the initial years, followed by relatively low abundance through the 1960s (Table 18; Figure 166). The index was variable but high through the 1970s and 1980s and then began to decline steadily through the 1990s. From the 2000s through present day, the index shows stable but low yellow eel abundance. There was a moderate decrease in the abundance of yellow eel in the terminal year.

6.2.3.4 Comparison with MARSS

For the years that the two composite index methods overlap, 1974–2020, the Conn and MARSS methods provide very similar trends in the data. The SAS preferred the MARSS method over the Conn, but the Conn index was maintained for analyses that required a longer time series.

6.3 Power Analysis

6.3.1 Background of Analysis and Model Description

Power analysis followed methods described in Gerrodette (1987) for both potential linear and exponential trends. A linear trend can be modeled as $A_i = A_1[1 + r(i - 1)]$ and an exponential trend as $A_i = A_1(1 + r)^{i-1}$ where A_i = the abundance index in year i , A_1 = the abundance index in year 1, and r = a constant increment of change as a fraction of the initial abundance index A_1 . The overall fractional change in abundance over n years can be expressed as $R = r(n - 1)$.

If α and β are the probabilities of a type 1 and type 2 errors respectively, the power of a linear trend $(1 - \beta)$ assuming $CV \sim 1/\sqrt{A}$ can be determined by satisfying the equation

$$r^2 n(n-1)(n+1) \geq 12 CV_1^2 (z_\alpha + z_\beta)^2 \left\{ 1 + \frac{3r}{2}(n-1) \left[1 + \frac{r}{3}(2n-1) + \frac{r^2}{6}n(n-1) \right] \right\}$$

and the power of an exponential trend can be determined by satisfying the equation

$$[\ln(1+r)]^2 n(n-1)(n+1) \geq 12 (z_\alpha + z_\beta)^2 \left\{ \frac{1}{n} \sum \ln[CV_1^2(1+r)^{i-1} + 1] \right\}$$

where CV_1 is an estimate of the coefficient of variation of the survey. For each of the surveys, the median CV of the survey was calculated over the entire time series of the survey and used as an estimate of CV_1 . Power was then calculated for an overall change (R) of $\pm 50\%$ over a 10 year time period ($r = 0.056$) for both a linear and exponential trend.

Power analysis was performed on all fishery-independent American eel surveys as a means to evaluate the precision of abundance indices.

6.3.2 Results

Median CV s of the surveys ranged from 0.01 to 0.48. Resulting estimates of power were a function of CV s with those surveys having low CV s having high power and those surveys having high CV s having low power. Power values ranged from 0.22 to 1.00 (Table 19). For all surveys, there is greater power to detect a decreasing trend compared to an increasing trend, which is a property of surveys whose $CV \sim 1/\sqrt{A}$. There was very little difference in power between linear and exponential trends. Although there was a large range in estimated power within each life stage, power tended to be highest for surveys assessing the yellow life stage.

The values of power presented in Table 19 can be interpreted as the probability of detecting a given linear or exponential trend of $\pm 50\%$ over a ten-year period if it actually occurs. These values do not reflect a retrospective power analysis and a survey with low power value may still be capable of detecting a statistically significant trend if given enough years of data.

6.4 Mann-Kendall Analysis

6.4.1 Background of Analysis and Model Description

The Mann-Kendall trend analysis is a non-parametric test for monotonic trend in time-ordered data (Gilbert 1987). The null hypothesis is that the time series is independent and identically distributed—there is no significant trend across time. The test allows for missing values and can account for tied values if present.

The Mann-Kendall test was applied to all YOY, elver, and yellow eel indices computed in this assessment. A two-tailed test was used to test for the presence of either an upward or downward trend over the entire time series. Trends were considered statistically significant at $\alpha = 0.05$.

6.4.2 Results

6.4.2.1 YOY Indices

The Mann-Kendall test detected significant trends in 6 of the 26 YOY indices evaluated (Table 20). Two of the indices with significant trends were found to be increasing and the four remaining significant trends were found to be decreasing.

6.4.2.2 Elver Indices

Of the nine elver indices evaluated, significant trends were detected in two (Table 21). One of the indices with significant trends was found to show decreases through time and one showed an increase over time.

6.4.2.3 Yellow Eel Indices

The Mann-Kendall test was applied to 15 yellow eel indices. The test detected statistically significant trends in seven of these indices (Table 22). Five of these indices were found to have significant decreasing trends and two were found to have significant increasing trends.

6.5 Regime Shift Analysis

The SAS explored two methods for detecting regimes in the American eel abundance data using the MARSS index.

6.5.1 Background of Analysis and Model Description

6.5.1.1 STARS

Sequential t-test Analysis of Regime Shifts (STARS) is a regime shift detection described in Rodionov (2004) and Rodionov and Overland (2005). STARS uses a series of sequential t-tests that compare the current, or most recent, value to the mean of the time series for the current regime to identify potential change points. A significantly different value indicates a potential

regime shift, and the following observations are used to confirm this. Some methods for regime shift detection have difficulty detecting shifts near the end of the time series, thus shifts cannot be detected in a timely fashion. The STARS method was developed to address this problem. The analysis was done using the shift detection add-in version 3.2 in Excel (<https://www.beringclimate.noaa.gov/regimes/help3.html>).

6.5.1.2 RPART

Regime shifts in the American eel data were also detected using chronological clustering (Legendre and Legendre 2012). This method uses a clustering algorithm that divides the productivity time series into regimes where the clusters are chosen to minimize the sum of squares within the clusters. The analysis was run using the RPART package in R (Therneau et al. 2015). To determine how many clusters provided the best model for understanding the regimes for productivity, the tree was pruned based on accompanying plots from the analysis.

6.5.2 Configuration

The MARSS YOY, elver, and yellow eel abundance indices were tested using both STARS and RPART regime test methods. For STARS, a regime cut-off length of ten years was used although regimes shorter than ten years may still be detected by the analysis. A length of five years was also tested. Huber's $h=2$ was used for down-weighting outliers, although values from 1.345 to 6 were tested as sensitivity runs. A significance value of $P=0.05$ was used, although $P=0.10$ was tested as well. For RPART, nothing has to be specified before running the analysis, but trees are pruned based on outputs to determine how many splits there should be in the data.

6.5.3 Results

Both methods detected the same time periods for regimes in the American eel abundance index data. For YOY data, there were two regimes detected by both analyses: 1987-2002 (high YOY abundance regime) and 2003–2020 (low YOY abundance regime). There were also two regimes predicted in the yellow eel index: 1974–1988 (high yellow eel abundance regime) and 1989–2020 (low yellow eel abundance regime). No regimes were detected in the elver index time series. The YOY and yellow eel results are consistent with the previously used depleted determination, as both YOY and yellow eel stages are in low abundance regimes.

6.6 Traffic Light Analysis

6.6.1 Background of Analysis and Model Description

The TLA is a statistically-robust way to incorporate multiple data sources (both fishery-independent and -dependent) into a single, easily understood metric for management advice (Caddy 1998, 1999). It is often used for data-limited species or species that are not assessed on a frequent basis. The name comes from assigning a color (red, yellow, or green) to categorize relative levels of indicators on the condition of the fish population (abundance metric) or fishery (harvest metric). For example, as harvest or abundance increase relative to their long-

term mean, the proportion of green in a given year will increase, and as harvest or abundance decrease, the amount of red in that year becomes more predominant.

The 2012 stock assessment (ASMFC 2012) used the TLA to summarize the trends in abundance indices, color coding them by region and year as ‘green’ (metric above 75th percentile), ‘yellow’ (between 25th and 75th percentile), and ‘red’ (below the 25th percentile of the data). This yielded complex spatial and temporal patterns in the indices that were difficult to interpret. The Peer Review Panel noted at that time that the TLA could be used to put the abundance indices in the broader context of trends in the environment (e.g., regional temperatures and salinities), the American eel’s biology (e.g., growth, condition, and early life history) and loss of its habitat (e.g., dam construction). Ultimately, they did not recommend its use for managing American eels.

6.6.2 Configuration

The SAS re-explored that application of a TLA for this assessment using both the previous methods and a revised approach. As was done in the 2012 benchmark, the SAS used the TLA to summarize trends in the abundance indices, color coding them by ‘green’ (metric above 75th percentile), ‘yellow’ (between 25th and 75th percentile), and ‘red’ (below the 25th percentile of the data). This time, the data were not analyzed regionally and the Conn and MARSS YOY and yellow eel abundances were used instead of the composite indices used in the last assessment. The SAS also considered some other time series to address previous peer review comments including commercial landings, number of dams, and commercial mean length. The SAS ultimately decided not to use the commercial landings because other applications of the TLA consider high landings to be good. Given the stock of American eel is depleted and there is a coastwide cap in place, the use of landings was not appropriate and thus this time series was removed from the TLA. The SAS explored a time series of dam construction for consideration of an indicator for American eels but ultimately could not find a comprehensive data set to use. Commercial lengths from the Chesapeake Bay region were used for the commercial mean length time series. Lengths were available from Delaware, Maryland, and Virginia from 1989 through the present (Figure 167) and comprehensive sex data were available from 2006 on (Figure 168 and Figure 169) but most of the sexed lengths were from Maryland.

Another application of the TLA was done that used a reference period to compare values to, similar to the approach used for Atlantic croaker and spot (ASMFC 2020a, 2020b). In general practice when applying this type of TLA, the green/yellow boundary is typically set at the long-term mean of the data series reference period (Halliday et al. 2001) of the indicator and the yellow/red boundary is set at 60% of the long-term mean, which would indicate a 40% decline from the series mean. Index values in the intermediate zone can be represented by a mixture of either yellow/green or yellow/red depending on where they fall in the transition zone. Since increasing proportions of red reflect decreasing trends away from the time series mean, the relative proportion of red of the indicator may offer one way of determining if any management response is necessary. A reference period is used to compare values to and the reference period should be from a time when the stock was considered to be in good condition.

For American eels, the SAS agreed that the reference period should be in the 1970s or 1980s before the relative abundance numbers began to dramatically decrease.

6.6.3 Results

Using the TLA methods from ASMFC 2012, each time series was evaluated using the color coding of ‘green’ (metric above 75th percentile), ‘yellow’ (between 25th and 75th percentile), and ‘red’ (below the 25th percentile of the data). Both YOY and yellow eel indices indicated green values for the 1980s, changing to orange, then to red by the end of the time series (Table 23). Commercial mean length did not have any clear patterns through the years of available data.

To use the other TLA approach, a reference period is chosen that should be consistent for all the time series analyzed and be from a period of time when the stock was in a good condition. Therefore, the 1980s should be used as a reference period for American eels but using the 1980s as a reference period was problematic. Much of the available fishery-independent data does not go back that far. For example, YOY data only go back to 1987, at which point the population was already showing a decline. Additionally, length data from the Chesapeake Bay is not available from the early 1980s. Therefore, this approach was abandoned by the SAS.

6.7 Egg-per-Recruit

6.7.1 Background of Analysis and Model Description

An egg-per-recruit (EPR) model was developed for American eels to evaluate the relative effects of fishing mortality and to compare harvest strategies targeting yellow eel versus glass eel life stages. The model was based on the EPR model by Sweka et al. (2014) which evaluated the effects of downstream fish passage mortality on EPR in the Susquehanna River. Because life history parameters can vary for American eels along a watershed gradient, the SAS two sets of life history parameters were considered: 1) parameters for eels that remain in estuarine environments and 2) parameters for eels that migrate to inland waters prior to emigration to the sea for spawning.

Because American eels are semelparous and leave the system once mature, the number of females remaining within subsequent age classes in a river reach (estuary versus inland) is a function of natural mortality within the reach and the proportion that remain immature:

$$N_i = N_{i-1}(1 - \rho_{i-1}) \cdot e^{-M_{i-1} - F_{i-1} \cdot R_{i-1}}$$

where N_i is the number of females of age i , $\rho_{i,r}$ is the proportion of females that are mature at age i , M_i is the natural mortality of females of age i , F_i is the fishing mortality of females of age i , and R_i is the recruitment to the fishery of females of age i . Recruitment was a function of length at age and assumed values of 1.0 for ages that had lengths > 228.6 mm (9 inches) corresponding to the minimum length of yellow eels in the fishery under current management. The number of eggs produced by an age class of females is:

$$E_i = \rho_i \cdot \theta_i \cdot N_i$$

where θ_i is the fecundity of a female eel of age i . The total eggs-per-recruit is the sum of all eggs produced over all age classes divided by the number of initial recruits:

$$EPR = \sum_{i=1}^n E_i / N_0$$

6.7.2 Configuration

The model was parameterized using a combination of empirical data on American eel collected in the Susquehanna River and literature-derived values (Table 24). The growth rate for American eels that remain in the estuarine reach was equivalent to the mean growth rate observed in the Chesapeake Bay (72.5 mm/year; Fenske et al. 2010) and higher than American eels that migrated to the inland reach (38.5 mm/year). The growth rate for American eels in the inland reach was equivalent to growth rates from upstream areas in the Hudson River, NY (Morrison and Secor 2003) and Shenandoah River, VA (Goodwin 1999). Maturity in each reach was modeled as a logistic regression function of length:

$$\rho_{i,estuary} = 1/[1 + e^{-(-10.43+0.02 \cdot L_i)}] \text{ and } \rho_{i,inland} = 1/[1 + e^{-(-13.83+0.02 \cdot L_i)}]$$

where L is the total length (mm) of a female American eel of age i in the estuarine or inland reach. The estuarine maturity schedule followed that of the general stock assessment model employed by the Atlantic States Marine Fisheries Commission (ASMFC 2012) and the inland maturity schedule was derived from maturity-at-size data from the Shenandoah River (Sheila Eyler, U.S. Fish & Wildlife Service, unpublished data). These two models assume American eels that remain in the estuary mature at a smaller size than those in inland waters. Fecundity was also modeled as a function of length (cm) and was the average of two published functions (Tremblay 2009; Barbin and McCleave 1997):

$$\theta_i = (308.32 \cdot L_i^{2.293} + 18.20 \cdot L_i^{2.964})/2$$

Natural mortality of glass eels (age 0) was set to 3.91 while natural mortality for ages 1 and older was modeled as a function of weight at age (Lorenzen 1996; ASMFC 2012):

$$M_i = 0.492 \cdot W_i^{-2.88}$$

where $W_{i,r}$ is the weight of an age i eel and was estimated from a general weight-length equation (ASMFC 2012):

$$W_i = 3.44 \times 10^{-7} \cdot L_i^{3.27}$$

Natural mortality of eels in the estuary was assumed to be greater than in inland environments because eel predators in larger estuary waters are rarely found in smaller watersheds (Buckel

and Conover 1997; Griffin and Margraf 2003; Walter and Austin 2003; Machut et al. 2007). Therefore, inland natural mortality was modeled by dividing the natural mortality by an assumed ratio of estuary-to-inland natural mortality (2.0) for each age/size class.

American eel EPR was evaluated for F ranging from 0 to 1.0 for both sets of life history parameters (estuarine and inland). When modeling a glass eel harvest strategy, the SAS assumed no fishing mortality occurred on eels greater than age 0. Conversely, when modeling a yellow eel harvest strategy, it was assumed that no fishing mortality occurred on age 0. These scenarios represented the extremes in potential harvest management strategies. The uncertainty in life history parameters for American eels was captured by conducting Monte Carlo simulations of EPR that allowed life history parameters to vary according to uniform distributions (Table 24) and 10,000 simulations were ran for each combination of harvest strategy (glass versus yellow) and location within a watershed (estuarine versus inland).

6.7.3 Results

American eel EPR declined with increasing values of F , but the decline was greater for a yellow eel fishery compared to a glass eel fishery (Figure 170). The relative decline in EPR with increasing F was similar between estuary and inland regions for a glass eel fishery. This was expected because mortality due to the fishery was concentrated on a single initial age class and survivors are free from fishing mortality; however, increasing F had a much greater effect on a yellow eel fishery in the inland region compared to the estuary region. The reason for this disproportionate effect is because yellow eels in the inland region had slower growth rates and matured at later ages compared to the estuary, thus resulting in more years of potential harvest prior to emigration for spawning.

If a traditional F benchmark such as F_{40} (the fishing mortality required to maintain 40% of the unfished EPR) were chosen for American eels, the target F for glass eels would be approximately 0.90 (Figure 171). The same benchmark for yellow eels would be much lower at approximately 0.23 in the estuary and 0.06 in inland waters.

These results indicate a glass eel fishery could withstand a greater amount of fishing mortality than a yellow eel fishery. The reason for this disparity is the much greater natural mortality glass eels experience compared to yellow eels. The addition of fishing mortality to natural mortality at the glass eel stage has a much lower relative effect on total mortality compared to the addition of fishing mortality to natural mortality at the yellow eel stage.

6.8 Surplus Production Model

6.8.1 Background of Analysis and Model Description

Surplus production models combine the effects of recruitment, growth, and mortality into a single function and assume no size or age structure in the population. It requires a time series of fishery removals and one or more time series of CPUE from a survey. Surplus production models, both age-structured and catch-free, were developed for American eels during the 2012

benchmark stock assessment (ASMFC 2012) but were not used for developing reference points, determining stock status, or management. In 2012, various iterations of the model were attempted using regional and coastwide indices of abundance, but stable solutions could not be found.

For this assessment two types of surplus production models were explored; a typical biomass-based approach using ASPIC (Prager 1994) and a time-varying intrinsic growth surplus production (TVr) approach (Nesslage and Wilberg 2019).

Surplus production models make several assumptions including:

- There is no size or age structure in the population
- The population is closed
- The environment is constant
- Abundance indices are proportional to the true population
- Total catch is known without error
- The stock responds instantaneously to changes
- The intrinsic rate of increase (r) and carrying capacity (K) remains constant except for the TVr approach

The application of a surplus production model for American eels violates nearly every assumption. For example, it is known that American eels are one, panmictic population including American eels in inland waters, Canada, and the Caribbean; those regions are not included in this assessment and thus the population is not closed nor is the environment closed. While the landings from 1998–2020 represent validated data from Maine to Florida from ACCSP (see Section 4), historic landings are known to be incomplete and possibly inaccurate. Given the loss of American eel habitat through the damming of waterways, the carrying capacity of the population has likely been greatly reduced over time as noted in the previous stock assessment (ASMFC 2012) and is not expected to be constant throughout the time series. Surplus production models also do not perform well when the data represents a “one-way trip” or a constant decline in the time series without a period of recovery or contrast in the data. Both the landings and MARSS index suggest one-way trips over the years of 1974–2020 (Figure 172).

6.8.2 Configuration

6.8.2.1 Units

The surplus production model requires a time series of catch and one or more indices of abundance. Commercial yellow eel landings in pounds were used for the time series of catch. The abundance indices for American eels were all calculated in numbers, as were the aggregate

coastwide MARSS yellow eel index. The Conn index was also tested since it provides a longer time series. The SAS discussed the best way to get the two inputs in the same units. Not all surveys used in the coastwide indices had comprehensive weight or length data that could be used to convert the 16 individual yellow eel surveys from numbers to pounds. The SAS concluded that a coastwide aggregate yellow eel index in MARSS or Conn in weight would likely have a similar pattern to that in numbers and that not enough data were available to do a meaningful conversion without borrowing data from other regions and sources. Therefore, the SAS explored converting landings into numbers and ACCSP provided conversion factors, where available. In the ACCSP data warehouse, conversion factors are used to standardize the reported quantity unit (e.g., pounds, numbers, bushels) into a common currency, usually pounds. Some American eel landings have been reported to ACCSP units other than pounds and therefore conversion factors are used to convert those to pounds, the unit traditionally used for American eel commercial landings. On average, the conversion factor was 0.96 pounds for one American eel. Therefore, the landings in pounds would roughly convert to a similar scale and pattern for landings in numbers. For exploring the application of a surplus production model for American eels, the SAS proceeded with the inputs in different units assuming that the trends would be fairly consistent once converted to a common unit.

6.8.2.2 Starting Values

The starting values for the surplus production model were calculated as follows:

- 1) $B_1/K = 0.5$
- 2) $MSY = 1/2 * \text{Maximum Catch}$
- 3) $K = 10 * \text{Maximum Catch}$
- 4) $q = \text{Average Index Value} / (2 * \text{Maximum Catch})$

Where B_1 is initial biomass, MSY is maximum sustainable yield, K is carrying capacity, and q is catchability. Both MSY and K had minimum and maximum constraints of 1/8 and 8 times their values.

The initial runs of the ASPIC surplus production model produced warning messages and did not result in reasonable solutions (e.g., very low estimates of r , very high estimates of B_1) and the model was rerun with different iterations of the starting values from those described above in an attempt to find a stable solution. Additionally, different start years were attempted and using individual surveys instead of the coastwide aggregate yellow eel survey. For the TVr approach, starting values were set similarly to the ASPIC approach, with a total of two iterations. One iteration allowed for the intrinsic growth rate to vary, while the other allowed for the carrying capacity to vary.

6.8.2.3 Outputs

Both surplus production models estimated MSY and the associated MSY-based reference points of B_{MSY} , the stock biomass associated with MSY, and F_{MSY} , the fishing mortality that maximizes the yield from the population. These absolute values are usually imprecise (Prager 1994) for the ASPIC approach since it requires good estimates of catchability (q). Relative biomass (B/B_{MSY}) and relative fishing mortality (F/F_{MSY}) can be used to determine overfishing and overfished status. Additionally, both iterations of the TVr approach failed to reach convergence in most attempts and when it did so tended to hit the constraining bounds outlined above.

6.8.3 Results

The surplus production model was run with the coastwide landings and MARSS yellow eel index for the years of 1974–2020. The results produced an error code in ASPIC indicating that the estimate of MSY was at or near the minimum bound and that the solution may be trivial. There were also convergence issues with the model. Inspection of the resulting estimates show low estimates of r and MSY and high estimates of initial biomass and K (Table 25). Previous estimates of K from the 2012 stock assessment were around 40 million pounds and was found to be reasonable estimates by the Peer Review Panel. Likewise, the TVr approach produced unrealistic values of both r and K when those parameters were allowed to vary.

The ASPIC model was also run using the Conn index since it had a longer time series (1955–2020) and more contrast in the data and less of a one-way trip pattern. Similar to the run with the MARSS index, the solution for the ASPIC approach was reported to be trivial but conversely, the estimate of MSY was at or near the maximum bound. There were also convergence issues. The ASPIC model with the Conn resulted in more reasonable estimates for carrying capacity, but unreasonably high estimates of r given what is known about the life history of American eels (Table 25). Initial biomass and MSY were also estimated to be very large and relative fishing mortality was estimated at nearly zero.

Other iterations of both surplus production models were attempted using different starting values and bounds, indices of relative abundance, and start years. No runs for either approach produced results that were reasonable given what is known about American eels or did not have convergence issues or other error messages. Since the SAS agreed that the model likely is not appropriate for the species and too many assumptions were violated, further development of the surplus production model was abandoned.

6.9 Delay-Difference Model

6.9.1 Background of Analysis and Model Description

The delay-difference model is a variation of a biomass dynamic model that includes biological parameters, can be fitted directly to time series data, and accounts for changes in growth and recruitment over time (Hilborn et al. 1992). Biomass of age-structured populations are predicted directly from previous years' biomass and parameters for survival, growth, and

recruitment (Deriso 1980; Schnute 1985, 1987; Fournier and Doonan 1987). A primary benefit of this approach is that simulation of age structure is not required, though the model is observation error only and does not estimate recruitment deviations.

The delay-difference model was used in the ASMFC's 2020 American shad benchmark stock assessment. During the peer review, it was recommended that future assessments using the delay-difference model should employ the version in the SAMtool package (Huynh et al. 2022) instead of the DLMtool package (Carruthers and Hordyk 2019) because it allows for a wider range of model options and outputs. Following that advice, the SAS used the delay-difference model in SAMtool to estimate biomass and fishing mortality of the coastwide American eel population.

6.9.2 Configuration

Delay-difference models can be conditioned on either catch or effort. When conditioned on catch, the model estimates a predicted index. When conditioned on effort, the model estimates predicted catch. Effort is calculated in the model as the ratio of catch and index. Then the fishing mortality is set proportional to effort. In early discussions, the SAS made the decision to condition on effort rather than catch for two reasons. First, models conditioned on catch had lower convergence and provided unrealistic numbers (e.g., quadrillions of pounds of biomass estimates). The second reason, specifically in Delaware but perhaps in other places, is that catch after 2008 is not considered reflective of the population trends due to reduced fishing effort caused by the restriction of female horseshoe crabs as a bait. Despite those reasons, the SAS ultimately preferred conditioning the model on catch rather than effort given that the group has more faith in the time series of catch than the MARSS index for yellow eel. The preferred delay-difference model used for American eels is conditioned on catch.

Inputs into the model consist of a time series of relative total abundance, a time series of total annual catch, estimates of life history parameters: length at 50% maturity, maximum age, natural mortality, von Bertalanffy growth parameters (K , L_{∞} , t_0), and weight-length relationship alpha and beta parameters. The SAS explored a wide range of inputs for each parameter and decisions for selection of each major input is briefly discussed.

Initially, the SAS considered doing system-specific models similar to the approach used in the American shad stock assessment. A Chesapeake Bay-centered model was developed as a proof of concept, but many regions do not have data to support regional delay-difference models. It was recognized that identifying within system parameters would be just as challenging as coastwide parameters since American eel characteristics vary within a system too. Additionally, splitting the harvest between systems would add complications since the population is essentially one unit and the fishery is on both sexes across the coast. Due to these limitations, the SAS decided to develop a coastwide delay-difference model.

The SAS discussed a preference for a female-only model due to differences in size, growth, and maturity between the sexes however, it was acknowledged that sex-specific landings and indices were not available, requiring a model that is based on all sexes.

The SAS chose the yellow eel MARSS index as the preferred index of relative total abundance. Initial runs of the model evaluated the use of the YOY, elver, and yellow eel indices from both the MARSS and Conn (2010) approaches. Some SAS members had concerns about standardizing indices to their means when there are different time series lengths, as is the practice for Conn (2010), and therefore the group decided that the MARSS approach is slightly preferred over the Conn. Highest convergence from the MARSS indices occurred with the yellow eel index model runs. The YOY index was decided against inclusion since it provides a disconnect in life history stages since catch is of yellow eels.

While the time series of yellow eel harvest spans a longer period of time, the harvest from 1974 through 2019 was selected to coincide with the years of the abundance index.

Previous American eel stock assessments used natural mortality of 0.15 to 0.25. As there were no new studies to inform selection of natural mortality, the SAS chose to explore the same range of values. The preferred model uses a natural mortality of 0.15, which was selected due to higher rates of model convergence.

Reviewing the previous stock assessments and literature provided a range of maximum ages between 12 and 43 years. The SAS explored maximum ages of 12, 20, and 43 years, before settling on 12 years due to the younger age and higher abundance of male silver eels.

The SAS explored several variations of growth parameters. Initially, the model used values from the 2017 stock assessment update as a proof of concept. The SAS evaluated regional growth data but noted a lot of unreasonable L_{∞} values including in the Chesapeake Bay. The SAS explored use of von Bertalanffy growth parameters that were assumed to represent the “average eel” (i.e., Chesapeake Bay region). When this approach was found to be insufficient, the SAS performed a bootstrapping approach for generating growth parameters pooled between the sexes and all areas, resulting in growth parameters of $L_{\infty} = 452.7$ mm, $K = 0.4864$, and $t_0 = -0.3349$.

No studies were available to inform the length at 50% maturity (L_{50}) across the coastwide population. The SAS began by exploring L_{50} as a percentage of L_{∞} . Once the growth bootstrapping analysis was performed (Section 2.5.2), the L_{∞} from that analysis was used. Initial discussions suggested that L_{50} should be close to the value used for L_{∞} given the life cycle of American eel and a value of 90% of L_{∞} was used. Additional values from 50% to 90% of L_{∞} were tested as well. The SAS decided that a value of 80% of L_{∞} was most appropriate given the growth equation compared to the average size mature eels observed during state surveys.

In initial runs of the model, the model estimated the steepness value of the Beverton-Holt stock-recruitment relationship. The steepness parameter controls the response of stock productivity to changes in spawning biomass. The model estimated steepness at 0.9, but that value is more appropriate for a species like Atlantic menhaden *Brevoortia tyrannus* than a species with the life history of American eels. The SAS decided to fix steepness and explored a range of values from 0.2 to 0.9. A likelihood profile across steepness values indicated that a

steepness of 0.3 or 0.4 was appropriate. After reviewing the available stock-recruitment literature, the SAS decided to use a steepness value of 0.35 for the preferred model run.

Another recommendation of the American shad peer review was the incorporation of an initial depletion value that would reflect the decrease in the population from historical values to the beginning of the model period (ASMFC 2020c). The SAS explored values of 1 (no depletion), 0.75, 0.5, and 0.25. Many of the top models favored the use of a value of “1” but it was noted that the stock was depleted from historic levels. The SAS looked to the USGS team to find an appropriate value given the substantial habitat loss by the 1990s. The USGS team indicated that their work (Section 3.1) on estimating the accessibility of the Chesapeake Bay to American eels showed that 71% of those waterways have no ocean access while 29% have ocean access. The takeaway was that 29% is an initial estimate of what is completely open without considering dam influences. The SAS explored this value as well, but eventually decided not to employ initial depletion. Use of an initial depletion value scales the population down to reflect the “known” decrease, but the SAS did not feel this added valuable information since any initial depletion value is an assumption and likely to be falsely interpreted as a known historical abundance of American eels. Since the model initiates in 1974 and many dams had been in place decades before that, the SAS felt it was best to proceed under the assumption that the population had achieved a new equilibrium before the start of the model.

6.9.3 Results

Total commercial fishery catch (Figure 173A) and MARSS yellow eel abundance index were available for years between 1974 and 2019 (Figure 173B). The model-estimated abundance index was significantly smoothed compared to the MARSS yellow eel index, which fluctuated to a greater extent throughout the time series. Both the abundance index and catch displayed drastic declining trends across the time series (Figure 173A, B). Initial biomass (B_0) was estimated at 41.2 million pounds and decreased rapidly over the first twenty-three years of the run, then stabilized around 13.4 million pounds for the rest of the time period (Figure 173C). Fishing mortality during the first half of the time series generally exceeded 0.1, before dropping in 1997 and remaining below 0.1 for the remainder of the time series (Figure 173D).

6.9.4 Reference Points and Stock Status

The SAS chose overfished and overfishing reference points of 40% unfished biomass (B_{40}) and the fishing mortality (F_{40}) needed to sustain the population at B_{40} . B_{40} was deemed a more appropriate reference point rather than MSY because results from yield-per-recruit (YPR) analysis generated as part of the SAMtool delay-difference model did not show an asymptote or a decline in YPR with increasing fishing mortality. The European Union has specified a 40% escapement target for European eels from all rivers (EU 2007) and ICES suggested the use of a fishing mortality benchmark for European eels that preserved 50% of the spawning stock biomass (ICES 2001). The delay-difference model estimated the unfished biomass (B_0) was 45.89 million pounds and thus B_{40} would be 18.36 million pounds. F_{40} was determined by

projecting the delay-difference model forward in a deterministic fashion and solving for the fishing mortality that maintained the population at B_{40} .

The underlying population dynamics model was:

$$B_t = s_{t-1}(\tilde{a}N_{t-1} + \rho B_{t-1}) + w_k R_t$$

$$N_t = s_{t-1}N_{t-1} + R_t$$

where t is time, B is biomass, N is abundance, R is recruitment, w is weight at the age k of 50% maturity.

$$\tilde{a} = W_\infty(1 - \rho)$$

where W_∞ is the maximum weight of an individual.

$$\rho = \frac{w_a - W_\infty}{w_{a-1} - W_\infty}$$

where $a = k + 2$.

The model assumed a maximum length (L_∞) from a von Bertalanffy growth model of 452.7 mm (Section 2.5.2) to estimate W_∞ from a weight-length regression equation ($W = 0.00000000105 \cdot L^{3.22}$). Length at 50% maturity was set to 80% of L_∞ , which corresponded to an age of 3.

Recruitment followed a Beverton-Holt relationship:

$$R_t = \frac{aB_{t-k}}{1 + \beta B_{t-k}}$$

$$a = \frac{4hR_0}{(1 - h)B_0}$$

$$\beta = \frac{5h - 1}{(1 - h)B_0}$$

where h = steepness and was set to 0.35 as this provided the best fit of the delay-difference model to observed data.

The model started at $B_0 = 45.89$ million pounds and $N_0 = 160.46$ million individuals and was projected forward for 200 years to insure stability at a given level of fishing mortality. The fishing mortality needed to stabilize the population at B_{40} was then solved for and was $F_{40} = 0.085$ (Figure 174).

Comparing estimated F from the delay-difference model to the F_{40} reference point showed overfishing was occurring in the majority of years from 1974–1996. After 1996, there were some years where F_{40} was exceeded, but in recent years, annual estimates of F were less than F_{40} . Although, overfishing was not occurring in recent years, the population of American eels

has been less than the B_{40} reference point since 1987 and continues to be overfished (Figure 175).

The estimated F from the delay-difference model averaged 0.077 from 1997–2019, which was lower than the F_{40} reference point of 0.085. Given the length of time that the average F has been below F_{40} , it is surprising that the estimated biomass from the delay-difference model has not shown an increase, but has remained at a low and stable level. This could indicate that factors in addition to fishing pressure (e.g., habitat loss) are also limiting American eel population growth.

The SAS had some reservations using the delay-difference model to manage the coastwide American eel stock. While the model was developed for an “average eel” there are no considerations in the model for the large differences observed in American eel size, growth, sex, and behavior along the coast or even between coastal and freshwater habitats. Also, combined sexes in the delay-difference model are likely problematic. As parameterized, the model uses biomass in year $t-3$ to estimate recruits in year t because the age corresponding to the length at 50% maturity would be age 3. If the majority of eggs are produced from females who mature at ages greater than age 3 (very likely for silver eels from inland waters), then the structure of the model does not adequately represent the life history of the species. Managing based on a model for an average eel is probably not appropriate for the coastwide population.

6.10 Index-Based Methods

6.10.1 Background of Analysis and Model Description

Given the performance of the delay-difference model, the SAS began exploring other avenues for providing management advice. One promising avenue was to use index-based methods. A recent research track assessment conducted by the Northeast Fisheries Science Center (NEFSC) examined a number of different methodologies for providing catch advice in cases where a retrospective pattern in an age-structured assessment became problematic (NEFSC 2020).

NEFSC (2020) examined a plethora of different data-limited options in their management track assessment (Table 26). While their focus was on resolving and providing management in the face of age-structured assessments with diagnostic issues, the SAS used and examined some of these methods for American eels. Based on the data the SAS had in hand, as well as familiarity with the methods, the SAS explored the PlanB, Islope, I_{TARGET} , and Skate methods. The other methods required either age, known fishery selectivity, assumptions that fishing mortality should equal natural mortality, or some other data facet unknown for American eels (Table 26). Additionally, AIM (An Index Method) was explored for this assessment with unsatisfactory results since the data suggested a one-way trip and there was no relationship between a replacement rate and relative F .

After completing a preliminary analysis of PlanB, Islope, and Skate methods, the SAS found that each of the methods had issues and were providing very high estimates of removable biomass.

Further, the Skate method relied on the index producing an effective fishing mortality which was then applied to biomass, which the SAS did not find appealing.

While NEFSC (2020) indicated that PlanB and ISlope were suited for stock rebuilding, they also indicated “The index-based methods that change the catch advice based on recent trends in the surveys (e.g., PlanB, ISlope, DLM) do not appear well suited to applying a reduction to the catch advice.” Given these comments as well as a preliminary analysis that suggested high removals at what is likely a depleted stock (ASMFC 2017), the SAS focused on the I_{TARGET} method for providing management advice. Additionally, the SAS liked the feature of choosing the reference years as well as the target value given suggestions of a change in the carrying capacity of eels and the regime shift analysis (Section 6.4).

6.10.2 Configuration

Calculation of the I_{TARGET} method is fairly straightforward and is based on Carruthers et al. (2015). From Table 26;

$$C_{targ,y+1:y+2} = \left[0.5C_{ref} \left(\frac{\bar{I}_{5,y} - I_{thresh}}{I_{target} - I_{thresh}} \right) \right] \quad \bar{I}_{5,y} \geq I_{thresh}$$

$$C_{targ,y+1:y+2} = \left[0.5C_{ref} \left(\frac{\bar{I}_{5,y}}{I_{thresh}} \right)^2 \right] \quad \bar{I}_{5,y} < I_{thresh}$$

Where C_{TARGET} is the catch target or the management advice in a given year, C_{REF} is the average catch over the reference period, I is the index with \bar{I} being the average index value (here over three years), I_{TARGET} being the index target, and $I_{THRESHOLD}$ as the index threshold. $I_{THRESHOLD}$ is defined in NEFSC (2020) as 0.8 of I_{TARGET} . I_{TARGET} is defined further as the index average over the reference period times some multiple $I_{TARG MULT}$.

After discussions among the SAS, it was suggested to define the reference period as 1974 (the first year of the MARSS yellow eel index) to 1988 based on the regime change analysis (Section 6.4) as well as the fact this seemed to be a stable, if variable, point for both landings and index (Figure 176), affecting both the C_{REF} and the calculation of I_{TARGET} . Further discussions resulted in a modification of the method. As the MARSS index is already smoothed, a five-year average was replaced by a three-year average for calculations. The use of 0.8 for defining $I_{THRESHOLD}$ was retained, as there was no a priori reason to modify it.

There was, however, debate amongst the SAS as to the value of $I_{TARG MULT}$ which affects the calculation of I_{TARGET} . NEFSC (2020) used an $I_{TARG MULT}$ equal to 1.5, indicating that the average index value during the reference period represented one-half the biomass target. Another option was to set the $I_{TARG MULT}$ at 1.0, indicating that the average index over the reference period represented the biomass target for the population. In essence, setting the $I_{TARG MULT}$ to 1.5 was more conservative, while setting the $I_{TARG MULT}$ to 1.0 was less conservative.

Ultimately the SAS compromised on a $I_{TARG\ MULT}$ value of 1.25. This was in part due to the knowledge that since the reference period it is likely that the carrying capacity of the stock has declined due to habitat loss; however, this was balanced by the knowledge that fishing and exploitation and stock depletion have been occurring well before the reference period. Given this, the SAS was uncomfortable using a $I_{TARG\ MULT}$ of 1.0 or at 1.5. The choice of the $I_{TARG\ MULT}$ at 1.5, 1.25, and 1.0 are given as sensitivities.

6.10.3 Results

Results for the I_{TARGET} method using a reference period of 1974–1988, an $I_{TARG\ MULT}$ of 1.25, using a three-year average for the index, and 0.8 as a value to derive $I_{THRESHOLD}$ is given in Figure 177. Note using this configuration, recommended removals have always been below actual removals, often by a wide margin. This is further illustrated in Table 27, where the recommendations from the base case have never exceeded the actual removals, though the gap between recommended and actual has decreased in 2020.

As mentioned previously, a sensitivity was undertaken to examine different assumptions around $I_{TARG\ MULT}$ with both 1.0 and 1.5 examined (Figure 178) as expected the $I_{TARG\ MULT}$ had a large effect on the recommended removals (Table 27). It is notable that any of the assumptions around $I_{TARG\ MULT}$ produced recommendations that are generally far below the actual removals, except in 2020. Further, all estimates of recommended removals are far below the current catch cap (916,473 pounds) instituted by ASMFC.

7 STOCK STATUS

7.1 Current Overfishing, Overfished/Depleted Definitions

No overfishing determination could be made based on the analyses performed during the previous stock assessments (ASMFC 2012, 2017). From a biological perspective, much is still unknown about the species. Information is limited about their abundance, status at all life stages, and habitat requirements. According to the 2017 stock assessment update, the American eel population remains depleted in US waters. The stock is at or near historically low levels due to a combination of historical overfishing, habitat loss, food web alterations, predation, turbine mortality, environmental changes, toxins and contaminants, and disease. Trend analyses of abundance indices indicated large declines in abundance of yellow eels during the 1980s through the early 1990s, with primarily neutral or stable abundance from the mid-1990s through 2016.

7.2 Stock Status Determination

The SAS developed reference points for the delay-difference model in order to determine stock status (Section 6.9.4) but is not recommending this approach because of multiple concerns with the application of that model.

Instead of using the delay-difference model, the SAS proposes that the I_{TARGET} method should be used to both determine stock status and provide catch advice for American eels. Using this methodology, the target biomass would be set at the three-year average of the MARSS index associated with I_{TARGET} (1.103) and which corresponds to a B_{TARGET} . The threshold would be set at the three-year average of the MARSS index associated with the $I_{THRESHOLD}$ (0.882) using the base case for both the reference period and the $I_{TARG\ MULT}$ (Section 6.10).

The I_{TARGET} method does not lend itself well to defining exploitation-based reference points. Relative exploitation could be based on the ratio of realized catch divided by advised catch, with values greater than one defined as overfishing occurring. However, given the uncertainty in the MARSS index, as well as the use of a three-year running average within the I_{TARGET} method, the SAS was uncomfortable determining if eel was experiencing overfishing.

Based on the results of the I_{TARGET} method, the stock would be considered overfished (Figure 176-Figure 178) as the current three-year average of the MARSS index (0.348) is below the $I_{THRESHOLD}$ (0.882). This result is in line with other methods (e.g., Conn index, MARSS index, regime shift analysis, delay-difference model, Mann-Kendall Test) that also show the stock as depleted or experiencing downward trends in the abundance data. Likewise, using the I_{TARGET} method, it can be inferred that the stock could also be experiencing overfishing as catches have been well above recommended removals (Table 27).

While the American eel stock is overfished, the SAS was unable to determine if overfishing was occurring. However, the SAS suggests that American eels likely have been experiencing overfishing in the last few decades based on the I_{TARGET} method and supported by additional methods explored in this assessment. As such, coastwide yellow eel catch levels should be reduced as the index-based method of I_{TARGET} suggests catches in recent years should be more in-line with 200,000-300,000 pounds rather than the current coastwide cap of 916,473 pounds.

8 CONCLUSIONS

The abundance indices developed and used in this assessment are more robust and better defined than previous assessments. The trends in abundance produced by the MARSS and Conn methods were similar, as were results from models detecting regime shifts, indicating low abundance of American eel in recent years (1989–2020). Until sufficient data are available at an appropriate scale that encompasses the range inhabited by American eels to support more complex model-based assessments, abundance indices and index-based methods are the best tool for guiding management decisions.

The YOY monitoring effort, now in its 21st year at many sites, provides an indication of recruitment that has been relatively stable coastwide. There are clear latitudinal trends in recruitment in some years, whereas recruitment varies widely in others. As a result, the idea of selecting sentinel sites along the coast to monitor recruitment will likely not produce the desired result of tracking population trends. A relatively consistent level of YOY recruitment for the combined indices coastwide (using the Conn or MARSS method) is not surprising given that

the assessment of yellow eel remains at a consistent, but level of low abundance during the same time period. Unfortunately, YOY indices that coincide with historic periods of higher yellow eel abundance are not available to know what recruitment looked like when there was higher spawning biomass. The analysis of glass eel biological characteristics from the YOY monitoring effort shows stable patterns over time. Glass eel weight and length are consistent within sites, with a latitudinal gradient in length with smaller glass eels captured south of Chesapeake Bay. Pigment stages of glass eels show an increase in pigment stage with an increase in water temperature and time, but no relationship with glass eel length, weight, or relative condition.

Given the lack of trends in length, weight, and pigmentation within sites over time, the SAS and TC recommend that biological sampling for state-mandated YOY surveys should not be required. Sites will continue to monitor YOY eel counts at the sites and collect associated environmental data. This should help reduce the burden on the states while still tracking YOY data along the coast. If any concerning trends emerge, biological sampling can be increased back to current levels as needed.

The development of GIS-based habitat models provides an additional path forward towards assessing American eels. Other regions around the world are adopting a similar approach since all catadromous eels share the commonality of a complex life history and highly variable population parameters throughout their range (Hoyle 2016); however, due to limited historical data, it is difficult to assess habitat availability for the American eels beyond their current habitat use.

Many of the analyses explored in this benchmark indicate decreasing or low population trends (e.g., Conn index, MARSS index, regime shift analysis, delay-difference model, Mann-Kendall Test). All lines of evidence indicate the population is at low levels and the stock status of American eels, as determined by the I_{TARGET} approach, is overfished and likely experiencing overfishing.

9 RESEARCH RECOMMENDATIONS

Research recommendations are broken down into future research and data collection and assessment methodology. Research recommendations from ASMFC 2012, 2017 remain important, but the following list is specific to what the SAS thinks could improve the next stock assessment. The SAS recommends an update be considered in five years and a new benchmark be considered in ten years.

9.1 Future Research and Data Collection

- Improve upstream and downstream passage for all life stages of American eels.
- Continue to improve the accuracy of commercial catch and effort data through ACCSP and state partners.

- Characterize the length, weight, age, and sex structure of commercially harvested American eels along the Atlantic coast over time.
- Research coastwide prevalence of the swim bladder parasite *Anguillacolla crassus* and its effects on the American eel's growth and maturation, migration to the Sargasso Sea, and spawning potential.
- Improve understanding of the spawning contribution of unexploited portions of the stock (i.e., freshwater areas of coastal US).
- Characterize the length, weight, and sex structure in unharvestable habitats.
- Conduct a tagging study throughout the species range.
- Quantify recreational removals in marine and freshwater habitats and characterize length, weight, and sex structure.
- Evaluate the passage/passage efficiency of American eels through existing fishways at dams/barriers and evaluate barrier physical attributes (height, material) that can be passed by eel without fishways.
- Evaluate the use vs. availability of habitat in the inland portion of the species range, and how habitat availability has changed through time, including opening of habitat from recent dam and barrier removals. This could and should include assisted migration by trucking around dams.
- To the extent that the data allows, account for the proportion of the population (yellow, silver phase) represented by the inland portion of the species range.
- Evaluate the relative impact that commercial harvest has on population status versus the accessibility to inland habitats.

9.2 Assessment Methods

- Develop methods to assess spawner escapement and biological information pertinent to silver eels in major river basins.
- Perform a range-wide American eel assessment with various countries and agencies (e.g., Canada DFO, ASMFC, USFWS, Caribbean, US Gulf and inland states).
- Explore methods to characterize data by sex to support a female-only delay-difference model.

10 MINORITY OPINION

No minority opinions were submitted during the development of this stock assessment.

11 REFERENCES

- Adams, C.C., and T.L. Hankinson. 1928. The ecology and economics of Oneida Lake fish. Transactions of the American Fisheries Society 45(3):155–169.
- ASMFC (Atlantic States Marine Fisheries Commission). 2000a. Interstate fishery management plan for American eel (*Anguilla rostrata*). ASMFC, Fishery Management Report No. 36, Washington, D.C. 93 p.
- _____. 2000b. Standard procedures for American eel young of the year survey: substituting the protocol outlined in the interstate fishery management plan for American eel. Prepared by the AMSFC American Eel Technical Committee. ASMFC, Washington, D.C. 3 p.
- _____. 2001. Proceedings of the workshop on ageing and sexing American eel. ASMFC, Special Report No. 72, Washington, D.C. 25 p.
- _____. 2005. American eel stock assessment report for peer review. ASMFC, Washington, D.C. 121 p.
- _____. 2006a. Terms of reference and advisory report to the American eel stock assessment peer review. ASMFC, Stock Assessment Report No. 06-01, Washington, D.C. 29 p.
- _____. 2006b. Update of the American eel stock assessment report. ASMFC, Washington, D.C. 51 p.
- _____. 2012. American Eel Benchmark Stock Assessment. Stock Assessment Report 12- 01 of the Atlantic States Marine Fisheries Commission. 342 pp.
- _____. 2014. Addendum IV to the Interstate Fishery Management Plan for American Eel. Approved October, 2014. ASMFC, Arlington, VA. 26 pp.
- _____. 2017a. American Eel Stock Assessment Update. ASMFC, Arlington, VA. 123 pp
- _____. 2017b. American Eel Ageing Report. ASMFC, Arlington, VA. 413 pp
- _____. 2020a. Addendum III to the Omnibus Amendment to the Interstate Fishery Management Plans for Spanish Mackerel, Spot, and Spotted Sea Trout. ASMFC, Arlington, VA. 15 pp.
- _____. 2020b. Atlantic Croaker Addendum III Revisions to Management using the Traffic Light Approach. ASMFC, Arlington, VA. 15 pp.
- _____. 2020c. 2020 American Shad Benchmark Stock Assessment and Peer Review Report. ASMFC, Arlington, VA. 1188 pp.

- Avise, J.C., G.S. Helfman, N.C. Saunders, and L.S. Hales. 1986. Mitochondrial DNA differentiation in North Atlantic eels: population genetic consequences of an unusual life history pattern. *Proceedings of the National Academy of Sciences of the United States of America* 83(12):4350–4354.
- Barbin, G.P., and J.D. McCleave. 1997. Fecundity of the American Eel *Anguilla rostrata* at 45°N in Maine, U.S.A. *Journal of Fish Biology* 51:840–847.
- Beguer-Pon, M.B., M. Castonguay, S. Shan, J. Benchetrit, and J.J. Dodson. 2015. Direct observations of American eels migrating across the continental shelf to the Sargasso Sea. *Nature Communications* 6:8705.
- _____, S. Shan, M. Castonguay, and J.J. Dodson. 2017. Behavioural variability in the vertical and horizontal oceanic migrations of silver American eels. *Marine Ecology Progress Series* 585: 123–142.
- Bevacqua, D., P. Melia, G.A. De Leo, and M. Gatto. 2011. Intra-specific scaling of natural mortality in fish: the paradigmatic case of the European eel. *Oecologia* 165:333–339.
- Bigelow, H.B., and W.C. Schroeder. 1953. Fishes of the Gulf of Maine. *Fishery Bulletin* 53(1). 577 p.
- Bonvechio, K.I., B. Barthel, and J. Carroll. 2018. Health and genetic structure of the American eel in Florida. *Southeastern Naturalist* 17:438–455.
- Buckel, J.A., and D.O. Conover. 1997. Movements, feeding periods, and daily ration of piscivorous young-of-the-year Bluefish, *Pomatomus saltatrix*, in the Hudson River estuary. *Fishery Bulletin* 95(4):665–679.
- Busch, W.-D.N., and D.P. Braun. 2014. A case for accelerated reestablishment of American eel in the Lake Ontario and Lake Champlain watersheds. *Fisheries* 39:298–304.
- Caddy, J.F. 1998. A short review of precautionary reference points and some proposals for their use in data-poor situations. *FAO Fisheries Technical Paper No. 379*. 30 p.
- _____. 1999. Deciding on precautionary management measures for a stock based on a suite of limit reference points (LRPs) as a basis for a multi-LRP harvest law. *NAFO Scientific Council Studies* 32:55–68.
- Cairns, D.K. 2020. Landings, abundance indicators, and biological data for a potential range-wide American eel stock assessment. *Canadian Data Reports of Fisheries and Aquatic Science No. 1311*: v + 180 p.
- _____, T.S. Avery, J. Benchetrit, V. Bornarel, J.M. Casselman, M. Castonguay, S.K. Crow, M. Dorow, H. Drouineau, J. Frankowski, H.S. Galbraith, A. Haro, S.D. Hoyle, D.C. Knickle, M.A. Koops, L.A. Poirier, M.B. Rudd, J.T. Thorson, E.K. Williams, J. Young and X. Zhu.

2021. Methods and data sources to support American eel population analysis. Department of Fisheries and Oceans Canadian Science Advisory Secretariat Research Document 2020/031. vi + 77 p.

- _____, J. Benchetrit, L. Bernatchez, V. Bornarel, J.M. Casselman, M. Castonguay, A.R. Charsley, M. Dorow, H. Drouineau, J. Frankowski, A. Haro, S.D. Hoyle, D.C. Knickle, M.A. Koops, L.A. Poirier, J.T. Thorson, J. Young, and X. Zhu. 2022. Thirteen novel ideas and underutilized resources to support progress toward a range-wide American eel stock assessment. *Fisheries Management and Ecology*. DOI: 10.1111/fme.12572.
- _____, G. Chaput, L.A. Poirier, T.S. Avery, M. Castonguay, A. Mathers, J.M. Casselman, R.G. Bradford, T. Pratt, G. Verreault, K. Clarke, G. Veinott, and L. Bernatchez. 2013. Recovery potential assessment for the American eel (*Anguilla rostrata*) for eastern Canada: life history, distribution, reported landings, status indicators, and demographic parameters. Canadian Science Advisory Secretariat Research Document 2013/134. 157 p.
- Camhi, M., M. Bednarski, J. LaBelle, and J. Waldman. 2021. Abundance and Distribution of American Eel in a Heavily Dammed Urban River. *North American Journal of Fisheries Management* 41(4): 1131–1140.
- Campbell, D.M., R.G. Bradford, and K.M.M. Jones. 2013. Occurrences of *Anguillicoloides crassus*, an invasive parasitic nematode, infecting American eel (*Anguilla rostrata*) collected from New Brunswick and Nova Scotia Rivers: 2008-2009. DFO Canadian Science Advisory Secretariat Research Document 2012/082. iv + 19 p.
- Carruthers, T., and A.R. Hordyk. 2019. DLMtool: Data-Limited Methods Toolkit.
- _____, and A.R. Hordyk. 2018. The Data-Limited Methods Toolkit (DLM tool): An R package for informing management of data-limited populations. *Methods in Ecology and Evolution* 9(12):2388–2395. John Wiley & Sons, Ltd (10.1111).
- _____, L. Kell, D. Butterworth, M. Maunder, H. Geromont, C. Walters, M. McAllister, R. Hillary, P. Levontin, T. Kitakado, and C. Davies. 2015. Performance review of simple management procedures. *ICES Journal of Marine Science* 73(2):464–482.
- Chaput, G., D.K. Cairns, S. Bastien-Daigle, C. LeBlanc, L. Robichaud, J. Turple, and C. Girard. 2014a. Recovery potential assessment for the American eel (*Anguilla rostrata*) for eastern Canada: mitigation options. Canadian Science Advisory Secretariat Research Document 2013/133. 30 p.
- _____, T.C. Pratt, D.K. Cairns, K.D. Clarke, R.G. Bradford, A. Mathers, and G. Verreault. 2014b. Recovery potential assessment for the American eel (*Anguilla rostrata*) for eastern Canada: description and quantification of threats. Canadian Science Advisory Secretariat Research Document 2013/135. 90 p.

- Chen, Y., D.A. Jackson, and H.H. Harvey. 1992. A comparison for von Bertalanffy and polynomial functions in modeling fish growth data. *Canadian Journal of Fisheries and Aquatic Sciences* 49(6):1228–1235.
- Chisnall, B.L., and J.M. Kalish. 1993. Age validation and movement of freshwater eels (*Anguilla dieffenbachii* and *A. australis*) in a New Zealand pastoral stream. *New Zealand Journal of Marine and Freshwater Research* 27(3):333–338.
- Conn, P.B. 2010. Hierarchical analysis of multiple noisy abundance indices. *Canadian Journal of Fisheries and Aquatic Sciences* 67(1): 108–120.
- Cornic, M., Zhu, X., Cairns, D.K. 2021. Stock-wide assessment framework for American eel: review of trends and approaches to assessment. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/032. x + 77 p.
- COSEWIC. 2006. COSEWIC assessment and status report of the American eel in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa.
- _____. 2012. COSEWIC assessment and status report on the American eel *Anguilla rostrata* in Canada. Committee on the Status of Endangered Wildlife in Canada, Ottawa. 109 p.
- Cote, C.L., M. Castonguay, G. Verreault, and L. Bernatchez. 2009. Differential effects of origin and salinity rearing conditions on growth of glass eels of the American eel *Anguilla rostrata*: implications for stocking programmes. *Journal of Fish Biology* 74(9):1934–1948.
- _____, P.A. Gagnaire, V. Bourret, G. Verreault, M. Castonguay, and L. Bernatchez. 2013. Population genetics of the American eel (*Anguilla rostrata*): $F_{st} = 0$ and North Atlantic Oscillation effects on demographic fluctuations of a panmictic species. *Molecular Ecology* 22:1763–1776.
- _____, S.A. Pavey, J.A. Stacey, T.C. Pratt, M. Castonguay, C. Audet, and L. Bernatchez. 2015. Growth, female size, and sex ratio variability of American eel of different origins in both controlled conditions and the wild: implications for stocking programs. *Transactions of the American Fisheries Society* 144:246–257.
- Couillard, C.M., P.V. Hodson, and M. Castonguay. 1997. Correlations between pathological changes and chemical contamination in American eels, *Anguilla rostrata*, from the St. Lawrence River. *Canadian Journal of Fisheries and Aquatic Sciences* 54(8): 1916–1927.
- Davey, A.J.H, and D.J. Jellyman. 2005. Sex determination in freshwater eels and management options for manipulation of sex. *Reviews in Fish Biology and Fisheries*. 15(1-2):37–52.
- DFO. 2010. Status of American eel and progress on achieving management goals. Canadian Science Advisory Secretariat Advisory Report 2010/062.

- _____. 2013. Recovery potential assessment of American Eel (*Anguilla rostrata*) in eastern Canada. Canadian Science Advisory Secretariat Science Advisory Report 2013/078. 65 pp.
- _____. 2019. Assessment of the Maritimes Region American eel and elver fisheries. Canadian Science Advisory Secretariat Science Advisory Report 2019/054.
- Denny, S.K., A. Denny, and T. Paul. 2013. Distribution, prevalence and intensity of *Anguillicoloides crassus* in the American eel, *Anguilla rostrata*, in the Bras d'Or Lakes, Nova Scotia. *BioInvasions Record*: 2(1).
- Deriso, R.B. 1980. Harvesting Strategies and Parameter Estimation for an Age-Structured Model. *Canadian Journal of Fisheries and Aquatic Sciences* 37(2):268–282.
- Efron, B., and R.J. Tibshirani. 1993. *An introduction to the bootstrap*. Chapman and Hall, New York. 436 p.
- EU (European Union). 2007. Council Regulation (EC) No 1100/2007 of 18 September 2007 establishing measures for the recovery of the stock of European eel. *Official Journal of the European Union*, L 248:17–23.
- Eyler, S.M., S.A. Welsh, D.R. Smith, and M.M. Rockey. 2016. Downstream passage and impact of turbine shutdowns on survival of silver American eels at five hydroelectric dams on the Shenandoah River. *Transactions of the American Fisheries Society* 145:964–976.
- Facey, D.E., and G.W. LaBar. 1981. Biology of American eels in Lake Champlain, Vermont. *Transactions of the American Fisheries Society* 110(3):396–402.
- _____, and M.J. Van Den Avyle. 1987. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic)—American eel. USFWS Biological Report 82 (11.74). U.S. Army Corps of Engineers, TR EL-82-4. 28 p.
- Fahay, M.P. 1978. Biological and fisheries data on American eel, *Anguilla rostrata* (LeSueur). National Marine Fisheries Service Northeast Fisheries Center, Sandy Hook Laboratory, Technical Series Report 17, Highlands, N.J. 96 p.
- Fenske, K.H., D.H. Secor, and M.J. Wilberg. 2010. Demographics and parasitism of American eels in the Chesapeake Bay, USA. *Transactions of the American Fisheries Society* 139:1699–1710.
- Fournier, D.A., and I.J. Doonan. 1987. A Length-Based Stock Assessment Method Utilizing a Generalized Delay-Difference Model. *Canadian Journal of Fisheries and Aquatic Sciences* 44(2):422–437.
- Gerrodette, T. 1987. A power analysis for detecting trends. *Ecology* 68:1364–1372.

- Goode, G.B. 1884. The fisheries and fishery industries of the United States.
- Goodwin, K.R. 1999. American Eel subpopulation characteristics in the Potomac River drainage, Virginia. Master's thesis. Virginia Polytechnic Institute and State University, Blacksburg. 107 p.
- Greene, K.E., J.L. Zimmerman, R.W. Laney, and J.C. Thomas-Blate. 2009. Atlantic coast diadromous fish habitat: a review of utilization, threats, recommendations for conservation, and research needs. ASMFC, Habitat Management Series No. 9, Washington, D.C.
- Griffin, J.C., and F.J. Margraf. 2003. The diet of Chesapeake Bay striped bass in the late 1950s. *Fisheries Management and Ecology* 10:323–328.
- Haddon, M. 2001. Modelling and quantitative methods in fisheries. Chapman and Hall/CRC, Boca Raton, FL. 406 p.
- Haro, A.J., and W.H. Krueger. 1991. Pigmentation, otolith rings, and upstream migration of Juvenile American eels (*Anguilla rostrata*) in a coastal Rhode Island stream. *Canadian Journal of Zoology* 69(3):812–814.
- Hein, J.L., S.A. Arnott, W.A. Roumillat, D.M. Allen, and I. de Buron. 2014. Invasive swimbladder parasite *Anguillicoloides crassus*: infection status 15 years after discovery in wild populations of American eel *Anguilla rostrata*. *Diseases of aquatic organisms* 107(3):199–209.
- _____, I. de Buron, W.A. Roumillat, W.C. Post, A.P. Hazel, and S.A. Arnott. (2016). Infection of newly recruited American eels (*Anguilla rostrata*) by the invasive swimbladder parasite *Anguillicoloides crassus* in a US Atlantic tidal creek. *ICES Journal of Marine Science* 73(1):14–21.
- Helfman, G.S., E.L. Bozeman, and E.B. Brothers. 1984. Comparison of American eel growth rates from tag returns and length-age analyses. *Fishery Bulletin* 82(3):519–522.
- Hewitt, D.A. and J.M. Hoenig. 2005. Comparison of two approaches for estimating natural mortality based on longevity. *Fishery Bulletin* 103:433–437.
- Hilborn, R., C.J. Walters, R. Hilborn, and C.J. Walters. 1992. Delay Difference Models. Pages 330–348 *Quantitative Fisheries Stock Assessment*. Springer US.
- Hitt, N.P., S. Eyler, and J.E. Wofford. 2012. Dam removal increases American eel abundance in distant headwater streams. *Transactions of the American Fisheries Society* 141(5):1171–1179.

- Holmes, E.E., E.J. Ward, and M.D. Scheuerell. 2018. Analysis of multivariate time-series using the MARSS package, version 3.10.10. Norwest Fisheries Science Center, NOAA, Seattle, WA, USA.
- Hoyle, S.D. 2016. Feasibility of longfin eel stock assessment. New Zealand Fisheries Assessment Report 29:27.
- Huynh, Q., T. Carruthers, and A. Hordyk. 2022. SAMtool: Stock Assessment Methods Toolkit. <https://openmse.com>, <https://github.com/Blue-Matter/SAMtool>.
- ICES (International Council for the Exploration of the Sea). 2001. Report of the ICES/EIFAC working group on eels. ICES. C.M. 2002/ACFM:03, Copenhagen.
- _____. 2013. Report of the Workshop on Evaluation Progress Eel Management Plans (WKEPEMP), 13–15 May 2013, Copenhagen, Denmark. (ICES CM 2013/ACOM: 32). https://stecf.jrc.ec.europa.eu/documents/43805/595626/wkepemp_2013.pdf
- _____. 2021a. Joint EIFAAC/ICES/GFCM Working Group on Eels (WGEEL). ICES Scientific Reports. 3:85. 205 pp. <https://doi.org/10.17895/ices.pub.8143>
- _____. 2021b. Workshop on the future of eel advice (WKFEA). ICES Scientific Reports 3:13. 67 pp. Available at <https://doi.org/10.17895/ices.pub.5988>.
- Jacoby, D., J. Casselman, M. DeLucia, G.A. Hammerson, and M. Gollock. 2014. *Anguilla rostrata*. The IUCN Red List of Threatened Species 2014: e.T191108A72965914. <http://dx.doi.org/10.2305/IUCN.UK.2014-3.RLTS.T191108A72965914.en>.
- Jessop, B.M. 2010. Geographic effects on American eel (*Anguilla rostrata*) life history characteristics and strategies. Canadian Journal of Fisheries and Aquatic Sciences 67(2):326–346.
- _____. 2018. American eel fecundity and ovary maturation in relation to body size and geographic distribution. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 10:169–189.
- _____. 2020. Oceanic environmental effects on American eel recruitment to the East River, Chester, Nova Scotia. Marine and coastal Fisheries 12:222–237.
- Kahn, D.M. 2019. Trends in abundance and fishing mortality of American eels. Fisheries 44(3): 130–136.
- Kaifu, K. 2019. Challenges in assessments of Japanese eel stock. Marine Policy 102:1–4.
- Krueger, W.H., and K. Oliveira. 1999. Evidence for environmental sex determination in the American eel, *Anguilla rostrata*. Environmental Biology of Fishes. 55:381–389.

- Kwak, T.J., A.C. Engman, and C.G. Lilyestrom. 2019. Ecology and conservation of the American eel in the Caribbean region. *Fisheries Management and Ecology* 26(1):42–52.
- Lane, J.P. 1978. Eels and their utilization. *Marine Fisheries Review* 40(4):1–20.
- Legendre, P., and L.F. Legendre. 2012. *Numerical ecology* (Vol. 24). Elsevier
- Liew, P.K.L. 1974. Age determination of American eels based on the structure of their otoliths. Pages 124–136 *In*: T.B. Bagenal (editor), *Proceedings of an International Symposium on the Ageing of Fish*, University of Reading, Unwin Brothers, Surrey, England. 234 p.
- Lin, Y., and B.M. Jessop. 2020. Application of generalized depletion model to recruitment of American eel elvers and empirical support from survey data. *Transactions of the American Fisheries Society* 149:576–586.
- Lorenzen, K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. *Journal of Fish Biology* 49(4):627–647.
- Machut, L.S., K.E. Limburg, R.E. Schmidt, and D. Dittman. 2007. Anthropogenic impacts on American Eel demographics in Hudson River tributaries, New York. *Transactions of the American Fisheries Society* 136(6):1699–1713.
- Mathers, A., and T.C. Pratt. 2011. 2010 Update on the status and progress on management goals for American Eel in Ontario. Research document(Canadian Science Advisory Secretariat), (2011/046).
- McCleave, J. D. 2008. Contrasts between spawning times of *Anguilla* species estimated from larval sampling at sea and from otolith analysis of recruiting glass eels. *Marine Biology* 155(3): 249.
- Mensingher, M.A., E.J. Blomberg, and J.D. Zydlewski. 2021. The consequences of dam passage for downstream-migrating American eel in the Penobscot River, Maine. *Canadian Journal of Fisheries and Aquatic Science* 78:1181–1192.
- Miller, M.J., S. Bonhommeau, P. Munk, M. Castonguay, R. Hanel, and J.D. McCleave. 2015. A century of research on the larval distributions of the Atlantic eels: a re-examination of the data. *Biological Reviews* 90:1035–1064.
- Minkinen, S., and I. Park. 2014. American eel sampling at Conowingo Dam, 2013. USFWS Technical Report.
- Morin, J., and M. Leclerc. 1998. From pristine to present state: hydrology evolution of Lake Saint-François, St. Lawrence River. *Canadian Journal of Civil Engineering* 25:864–879.

- Morrison, W. E., and D. H. Secor. 2003. Demographic attributes of yellow-phase American Eels (*Anguilla rostrata*) in the Hudson River estuary. *Canadian Journal of Fisheries and Aquatic Sciences* 60(12):1487–1501.
- NASEM (National Academies of Sciences, Engineering, and Medicine). 2017. Review of the Marine Recreational Information Program. The National Academies Press, Washington, D.C. 186 p.
- NatureServe. 2006. Draft Native freshwater range of the American eel, June 2006. USFWS mapping contract with NatureServe. Source documents, maps, email contacts, source criteria. 74p.
- NEFSC (Northeast Fisheries Science Center). 2020. Research Track Assessment for Index-Based Methods and Control Rules. Woods Hole, MA. 59 p.
- NRC (National Research Council). 2006. Review of recreational fisheries survey methods. Committee on the Review of Recreational Fisheries Survey Methods, National Research Council. The National Academies Press, Washington, D.C. 202 p.
- Nelson, G., B. Chase, and J. Stockwell. 2003. Food Habits of Striped Bass (*Morone saxatilis*) in Coastal Waters of Massachusetts. *Journal of Northwest Atlantic Fishery Science* 32:1–25.
- Nesslage, G.M., and M.J. Wilberg. 2019. A performance evaluation of surplus production models with time-varying intrinsic growth in dynamic ecosystems. *Canadian Journal of Fisheries and Aquatic Sciences*. DOI: 10.1139/cjfas-2018-0292.
- Normandeau Associates. 2018. Muddy Run Pumped Storage Project Conowingo Eel Collection Facility. Reported prepared for Exelon. 80 p.
- _____. 2021. Muddy Run Pumped Storage Project Conowingo Eel Collection Facility. Reported prepared for Exelon. 66 p.
- Oliveira, K. 1996. Field validation of annular growth rings in the American eel, *Anguilla rostrata*, using tetracycline-marked otoliths. *U.S. National Marine Fisheries Service Fishery Bulletin*. 94:186–189.
- _____, and J.D. McCleave. 2000. Variation in population and life history traits of the American eel, *Anguilla rostrata*, in four rivers in Maine. *Environmental Biology of Fishes* 59(2):141–151.
- Pavey, S.A., J.Gaudin, E. Normandeau, M. Dionne, M. Castonguay, C. Audet., and L. Bernatchez. 2015. RAD sequencing highlights polygenic discrimination of habitat ecotypes in the panmictic American eel. *Current Biology* 25:1666–1671.

- Prager, M. H. 1994. A suite of extensions to a nonequilibrium surplus-production model. *Fishery Bulletin* 92:374–389.
- Pratt, T.C., R.G. Bradford, D.K. Cairns, M. Castonguay, G. Chaput, K.D. Clarke, and A. Mathers. 2014. Recovery potential assessment for the American eel (*Anguilla rostrata*) in eastern Canada: functional description of habitat. Canadian Science Advisory Secretariat Research Document 2013/132. 49 p.
- _____, L.M. O'Connor, J.A. Stacey, D.R. Stanley, A. Mathers, L.E. Johnson,... and J. Pearce. 2019. Pattern of *Anguillicoloides crassus* infestation in the St. Lawrence River watershed. *Journal of Great Lakes Research* 45(5):991–997.
- R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (<https://www.R-project.org/>)
- Rodionov, S.N. 2004. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, 31(9).
- _____, and J.E. Overland. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. *ICES Journal of Marine Science* 62(3), 328-332.
- Roncarati, A., P. Melotti, O. Mordenti, and L. Gennari. 1997. Influence of stocking density of European eel (*Anguilla anguilla*, L.) elvers on sex differentiation and zootechnical performances. *Journal of Applied Ichthyology* 13(3):131–136.
- Rypina, I.I., J.K. Llopiz, L.J. Pratt, and M.S. Lozier. 2014. Dispersal pathways of American eel larvae from the Sargasso Sea. *Limnology and Oceanography* 59(5):1704–1714.
- _____, L.J. Pratt, and M.S. Lozier. 2016. Influence of ocean circulation changes on the inter-annual variability of American eel larval dispersal. *Limnology and Oceanography* 61(5):1574–1588.
- SC DNR (South Carolina Department of Natural Resources). 2020. Addressing crucial American Eel life history questions: Baseline data on the age and sex composition of American Eels in South Carolina, with a comparison of different ageing methodologies. Final Report. South Carolina State Wildlife Grant SC-T_F18AF00965.
- Schmitt, J.D., E.M. Hallerman, A.J. Bunch, Z. Moran, J.A. Emmel, and D.J. Orth. 2017. Predation and prey selectivity by nonnative catfish on migrating Alosines in an Atlantic slope estuary. *Marine and Coastal Fisheries* 9:108–125.
- _____, B.K. Peoples, A.J. Bunch, L. Castello, and D.J. Orth. 2019a. Modeling the predation dynamics of invasive blue catfish (*Ictalurus furcatus*) in Chesapeake Bay. *Fishery Bulletin* 117:277–290.

- _____, B.K. Peoples, A.J. Bunch, L. Castello, and D.J. Orth. 2019b. Feeding ecology of generalist consumers: a case study of invasive blue catfish (*Ictalurus furcatus*) in Chesapeake Bay. Virginia, USA. *Environmental Biology of Fishes* 102:443–465.
- Schnute, J. 1985. A General Theory for Analysis of Catch and Effort Data. *Canadian Journal of Fisheries and Aquatic Sciences* 42(3):414–429.
- _____. 1987. A General Fishery Model for a Size-Structured Fish Population. *Canadian Journal of Fisheries and Aquatic Sciences* 44(5):924–940.
- SEDAR (SouthEast Data, Assessment, and Review). 2020. SEDAR 69: Atlantic Menhaden Ecological Reference Points Stock Assessment Report. SEDAR, North Charleston SC. 560 p. <http://sedarweb.org/sedar-69>
- Sweka, J.A., S. Eyler, and M.J. Millard. 2014. An egg-per-recruit model to evaluate the effects of upstream transport and downstream passage mortality of American eel in the Susquehanna River. *North American Journal of Fisheries Management* 34(4):764–773.
- Tesch, R.W. 1977. *The eel: biology and management of anguillid eels*. Chapman and Hall, London. 434 p.
- Therneau, T., B. Atkinson, and B. Ripley. 2015. rpart: recursive partitioning and regression trees. R package version 4.1- 9. <http://CRAN.R-project.org/package=rpart>
- Tremblay, V. 2009. Reproductive strategy of female American Eels among five subpopulations in the St. Lawrence River watershed. Pages 85–102 *In*: J. M. Casselman and D. K. Cairns (editors), *Eels at the edge: science, status, and conservation concerns*. American Fisheries Society, Symposium 58, Bethesda, Maryland. 449 p.
- Turner, S.M., B.C. Chase, and M.S. Bednarski. 2018. Evaluating the Effect of Dam Removals on Yellow-Phase American Eel Abundance in a Northeastern US Watershed. *North American Journal of Fisheries Management* 38(2):424–431.
- USFWS (U.S. Fish and Wildlife Service). 2007. Endangered and threatened wildlife and plants—12-month finding on a petition to list the American eel as threatened or endangered. Notice of 12-month petition finding. *Federal Register* 72:22(2 February 2007):4967–4997.
- _____. 2011. Endangered and threatened wildlife and plants—90-day finding on a petition to list the American eel as threatened. Proposed rules. *Federal Register* 76:189(29 September 2011):60431–60444.
- _____. 2015. Endangered and threatened wildlife and plants—12-month finding on a petition to list the American eel as threatened or endangered. Notice of 12-month petition finding. *Federal Register*. U.S. Government Printing Office, Washington, D.C. (8 October 2015). Docket Number FWS-HQ-ES-2015-0143.

- Van Den Avyle, M.J. 1984. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic)—American eel. USFWS FWS/OBS-82/11.24. U.S. Army Corps of Engineers, TR EL-82-4. 20 p.
- Verdon, R., D. Desrochers, and P. Dumont. 2003. Recruitment of American eels in the Richelieu River and Lake Champlain: provision of upstream passage as a regional scale solution to a large scale problem. *American Fisheries Society Symposium* 33:125–138.
- Waldt, E.M., R. Abbett, J.H. Johnson, D.E. Dittman, and J.E. McKenna. 2013. Fall diel diet composition of American eel (*Anguilla rostrata*) in a tributary of the Hudson River, New York, USA. *Journal of Freshwater Ecology* 28(1):91–98.
- Walter, J., and H. Austin. 2003. Diet Composition of Large Striped Bass (*Morone saxatilis*) In "Chesapeake Bay" (2003). VIMS Articles. 572.
<https://scholarworks.wm.edu/vimsarticles/572>
- Warshafsky, Z.T., T.D. Tuckey, W.K. Vogelbein, R.J. Latour, and A.R. Wargo. 2019. Temporal, spatial, and biological variation of nematode epidemiology in American eels. *Canadian Journal of Fisheries and Aquatic Science* 76:1808–1818.
- Walter III, JF., and H.M. Austin. 2003. Diet composition of large Striped Bass (*Morone saxatilis*) in the Chesapeake Bay. *Fishery Bulletin* 101(2):414–423.
- Wirth, T., and L. Bernatchez. 2003. Decline of North Atlantic eels: a fatal synergy? *Proceedings of the Royal Society of London, Series B, Biological Sciences* 270(1516):681–688.
- Zar, J.H. 1999. *Biostatistical analysis*, 4th edition. Prentice Hall, Upper Saddle River, New Jersey.

12 TABLES

Table 1. Number of American eel ages supplied for this assessment by agency. Collection years and months are reported, along with the average age of samples and a range.

| Agency | Years | Months | Age Range | Average Age | Number of Age Samples | |
|--------|-----------|---------|-----------|-------------|-----------------------|-----------|
| | | | | | Commercial | FI Survey |
| NJ DFW | 2006-2019 | Apr-Dec | 1-15 | 4.6 | 2,663 | |
| DE DFW | 2012-2015 | Apr-Nov | 2-13 | 4.6 | 978 | |
| MD DNR | 1998-2019 | Apr-Dec | 1-15 | 4.4 | 4,766 | 1,769 |
| GA DNR | 2013 | Aug-Dec | 3-9 | 5.2 | 74 | |

Table 2. Parameter estimates (standard error in parentheses) of the allometric length (mm)-weight (g) relation fit to available data for American eel by region, sex, and all data pooled. Asterisks (*) denotes standard errors that are $\geq 30\%$ of the parameter estimate.

| Group | Subset | n | a | b |
|--------|------------------------------|--------|---------------------|----------------|
| None | all | 81,830 | 4.50E-07(7.47E-09) | 3.23(2.58E-03) |
| Region | Gulf of Maine | 4,739 | 7.40E-07(3.40E-08) | 3.15(7.09E-03) |
| | Southern New England | 166 | 5.11E-05(4.12E-05*) | 2.52(1.24E-01) |
| | Hudson River | 2,413 | 1.14E-06(1.83E-07) | 3.08(2.50E-02) |
| | Del Bay/Mid-Atl Coastal Bays | 15,694 | 6.05E-07(2.75E-08) | 3.18(7.11E-03) |
| | Chesapeake Bay | 44,251 | 2.99E-07(4.91E-09) | 3.29(2.54E-03) |
| | South Atlantic | 14,567 | 4.83E-07(3.51E-08) | 3.23(1.15E-02) |
| Sex | Female | 4,319 | 6.54E-07(3.68E-08) | 3.17(8.74E-03) |
| | Male | 2,930 | 1.75E-06(2.03E-07) | 3.00(1.99E-02) |

Table 3. Parameter estimates (standard error in parentheses) for the linear regression of length (mm) on age (years) fit to available data for American eel by region, sex, and all data pooled.

| Group | Subset | n | Intercept | Slope |
|--------|----------------------|--------|-----------|-----------|
| None | All | 20,577 | 348(1.4) | 8.5(0.2) |
| Region | Gulf of Maine | 2,377 | 87(3.0) | 23.5(0.3) |
| | Southern New England | 475 | 192(18.7) | 14.5(1.6) |
| | Hudson River | 914 | 264(8.5) | 12.5(0.6) |
| | Del Bay/Mid-Atl CB | 7,091 | 293(2.9) | 27.2(0.7) |
| | Chesapeake Bay | 8,488 | 272(2.7) | 27.5(0.5) |
| | South Atlantic | 1,232 | 323(9.2) | 27.6(1.9) |
| Sex | Female | 3,798 | 350(2.6) | 8.1(0.3) |
| | Male | 2,709 | 297(1.3) | 3.1(0.2) |

Table 4. Parameter estimates (standard error in parentheses) of the von Bertalanffy age-length model fit to available data for American eel by region, sex, and all data pooled. Asterisks (*) denotes standard errors that are $\geq 30\%$ of the parameter estimate.

| Group | Subset | n | Linf | K | T ₀ |
|--------|------------------------------|--------|---------------------------|--------------|----------------|
| None | all | 20,577 | 441(2.0) | 0.52(0.014) | -0.4(0.1) |
| Region | Gulf of Maine | 2,377 | 1414(196.1) | 0.02(0.004) | -2.2(0.3) |
| | Southern New England | 475 | <i>failed to converge</i> | | |
| | Hudson River | 914 | 482(5.2) | 0.28(0.018) | 0.5(0.1) |
| | Del Bay/Mid-Atl Coastal Bays | 7,091 | 626(127.3) | 0.14(0.018) | -3.5(0.9) |
| | Chesapeake Bay | 8,488 | 1647(639.7) | 0.023(0.012) | -7.8(0.9) |
| | South Atlantic | 1,232 | 591(31.8) | 0.23(0.052) | -1.9(0.7) |
| Sex | Female | 3,798 | 618(45.9) | 0.05(0.012) | -16.4(2.9) |
| | Male | 2,709 | <i>failed to converge</i> | | |

Table 5. Summary of available age-length data for American eel from along the Atlantic Coast.

| Age | n Lengths |
|------------|------------------|
| 0 | 106,513 |
| 1 | 285 |
| 2 | 1,875 |
| 3 | 3,657 |
| 4 | 4,177 |
| 5 | 3,489 |
| 6 | 2,047 |
| 7 | 1,209 |
| 8 | 786 |
| 9 | 524 |
| 10 | 411 |
| 11 | 369 |
| 12 | 377 |
| 13 | 335 |
| 14 | 251 |
| 15 | 186 |
| 16 | 153 |
| 17 | 105 |
| 18 | 95 |
| 19 | 72 |
| 20 | 56 |
| 21 | 52 |
| 22 | 21 |
| 23 | 13 |
| 24 | 11 |
| 25 | 6 |
| 26 | 1 |
| 27 | 4 |
| 28 | 2 |
| 29 | 0 |
| 30 | 0 |
| 31 | 0 |
| 32 | 1 |
| 33 | 1 |
| 34 | 0 |
| 35 | 0 |
| 36 | 0 |
| 37 | 1 |

Table 6. Validated state landings of commercial yellow eels, in pounds, from Maine to Florida for 1998-2020. Landings for 2020 are considered preliminary and are likely to change.

| Year | ME | NH | MA | RI | CT | NY | NJ | DE | MD | PRFC | VA | NC | SC | GA | FL | Total (lbs) |
|-------|--------|---|-------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---|---|--------|-------------|
| 1998 | 0 | Time series average of less than 400 pounds | 3,456 | 967 | 5,606 | 16,867 | 94,327 | 131,478 | 301,833 | 209,008 | 123,837 | 91,084 | Time series average of less than 400 pounds | Time series average of less than 400 pounds | 13,819 | 992,741 |
| 1999 | 0 | | 3,456 | 140 | 10,250 | 7,882 | 90,252 | 128,978 | 305,812 | 163,351 | 183,255 | 99,939 | | | 17,533 | 1,011,093 |
| 2000 | 0 | | 2,976 | 25 | 4,643 | 5,824 | 45,393 | 119,180 | 259,552 | 208,549 | 114,972 | 127,099 | | | 6,054 | 894,577 |
| 2001 | 9,007 | | 3,867 | 14,357 | 1,724 | 18,192 | 57,700 | 121,515 | 271,178 | 213,440 | 97,032 | 107,070 | | | 14,218 | 929,523 |
| 2002 | 11,617 | | 3,949 | 22,965 | 3,710 | 30,930 | 64,600 | 99,529 | 208,659 | 128,595 | 75,549 | 59,940 | | | 7,587 | 717,698 |
| 2003 | 15,312 | | 4,047 | 24,883 | 1,868 | 8,296 | 100,701 | 155,516 | 346,412 | 123,450 | 121,091 | 172,065 | | | 8,486 | 1,082,614 |
| 2004 | 34,841 | | 5,328 | 19,858 | 1,374 | 5,354 | 120,607 | 137,489 | 273,142 | 116,263 | 123,812 | 128,875 | | | 7,330 | 974,508 |
| 2005 | 17,189 | | 3,073 | 22,001 | 337 | 27,726 | 148,127 | 111,200 | 378,659 | 103,628 | 81,563 | 49,278 | | | 3,913 | 946,694 |
| 2006 | 18,619 | | 3,676 | 1,034 | 3,443 | 10,601 | 158,917 | 123,994 | 362,966 | 83,622 | 104,441 | 33,581 | | | 1,248 | 907,007 |
| 2007 | 13,120 | | 2,853 | 1,230 | 935 | 14,881 | 169,902 | 139,647 | 343,141 | 97,361 | 69,177 | 37,937 | | | 7,379 | 897,943 |
| 2008 | 12,496 | | 3,297 | 8,866 | 6,046 | 15,025 | 137,687 | 80,002 | 381,993 | 71,655 | 84,031 | 23,833 | | | 15,624 | 841,065 |
| 2009 | 2,525 | | 1,217 | 4,855 | 435 | 12,676 | 118,533 | 59,619 | 335,575 | 58,863 | 117,974 | 65,481 | | | 6,824 | 784,577 |
| 2010 | 3,038 | | 322 | 3,860 | 167 | 12,179 | 105,089 | 69,355 | 524,768 | 57,755 | 77,263 | 122,104 | | | 11,287 | 987,290 |
| 2011 | 4,065 | | 408 | 2,038 | 60 | 36,451 | 120,576 | 92,181 | 715,162 | 29,010 | 103,222 | 61,960 | | | 25,601 | 1,190,764 |
| 2012 | 11,275 | | 462.3 | 1,484 | 2,228 | 35,603 | 113,806 | 54,304 | 590,412 | 90,037 | 121,605 | 64,110 | | | 11,845 | 1,099,214 |
| 2013 | 6,691 | | 2,530 | 2,244 | 546 | 42,845 | 90,244 | 82,991 | 587,872 | 32,290 | 100,379 | 33,980 | | | 15,059 | 999,072 |
| 2014 | 7,578 | | 3,903 | 2,353 | 1,390 | 38,143 | 91,225 | 62,388 | 619,935 | 49,293 | 109,537 | 60,755 | | | 14,092 | 1,060,725 |
| 2015 | 4,142 | | 2,213 | 1,538 | 2,271 | 50,194 | 88,828 | 44,708 | 493,043 | 31,588 | 86,715 | 57,791 | | | 5,632 | 868,663 |
| 2016 | 6,811 | | 1,705 | 2,651 | 2,445 | 36,371 | 67,422 | 44,558 | 583,578 | 58,223 | 96,336 | 39,911 | | | 6,034 | 946,110 |
| 2017 | 6,358 | | 592 | 2,968 | 905 | 41,732 | 77,499 | 29,945 | 541,270 | 33,555 | 97,328 | 24,752 | | | 7,456 | 864,360 |
| 2018 | 2,832 | 375 | 3,988 | 3,268 | 39,218 | 69,679 | 31,378 | 514,226 | 31,151 | 57,281 | 18,058 | 4,659 | 776,131 | | | |
| 2019 | 2567 | 1,577 | 4,056 | 5,275 | 33,039 | 76,241 | 13,628 | 331,878 | 27,111 | 34,247 | 8,140 | 1,542 | 539,301 | | | |
| 2020* | | | 1,425 | 2,783 | 9,865 | 23,340 | 1,942 | 134,024 | 24,971 | 14,799 | 3,291 | 499 | 218,005 | | | |

Table 7. Commercial yellow eel landings, 1904-2020. Landings from 1904-1997 are estimated from historical records. Landings from 1998-2019 were validated by ACCSP. 2020 data is considered preliminary.

| Year | Pounds | Year | Pounds | Year | Pounds |
|------|-----------|------|-----------|------|-----------|
| 1904 | 29,398 | 1955 | 1,373,978 | 1994 | 1,586,665 |
| 1908 | 44,585 | 1956 | 1,448,058 | 1995 | 1,339,690 |
| 1909 | 7,414 | 1957 | 1,260,997 | 1996 | 1,600,445 |
| 1913 | 130,086 | 1958 | 1,390,175 | 1997 | 828,071 |
| 1916 | 66,990 | 1959 | 1,329,426 | 1998 | 992,741 |
| 1917 | 43,191 | 1960 | 888,605 | 1999 | 1,011,093 |
| 1918 | 47,390 | 1961 | 836,994 | 2000 | 894,577 |
| 1922 | | 1962 | 664,092 | 2001 | 929,523 |
| 1924 | 43,249 | 1963 | 987,741 | 2002 | 717,698 |
| 1925 | 58,435 | 1964 | 1,072,243 | 2003 | 1,082,614 |
| 1926 | 36,099 | 1965 | 1,563,100 | 2004 | 974,508 |
| 1927 | 30,767 | 1966 | 1,277,700 | 2005 | 946,694 |
| 1928 | 41,211 | 1967 | 1,596,947 | 2006 | 907,007 |
| 1929 | 62,071 | 1968 | 1,663,620 | 2007 | 897,943 |
| 1930 | 39,652 | 1969 | 1,872,026 | 2008 | 841,065 |
| 1931 | | 1970 | 2,158,000 | 2009 | 784,577 |
| 1932 | 50,784 | 1971 | 2,483,484 | 2010 | 987,290 |
| 1933 | 40,247 | 1972 | 1,595,776 | 2011 | 1,190,764 |
| 1934 | 58,307 | 1973 | 1,346,769 | 2012 | 1,099,214 |
| 1935 | 46,243 | 1974 | 3,110,169 | 2013 | 999,072 |
| 1936 | 45,718 | 1975 | 3,573,132 | 2014 | 1,060,725 |
| 1937 | 34,989 | 1976 | 2,502,037 | 2015 | 868,663 |
| 1938 | 43,964 | 1977 | 2,118,940 | 2016 | 946,110 |
| 1939 | 33,099 | 1978 | 3,603,227 | 2017 | 864,360 |
| 1940 | 33,850 | 1979 | 3,667,066 | 2018 | 776,131 |
| 1941 | 35,556 | 1980 | 3,379,200 | 2019 | 539,301 |
| 1942 | 19,031 | 1981 | 3,057,253 | 2020 | 218,005 |
| 1943 | 22,178 | 1982 | 2,267,321 | | |
| 1944 | 11,512 | 1983 | 1,797,503 | | |
| 1945 | 19,293 | 1984 | 2,491,947 | | |
| 1946 | 24,632 | 1985 | 2,143,703 | | |
| 1947 | 24,567 | 1986 | 2,004,078 | | |
| 1948 | 15,973 | 1987 | 1,640,431 | | |
| 1949 | 19,486 | 1988 | 1,445,105 | | |
| 1950 | 2,103,285 | 1989 | 1,680,693 | | |
| 1951 | 1,849,638 | 1990 | 1,549,164 | | |
| 1952 | 1,618,200 | 1991 | 1,714,400 | | |
| 1953 | 1,411,593 | 1992 | 1,439,688 | | |
| 1954 | 1,193,140 | 1993 | 1,596,202 | | |

Table 8. Annual recreational harvest (Type A + B1) and released alive (Type B2) estimates for American eels along the U.S. east coast as estimated by MRIP, 1981–2019. Proportional standard error (PSE) values greater than 50 indicate an imprecise estimate and are highlighted in pink.

| Year | Total Harvest (A+B1) | PSE | Harvest (A+B1) Total Weight (lb) | PSE | Harvest (A+B1) Total Weight (kg) | PSE | Released Alive (B2) | PSE |
|------|----------------------|------|----------------------------------|------|----------------------------------|------|---------------------|------|
| 1981 | 345,745 | 32.2 | 348,961 | 29.4 | 158,288 | 29.4 | 253,712 | 33.7 |
| 1982 | 583,954 | 27.7 | 402,936 | 19.8 | 182,770 | 19.8 | 237,000 | 38.6 |
| 1983 | 283,193 | 51.3 | 399,566 | 61.2 | 181,242 | 61.2 | 278,063 | 32.7 |
| 1984 | 216,756 | 32.8 | 211,703 | 31.5 | 96,028 | 31.5 | 125,987 | 32.9 |
| 1985 | 413,188 | 35.8 | 375,122 | 39.2 | 170,154 | 39.2 | 164,441 | 23.2 |
| 1986 | 407,478 | 45.4 | 394,427 | 48.0 | 178,911 | 48.0 | 272,637 | 27.5 |
| 1987 | 106,042 | 35.5 | 109,515 | 45.0 | 49,676 | 45.0 | 253,065 | 30.7 |
| 1988 | 275,933 | 26.7 | 228,575 | 27.8 | 103,681 | 27.8 | 211,949 | 21.7 |
| 1989 | 147,906 | 26.0 | 185,379 | 28.3 | 84,087 | 28.3 | 333,884 | 24.0 |
| 1990 | 79,615 | 30.3 | 98,068 | 30.5 | 44,483 | 30.5 | 205,143 | 20.7 |
| 1991 | 183,068 | 30.2 | 160,051 | 27.8 | 72,599 | 27.8 | 197,984 | 27.1 |
| 1992 | 130,003 | 47.8 | 57,381 | 40.4 | 26,028 | 40.4 | 127,573 | 25.1 |
| 1993 | 172,408 | 39.5 | 164,114 | 47.1 | 74,442 | 47.1 | 193,369 | 19.7 |
| 1994 | 112,381 | 30.7 | 110,976 | 38.5 | 50,338 | 38.5 | 145,291 | 19.6 |
| 1995 | 20,359 | 51.6 | 24,897 | 52.3 | 11,293 | 52.3 | 192,650 | 27.4 |
| 1996 | 43,388 | 35.1 | 33,294 | 40.3 | 15,102 | 40.3 | 169,983 | 22.0 |
| 1997 | 78,187 | 65.4 | 78,268 | 49.6 | 35,502 | 49.6 | 91,594 | 36.1 |
| 1998 | 20,121 | 43.5 | 32,343 | 47.0 | 14,671 | 47.0 | 144,150 | 32.7 |
| 1999 | 20,249 | 44.9 | 35,128 | 64.3 | 15,934 | 64.3 | 100,894 | 27.2 |
| 2000 | 114,158 | 92.9 | 59,770 | 97.7 | 27,112 | 97.7 | 149,152 | 34.3 |
| 2001 | 32,026 | 74.0 | 22,309 | 65.6 | 10,119 | 65.6 | 84,368 | 28.7 |
| 2002 | 14,236 | 47.7 | 16,620 | 61.4 | 7,539 | 61.4 | 139,477 | 25.9 |
| 2003 | 151,008 | 80.4 | 4,670 | 71.3 | 2,118 | 71.3 | 322,919 | 17.5 |
| 2004 | 134,759 | 50.4 | 129,412 | 55.7 | 58,701 | 55.7 | 204,406 | 24.4 |
| 2005 | 23,006 | 53.9 | 19,502 | 58.5 | 8,846 | 58.5 | 178,189 | 34.5 |
| 2006 | 64,147 | 60.1 | 40,387 | 57.9 | 18,319 | 57.9 | 377,834 | 43.2 |
| 2007 | 102,962 | 60.2 | 83,649 | 67.3 | 37,943 | 67.3 | 242,656 | 40.3 |
| 2008 | 9,245 | 56.4 | 2,856 | 71.7 | 1,295 | 71.7 | 173,235 | 36.0 |
| 2009 | 48,518 | 63.0 | 25,374 | 72.8 | 11,510 | 72.8 | 285,954 | 27.0 |
| 2010 | 371,184 | 78.1 | 97,425 | 58.5 | 44,192 | 58.5 | 304,511 | 27.6 |
| 2011 | 40,789 | 59.5 | 38,918 | 87.8 | 17,653 | 87.8 | 302,883 | 24.9 |
| 2012 | 93,736 | 49.6 | 31,745 | 56.9 | 14,400 | 56.9 | 445,654 | 25.7 |
| 2013 | 33,083 | 50.2 | 18,329 | 28.7 | 8,314 | 28.7 | 430,905 | 24.6 |
| 2014 | 23,206 | 53.0 | 51,588 | 63.0 | 23,400 | 63.0 | 480,481 | 52.3 |
| 2015 | 11,510 | 55.4 | 21,866 | 90.5 | 9,918 | 90.5 | 181,830 | 26.8 |
| 2016 | 155,099 | 22.6 | 223,854 | 20.4 | 101,539 | 20.4 | 201,875 | 31.2 |
| 2017 | 63,500 | 84.7 | 94,229 | 76.9 | 42,742 | 76.9 | 246,360 | 22.6 |
| 2018 | 148,807 | 67.3 | 142,169 | 67.7 | 64,487 | 67.7 | 145,357 | 43.2 |
| 2019 | 14,052 | 69.7 | 16,743 | 93.9 | 7,595 | 93.9 | 117,157 | 30.5 |

Table 9. Annual number of total intercepts and intercepts that encountered American eels in the MRIP survey, 1981–2019.

| Year | Intercepts | Intercepts with Am Eel | % Intercepts with Am Eel |
|-------------|-------------------|-------------------------------|---------------------------------|
| 1981 | 20,682 | 42 | 0.20 |
| 1982 | 26,851 | 37 | 0.14 |
| 1983 | 31,014 | 31 | 0.10 |
| 1984 | 26,560 | 26 | 0.098 |
| 1985 | 34,727 | 34 | 0.098 |
| 1986 | 38,076 | 46 | 0.12 |
| 1987 | 41,438 | 35 | 0.084 |
| 1988 | 50,587 | 49 | 0.097 |
| 1989 | 61,305 | 48 | 0.078 |
| 1990 | 59,842 | 29 | 0.048 |
| 1991 | 68,444 | 43 | 0.063 |
| 1992 | 79,746 | 20 | 0.025 |
| 1993 | 79,662 | 25 | 0.031 |
| 1994 | 89,772 | 32 | 0.036 |
| 1995 | 83,969 | 10 | 0.012 |
| 1996 | 84,920 | 17 | 0.020 |
| 1997 | 89,689 | 11 | 0.012 |
| 1998 | 94,211 | 9 | 0.0096 |
| 1999 | 102,314 | 10 | 0.0098 |
| 2000 | 97,930 | 6 | 0.0061 |
| 2001 | 114,874 | 7 | 0.0061 |
| 2002 | 110,342 | 11 | 0.010 |
| 2003 | 113,238 | 19 | 0.017 |
| 2004 | 94,341 | 14 | 0.015 |
| 2005 | 92,189 | 7 | 0.0076 |
| 2006 | 90,528 | 8 | 0.0088 |
| 2007 | 94,033 | 11 | 0.012 |
| 2008 | 92,270 | 6 | 0.0065 |
| 2009 | 85,407 | 8 | 0.0094 |
| 2010 | 97,157 | 9 | 0.0093 |
| 2011 | 91,092 | 5 | 0.0055 |
| 2012 | 94,565 | 15 | 0.016 |
| 2013 | 74,659 | 13 | 0.017 |
| 2014 | 84,302 | 15 | 0.018 |
| 2015 | 84,899 | 7 | 0.0082 |
| 2016 | 83,934 | 14 | 0.017 |
| 2017 | 85,590 | 9 | 0.011 |
| 2018 | 88,722 | 16 | 0.018 |
| 2019 | 87,340 | 6 | 0.0069 |

Table 10. Surveys considered for developing abundance indices for American eels. Table indicates which surveys were accepted for index development and which were rejected and why. Table continued on next page.

| State | Site | Start Year | End Year | Stage | Include? | Reason for Exclusion |
|-------|--|------------|----------|--------|----------|-----------------------|
| ME | West Harbor Pond | 2001 | 2019 | YOY | Y | |
| ME | Juvenile Finfish Beach Seine Survey | 2000 | 2019 | Elver | Y | |
| ME | Life Cycle Study | 2019 | 2019 | All | N | Time series too short |
| NH | Lamprey River | 2001 | 2020 | YOY | Y | |
| NH | Oyster River | 2014 | 2020 | YOY | N | Time series too short |
| NH | Rainbow Smelt Fyke Net Survey | 2008 | 2020 | Yellow | Y | |
| MA | Jones River | 2001 | 2019 | YOY | Y | |
| MA | Wankinco River | 2009 | 2019 | YOY | Y | |
| MA | Saugus River | 2009 | 2019 | Age-1 | Y | |
| MA | Rainbow Smelt Fyke Net Survey | 2004 | 2019 | Yellow | Y | |
| RI | Gilbert Stuart Dam | 2000 | 2019 | YOY | Y | |
| RI | Hamilton Fish Ladder | 2004 | 2019 | YOY | Y | |
| RI | Coastal Trawl | 1979 | 2019 | | N | Rarely encounters eel |
| RI | Narrangansett Bay Seine Survey | 1988 | 2019 | Yellow | N | Rarely encounters eel |
| RI | Coastal Ponds | 1992 | 2020 | Yellow | N | Rarely encounters eel |
| CT | Ingham Hill | 2007 | 2019 | YOY | Y | |
| CT | Farmill River | 2001 | 2014 | Yellow | Y | |
| CT | Eightmile River | 2001 | 2020 | Yellow | Y | |
| CT | Terry Brook | 2009 | 2020 | Yellow | N | Rarely encounters eel |
| NY | HRE Monitoring | 1974 | 2017 | YOY | Y | |
| NY | HRE Monitoring | 1974 | 2017 | Yellow | Y | |
| NY | Carmans River | 2000 | 2019 | YOY | Y | |
| NY | Hudson River | 2008 | 2020 | YOY | Y | |
| NY | Hudson Juvenile Alosine | 1985 | 2019 | Yellow | Y | |
| NY | Hudson Juv Striped Bass | 1980 | 2019 | Yellow | Y | |
| NY | Western Long Island | 1984 | 2019 | Yellow | N | Low % positive tows |
| NJ | Little Egg Inlet | 1992 | 2015 | YOY | Y | |
| NJ | Patcong Creek | 1999 | 2020 | YOY | Y | |
| NJ | Glass Eel Alternative Collector Survey | 2012 | 2020 | YOY | N | Time series too short |
| NJ | Barnegat Bay | 2012 | 2020 | YOY | N | Time series too short |
| NJ | Delaware Bay Trawl | 1991 | 2019 | Yellow | N | Low % positive tows |
| NJ | Delaware River Seine | 1998 | 2019 | Yellow | Y | |
| DE | DE River Commercial Eel Pots | 1999 | 2019 | Yellow | N | Survey design issues |
| DE | DE River Commercial Eel Pots | 2012 | 2019 | Yellow | N | Survey design issues |
| DE | Delaware Juvenile Trawl | 1980 | 2019 | Yellow | Y | |
| DE | Delaware River - Millsboro | 2000 | 2020 | YOY | Y | |
| PA | Delaware River Area 6 | 1999 | 2020 | Elver | Y | |
| PA | Delaware River Area 6 | 2005 | 2020 | Yellow | Y | |
| PA | Susquehanna River - Octoraro | 2015 | 2019 | Elver | N | Time series too short |
| MD | Susquehanna River - Conowingo | 2008 | 2019 | Elver | Y | |

| State | Site | Start Year | End Year | Stage | Include? | Reason for Exclusion |
|-------|---|------------|------------|--------|----------|---------------------------------|
| MD | MDDNR Striped Bass Seine | 1967 | 2019 | yellow | N | Low eel catch |
| MD | Turville Creek | 2000 | 2019 | YOY | Y | |
| MD | Sassafras | 2006 | 2019 | yellow | Y | |
| DC | DC Potomac | 2008 | 2019 | yellow | N | Data format issues |
| PRFC | Clark's Millpond | 2000 | 2016 | YOY | Y | |
| PRFC | Gardy's Millpond | 2000 | 2019 | YOY | Y | |
| PRFC | Clark's Millpond | 2000 | 2016 | Elver | Y | |
| PRFC | Gardy's Millpond | 2000 | 2019 | Elver | Y | |
| VA | VIMS Trawl Survey | 1955 | 2019 | yellow | Y | |
| VA | DWR Fish Passage Rappahannock, Appomattox | 2015, 2019 | 2015, 2019 | yellow | N | Time series too short |
| VA | DWR Rivanna Watershed Survey | 2019 | 2019 | yellow | N | Time series too short |
| VA | DWR Depletion Survey Lynchburg | 2019 | 2019 | yellow | N | Time series too short |
| VA | VIMS Trawl Short | 1996 | 2019 | yellow | Y | |
| VA | VIMS Seine Survey | 1967 | 2019 | yellow | Y | |
| VA | VIMS Seine Short | 1989 | 2019 | yellow | Y | |
| VA | Wormley Creek | 2001 | 2019 | YOY | Y | |
| VA | Bracken's Pond | 2000 | 2017 | YOY | Y | |
| VA | Kamp's Millpond | 2000 | 2019 | YOY | Y | |
| VA | Wareham's Pond | 2003 | 2019 | YOY | Y | |
| VA | Wormley Creek | 2001 | 2019 | Elver | Y | |
| VA | Bracken's Pond | 2000 | 2017 | Elver | Y | |
| VA | Kamp's Millpond | 2000 | 2019 | Elver | Y | |
| VA | Wareham's Pond | 2003 | 2019 | Elver | Y | |
| NC | Beaufort (BBISP) | 1987 | 2019 | YOY | Y | |
| NC | Pamlico Sound | 1971 | 2019 | mix | N | Rarely encounters eel |
| NC | Roanoke Rapids | 2010 | 2019 | yellow | N | Measures passage, not abundance |
| SC | Goose Creek | 2000 | 2015 | YOY | Y | |
| SC | Goose Creek | 2016 | 2020 | YOY | N | Time series too short |
| SC | various rivers electrofishing | 2010 | 2020 | yellow | N | Inconsistent methods |
| SC | Rediversion canal (fyke) | 2003 | 2003 | mix | N | Time series too short |
| SC | Rediversion canal (ladder corrugated) | 2004 | 2014 | mix | N | Time series too short |
| SC | Rediversion canal (ladder aluminum) | 2003 | 2020 | mix | Y | |
| GA | Altamaha Canal | 2001 | 2013 | YOY | Y | |
| GA | Hudson Creek | 2003 | 2013 | YOY | Y | |
| GA | Altamaha Pot Survey | 2013 | 2020 | yellow | N | Time series too short |
| FL | Guana | 2001 | 2020 | YOY | Y | |
| FL | Trawl FFR | 2015 | 2015 | YOY | N | Time series too short |
| FL | Fyke Net FFR | 2018 | 2018 | mix | N | Time series too short |
| FL | Electrofishing FFR | 2006 | 2020 | mix | N | Sampling method issues |
| FL | Various (MFR) | varies | varies | mix | N | Insufficient data |

Table 11. Young-of-year American eel surveys accepted for use in this assessment.

| State | Site | Abbreviation | Start Year | End Year |
|-------|----------------------------|--------------|------------|----------|
| ME | West Harbor Pond | MEWHP | 2001 | 2019 |
| NH | Lamprey River | NHLR | 2001 | 2020 |
| MA | Jones River | MAJR | 2001 | 2019 |
| MA | Wankinco River | MAWR | 2009 | 2019 |
| RI | Gilbert Stuart Dam | RIGSD | 2000 | 2019 |
| RI | Hamilton Fish Ladder | RIHFL | 2004 | 2019 |
| CT | Ingham Hill | CTIH | 2007 | 2019 |
| NY | HRE Monitoring | NYHRE | 1974 | 2017 |
| NY | Carmans River | NYCR | 2000 | 2019 |
| NY | Hudson River | NYHR | 2008 | 2020 |
| NJ | Little Egg Inlet | NJLEI | 1992 | 2015 |
| NJ | Patcong Creek | NJPC | 1999 | 2020 |
| DE | Delaware River - Millsboro | DEM | 2000 | 2020 |
| MD | Turville Creek | MDTC | 2000 | 2019 |
| PRFC | Clark's Millpond | PRFCCM | 2000 | 2013 |
| PRFC | Gardy's Millpond | PRFCGM | 2000 | 2019 |
| VA | Wormley Creek | VAMC | 2001 | 2019 |
| VA | Bracken's Pond | VABP | 2000 | 2015 |
| VA | Kamp's Millpond | VAKM | 2000 | 2019 |
| VA | Wareham's Pond | VAWP | 2003 | 2019 |
| NC | Beaufort (BBISP) | NCBB | 1987 | 2019 |
| SC | Goose Creek | SCGC | 2000 | 2015 |
| GA | Altamaha Canal | GAAC | 2001 | 2013 |
| GA | Hudson Creek | GAHC | 2003 | 2013 |
| FL | Guana | FLG | 2001 | 2020 |

Table 12. American eel elver surveys accepted for use in this assessment.

| State | Site | Abbreviation | Start Year | End Year |
|-------|-------------------------------------|--------------|------------|----------|
| ME | Juvenile Finfish Beach Seine Survey | MEJBS | 2000 | 2019 |
| MA | Saugus River | MASR | 2007 | 2019 |
| PA | Delaware River Area 6 | PAA6 | 1999 | 2020 |
| MD | Susquehanna River - Conowingo | MDSR | 2008 | 2019 |
| PRFC | Clark's Millpond | PRFCCM | 2000 | 2013 |
| PRFC | Gardy's Millpond | PRFCGM | 2000 | 2019 |
| VA | Wormley Creek | VAWC | 2001 | 2019 |
| VA | Bracken's Pond | VABP | 2000 | 2015 |
| VA | Kamp's Millpond | VAKM | 2000 | 2019 |
| VA | Wareham's Pond | VAWP | 2003 | 2019 |

Table 13. Yellow eel surveys accepted for use in this assessment.

| State | Site | Abbreviation | Start Year | End Year |
|-------|-------------------------------------|--------------|------------|----------|
| NH | Rainbow Smelt Fyke Net Survey | NHRS | 2008 | 2020 |
| MA | Rainbow Smelt Fyke Net Survey | MARH | 2004 | 2019 |
| CT | Farmill River | CTFR | 2001 | 2014 |
| CT | Eightmile River | CTER | 2001 | 2020 |
| NY | HRE Monitoring | NYHRE | 1974 | 2017 |
| NY | Hudson Juvenile Alosine | NYHJA | 1985 | 2019 |
| NY | Hudson Juv Striped Bass | NYHSB | 1980 | 2019 |
| NJ | Delaware River Seine | NJDRS | 1998 | 2019 |
| DE | Delaware Juvenile Trawl | DEJT | 1980 | 2019 |
| PA | Delaware River Area 6 | PAA6 | 2005 | 2020 |
| MD | Sassafras River | MDS | 2006 | 2019 |
| VA | VIMS Trawl Survey | VIMST | 1955 | 2019 |
| VA | VIMS Seine Survey | VIMSS | 1967 | 2019 |
| SC | Rediversion canal (aluminum ladder) | SCRC | 2003 | 2020 |

Table 14. Spearman's rank correlation between YOY indices with correlation coefficients above the gray line and p-values below the gray line. Correlation coefficients are statistically significant at $\alpha < 0.10$ and indicated with red fill. See Table 11 for survey abbreviations.

| | MEWHP | NHLR | MAJR | MAWR | RIGSD | RIHFL | CTIH | NYHRE | NYCR | NYHR | NJLEI | NJPC | DEM | MDTC | PRFCCM | PRFCGM | VAWC | VABP | VAKM | VAWP | NCBB | SCGC | GAAC | GAHC | FLG |
|--------|-------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| MEWHP | | 0.29 | -0.39 | -0.05 | 0.15 | -0.12 | -0.19 | -0.19 | 0.59 | 0.37 | 0.11 | 0.28 | 0.17 | -0.30 | -0.16 | 0.41 | -0.48 | -0.03 | 0.28 | 0.16 | -0.15 | 0.00 | 0.24 | 0.22 | -0.24 |
| NHLR | 0.23 | | -0.26 | -0.24 | 0.41 | -0.05 | -0.43 | -0.02 | 0.41 | 0.05 | -0.18 | 0.46 | 0.09 | -0.42 | -0.06 | 0.13 | 0.20 | 0.05 | 0.24 | 0.23 | -0.35 | -0.10 | 0.37 | -0.33 | -0.32 |
| MAJR | 0.10 | 0.27 | | 0.00 | -0.42 | 0.00 | 0.17 | 0.56 | -0.48 | -0.28 | 0.62 | 0.02 | -0.27 | -0.01 | -0.42 | 0.07 | -0.02 | 0.60 | 0.09 | -0.06 | 0.07 | 0.51 | 0.46 | 0.61 | 0.50 |
| MAWR | 0.87 | 0.48 | 1.00 | | 0.15 | 0.15 | 0.40 | 0.13 | 0.17 | 0.39 | 0.43 | -0.05 | 0.39 | 0.72 | -0.10 | 0.01 | 0.05 | 0.04 | -0.31 | 0.47 | -0.26 | -0.25 | 0.20 | 0.80 | -0.20 |
| RIGSD | 0.53 | 0.09 | 0.08 | 0.65 | | 0.39 | 0.04 | -0.04 | 0.42 | -0.56 | -0.40 | 0.29 | 0.21 | 0.03 | -0.02 | 0.19 | 0.27 | 0.07 | 0.23 | 0.34 | -0.34 | -0.34 | -0.21 | 0.06 | -0.18 |
| RIHFL | 0.65 | 0.85 | 0.99 | 0.67 | 0.14 | | -0.18 | -0.27 | -0.06 | -0.13 | -0.34 | -0.27 | 0.55 | 0.30 | 0.07 | 0.20 | 0.53 | -0.17 | 0.27 | 0.22 | -0.22 | -0.08 | -0.18 | 0.13 | -0.02 |
| CTIH | 0.53 | 0.14 | 0.58 | 0.22 | 0.90 | 0.55 | | 0.74 | -0.02 | -0.02 | 0.10 | -0.25 | -0.23 | 0.29 | -0.18 | -0.28 | -0.04 | 0.37 | 0.00 | 0.03 | -0.39 | 0.13 | 0.50 | 0.07 | 0.06 |
| NYHRE | 0.46 | 0.95 | 0.02 | 0.73 | 0.89 | 0.35 | 0.01 | | 0.02 | -0.45 | 0.35 | -0.20 | -0.14 | 0.20 | -0.09 | 0.23 | -0.01 | 0.57 | 0.47 | -0.50 | 0.13 | 0.45 | 0.35 | 0.41 | 0.53 |
| NYCR | 0.01 | 0.08 | 0.04 | 0.61 | 0.07 | 0.82 | 0.94 | 0.94 | | 0.37 | 0.02 | 0.25 | -0.02 | -0.26 | 0.27 | 0.28 | -0.26 | -0.30 | 0.18 | -0.04 | -0.28 | -0.29 | -0.34 | -0.01 | -0.33 |
| NYHR | 0.29 | 0.87 | 0.43 | 0.26 | 0.09 | 0.73 | 0.96 | 0.26 | 0.29 | | 0.60 | -0.07 | -0.07 | 0.16 | 0.40 | 0.16 | -0.41 | -0.54 | -0.61 | 0.02 | 0.05 | -0.20 | -0.40 | 0.80 | 0.10 |
| NJLEI | 0.69 | 0.52 | 0.01 | 0.34 | 0.13 | 0.29 | 0.80 | 0.09 | 0.94 | 0.21 | | 0.38 | -0.07 | -0.24 | -0.07 | 0.17 | -0.29 | 0.04 | -0.06 | -0.36 | 0.17 | 0.38 | 0.18 | 0.68 | 0.18 |
| NJPC | 0.26 | 0.05 | 0.93 | 0.88 | 0.24 | 0.33 | 0.43 | 0.44 | 0.31 | 0.85 | 0.15 | | -0.08 | -0.58 | 0.16 | 0.04 | -0.27 | 0.04 | 0.02 | 0.06 | -0.13 | -0.21 | 0.10 | 0.45 | -0.16 |
| DEM | 0.49 | 0.70 | 0.26 | 0.23 | 0.37 | 0.03 | 0.45 | 0.57 | 0.92 | 0.83 | 0.79 | 0.74 | | 0.34 | 0.10 | 0.05 | 0.41 | 0.18 | 0.17 | 0.05 | -0.45 | -0.26 | 0.23 | 0.32 | -0.17 |
| MDTC | 0.21 | 0.08 | 0.97 | 0.01 | 0.91 | 0.26 | 0.34 | 0.42 | 0.27 | 0.65 | 0.37 | 0.01 | 0.14 | | -0.29 | -0.34 | 0.22 | 0.19 | 0.21 | -0.95 | 0.16 | -0.07 | -0.51 | 0.18 | -0.02 |
| PRFCCM | 0.59 | 0.84 | 0.15 | 0.87 | 0.93 | 0.85 | 0.70 | 0.77 | 0.35 | 0.60 | 0.81 | 0.59 | 0.73 | 0.31 | | -0.14 | 0.15 | -0.24 | 0.28 | -0.77 | 0.11 | 0.04 | -0.51 | 0.18 | 0.25 |
| PRFCGM | 0.08 | 0.60 | 0.78 | 0.98 | 0.42 | 0.45 | 0.35 | 0.35 | 0.24 | 0.65 | 0.53 | 0.88 | 0.83 | 0.23 | 0.60 | | -0.31 | -0.12 | 0.25 | 0.13 | 0.20 | 0.07 | -0.10 | 0.22 | 0.23 |
| VAWC | 0.04 | 0.41 | 0.93 | 0.89 | 0.27 | 0.03 | 0.90 | 0.96 | 0.29 | 0.24 | 0.30 | 0.29 | 0.09 | 0.47 | 0.57 | 0.19 | | 0.17 | 0.33 | -0.09 | -0.27 | 0.13 | 0.64 | 0.51 | 0.31 |
| VABP | 0.91 | 0.85 | 0.02 | 0.94 | 0.79 | 0.59 | 0.33 | 0.02 | 0.25 | 0.27 | 0.88 | 0.89 | 0.51 | 0.47 | 0.40 | 0.66 | 0.54 | | 0.38 | -0.08 | -0.23 | 0.13 | 0.64 | 0.51 | 0.32 |
| VAKM | 0.25 | 0.33 | 0.72 | 0.36 | 0.32 | 0.31 | 1.00 | 0.05 | 0.45 | 0.06 | 0.83 | 0.94 | 0.47 | 0.47 | 0.28 | 0.29 | 0.90 | 0.21 | | -0.35 | -0.04 | 0.25 | 0.23 | 0.24 | 0.52 |
| VAWP | 0.56 | 0.39 | 0.82 | 0.17 | 0.20 | 0.42 | 0.91 | 0.07 | 0.87 | 0.97 | 0.26 | 0.84 | 0.85 | 0.00 | 0.00 | 0.64 | 0.55 | 0.78 | 0.18 | | -0.09 | -0.22 | 0.36 | -0.22 | -0.29 |
| NCBB | 0.55 | 0.15 | 0.78 | 0.43 | 0.14 | 0.41 | 0.19 | 0.48 | 0.24 | 0.88 | 0.42 | 0.57 | 0.05 | 0.57 | 0.69 | 0.39 | 0.17 | 0.32 | 0.88 | 0.73 | | 0.38 | -0.45 | -0.10 | 0.52 |
| SCGC | 0.99 | 0.71 | 0.05 | 0.59 | 0.20 | 0.81 | 0.73 | 0.08 | 0.27 | 0.70 | 0.15 | 0.46 | 0.32 | 0.81 | 0.89 | 0.79 | 0.56 | 0.63 | 0.36 | 0.50 | 0.14 | | 0.27 | 0.45 | 0.57 |
| GAAC | 0.44 | 0.21 | 0.12 | 0.75 | 0.49 | 0.63 | 0.25 | 0.25 | 0.26 | 0.60 | 0.55 | 0.76 | 0.46 | 0.08 | 0.08 | 0.73 | 0.67 | 0.02 | 0.45 | 0.31 | 0.13 | 0.37 | | 0.27 | -0.08 |
| GAHC | 0.52 | 0.33 | 0.05 | 0.10 | 0.85 | 0.73 | 0.88 | 0.21 | 0.98 | 0.20 | 0.02 | 0.19 | 0.34 | 0.59 | 0.59 | 0.52 | 0.81 | 0.11 | 0.48 | 0.53 | 0.77 | 0.17 | 0.42 | | 0.28 |
| FLG | 0.34 | 0.19 | 0.03 | 0.58 | 0.48 | 0.95 | 0.86 | 0.04 | 0.18 | 0.78 | 0.53 | 0.54 | 0.50 | 0.95 | 0.36 | 0.36 | 0.54 | 0.27 | 0.03 | 0.30 | 0.03 | 0.03 | 0.80 | 0.43 | |

Table 15. Spearman's rank correlation between elver indices with correlation coefficients above the gray line and p-values below the gray line. Correlation coefficients are statistically significant at $\alpha < 0.10$ and indicated with red fill. See Table 12 for survey abbreviations.

| | MEJBS | MASR | PAA6 | MDSR | PRFCCM | PRFCGM | VAWC | VABP | VAKM | VAWP |
|--------|-------|-------|-------|-------|--------|--------|-------|-------|-------|-------|
| MEJBS | | -0.45 | -0.53 | -0.51 | -0.13 | -0.05 | 0.19 | -0.29 | -0.17 | 0.54 |
| MASR | 0.17 | | 0.35 | 0.03 | 0.20 | 0.14 | 0.15 | -0.36 | -0.38 | -0.13 |
| PAA6 | 0.02 | 0.29 | | 0.26 | 0.28 | -0.05 | -0.06 | 0.33 | -0.13 | -0.03 |
| MDSR | 0.09 | 0.94 | 0.41 | | -0.09 | 0.52 | 0.02 | 0.40 | 0.30 | 0.15 |
| PRFCCM | 0.65 | 0.75 | 0.34 | 0.87 | | 0.41 | 0.21 | -0.27 | 0.62 | -0.43 |
| PRFCGM | 0.85 | 0.69 | 0.82 | 0.08 | 0.14 | | -0.19 | -0.29 | 0.24 | 0.16 |
| VAWC | 0.44 | 0.67 | 0.81 | 0.95 | 0.49 | 0.44 | | 0.19 | 0.16 | 0.18 |
| VABP | 0.28 | 0.43 | 0.22 | 0.32 | 0.34 | 0.28 | 0.51 | | -0.19 | 0.19 |
| VAKM | 0.47 | 0.25 | 0.59 | 0.34 | 0.02 | 0.30 | 0.50 | 0.49 | | -0.20 |
| VAWP | 0.03 | 0.73 | 0.90 | 0.65 | 0.21 | 0.54 | 0.51 | 0.56 | 0.45 | |

Table 16. Spearman's rank correlation between yellow eel indices with correlation coefficients above the gray line and p-values below the gray line. Correlation coefficients are statistically significant at $\alpha < 0.10$ and indicated with red fill. See Table 13 for survey abbreviations.

| | NHRS | MARS | CTFR | CTER | NYHRE | NYHJA | NYHSB | NJDRS | DEJT | PAA6 | MDS | VIMST | VIMSS | SCRC |
|-------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| NHRS | | 0.17 | -0.26 | -0.18 | 0.26 | 0.29 | 0.48 | -0.22 | -0.24 | 0.54 | -0.44 | 0.19 | -0.10 | 0.17 |
| MARS | 0.60 | | -0.01 | 0.15 | -0.35 | 0.20 | -0.06 | 0.16 | 0.07 | -0.05 | -0.56 | 0.06 | -0.15 | -0.20 |
| CTFR | 0.62 | 0.99 | | 0.50 | 0.68 | -0.02 | 0.19 | -0.07 | 0.21 | -0.12 | 0.29 | -0.37 | 0.02 | 0.63 |
| CTER | 0.60 | 0.60 | 0.10 | | 0.03 | 0.17 | -0.35 | -0.04 | -0.33 | -0.15 | -0.51 | -0.49 | 0.07 | -0.28 |
| NYHRE | 0.47 | 0.23 | 0.01 | 0.93 | | 0.17 | 0.59 | -0.27 | -0.22 | -0.05 | 0.75 | 0.47 | -0.36 | 0.58 |
| NYHJA | 0.35 | 0.46 | 0.96 | 0.52 | 0.35 | | 0.27 | 0.45 | -0.25 | 0.12 | -0.55 | 0.52 | -0.27 | -0.27 |
| NYHSB | 0.12 | 0.81 | 0.53 | 0.17 | 0.00 | 0.11 | | 0.09 | 0.12 | 0.30 | 0.23 | 0.61 | -0.13 | 0.14 |
| NJDRS | 0.50 | 0.56 | 0.83 | 0.87 | 0.25 | 0.03 | 0.68 | | 0.32 | 0.06 | -0.21 | 0.23 | -0.32 | -0.22 |
| DEJT | 0.46 | 0.79 | 0.49 | 0.19 | 0.19 | 0.14 | 0.47 | 0.15 | | 0.28 | 0.21 | -0.02 | 0.20 | -0.24 |
| PAA6 | 0.06 | 0.86 | 0.77 | 0.61 | 0.86 | 0.66 | 0.27 | 0.83 | 0.31 | | -0.20 | 0.56 | 0.00 | 0.16 |
| MDS | 0.15 | 0.04 | 0.49 | 0.07 | 0.01 | 0.04 | 0.43 | 0.46 | 0.47 | 0.49 | | 0.07 | 0.03 | 0.46 |
| VIMST | 0.56 | 0.83 | 0.21 | 0.05 | 0.00 | 0.00 | 0.00 | 0.29 | 0.89 | 0.03 | 0.82 | | 0.04 | 0.35 |
| VIMSS | 0.76 | 0.59 | 0.94 | 0.80 | 0.03 | 0.12 | 0.44 | 0.15 | 0.24 | 0.99 | 0.92 | 0.79 | | 0.15 |
| SCRC | 0.60 | 0.50 | 0.07 | 0.34 | 0.04 | 0.33 | 0.63 | 0.44 | 0.38 | 0.57 | 0.12 | 0.21 | 0.58 | |

Table 17. Estimate population growth rates from Multivariate Auto-Regressive State-Space (MARSS) models fit to time series of relative abundance indices for American eels life stages along the Atlantic coast.

| Life stage | Years | Number of surveys included | Growth Rate (95% CI) |
|-------------------|--------------|-----------------------------------|-----------------------------|
| Yellow | 1974 – 2020 | 14 | -0.023 (-0.058, 0.012) |
| Elver | 1999 – 2020 | 10 | 0.007 (-0.014, 0.027) |
| YOY | 1987 – 2020 | 25 | -0.010 (-0.042, 0.022) |

Table 18. YOY, elver, and yellow eel indices and CVs developed with the Conn (2010) method.

| Year | YOY | | Elver | | Yellow | |
|------|-------|------|-------|----|--------|------|
| | Index | CV | Index | CV | Index | CV |
| 1955 | | | | | 1.53 | 1.00 |
| 1956 | | | | | 0.99 | 0.91 |
| 1957 | | | | | 0.60 | 0.96 |
| 1958 | | | | | 0.91 | 0.90 |
| 1959 | | | | | 0.67 | 0.90 |
| 1960 | | | | | 0.57 | 0.93 |
| 1961 | | | | | 0.83 | 0.90 |
| 1962 | | | | | 0.61 | 0.91 |
| 1963 | | | | | 0.53 | 0.88 |
| 1964 | | | | | 0.43 | 0.92 |
| 1965 | | | | | 0.42 | 0.92 |
| 1966 | | | | | 0.66 | 0.88 |
| 1967 | | | | | 0.63 | 0.63 |
| 1968 | | | | | 2.09 | 0.53 |
| 1969 | | | | | 1.19 | 0.85 |
| 1970 | | | | | 0.42 | 0.64 |
| 1971 | | | | | 1.03 | 0.57 |
| 1972 | | | | | 0.43 | 0.64 |
| 1973 | | | | | 1.33 | 0.86 |
| 1974 | | | | | 1.56 | 0.32 |
| 1975 | | | | | 1.68 | 0.32 |
| 1976 | | | | | 1.67 | 0.32 |
| 1977 | | | | | 1.27 | 0.32 |
| 1978 | | | | | 0.89 | 0.33 |
| 1979 | | | | | 1.00 | 0.35 |
| 1980 | | | | | 0.97 | 0.27 |
| 1981 | | | | | 2.11 | 0.26 |
| 1982 | | | | | 2.13 | 0.26 |
| 1983 | | | | | 2.21 | 0.27 |
| 1984 | | | | | 2.35 | 0.26 |
| 1985 | | | | | 1.76 | 0.24 |
| 1986 | | | | | 1.69 | 0.24 |
| 1987 | 0.91 | 0.65 | | | 1.53 | 0.25 |

| Year | YOY | | Elver | | Yellow | |
|------|-------|------|-------|------|--------|------|
| | Index | CV | Index | CV | Index | CV |
| 1988 | 1.21 | 0.65 | | | 1.41 | 0.24 |
| 1989 | 1.65 | 0.65 | | | 1.10 | 0.23 |
| 1990 | 0.86 | 0.64 | | | 1.07 | 0.23 |
| 1991 | 0.60 | 0.70 | | | 0.97 | 0.23 |
| 1992 | 1.08 | 0.38 | | | 1.06 | 0.23 |
| 1993 | 1.31 | 0.38 | | | 0.70 | 0.23 |
| 1994 | 1.83 | 0.38 | | | 0.87 | 0.23 |
| 1995 | 1.50 | 0.38 | | | 0.92 | 0.23 |
| 1996 | 0.92 | 0.39 | | | 1.12 | 0.23 |
| 1997 | 0.93 | 0.39 | | | 1.00 | 0.26 |
| 1998 | 1.81 | 0.41 | | | 0.78 | 0.23 |
| 1999 | 0.73 | 0.38 | | | 0.93 | 0.23 |
| 2000 | 1.08 | 0.30 | 0.43 | 0.43 | 0.72 | 0.23 |
| 2001 | 1.61 | 0.27 | 1.47 | 0.36 | 0.78 | 0.18 |
| 2002 | 1.22 | 0.27 | 1.04 | 0.33 | 0.68 | 0.19 |
| 2003 | 0.88 | 0.25 | 1.06 | 0.34 | 0.61 | 0.18 |
| 2004 | 0.64 | 0.24 | 1.23 | 0.31 | 0.98 | 0.19 |
| 2005 | 1.12 | 0.25 | 0.77 | 0.31 | 0.67 | 0.18 |
| 2006 | 0.65 | 0.26 | 1.01 | 0.30 | 0.68 | 0.17 |
| 2007 | 0.90 | 0.24 | 1.02 | 0.37 | 0.68 | 0.17 |
| 2008 | 0.73 | 0.24 | 1.30 | 0.31 | 0.82 | 0.17 |
| 2009 | 0.57 | 0.24 | 0.61 | 0.30 | 0.92 | 0.16 |
| 2010 | 0.56 | 0.24 | 0.88 | 0.30 | 0.89 | 0.16 |
| 2011 | 0.60 | 0.24 | 0.81 | 0.29 | 0.85 | 0.16 |
| 2012 | 0.80 | 0.24 | 0.73 | 0.29 | 0.78 | 0.17 |
| 2013 | 0.99 | 0.24 | 1.17 | 0.31 | 0.90 | 0.17 |
| 2014 | 0.85 | 0.24 | 1.37 | 0.31 | 0.73 | 0.17 |
| 2015 | 0.83 | 0.24 | 1.11 | 0.31 | 0.82 | 0.17 |
| 2016 | 0.58 | 0.27 | 1.09 | 0.34 | 0.62 | 0.18 |
| 2017 | 0.71 | 0.26 | 0.92 | 0.31 | 0.73 | 0.18 |
| 2018 | 1.04 | 0.26 | 0.92 | 0.32 | 0.50 | 0.21 |
| 2019 | 0.81 | 0.29 | 1.06 | 0.35 | 0.68 | 0.19 |
| 2020 | 1.50 | 0.51 | | | 0.33 | 0.39 |

Table 19. Results of power analysis conducted on fishery-independent surveys of American eel along the Atlantic coast. Values of statistical power were calculated for linear and exponential trends of $\pm 50\%$ change over a 10-year period. Table continues on next several pages.

| State | Survey/Site | Life stage | Median CV | Linear+50 % | Linear-50% | Exponential+50 % | Exponential-50% |
|-------|-----------------------|------------|-----------|-------------|------------|------------------|-----------------|
| MA | Saugus River | Elver | 0.2181 | 0.60 | 0.79 | 0.60 | 0.80 |
| ME | ME Beach Seine | Elver | 0.3050 | 0.39 | 0.54 | 0.40 | 0.56 |
| PA | Delaware River Area 6 | Elver | 0.2018 | 0.65 | 0.84 | 0.66 | 0.85 |
| PA | Susquehanna River | Elver | 0.2233 | 0.58 | 0.77 | 0.59 | 0.78 |
| VA | Bracken's Pond | Elver | 0.2213 | 0.59 | 0.78 | 0.60 | 0.79 |
| VA | Clark's Millpond | Elver | 0.2190 | 0.59 | 0.78 | 0.60 | 0.79 |
| VA | Gardy's Millpond | Elver | 0.1870 | 0.71 | 0.88 | 0.72 | 0.89 |
| VA | Kamp's Millpond | Elver | 0.2327 | 0.55 | 0.74 | 0.56 | 0.75 |
| VA | Wareham's Pond | Elver | 0.2272 | 0.57 | 0.76 | 0.57 | 0.77 |
| VA | Wormley Creek | Elver | 0.2040 | 0.65 | 0.83 | 0.65 | 0.84 |
| SC | Patcong Creek | Mix | 0.3931 | 0.28 | 0.39 | 0.29 | 0.41 |
| MA | MA Rainbow Smelt | Yellow | 0.2483 | 0.51 | 0.69 | 0.51 | 0.71 |
| NH | NH Rainbow Smelt | Yellow | 0.0763 | 1.00 | 1.00 | 1.00 | 1.00 |
| CT | Eightmile River | Yellow | 0.0638 | 1.00 | 1.00 | 1.00 | 1.00 |
| CT | Farmill River | Yellow | 0.0433 | 1.00 | 1.00 | 1.00 | 1.00 |

| | | | | | | | |
|----|---------------------------------|--------|--------|------|------|------|------|
| NY | Alosine Beach Seine | Yellow | 0.2414 | 0.53 | 0.71 | 0.53 | 0.73 |
| NY | HRE Monitoring | Yellow | 0.0792 | 1.00 | 1.00 | 1.00 | 1.00 |
| NY | Striped Bass Beach Seine | Yellow | 0.2746 | 0.44 | 0.62 | 0.45 | 0.63 |
| DE | Delaware River Seine | Yellow | 0.4620 | 0.23 | 0.31 | 0.24 | 0.34 |
| DE | Delaware River Trawl | Yellow | 0.0113 | 1.00 | 1.00 | 1.00 | 1.00 |
| PA | Delaware River Area 6 | Yellow | 0.2318 | 0.55 | 0.74 | 0.56 | 0.75 |
| MD | South Atl.sSouth Atl.fras River | Yellow | 0.0939 | 1.00 | 1.00 | 1.00 | 1.00 |
| VA | VIMMS Seine (Short) | Yellow | 0.3079 | 0.38 | 0.53 | 0.39 | 0.56 |
| VA | VIMS Seine | Yellow | 0.4603 | 0.23 | 0.31 | 0.24 | 0.34 |
| VA | VIMS Trawl | Yellow | 0.2846 | 0.42 | 0.59 | 0.43 | 0.61 |
| VA | VIMS Trawl (Short) | Yellow | 0.2179 | 0.60 | 0.79 | 0.60 | 0.80 |
| MA | Wankinco River | YOY | 0.2751 | 0.44 | 0.61 | 0.45 | 0.63 |
| ME | West Harbor Pond | YOY | 0.4189 | 0.26 | 0.36 | 0.27 | 0.38 |
| NH | Jones River | YOY | 0.3650 | 0.30 | 0.43 | 0.31 | 0.45 |
| NH | Lamprey River | YOY | 0.3354 | 0.34 | 0.48 | 0.35 | 0.50 |
| CT | Ingam Hill | YOY | 0.1861 | 0.72 | 0.89 | 0.72 | 0.89 |
| NY | Carman's River | YOY | 0.1827 | 0.73 | 0.90 | 0.73 | 0.90 |
| RI | Gilbert Stuart Dam | YOY | 0.2179 | 0.60 | 0.79 | 0.60 | 0.80 |

| | | | | | | | |
|------|----------------------|-------|--------|------|------|------|------|
| RI | Hamiton Fish Ladder | YOY | 0.1978 | 0.67 | 0.85 | 0.67 | 0.86 |
| NY | HRE Monitoring | YOY | 0.1817 | 0.73 | 0.90 | 0.74 | 0.90 |
| NY | Hudson R.son River | YOY | 0.1064 | 0.99 | 1.00 | 0.99 | 1.00 |
| DE | Millsboro River | YOY | 0.2786 | 0.44 | 0.60 | 0.44 | 0.62 |
| NJ | Little Egg Inlet | YOY | 0.1683 | 0.79 | 0.93 | 0.79 | 0.94 |
| NJ | Patcong Creek | YOY | 0.2586 | 0.48 | 0.66 | 0.49 | 0.68 |
| MD | Turville Creek | YOY | 0.2261 | 0.57 | 0.76 | 0.58 | 0.77 |
| PRFC | Clark's Millpond | YOY | 0.2793 | 0.43 | 0.60 | 0.44 | 0.62 |
| PRFC | Gardy's Millpond | YOY | 0.2825 | 0.43 | 0.59 | 0.44 | 0.61 |
| VA | Bracken's Pond | YOY | 0.2325 | 0.55 | 0.74 | 0.56 | 0.75 |
| VA | Kamp's Millpond | YOY | 0.2774 | 0.44 | 0.61 | 0.45 | 0.63 |
| VA | Wareham's Pond | YOY | 0.2614 | 0.47 | 0.65 | 0.48 | 0.67 |
| VA | Wormley Creek | YOY | 0.2693 | 0.46 | 0.63 | 0.46 | 0.65 |
| FL | Guana River | YOY | 0.2560 | 0.49 | 0.67 | 0.50 | 0.68 |
| GA | Altamaha Canal | YOY | 0.3447 | 0.33 | 0.46 | 0.34 | 0.49 |
| GA | Hudson R.son Creek | YOY | 0.4805 | 0.22 | 0.30 | 0.23 | 0.33 |
| NC | Beufort (BBISP) | YOY | 0.2382 | 0.53 | 0.72 | 0.54 | 0.73 |
| SC | Gilbert Stuart Dam | YOY | 0.2030 | 0.65 | 0.83 | 0.66 | 0.84 |
| MA | South Atl.ugus River | Elver | 0.2181 | 0.60 | 0.79 | 0.60 | 0.80 |

Table 20. Results of the Mann-Kendall trend analysis applied to YOY indices. *P*-value is the two-tailed probability for the trend test and trend indicates the direction of the trend if a statistically significant temporal trend was detected (P -value < α ; $\alpha = 0.05$). NS = not significant.

| State | Site | Gear | n | tau | <i>P</i> -value | Trend |
|-------|----------------------|----------------------------------|----|--------|-----------------|-------|
| ME | West Harbor Pond | Irish Elver Ramp | 19 | 0.35 | 0.042 | ↑ |
| NH | Lamprey River | Irish Elver Ramp | 20 | 0.13 | 0.46 | NS |
| MA | Jones River | Sheldon Trap | 19 | -0.51 | 0.0026 | ↓ |
| MA | Wankinco River | Ramp | 11 | 0.35 | 0.16 | NS |
| RI | Gilbert Stuart Dam | Irish Elver Ramp | 20 | 0.15 | 0.38 | NS |
| RI | Hamilton Fish Ladder | Irish Elver Ramp | 16 | 0.067 | 0.75 | NS |
| CT | Ingham Hill | Irish Elver Ramp | 13 | 0.026 | 0.95 | NS |
| NY | Carmans River | Fyke Net | 20 | 0.18 | 0.28 | NS |
| NY | HRE Monitoring | Epibenthic sled and tucker trawl | 44 | -0.087 | 0.41 | NS |
| NY | Hudson River | Fyke Net | 11 | 0.78 | 0.0011 | ↑ |
| NJ | Little Egg Inlet | Plankton net | 24 | -0.36 | 0.016 | ↓ |
| NJ | Patcong Creek | Fyke Net | 21 | 0.21 | 0.19 | NS |
| DE | Millsboro River | Fyke Net | 21 | 0.12 | 0.45 | NS |
| MD | Turville Creek | Irish Elver Ramp | 20 | -0.084 | 0.63 | NS |
| PRFC | Clark's Millpond | Irish Elver Ramp | 14 | 0.14 | 0.51 | NS |
| PRFC | Gardy's Millpond | Irish Elver Ramp | 20 | -0.19 | 0.26 | NS |
| VA | Bracken's Pond | Irish Elver Ramp | 16 | -0.25 | 0.19 | NS |
| VA | Kamp's Millpond | Irish Elver Ramp | 20 | -0.22 | 0.18 | NS |
| VA | Wareham's Pond | Irish Elver Ramp | 16 | 0.33 | 0.079 | NS |
| VA | Wormley Creek | Irish Elver Ramp | 19 | -0.076 | 0.67 | NS |
| NC | Beaufort (BBISP) | Neuston plankton net | 33 | -0.13 | 0.31 | NS |
| SC | Goose Creek | Fyke Net | 16 | -0.43 | 0.022 | ↓ |
| GA | Altamaha Canal | Fyke Net | 13 | -0.21 | 0.36 | NS |
| GA | Hudson Creek | Fyke Net | 11 | -0.13 | 0.64 | NS |
| FL | Guana | Dip Net | 19 | -0.39 | 0.021 | ↓ |

Table 21. Results of the Mann-Kendall trend analysis applied to elver indices. *P*-value is the two-tailed probability for the trend test and trend indicates the direction of the trend if a statistically significant temporal trend was detected (*P*-value < α ; α = 0.05). NS = not significant.

| State | Site | Gear | n | tau | <i>P</i> -value | Trend |
|-------|-----------------------|----------------------|----|-------|-----------------|-------|
| ME | Beach Seine Survey | Beach Seine | 20 | 0.18 | 0.28 | NS |
| MA | Saugus Ramp | Ramp | 11 | -0.45 | 0.06 | NS |
| PA | Delaware River Area 6 | Electrofishing | 22 | -0.24 | 0.13 | NS |
| PA | Susquehanna River | Conowingo Elver Ramp | 12 | 0.061 | 0.84 | NS |
| PRFC | Clark's Millpond | Irish Elver Ramp | 14 | -0.16 | 0.44 | NS |
| PRFC | Gardy's Millpond | Irish Elver Ramp | 20 | 0.23 | 0.16 | NS |
| VA | Bracken's Pond | Irish Elver Ramp | 16 | 0.02 | 0.96 | NS |
| VA | Kamp's Millpond | Irish Elver Ramp | 20 | 0.053 | 0.77 | NS |
| VA | Wareham's Pond | Irish Elver Ramp | 16 | 0.4 | 0.034 | ↑ |
| VA | Wormley Creek | Irish Elver Ramp | 19 | -0.37 | 0.03 | ↓ |

Table 22. Results of the Mann-Kendall trend analysis applied to yellow eel indices. *P*-value is the two-tailed probability for the trend test and trend indicates the direction of the trend if a statistically significant temporal trend was detected (*P*-value < α ; $\alpha = 0.05$). NS = not significant.

| State | Site | Gear | n | tau | <i>P</i> -value | Trend |
|-------|--------------------------------------|----------------------------------|----|--------|-----------------|-------|
| NH | Rainbow Smelt Fyke Net Survey | Fyke Net | 11 | 0.018 | 1.0 | NS |
| MA | Rainbow Smelt Fyke Net Survey | Fyke Net | 16 | -0.17 | 0.39 | NS |
| CT | Eightmile River | Electrofishing | 17 | 0.030 | 0.90 | NS |
| CT | Farmill River | Electrofishing | 13 | 0.28 | 0.20 | NS |
| NY | HRE Monitoring Yellow | Epibenthic sled and tucker trawl | 44 | -0.29 | 0.0054 | ↓ |
| NY | Hudson Juvenile Alosine | Beach Seine | 35 | -0.43 | <0.001 | ↓ |
| NY | Hudson Juvenile Striped Bass | Beach Seine | 40 | -0.44 | <0.001 | ↓ |
| NJ | Delaware River | Seine | 22 | -0.29 | 0.063 | NS |
| DE | Delaware River Juvenile Trawl Survey | Trawl | 40 | 0 | 1.0 | NS |
| PA | Delaware River Area 6 | Electrofishing | 16 | -0.39 | 0.038 | ↓ |
| MD | Sassafras | Pot | 14 | 0.71 | <0.001 | ↑ |
| VA | VIMS Seine | Seine | 47 | 0.21 | 0.042 | ↑ |
| VA | VIMS Seine (Short) | Seine | 31 | 0.15 | 0.25 | NS |
| VA | VIMS Trawl | Trawl | 65 | -0.045 | 0.60 | NS |
| VA | VIMS Trawl (Short) | Trawl | 24 | -0.51 | <0.001 | ↓ |
| SC | Rediversion Canal | Aluminum ladder | 16 | 0.191 | 0.303 | NS |

Table 23. Traffic light representation of the two composite index methods for YOY and yellow eel indices and commercial mean lengths.

| Year | Conn Yellow | Conn YOY | MARSS Yellow | MARSS YOY | Mean Comm Length |
|------|-------------|----------|--------------|-----------|------------------|
| 1955 | 1.531 | | | | |
| 1956 | 0.989 | | | | |
| 1957 | 0.598 | | | | |
| 1958 | 0.912 | | | | |
| 1959 | 0.673 | | | | |
| 1960 | 0.569 | | | | |
| 1961 | 0.831 | | | | |
| 1962 | 0.612 | | | | |
| 1963 | 0.532 | | | | |
| 1964 | 0.429 | | | | |
| 1965 | 0.421 | | | | |
| 1966 | 0.659 | | | | |
| 1967 | 0.626 | | | | |
| 1968 | 2.090 | | | | |
| 1969 | 1.194 | | | | |
| 1970 | 0.419 | | | | |
| 1971 | 1.031 | | | | |
| 1972 | 0.433 | | | | |
| 1973 | 1.329 | | | | |
| 1974 | 1.555 | | 0.926 | | |
| 1975 | 1.683 | | 0.904 | | |
| 1976 | 1.670 | | 0.864 | | |
| 1977 | 1.269 | | 0.806 | | |
| 1978 | 0.887 | | 0.759 | | |
| 1979 | 0.995 | | 0.757 | | |
| 1980 | 0.971 | | 0.804 | | |
| 1981 | 2.107 | | 0.931 | | |
| 1982 | 2.125 | | 1.013 | | |
| 1983 | 2.215 | | 1.038 | | |
| 1984 | 2.353 | | 1.037 | | |
| 1985 | 1.760 | | 0.973 | | |
| 1986 | 1.686 | | 0.900 | | |
| 1987 | 1.534 | 0.906 | 0.807 | 298.62 | |
| 1988 | 1.409 | 1.213 | 0.718 | 296.94 | |
| 1989 | 1.104 | 1.649 | 0.626 | 295.53 | 446 |
| 1990 | 1.066 | 0.861 | 0.569 | 292.70 | 355 |
| 1991 | 0.968 | 0.596 | 0.534 | 291.77 | 461 |
| 1992 | 1.063 | 1.080 | 0.518 | 295.19 | 413 |
| 1993 | 0.703 | 1.306 | 0.486 | 300.93 | 579 |
| 1994 | 0.866 | 1.829 | 0.500 | 305.14 | 504 |
| 1995 | 0.915 | 1.498 | 0.527 | 300.87 | |
| 1996 | 1.123 | 0.917 | 0.548 | 292.44 | 665 |
| 1997 | 1.003 | 0.933 | 0.523 | 288.14 | 386 |
| 1998 | 0.784 | 1.812 | 0.496 | 287.22 | 367 |
| 1999 | 0.927 | 0.732 | 0.483 | 279.24 | 379 |
| 2000 | 0.723 | 1.077 | 0.447 | 278.74 | 336 |
| 2001 | 0.777 | 1.613 | 0.429 | 278.92 | 418 |
| 2002 | 0.681 | 1.218 | 0.388 | 263.76 | 431 |
| 2003 | 0.607 | 0.879 | 0.378 | 244.84 | 397 |
| 2004 | 0.982 | 0.638 | 0.436 | 228.84 | 326 |
| 2005 | 0.666 | 1.123 | 0.415 | 225.16 | 345 |
| 2006 | 0.680 | 0.650 | 0.422 | 212.56 | 356 |
| 2007 | 0.678 | 0.900 | 0.445 | 206.83 | 380 |
| 2008 | 0.817 | 0.732 | 0.503 | 195.69 | 319 |
| 2009 | 0.923 | 0.567 | 0.521 | 183.97 | 347 |
| 2010 | 0.886 | 0.560 | 0.514 | 178.95 | 367 |
| 2011 | 0.854 | 0.599 | 0.480 | 183.02 | 410 |
| 2012 | 0.781 | 0.804 | 0.470 | 191.60 | 366 |
| 2013 | 0.898 | 0.989 | 0.479 | 198.29 | 447 |
| 2014 | 0.733 | 0.855 | 0.452 | 197.12 | 340 |
| 2015 | 0.825 | 0.828 | 0.442 | 194.13 | 371 |
| 2016 | 0.625 | 0.581 | 0.408 | 190.37 | 367 |
| 2017 | 0.731 | 0.709 | 0.397 | 194.52 | 419 |
| 2018 | 0.503 | 1.036 | 0.361 | 202.07 | 397 |
| 2019 | 0.681 | 0.811 | 0.361 | 203.27 | 417 |
| 2020 | 0.330 | 1.496 | 0.323 | 203.75 | |

Table 24. Parameters used in the American eel egg-per-recruit model. Separate models were developed for eels occupying estuarine and inland waters.

| Parameter | Value/Equation | Source |
|-----------------------------------|---|---|
| Age of recruits | 0 | |
| Length of recruits | 55 mm | Typical glass eel size (ASMFC 2012) |
| Growth rate (estuary) | 72.5 mm/year (range: 65 – 80) | Fenske et al. 2010 |
| Growth rate (inland) | 38.5 mm/ year (range: 34 – 43) | Morrison and Secor 2003; Goodwin 1999 |
| Glass eel natural mortality | 3.91 | Assumed to correspond to survival = 2% |
| Age-specific natural mortality | $M_i = 0.492 \cdot W_i^{-2.88}$ ($\pm 10\%$) | ASMFC 2012 |
| Ratio of estuary to inland M | 2.0 (range: 1.0 – 3.0) | Assumed |
| Fecundity | $\theta_i = (308.32 \cdot L_i^{2.293} + 18.20 \cdot L_i^{2.964})/2$ | Tremblay 2009; Barbin and McCleave 1997 |
| Maturity schedule (estuary) | $\rho_i = 1/[1 + e^{-(-10.43+0.02 \cdot L_i)}]$ | ASMFC 2012 |
| Maturity schedule (inland) | $\rho_i = 1/[1 + e^{-(-13.83+0.02 \cdot L_i)}]$ | Eyler (Shanandoah River, unpublished data) |
| Weight-length relationship | $W_i = 0.00000034 \cdot L^{3.27}$ | ASMFC 2012 |
| Fishery Recruitment (yellow eels) | $R_i = 1.0$ if length ≥ 228.6 mm, else $R_i = 0.0$ | 9 inch (228.6 mm) minimum length limit on yellow eels |

Table 25. Parameter estimates from the surplus production model using the MARSS or Conn coastwide index and commercial yellow eel landings.

| Parameter | MARSS | Conn |
|--------------------|--------------|-------------|
| K | 74,770,000 | 34,140,000 |
| r | 0.012 | 1.757 |
| q | 1.01E-08 | 2.70E-08 |
| B_1 | 105,000,000 | 98,540,000 |
| B_1/K | 1.405 | 2.886 |
| MSY | 230,000 | 15,000,000 |
| B_{MSY} | 37,380,000 | 17,070,000 |
| B_{2020}/B_{MSY} | 0.99 | 1.99 |
| F_{2020}/F_{MSY} | 0.96 | 0.01 |

Table 26. Index-based methods used NEFSC (2020, Table 2.2) showing equations and details for each method.

| Method | Details |
|-----------------------|--|
| Plan B smooth (PlanB) | $C_{targ,y+1:y+2} = \bar{C}_{3,y}(e^\lambda),$ <p>Where $\bar{C}_{3,y}$ is the most recent three year average</p> $\bar{C}_{3,y} = \frac{1}{3} \sum_{t=1}^{t=3} C_{y-t},$ <p>and λ is the slope of a log linear regression of a LOESS-smoothed average index of abundance (spring and fall) with span = 0.3:</p> $\hat{I}_y = LOESS(\bar{I}_y), \text{ and } LN(\hat{I}_y) = b + \lambda y$ |
| Islope (Islope) | $C_{targ,y+1:y+2} = 0.8\bar{C}_{5,y}(1 + 0.4e^\lambda),$ where $\bar{C}_{5,y}$ is the most recent five-year average catch through year $y-1$: $\bar{C}_{5,y} = \frac{1}{5} \sum_{t=1}^{t=5} C_{y-t},$ <p>and λ is the slope of a log-linear regression of the most recent five years of the averaged index:</p> $LN(\bar{I}_y) = b + \lambda y$ |
| Itarget (Itarget) | $C_{targ,y+1:y+2} = \left[0.5C_{ref} \left(\frac{\bar{I}_{5,y} - I_{thresh}}{I_{target} - I_{thresh}} \right) \right] \quad \bar{I}_{5,y} \geq I_{thresh}$ $C_{targ,y+1:y+2} = \left[0.5C_{ref} \left(\frac{\bar{I}_{5,y}}{I_{thresh}} \right)^2 \right] \quad \bar{I}_{5,y} < I_{thresh}$ <p>C_{ref} is the average catch over the reference period (years 26 through 50):</p> $C_{ref} = \frac{1}{25} \sum_{y=26}^{y=50} C_y,$ <p>Itarget is 1.5 times the average index over the reference period:</p> $I_{target} = 1.5 \left(\frac{1}{25} \sum_{y=26}^{y=50} \bar{I}_y \right),$ <p>$I_{thresh} = 0.8 I_{target}$, and $\bar{I}_{5,y}$ is the most recent five year average of the combined</p> |

Table 26. *Continued.*

| | |
|--------------------------|--|
| <p>Skate (Skate)</p> | <p>$C_{\text{target},y+1:y+2} = F_{\text{rel}}\bar{I}_{3,y}$, where</p> $F_{\text{rel}} = \text{median} \left(\frac{\bar{C}_{3,Y}}{\bar{I}_{3,Y}} \right)$ <p>is the median relative fishing mortality rate calculated using a 3 year moving average of the catch and average survey index across all available years (Y):</p> $\bar{C}_{3,y} = \frac{1}{3} \sum_{t=1}^{t=3} C_{y-t}$ $\bar{I}_{3,y} = \frac{1}{3} \sum_{t=1}^{t=3} I_{y-t+1}$ |
|--------------------------|--|

Table 27. Coastwide removals (landings in lbs) and recommended removals by year under three assumptions of $I_{TARG\ MULT}$ Low = 1.0 (least conservative) Base =1.25, and High = 1.5 (most conservative).

| Year | Landings | Recommended removals (lbs.) | | |
|------|-----------|-----------------------------|--------------|---------------|
| | | Base | Low multiple | High multiple |
| 1990 | 1,549,164 | 675,391 | 1,055,298 | 469,021 |
| 1991 | 1,714,400 | 551,294 | 861,397 | 382,843 |
| 1992 | 1,439,688 | 484,406 | 756,884 | 336,393 |
| 1993 | 1,596,202 | 436,311 | 681,736 | 302,994 |
| 1994 | 1,586,665 | 417,655 | 652,586 | 290,038 |
| 1995 | 1,339,690 | 422,567 | 660,261 | 293,449 |
| 1996 | 1,600,445 | 457,967 | 715,573 | 318,033 |
| 1997 | 828,071 | 471,154 | 736,178 | 327,190 |
| 1998 | 992,741 | 453,191 | 708,110 | 314,716 |
| 1999 | 1,011,093 | 416,117 | 650,183 | 288,970 |
| 2000 | 894,577 | 375,333 | 586,458 | 260,648 |
| 2001 | 929,523 | 340,892 | 532,644 | 236,730 |
| 2002 | 717,698 | 295,221 | 461,283 | 205,015 |
| 2003 | 1,082,614 | 263,671 | 411,987 | 183,105 |
| 2004 | 974,508 | 266,817 | 416,902 | 185,290 |
| 2005 | 946,694 | 278,604 | 435,320 | 193,475 |
| 2006 | 907,007 | 298,977 | 467,152 | 207,623 |
| 2007 | 897,943 | 303,064 | 473,537 | 210,461 |
| 2008 | 841,065 | 346,381 | 541,220 | 240,542 |
| 2009 | 784,577 | 398,130 | 622,078 | 276,479 |
| 2010 | 987,290 | 436,544 | 682,100 | 303,155 |
| 2011 | 1,190,764 | 423,604 | 661,881 | 294,169 |
| 2012 | 1,099,214 | 395,865 | 618,540 | 274,907 |
| 2013 | 999,072 | 377,320 | 589,562 | 262,028 |
| 2014 | 1,060,725 | 362,820 | 566,906 | 251,958 |
| 2015 | 868,663 | 348,098 | 543,903 | 241,735 |
| 2016 | 946,110 | 313,154 | 489,303 | 217,468 |
| 2017 | 864,360 | 287,012 | 448,456 | 199,314 |
| 2018 | 776,131 | 251,177 | 392,464 | 174,428 |
| 2019 | 539,301 | 231,202 | 361,253 | 160,557 |
| 2020 | 218,005 | 201,516 | 314,869 | 139,942 |

13 FIGURES

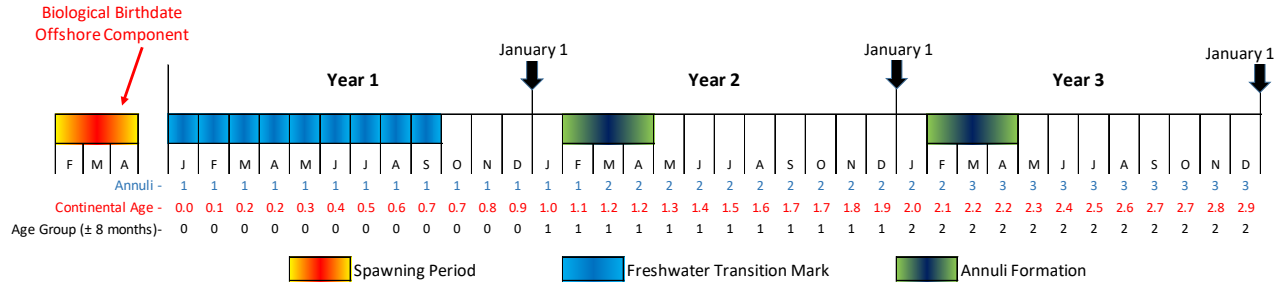


Figure 1. Proposed ageing timeline for American eel as developed for the Gulf and Atlantic States Marine Fisheries Commissions joint ageing manual which is currently in preparation. As noted in the draft manual, further work is needed to identify the annuli deposition period, but deposition likely occurs when water temperatures reach 10° C.

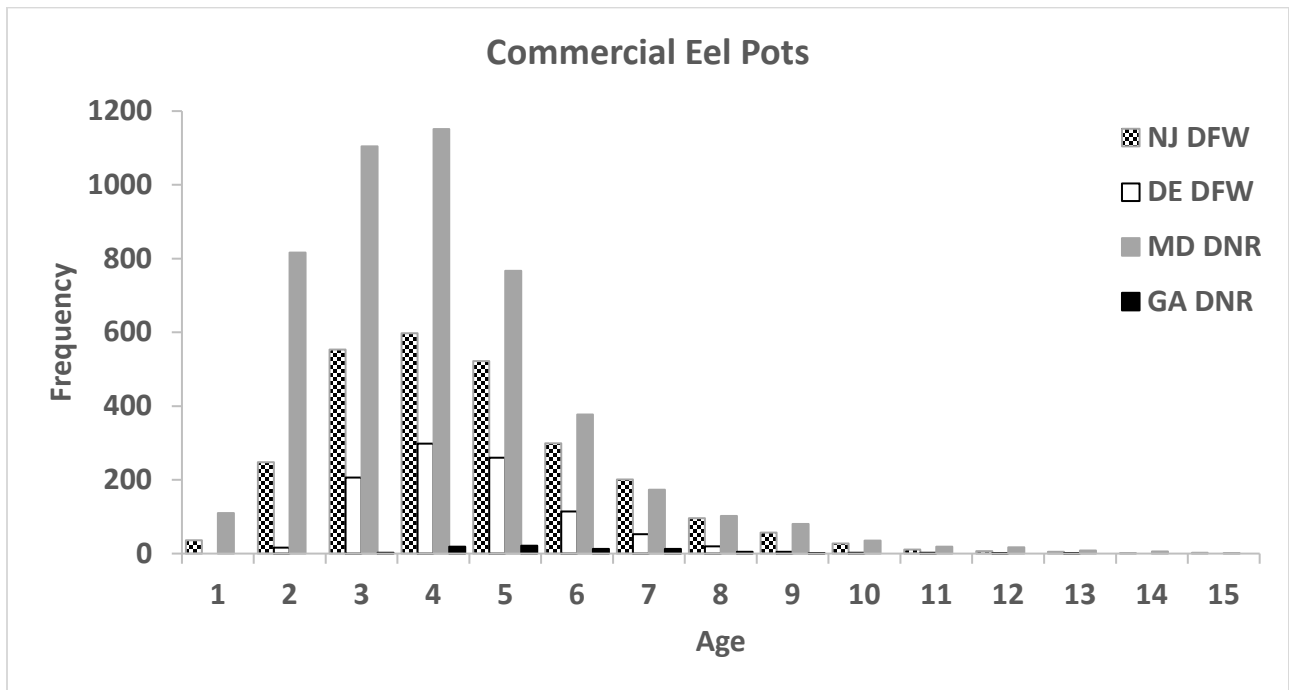


Figure 2. Age frequency by agency for commercial eel pot biosampling programs.

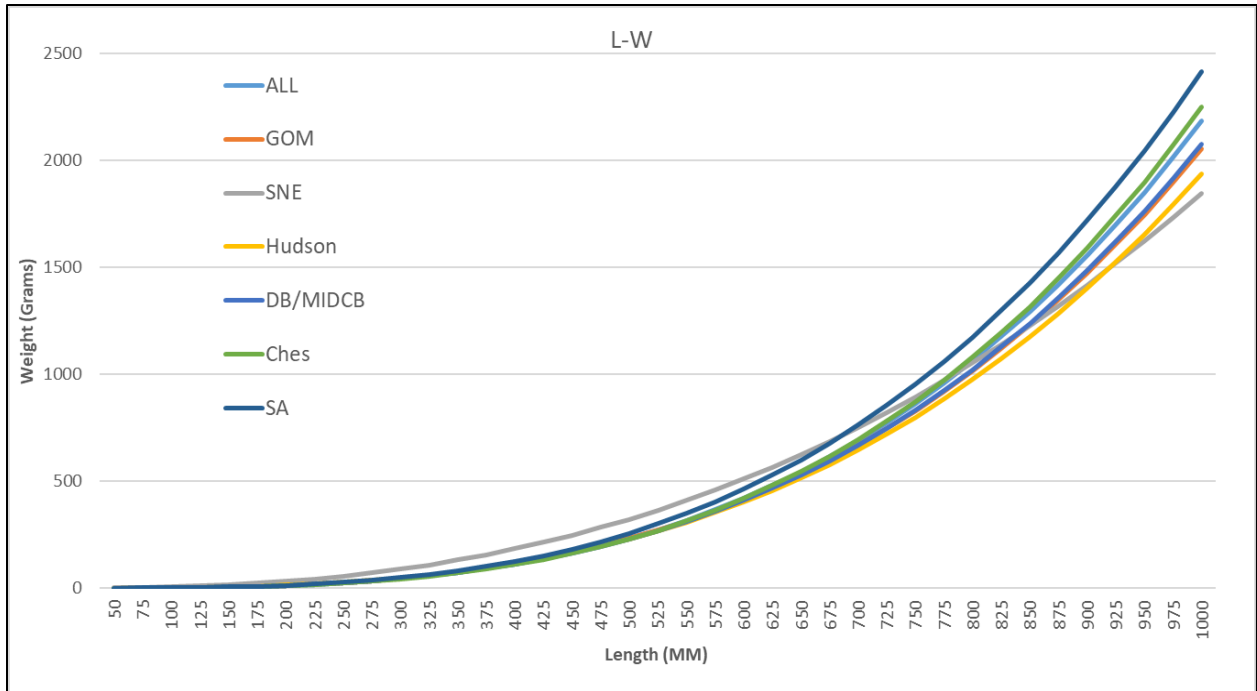


Figure 3. Predicted length-weight relation for American eel based on available data, by region and all pooled.

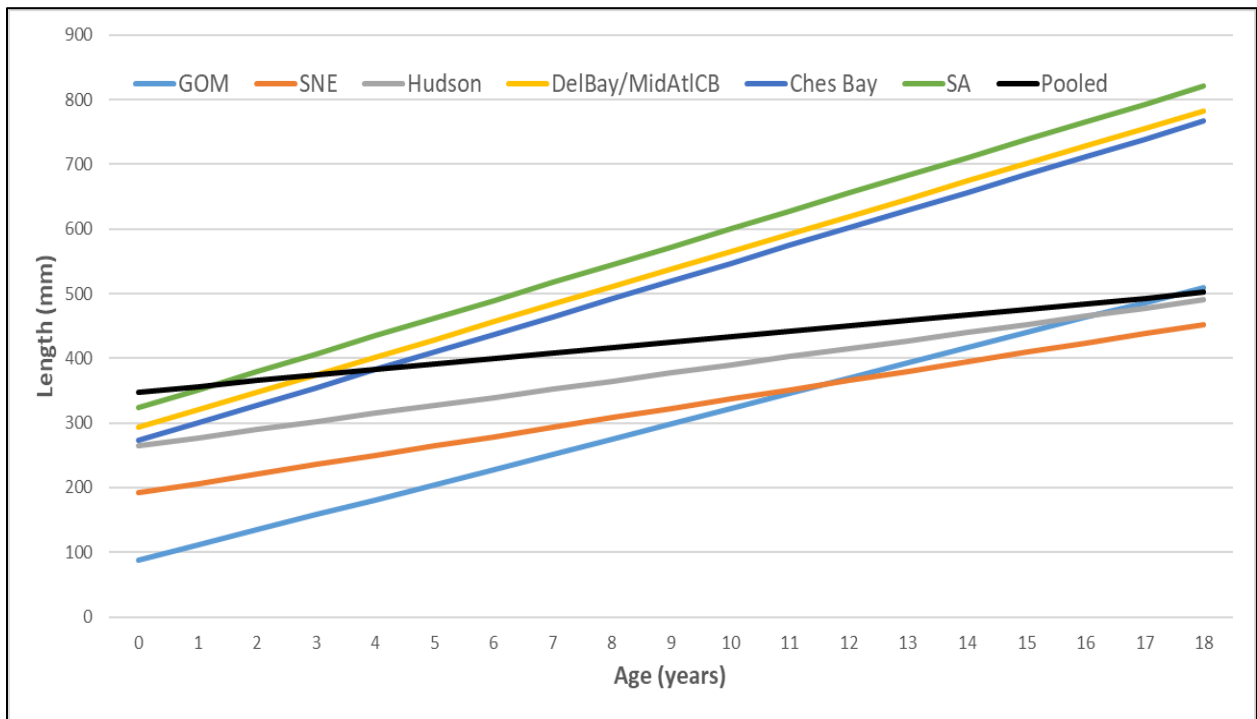


Figure 4. Predicted linear age-length relation for American eel based on available data, by region and all pooled.

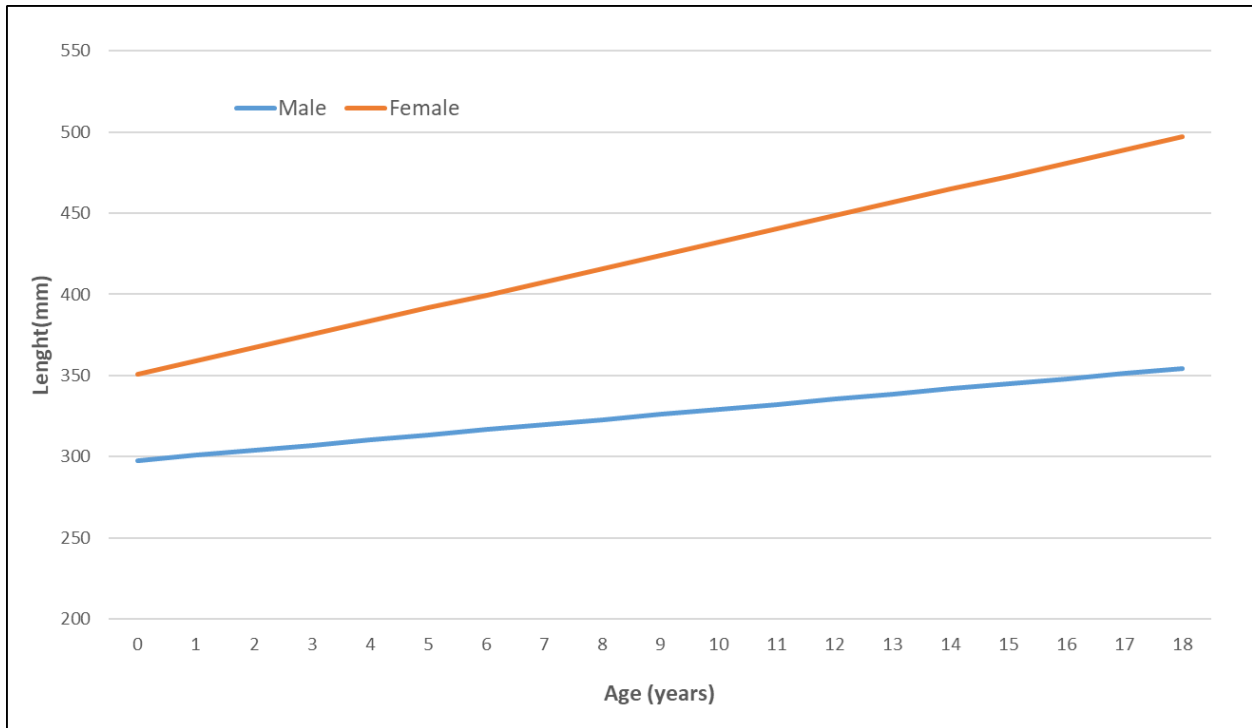


Figure 5. Predicted linear age-length relation for American eel based on available data, by sex.

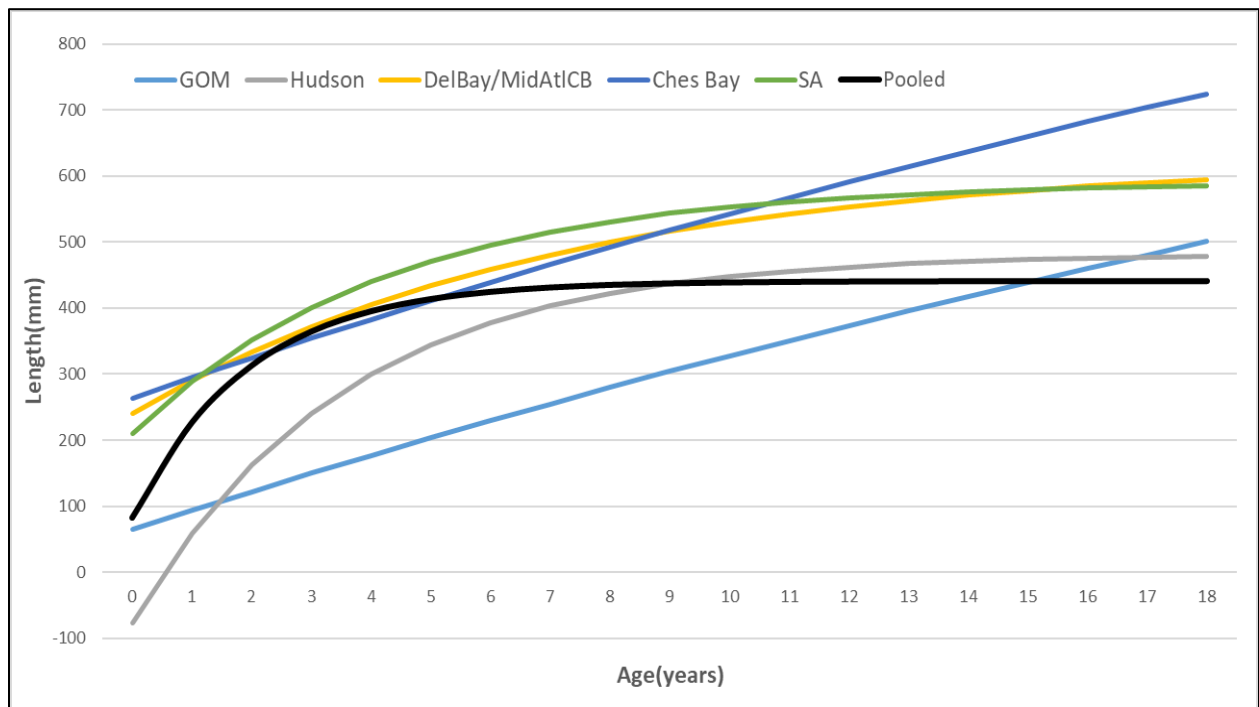


Figure 6. Predicted von Bertalanffy age-length relation for American eel based on available data, by region and all pooled.

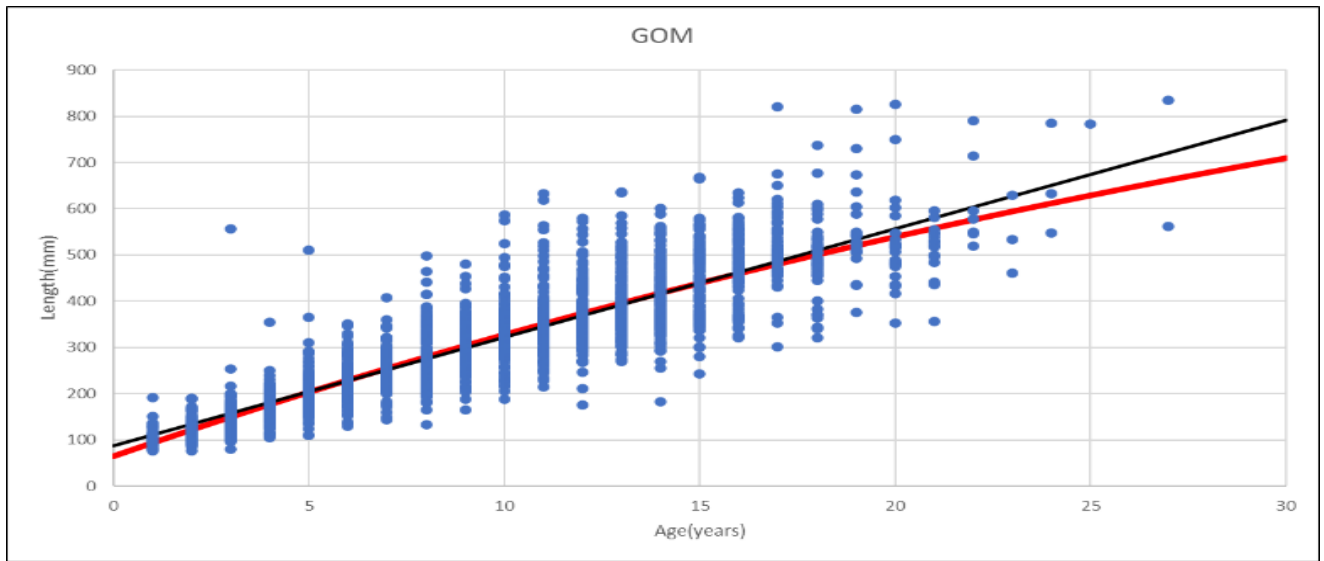


Figure 7. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data in the Gulf of Maine (GOM).

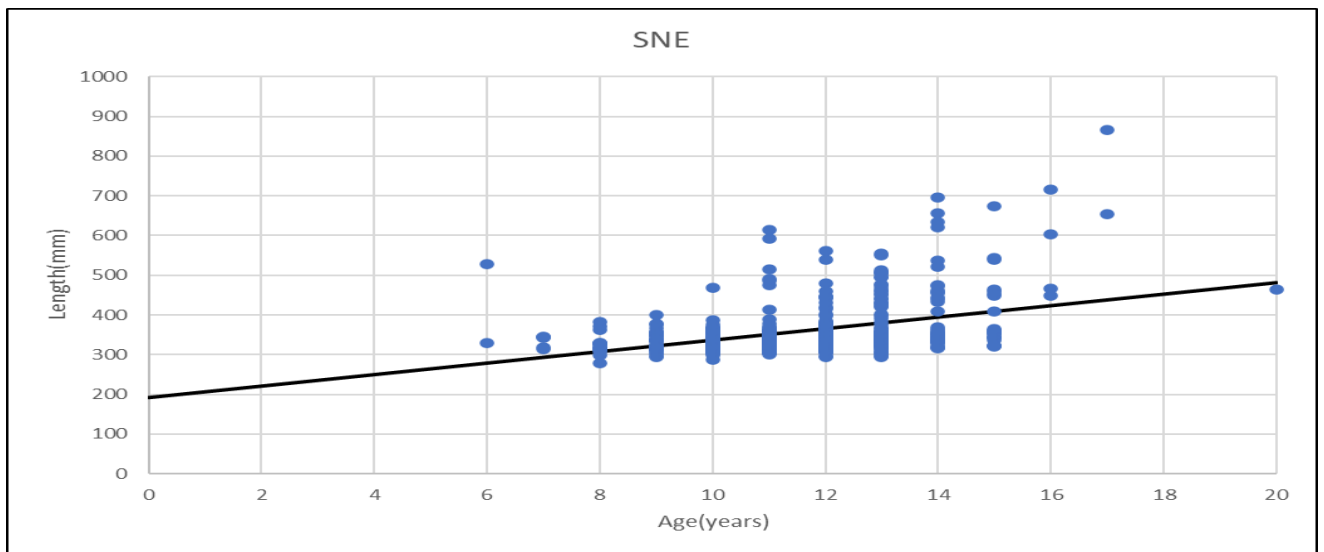


Figure 8. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data in Southern New England (SNE).

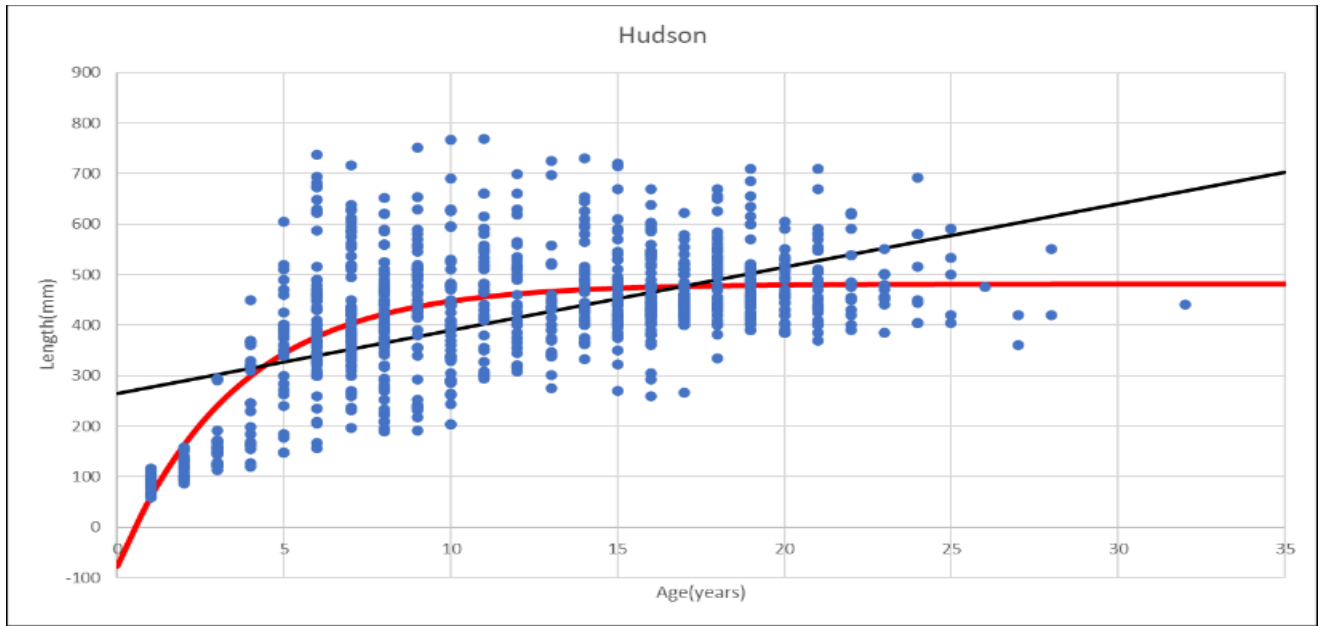


Figure 9. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data in the Hudson River.

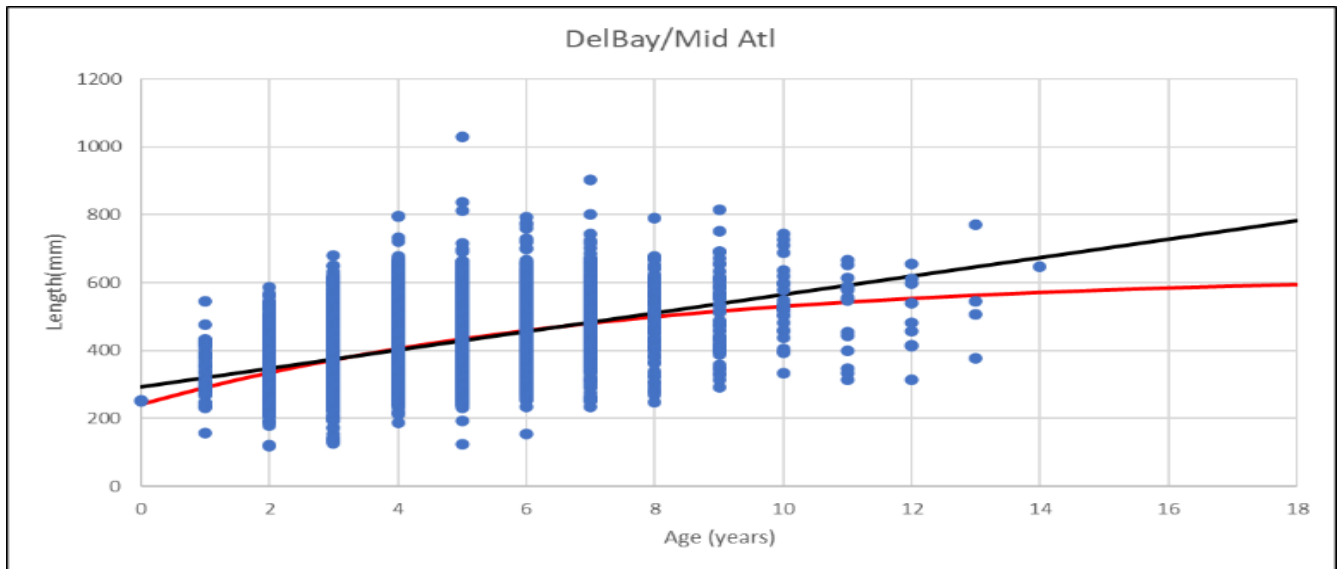


Figure 10. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data in the Delaware Bay/Mid-Atlantic Region.

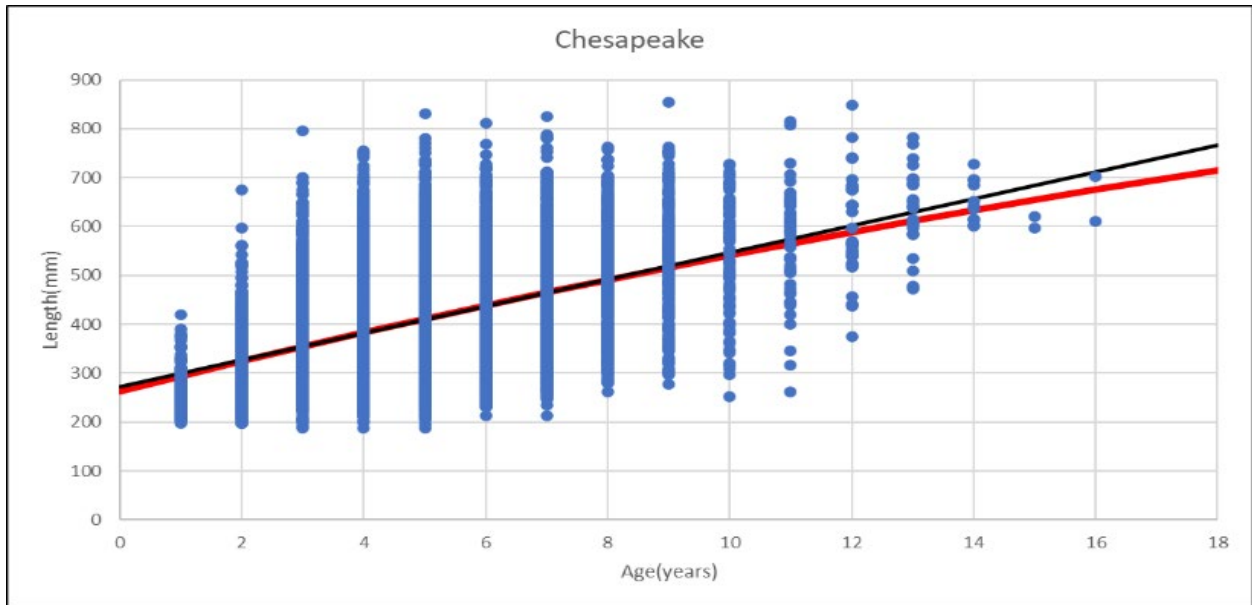


Figure 11. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data in the Chesapeake Bay Region.

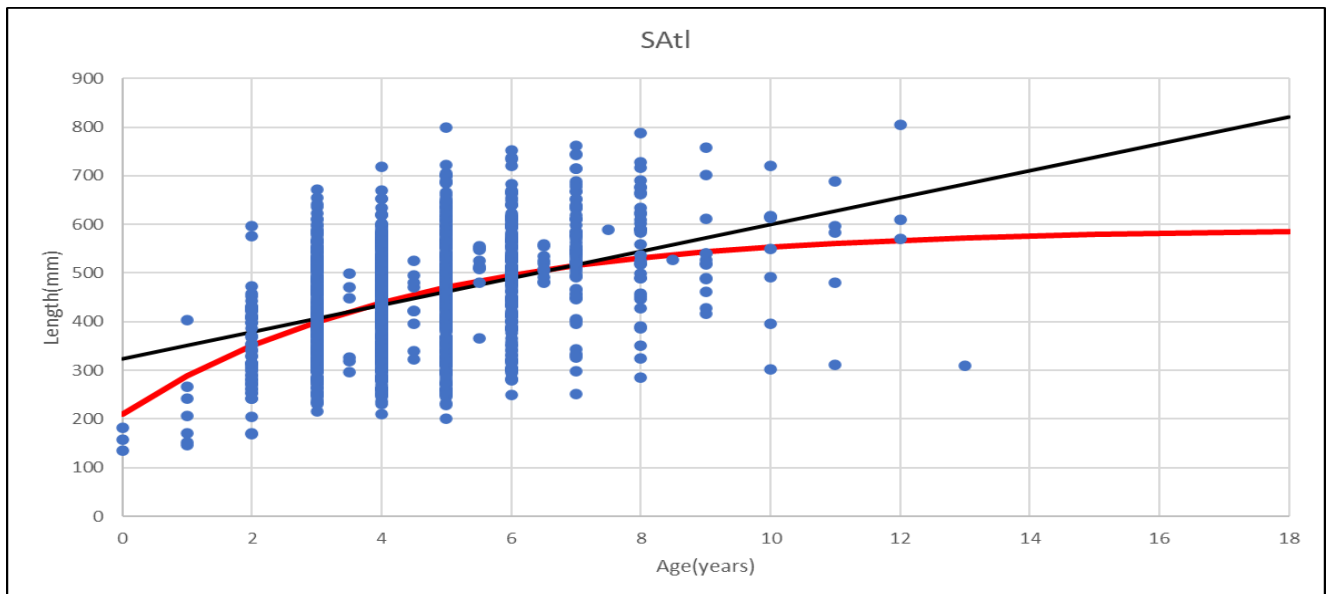


Figure 12. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data in the South Atlantic (SATl) Region.

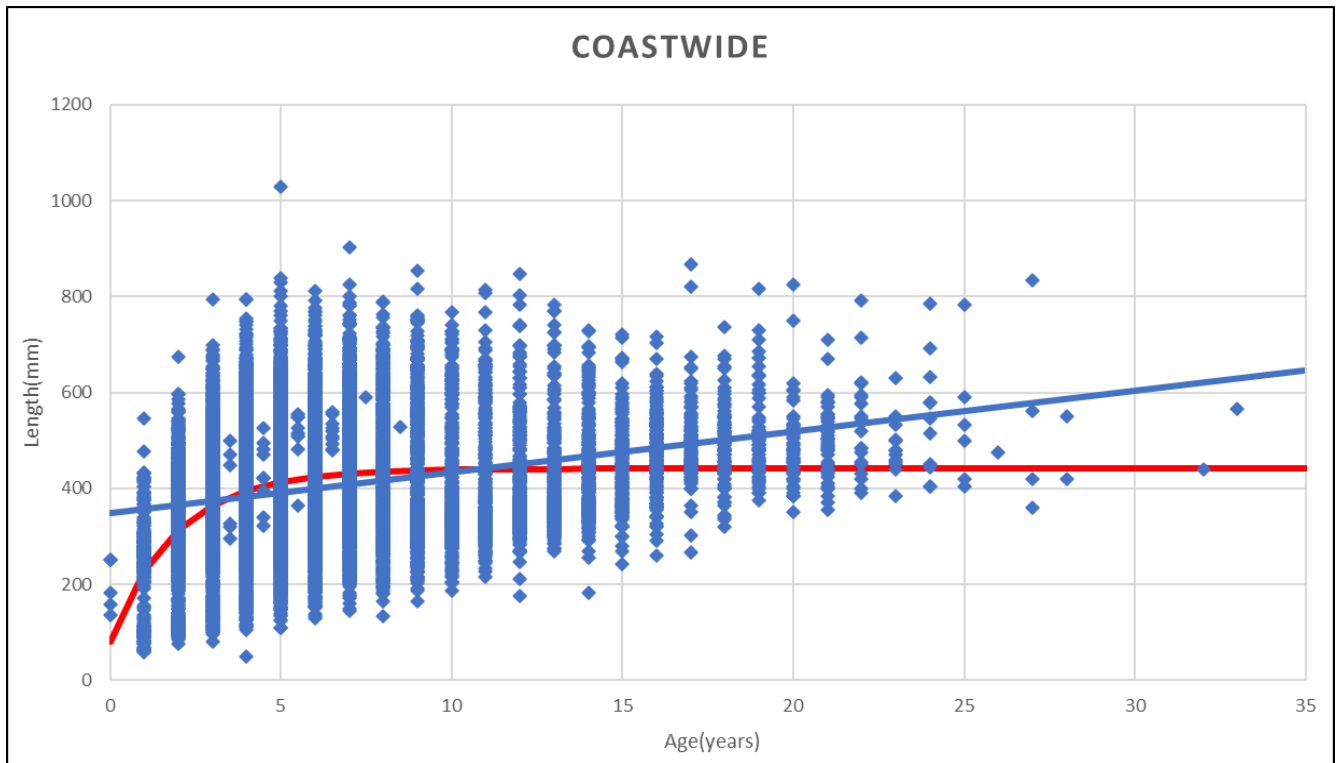


Figure 13. Scatter plot of length-at-age with predicted von Bertalanffy and linear age-length relation for American eel based on available data coastwide.

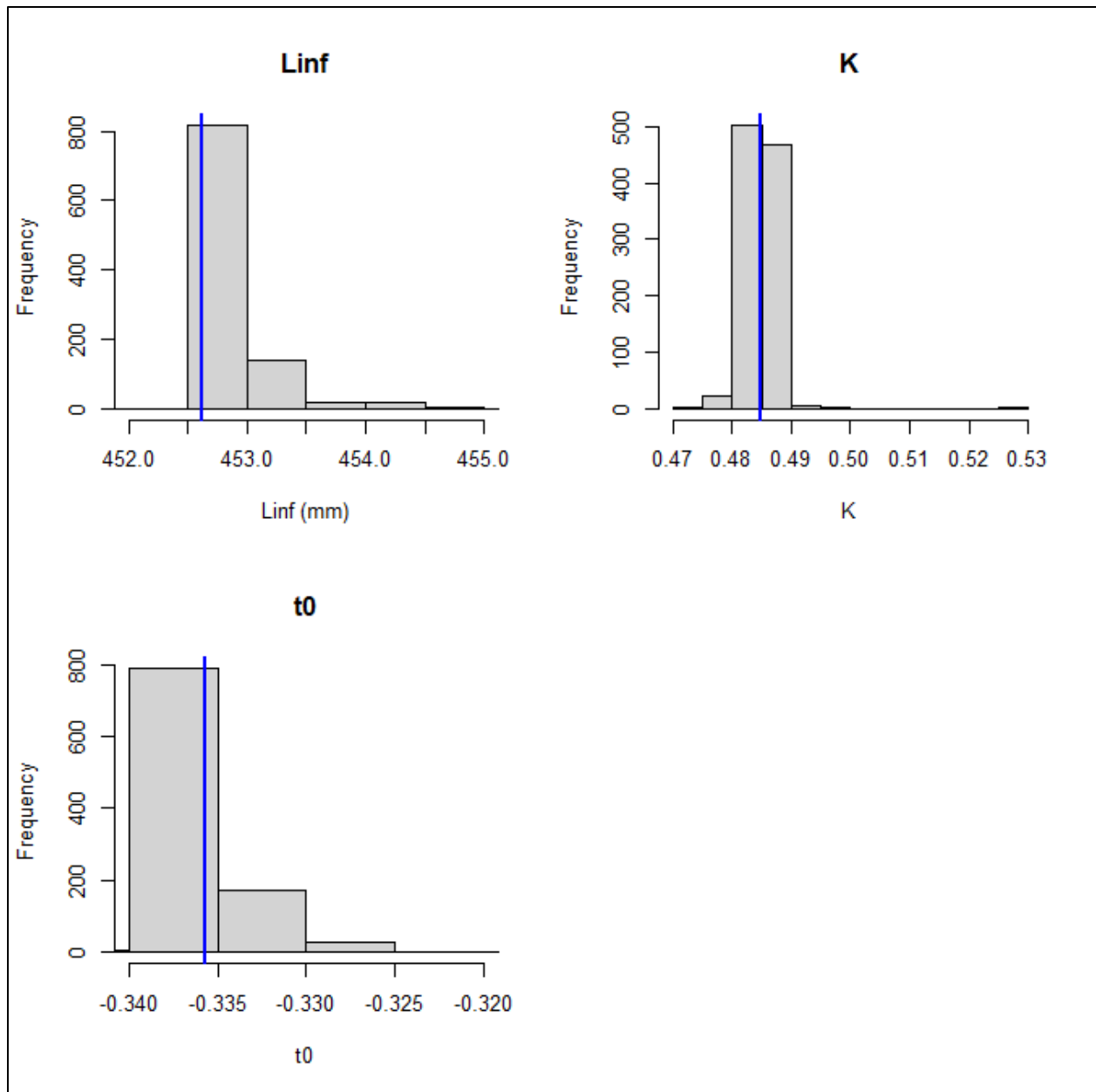


Figure 14. Histograms of the bootstrap estimates for the von Bertalanffy age-length growth model parameters. The vertical blue lines represent the median values of the distributions.

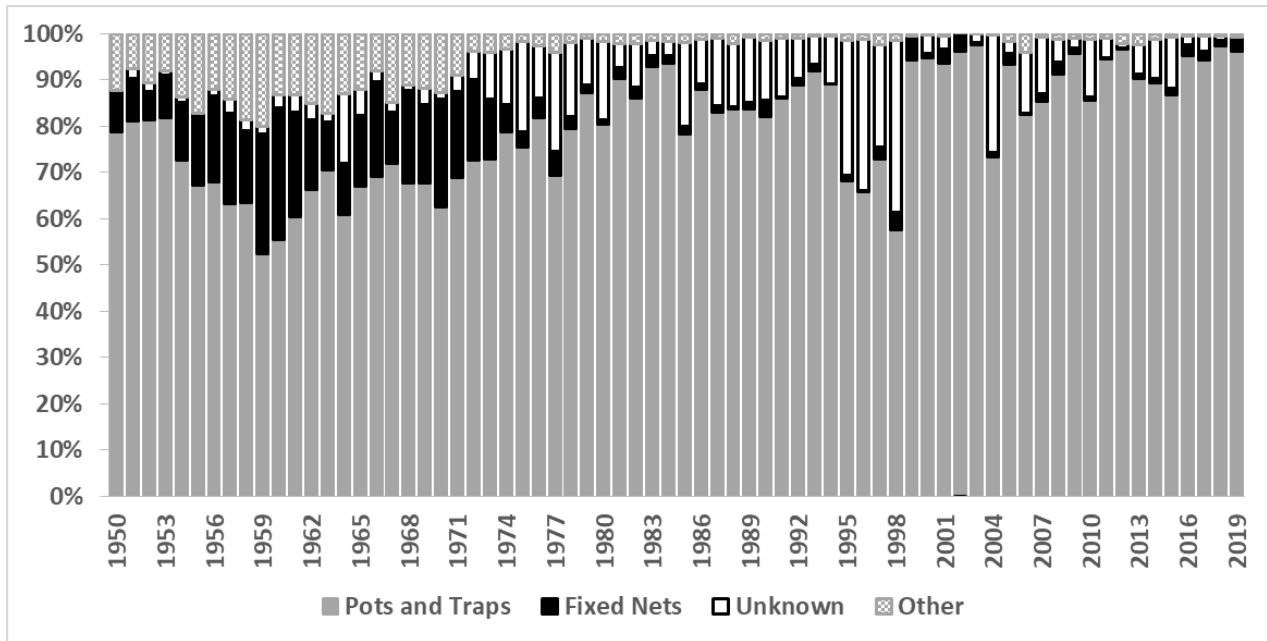


Figure 15. Percent of coastwide commercial landings by gear type, 1950-2019.

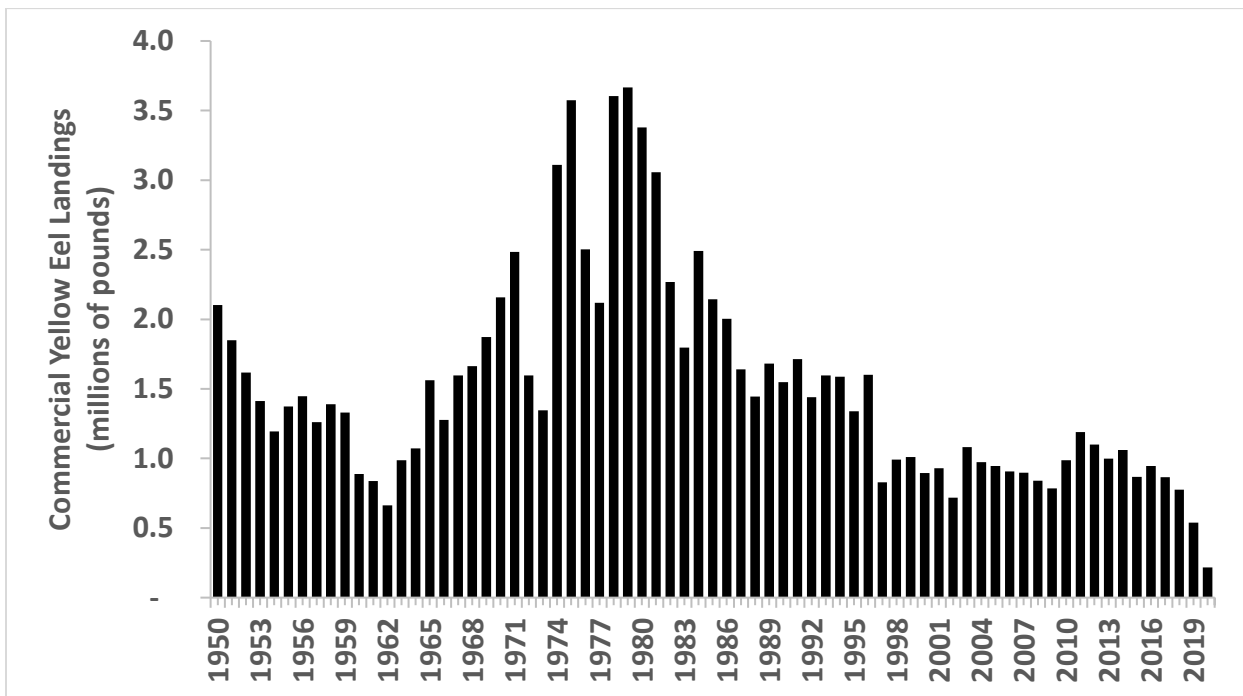


Figure 16. Coastwide commercial yellow eel landings, 1950-2020, in millions of pounds. Historical landings (1950-1997) should be interpreted with caution as there are several data caveats associated with the historical records. Landings 1998-2020 were validated through ACCSP and 2020 is considered preliminary.

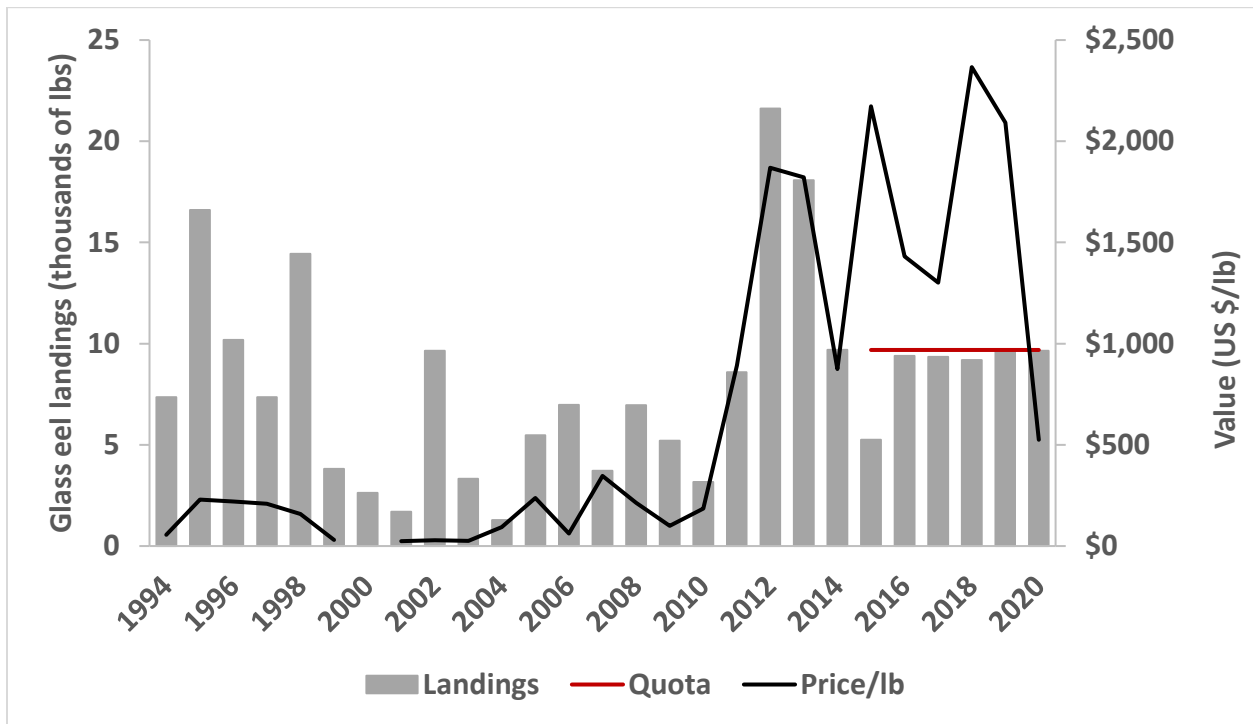


Figure 17. Maine’s glass eel landings and price per pound (lb), 1995-2020. The state has had a glass eel quota since 2015, indicated on the graph in red. Source: Maine Department of Marine Resources, www.maine.gov/dmr/commercial-fishing/landings/documents/elver.table.pdf.

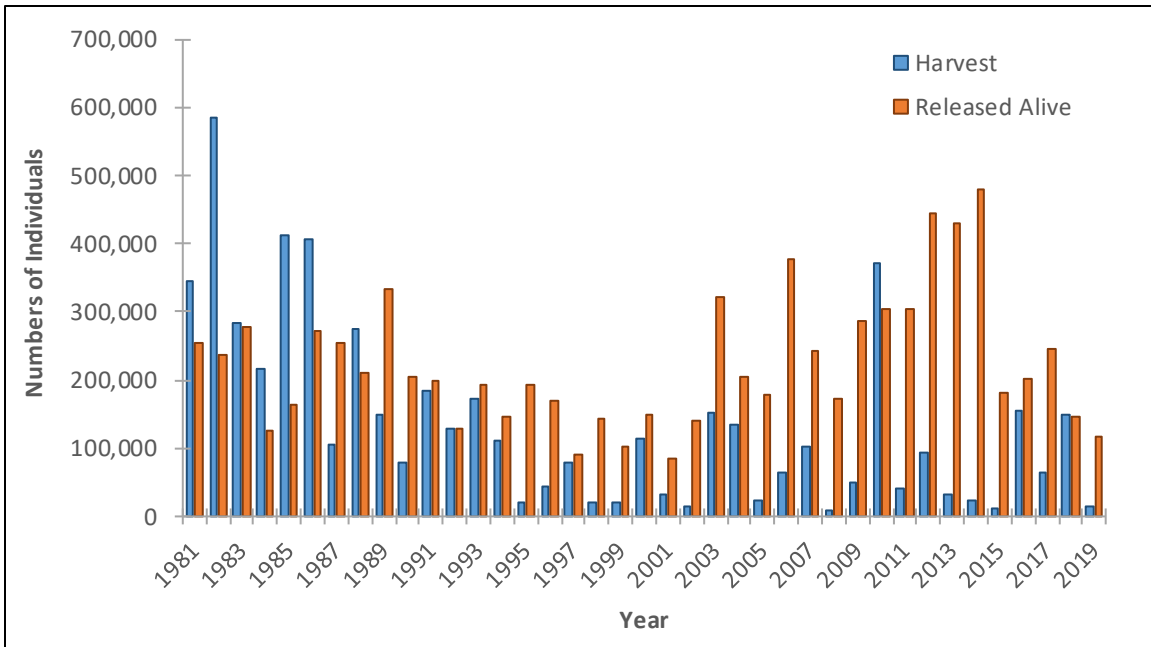


Figure 18. Annual recreational harvest (Type A + B1) and released alive (Type B2) estimates for American eel along the U.S. east coast as estimated by MRIP, 1981–2019.

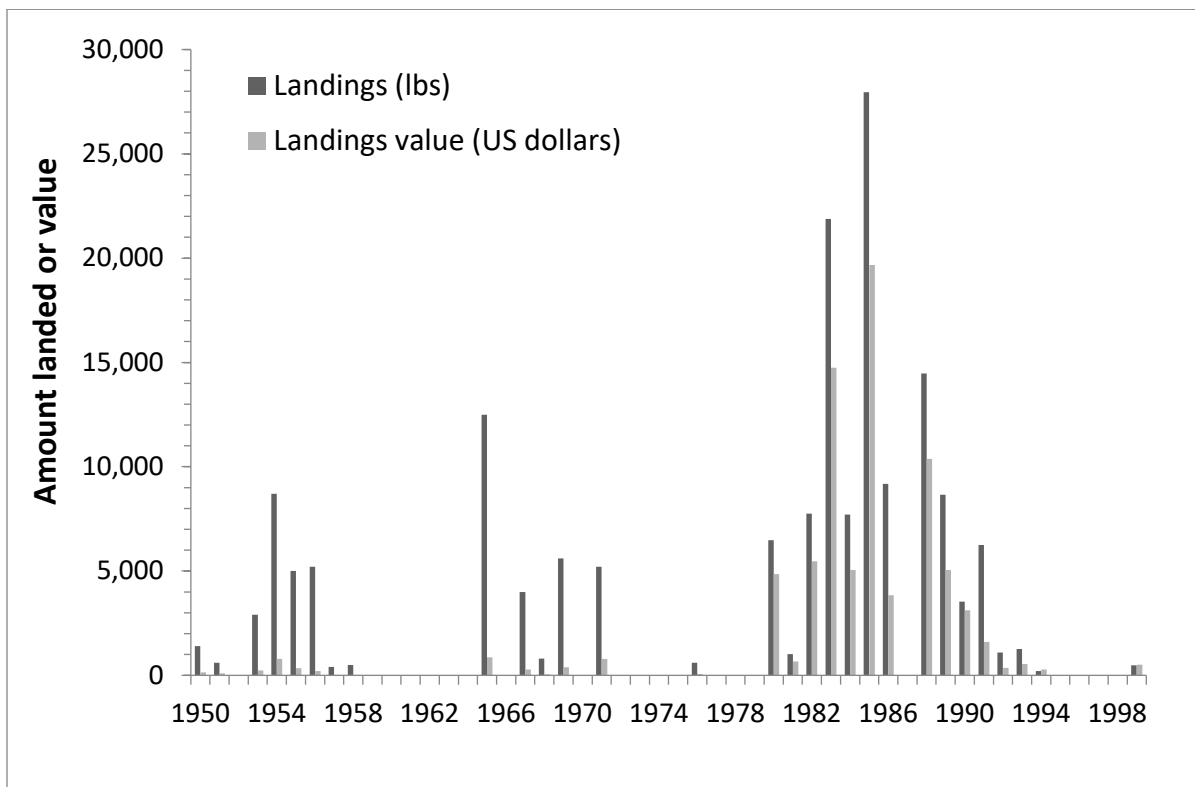


Figure 19. Total weight (lbs) and value (US dollars) of American eel commercial landings in the Gulf of Mexico, 1950–1999. Recent landings are confidential.

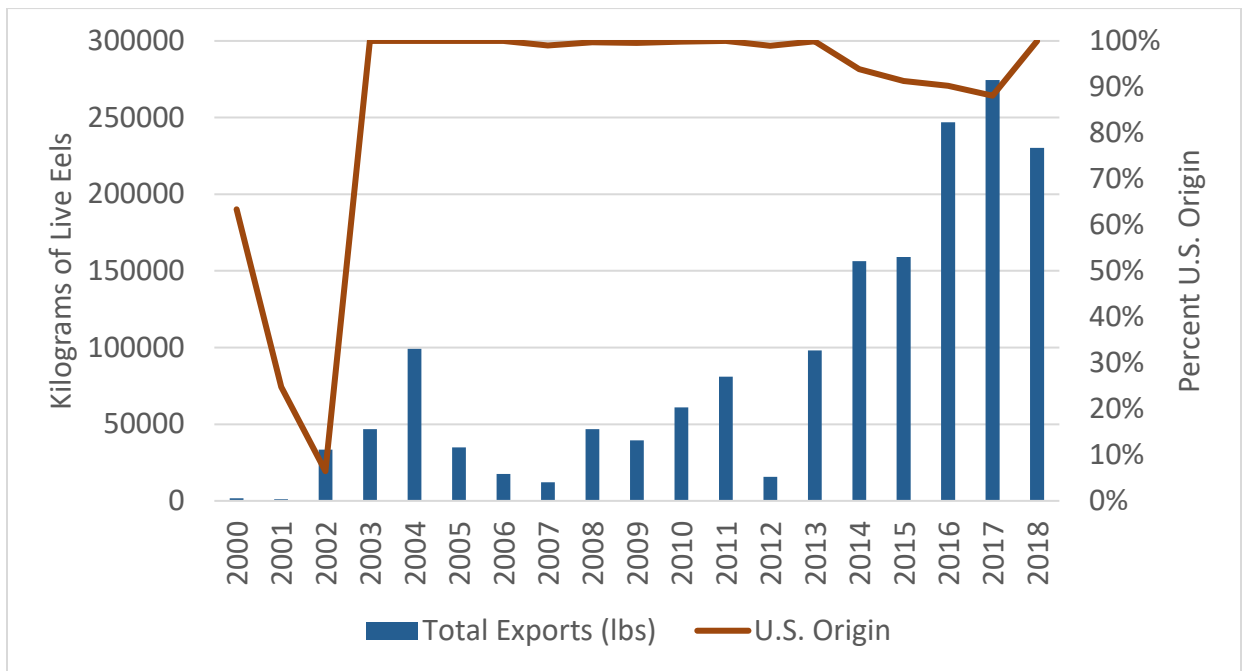


Figure 20. Export of live American eels from the Atlantic coast and the percent that are of U.S. origin, 2000-2018 (source: U.S. Fish and Wildlife Service in the Law Enforcement Management Information System).

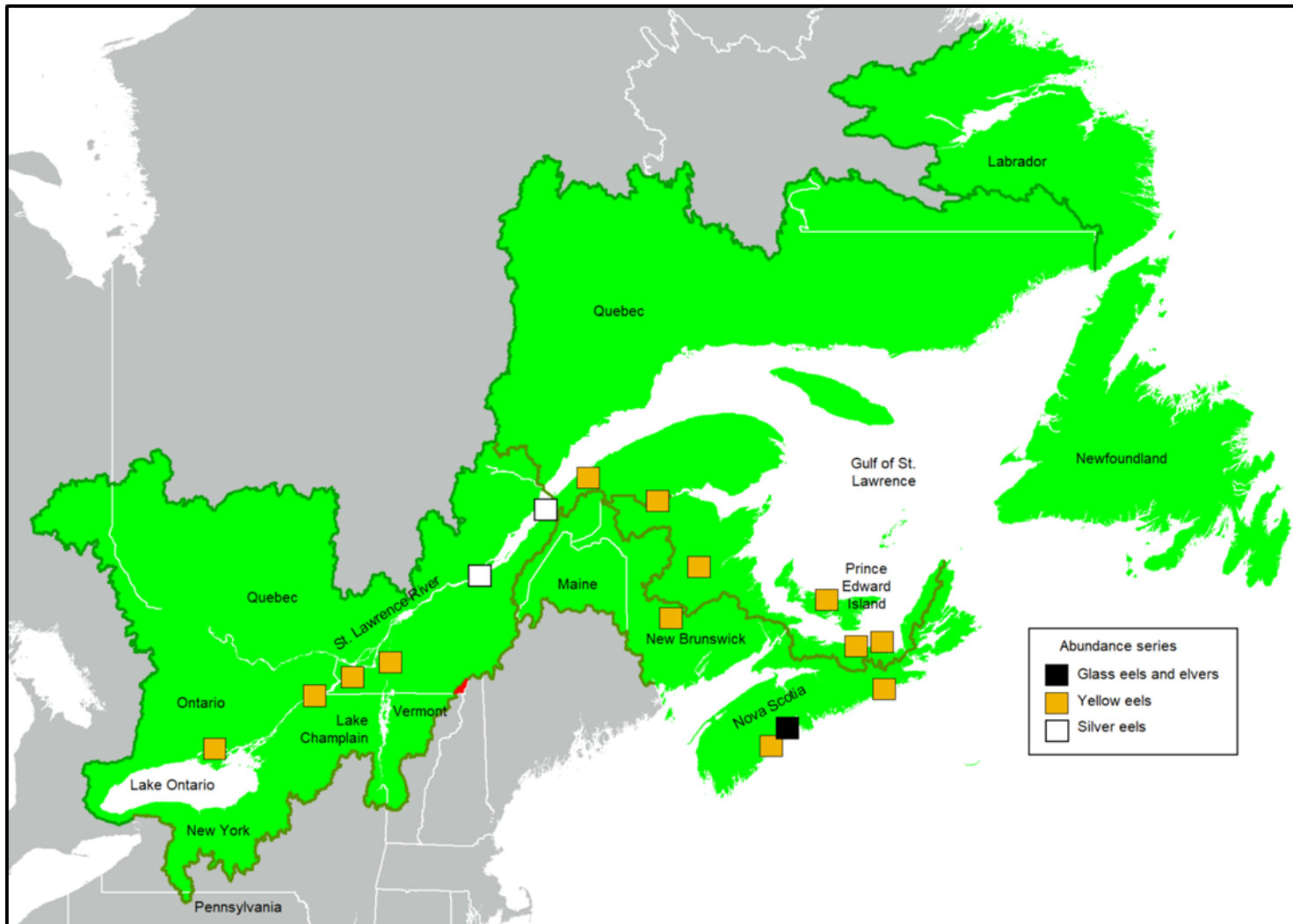


Figure 21. Plausible historical range of the American eel in Canada and areas of the US which drain through Canada (green) (Cairns 2020), and locations of abundance series which are accepted as meeting quality standards (Cornic et al. 2021). Range is drawn to watershed boundaries and to major natural barriers to upstream passage. The red polygon indicates the part of Quebec which drains through the US to the Atlantic Ocean.

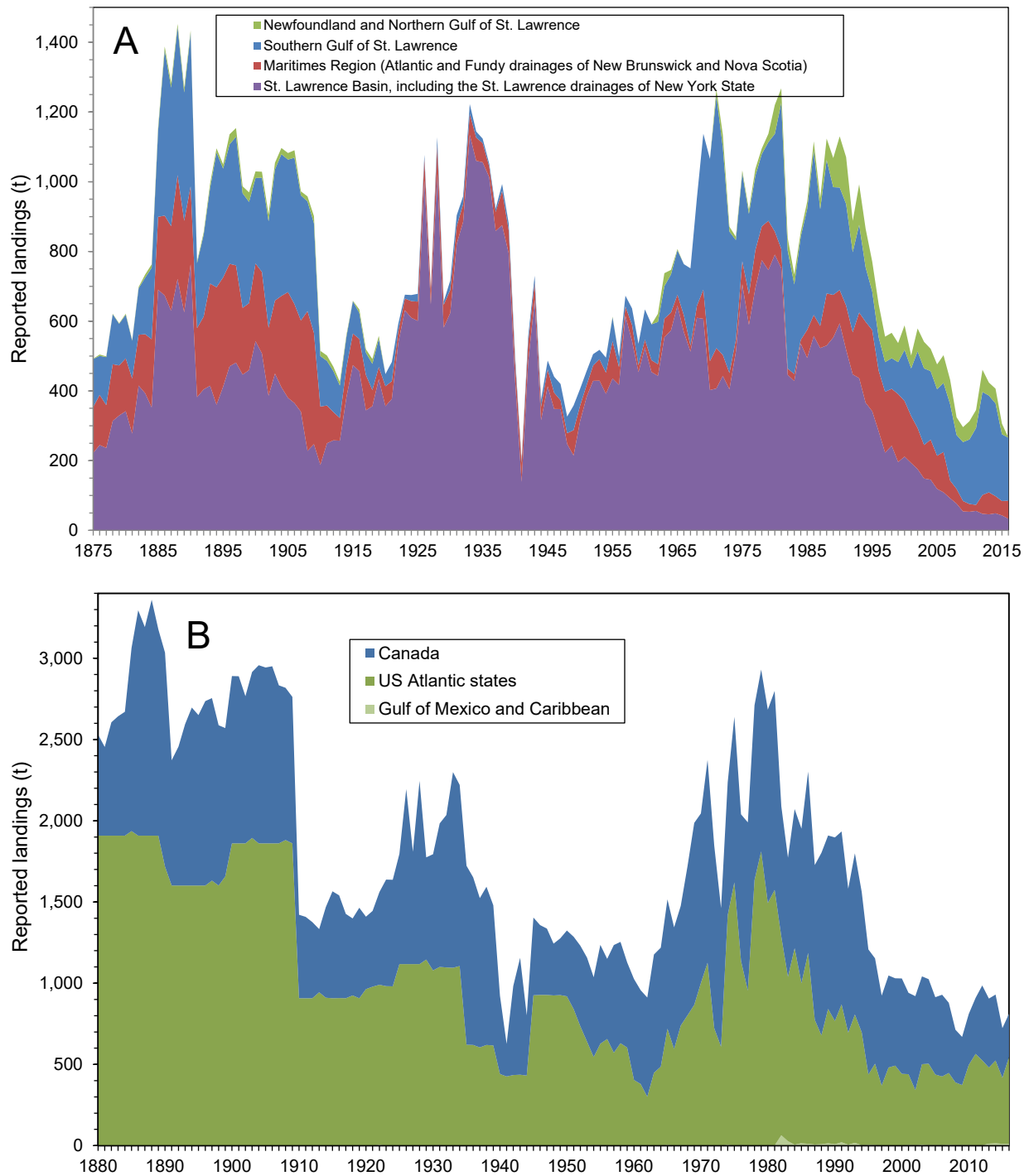


Figure 22. Reported American eel landings (in tonnes) in Canada and US waters that drain through Canada (A) and range-wide (B). Data from Cairns (2020). For (B), US data for 1880-1919 are means by decade and data for 1920-1949 are means by 5-year period.

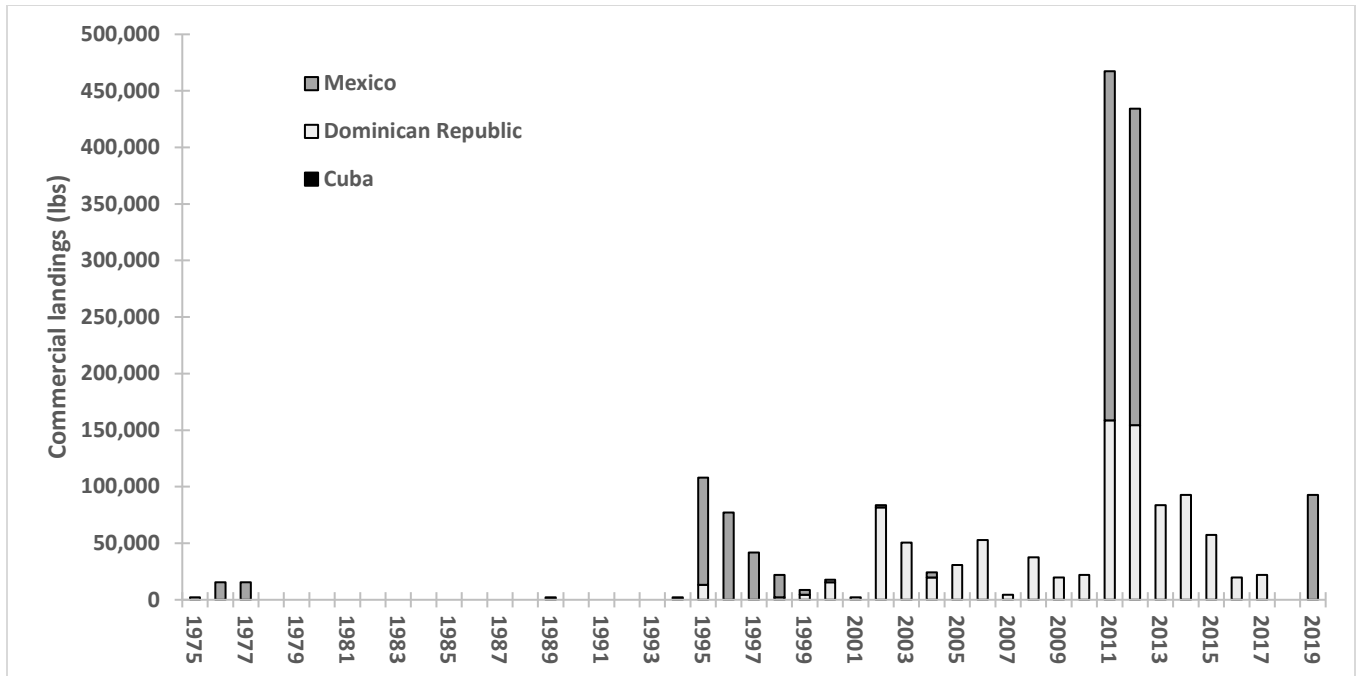


Figure 23. Annual commercial landings (live weight) of American eel reported by the FAO from Central and South America, 1975–2019. No landings were reported between 1950-1974, 1978-1988, and 1990-1993. Cuba’s only reported American eel landings were approximately 2,200 pounds in 1989 and 1994.

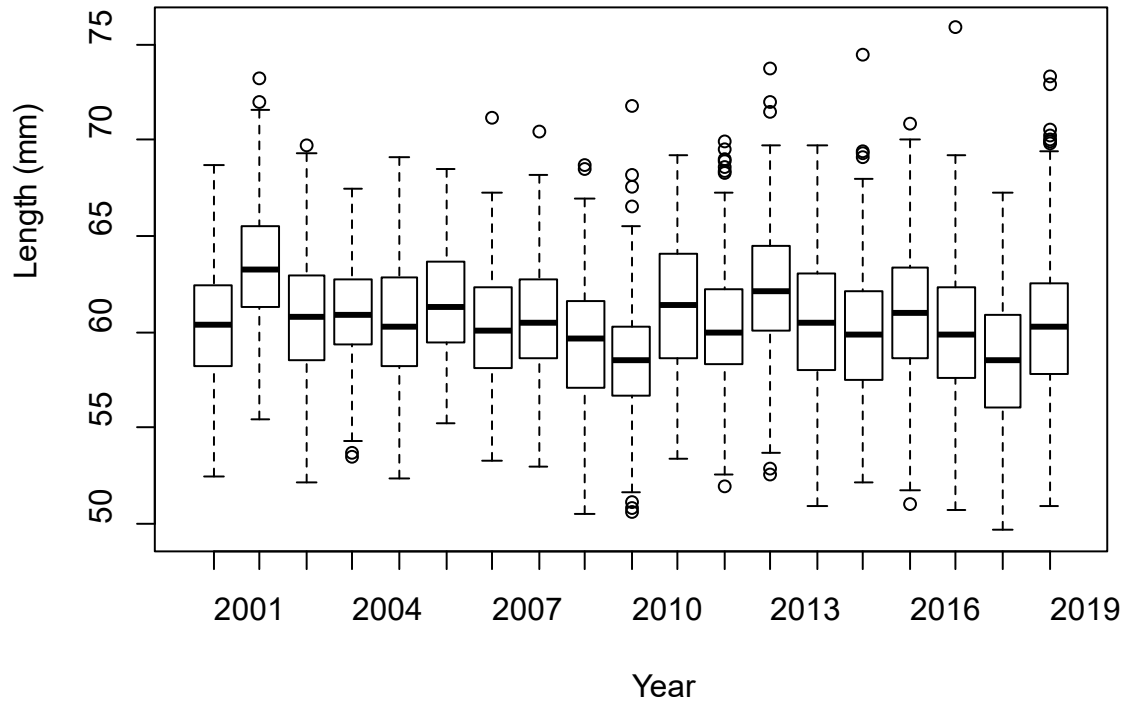


Figure 24. Boxplot of American eel YOY lengths recorded in the Maine West Harbor Pond Survey.

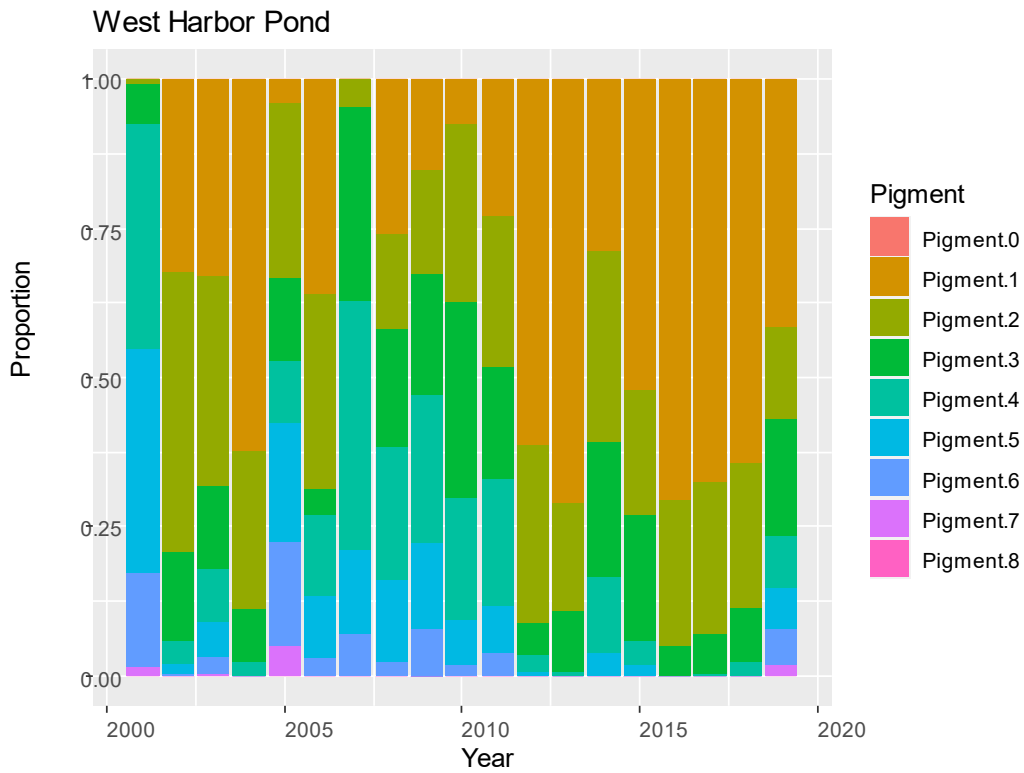


Figure 25. Distribution of pigment stages in the West Harbor Pond YOY American eel survey.

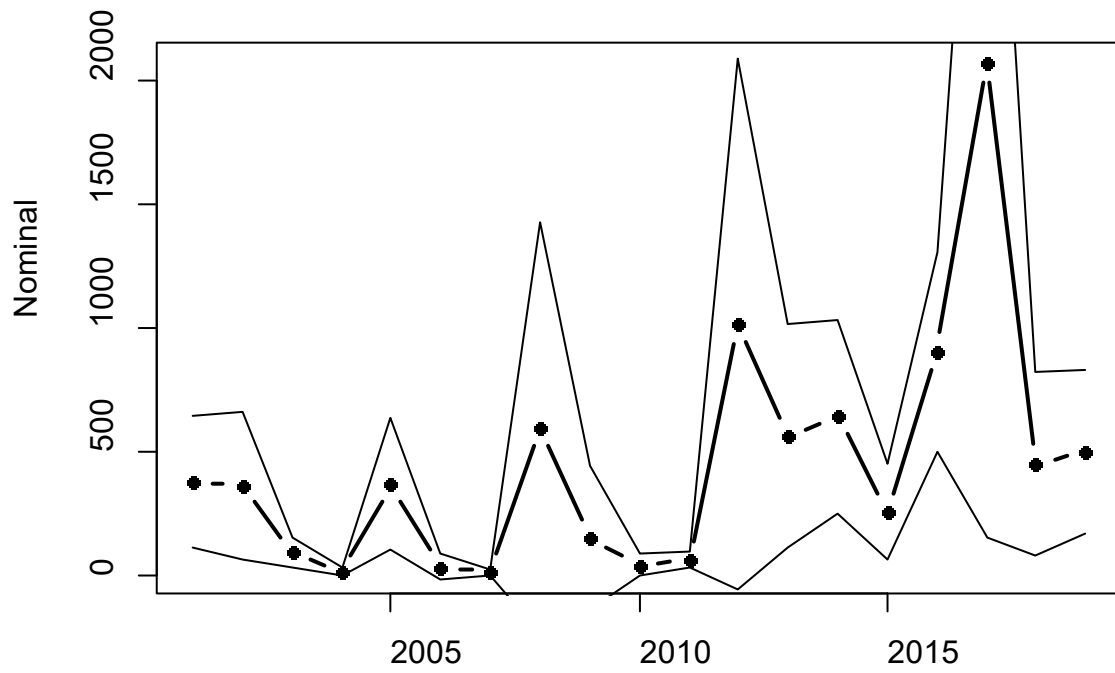


Figure 26. Nominal index of relative abundance of YOY eel developed from Maine’s West Harbor Pond Survey with 95% confidence intervals.

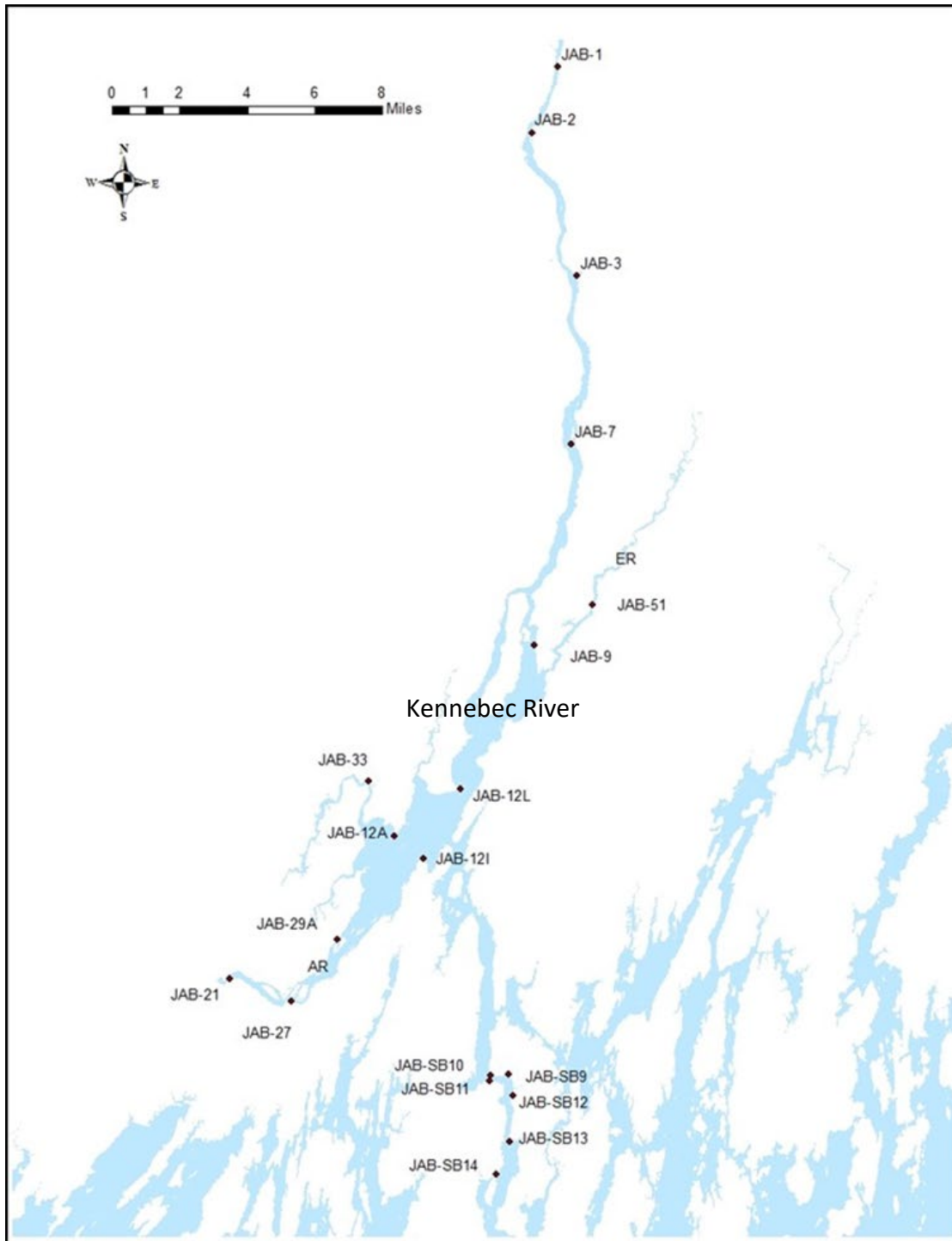


Figure 27. Map of the sites surveyed in Maine’s Juvenile Finfish Beach Seine Survey.

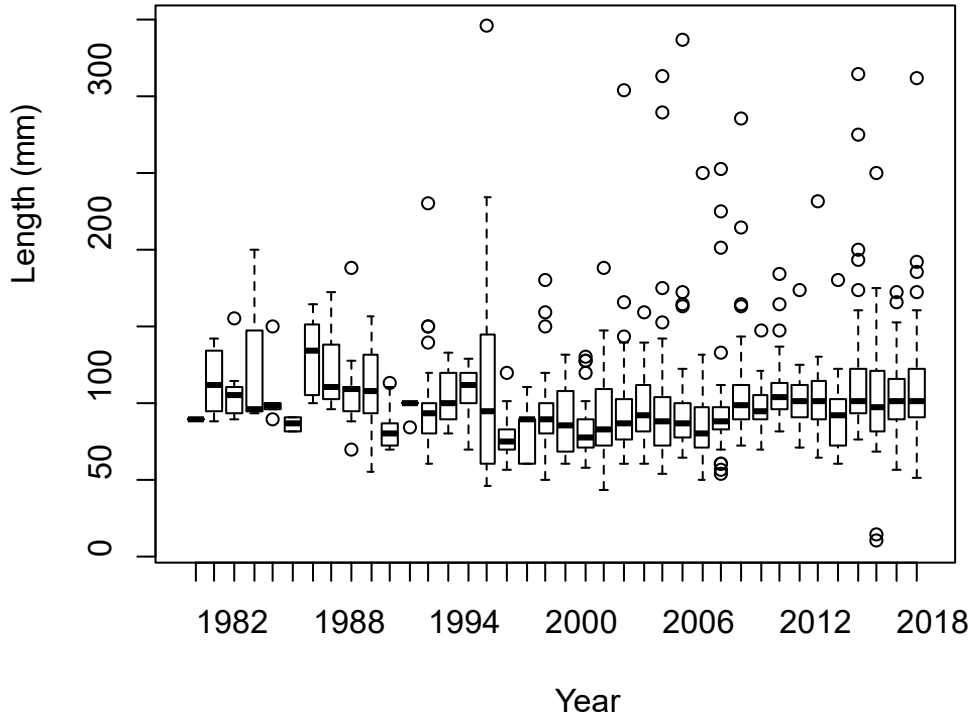


Figure 28. Boxplot of American eel lengths recorded in the Maine Juvenile Finfish Beach Seine Survey.

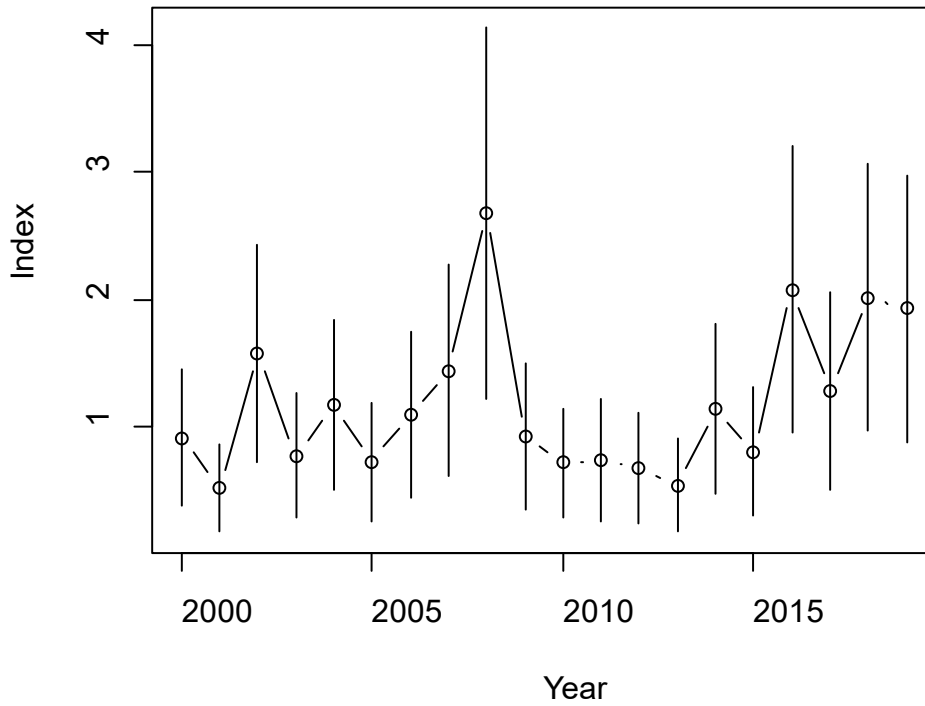


Figure 29. Standardized index of relative elver abundance developed from Maine's Juvenile Finfish Beach Seine Survey with 95% confidence intervals.

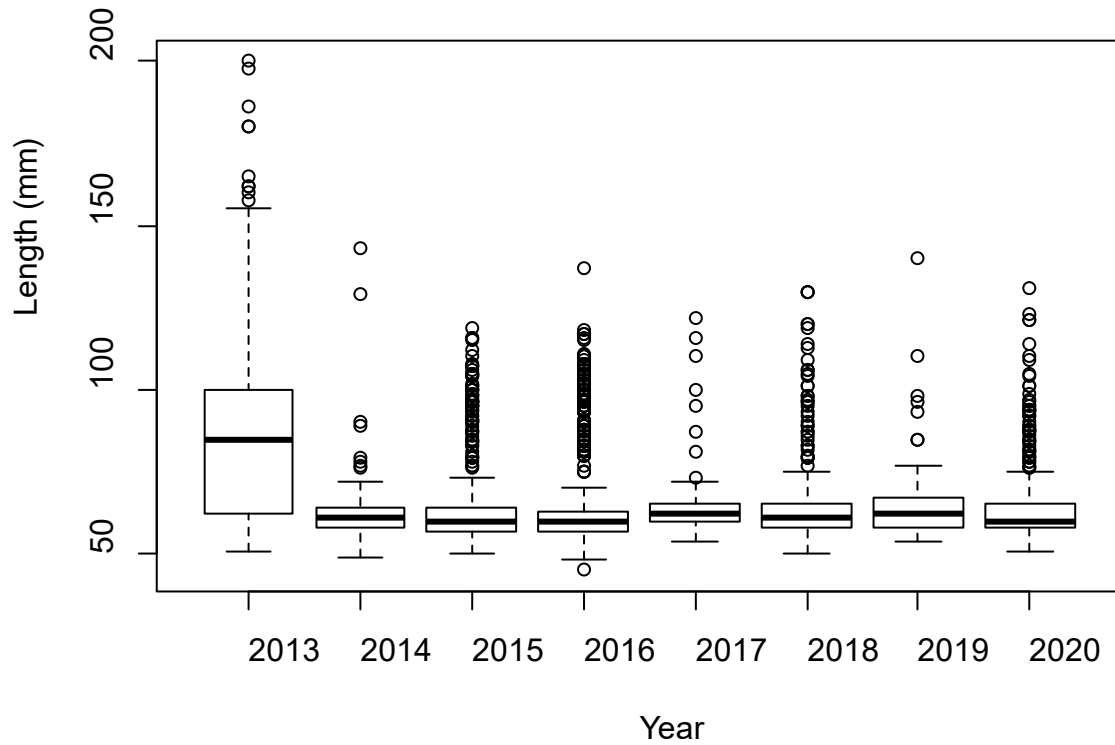


Figure 30. Boxplot of American eel YOY lengths recorded in the New Hampshire Lamprey River Survey.

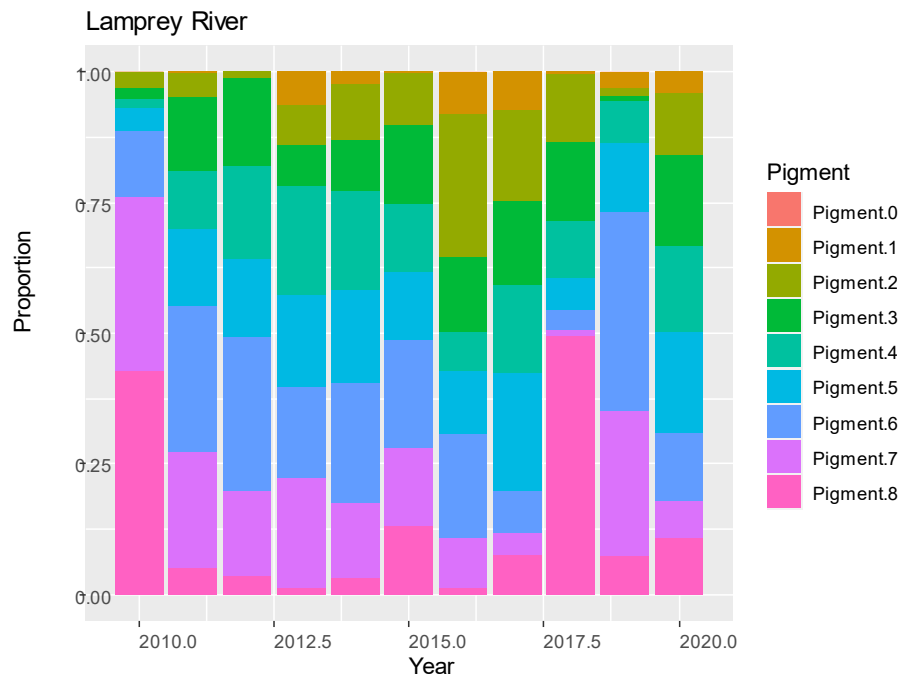


Figure 31. Distribution of pigment stages in the Lamprey River YOY American eel survey.

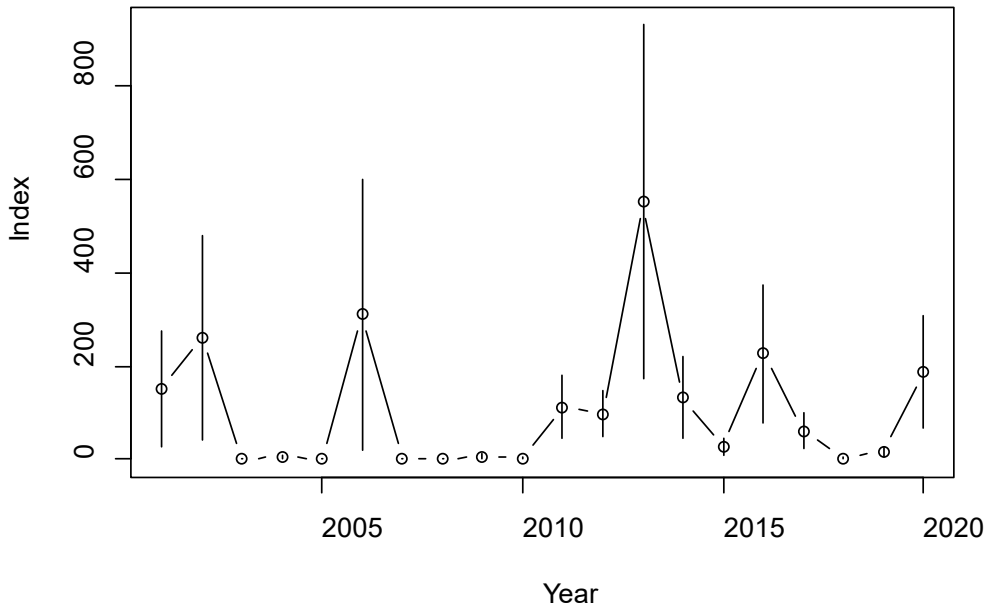


Figure 32. Standardized index of relative YOY abundance developed from New Hampshire’s Lamprey River Survey with 95% confidence intervals.

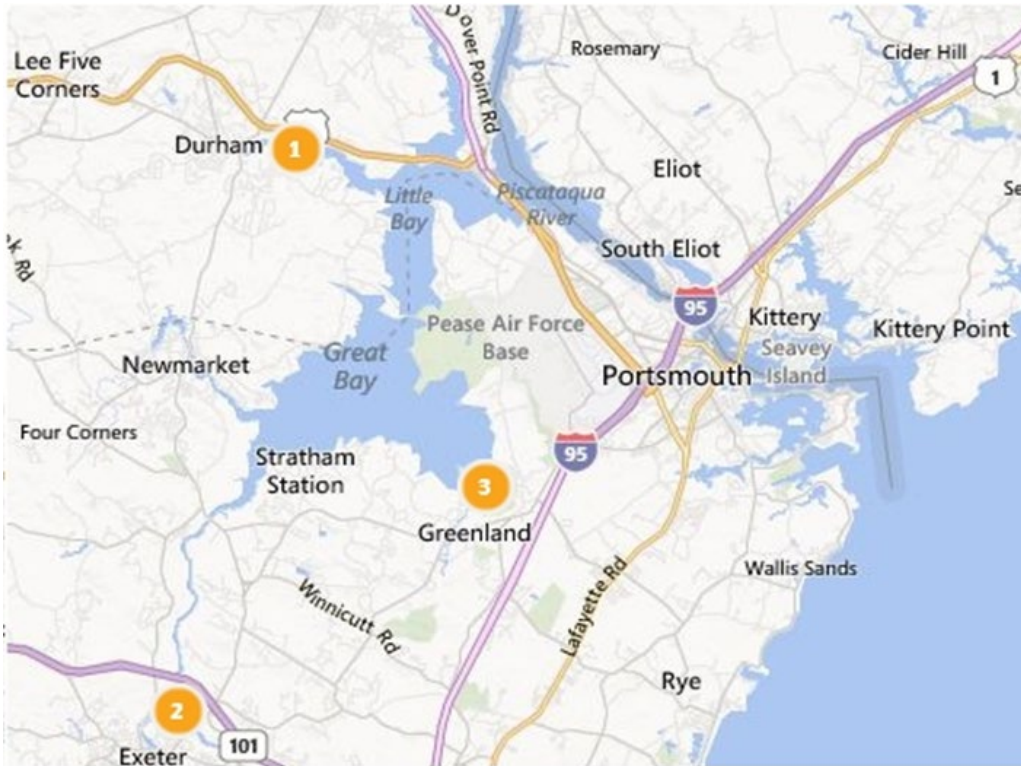


Figure 33. Map of the New Hampshire Fish and Game Rainbow Smelt Fyke Survey fixed station sampling locations where (1) indicates Oyster River, (2) Squamscott River, and

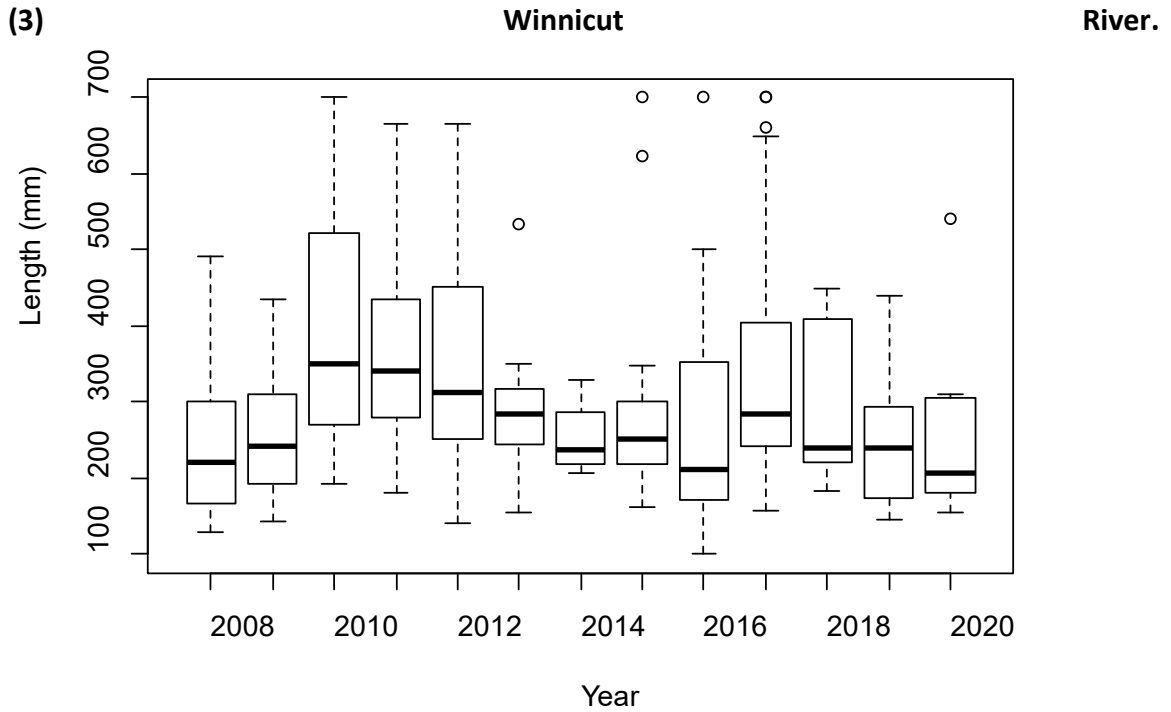


Figure 34. Boxplot of American eel lengths recorded in the New Hampshire Fish and Game Rainbow Smelt Fyke Survey.

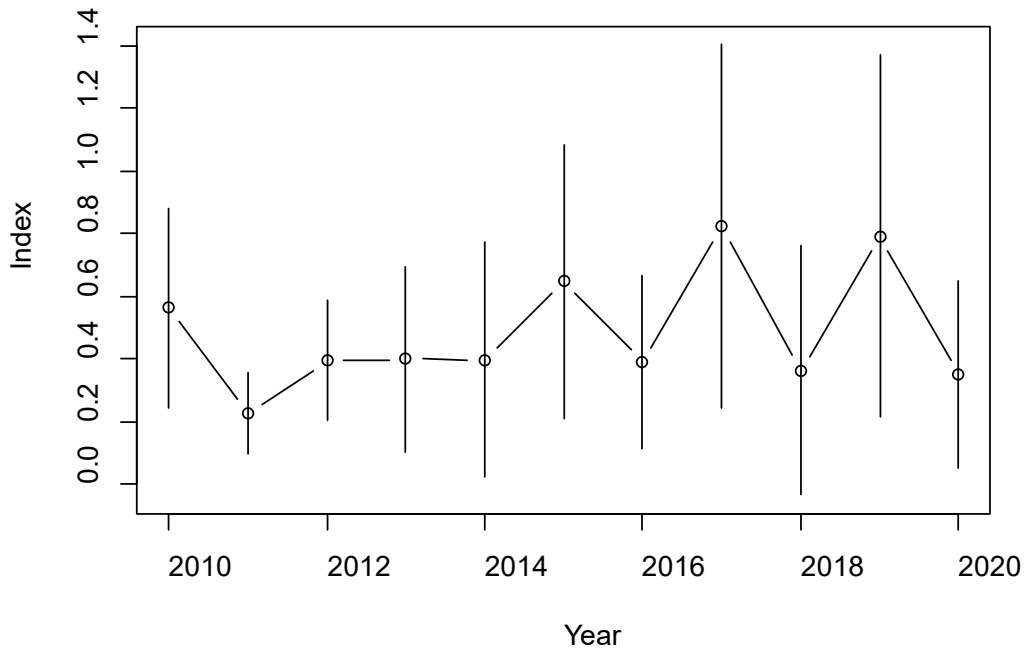


Figure 35. Standardized index of relative abundance of yellow eel developed from the New Hampshire Fish and Game Rainbow Smelt Fyke Survey with 95% confidence intervals.

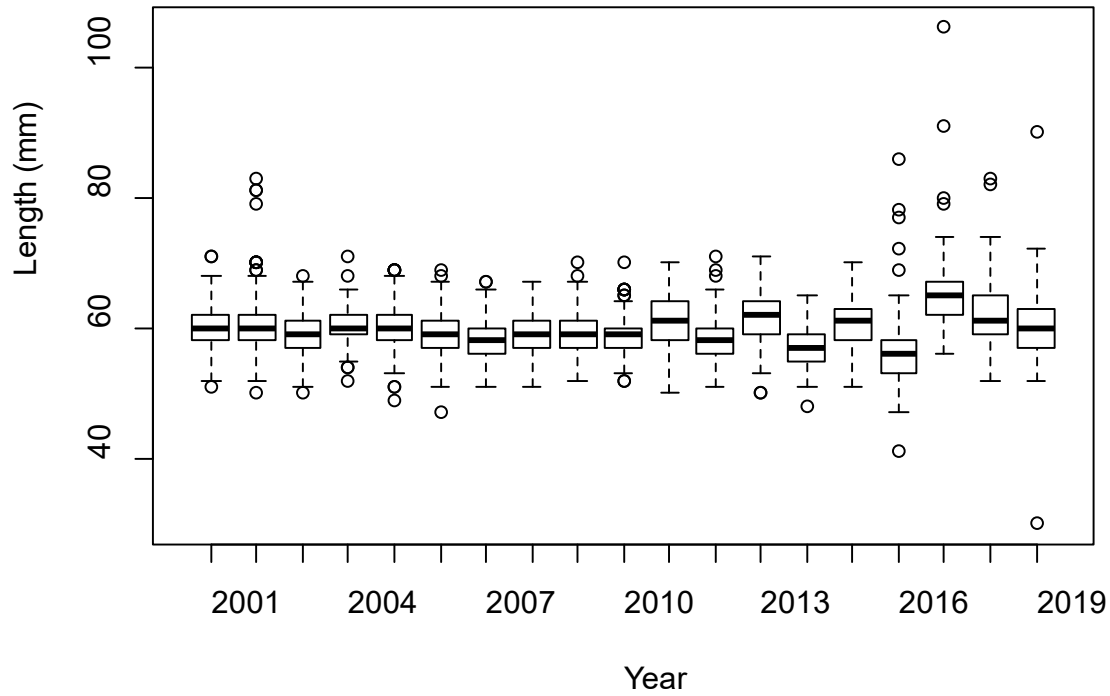


Figure 36. Boxplot of American eel YOY lengths recorded in the Massachusetts Jones River Survey.

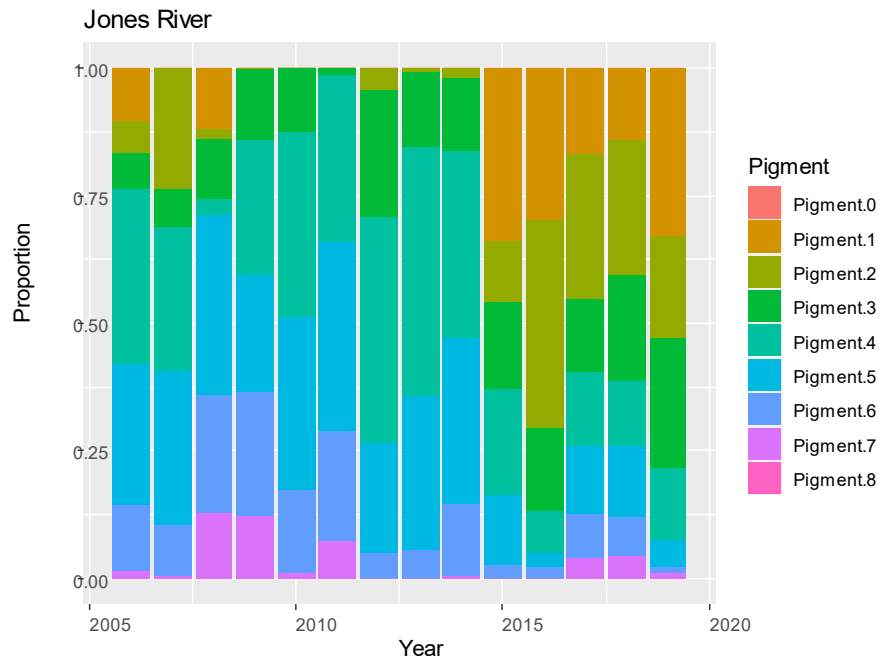


Figure 37. Distribution of pigment stages in the Jones River YOY American eel survey.

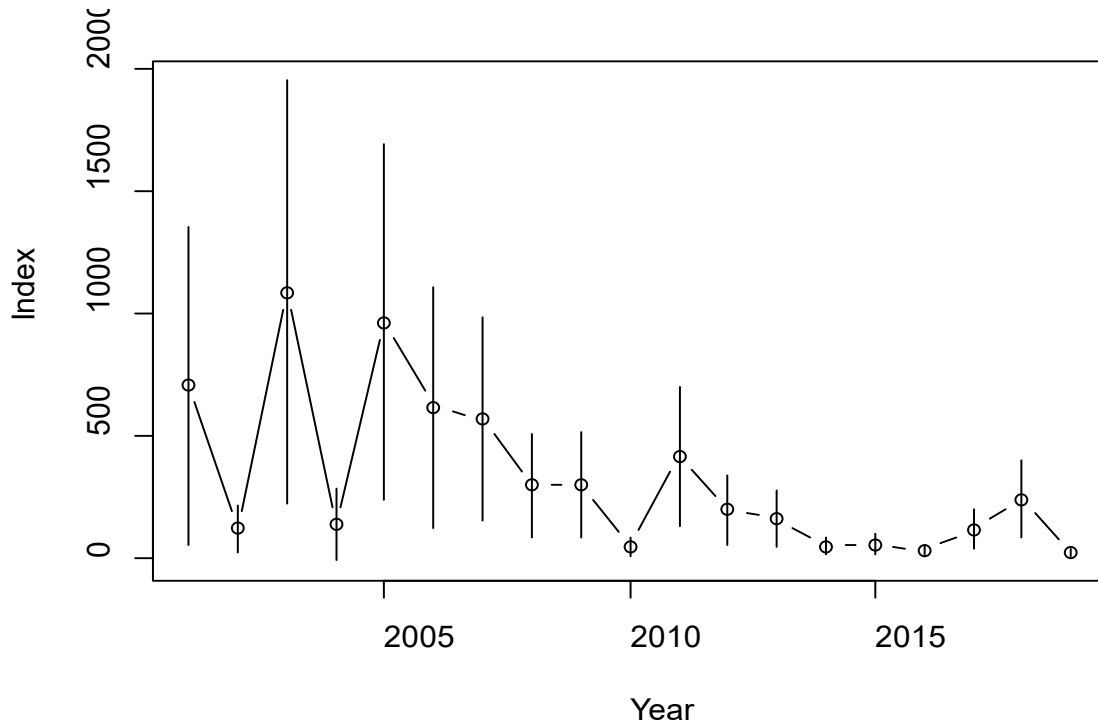


Figure 38. Standardized index of relative YOY abundance developed from Massachusetts's Jones River Survey with 95% confidence intervals.

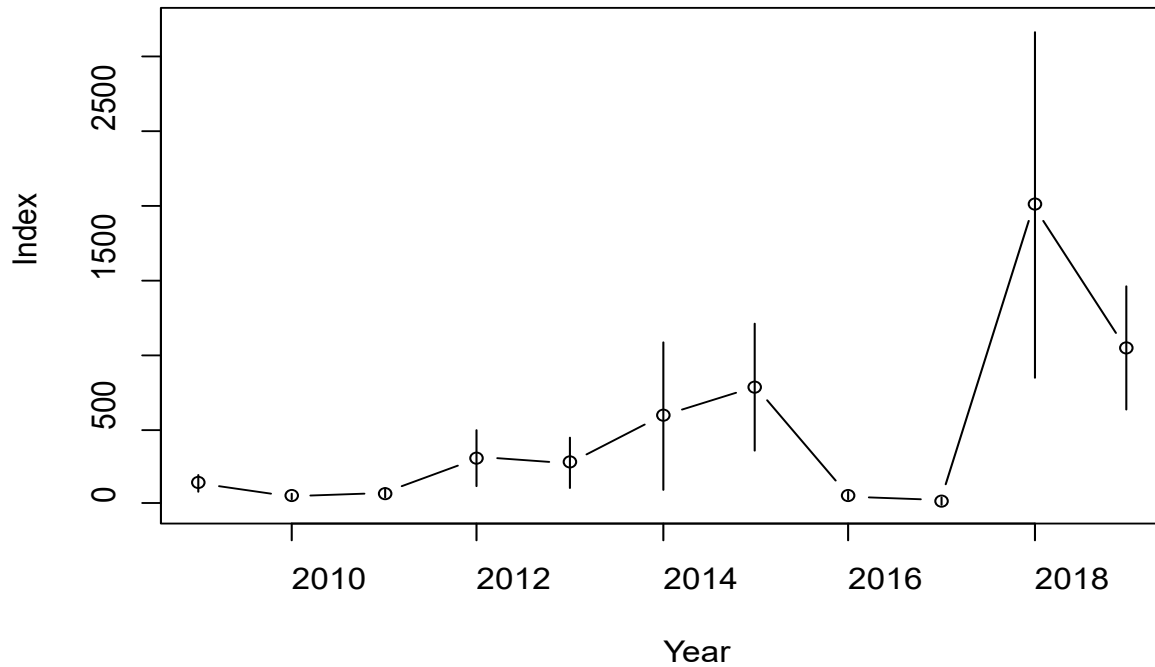


Figure 39. Standardized index of relative YOY abundance developed from Massachusetts's Wankinco River Ramp Survey with 95% confidence intervals.

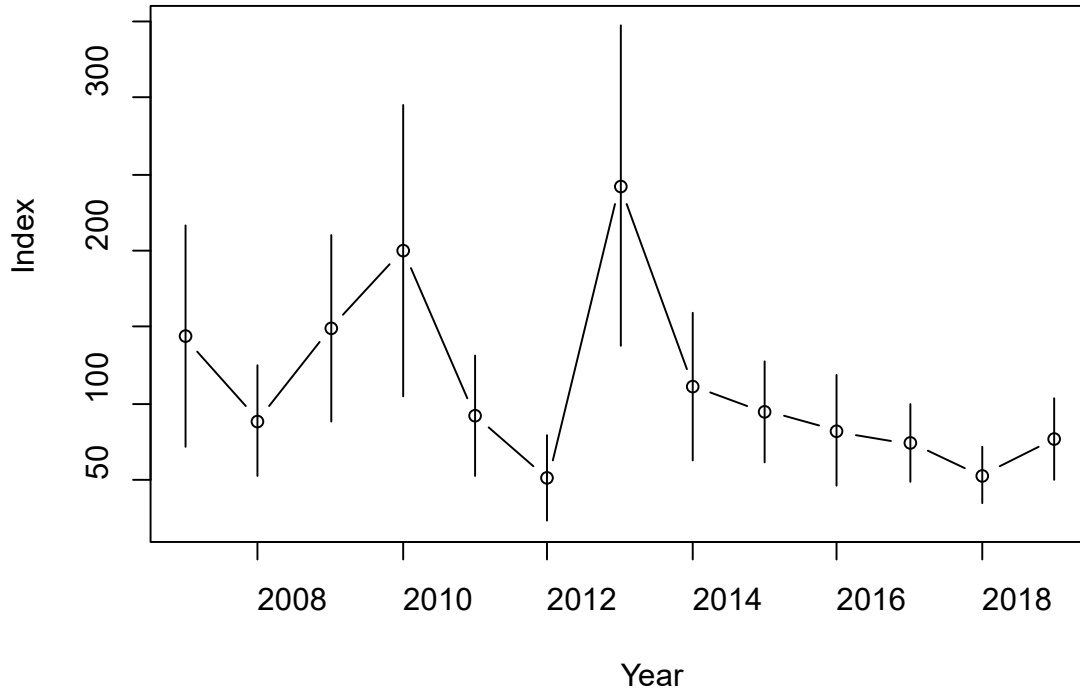


Figure 40. Standardized index of relative elver abundance developed from Massachusetts’s Saugus River Ramp Survey with 95% confidence intervals.

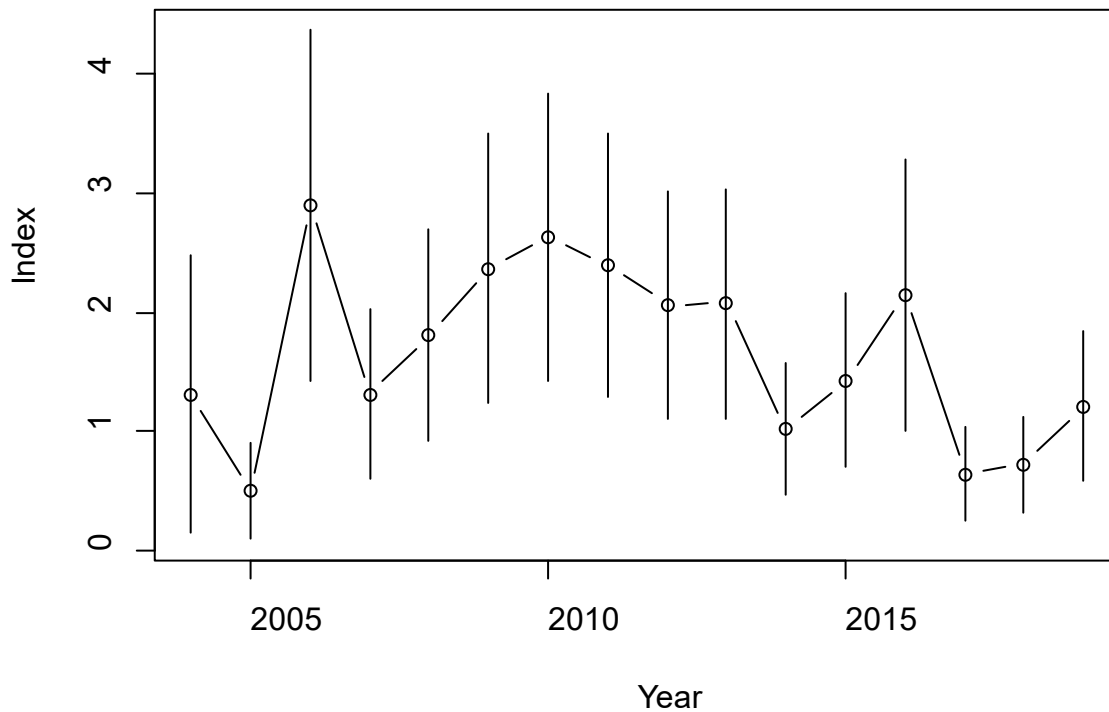


Figure 41. Standardized index of relative abundance of yellow eel developed from the Massachusetts Rainbow Smelt Fyke Survey with 95% confidence intervals.

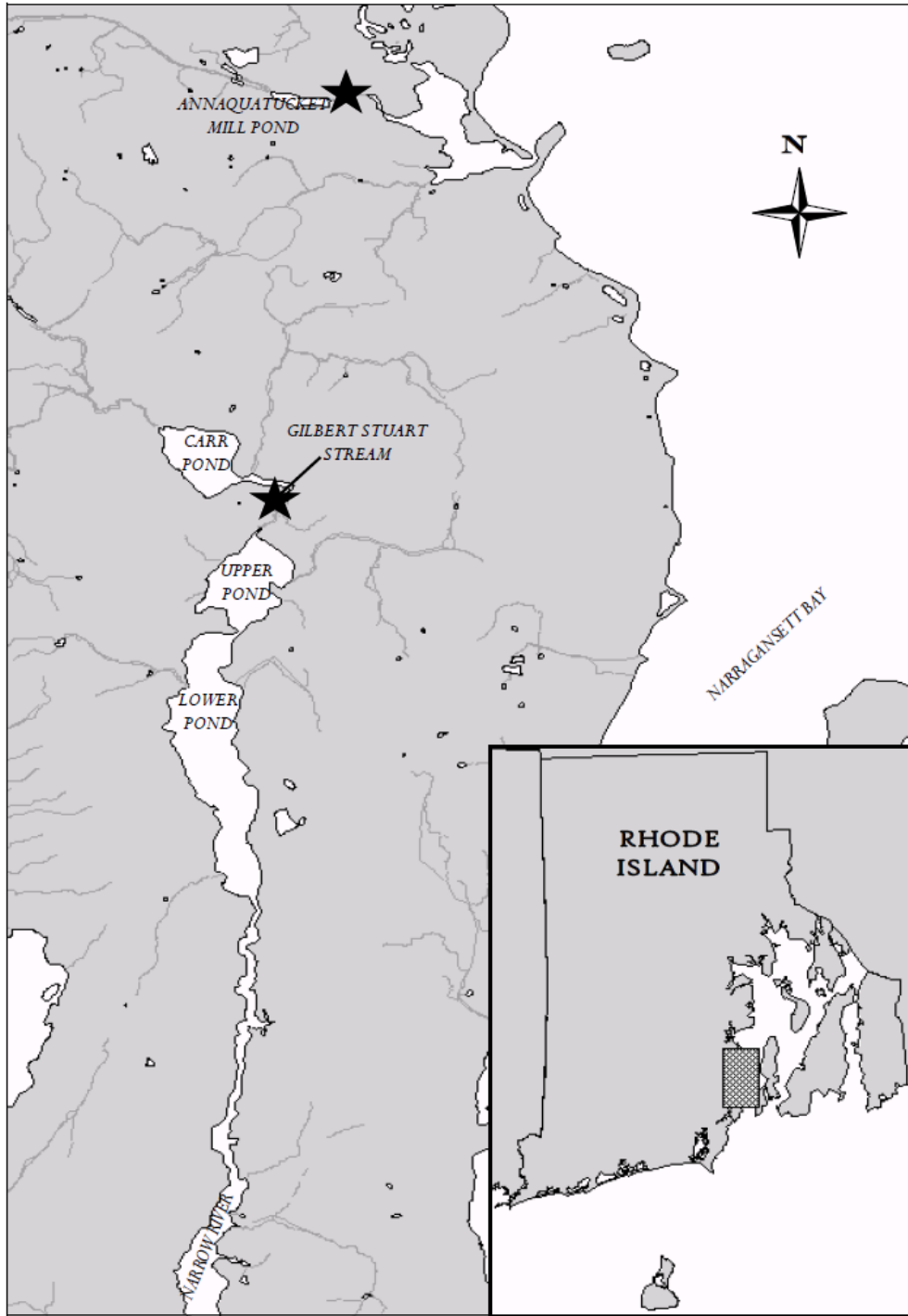


Figure 42. Map of American eel monitoring sites in Rhode Island including the YOY survey at Gilbert Stuart Stream.

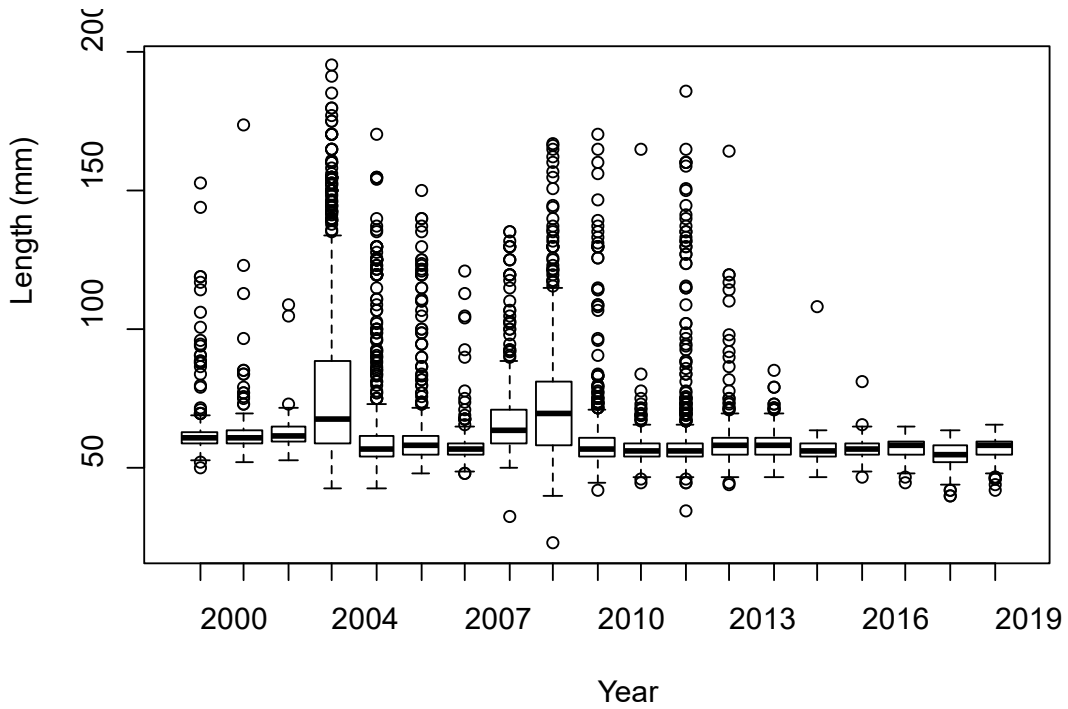


Figure 43. Boxplot of American eel YOY lengths recorded in the Rhode Island Gilbert Stuart Dam Survey.

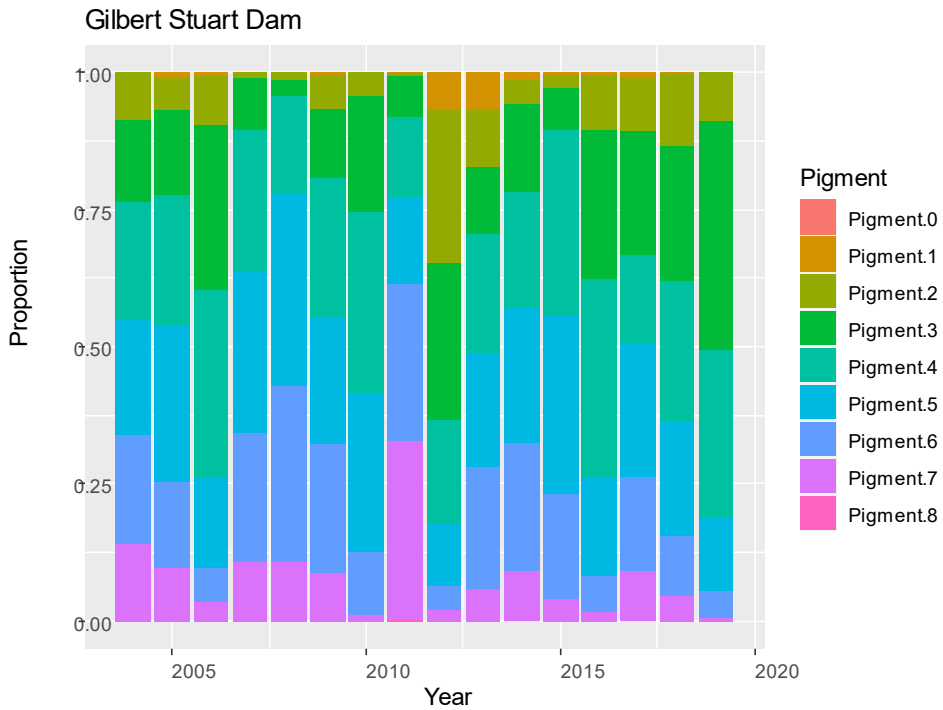


Figure 44. Distribution of pigment stages in the Gilbert Stuart Dam YOY American eel survey.

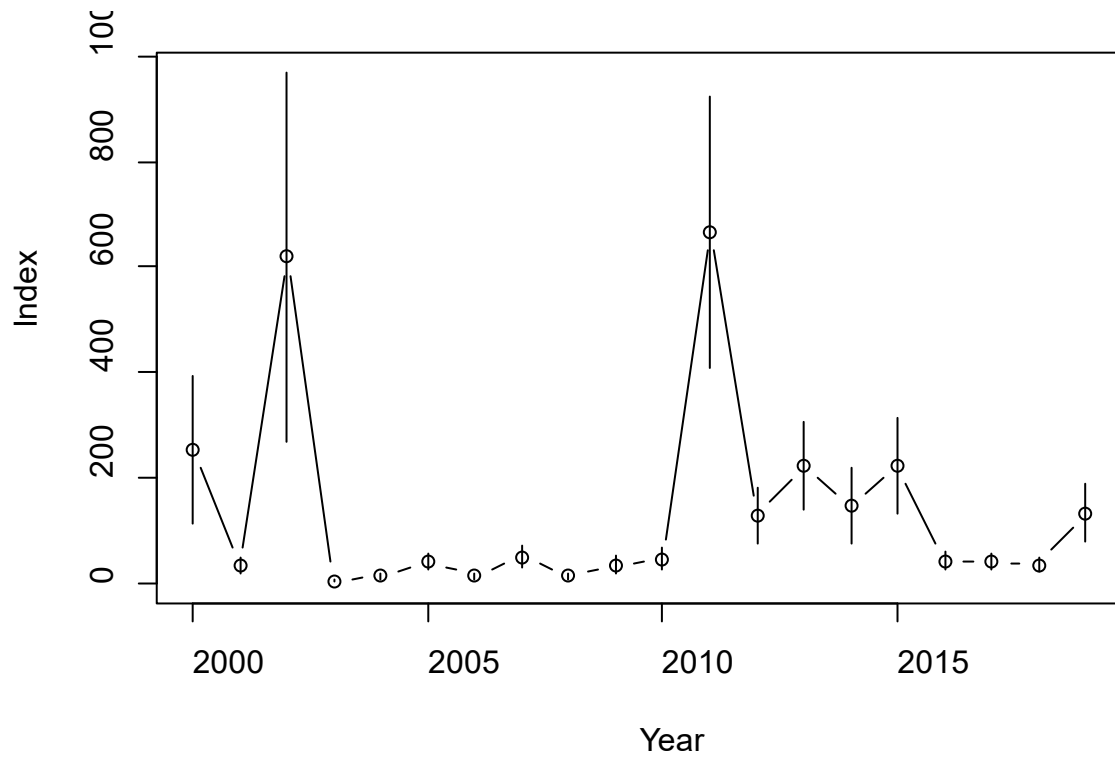


Figure 45. Standardized index of relative YOY abundance developed from Rhode Island’s Gilbert Stuart Dam Survey with 95% confidence intervals.



Figure 46. Map of American eel YOY survey at the Hamilton Fish Ladder.

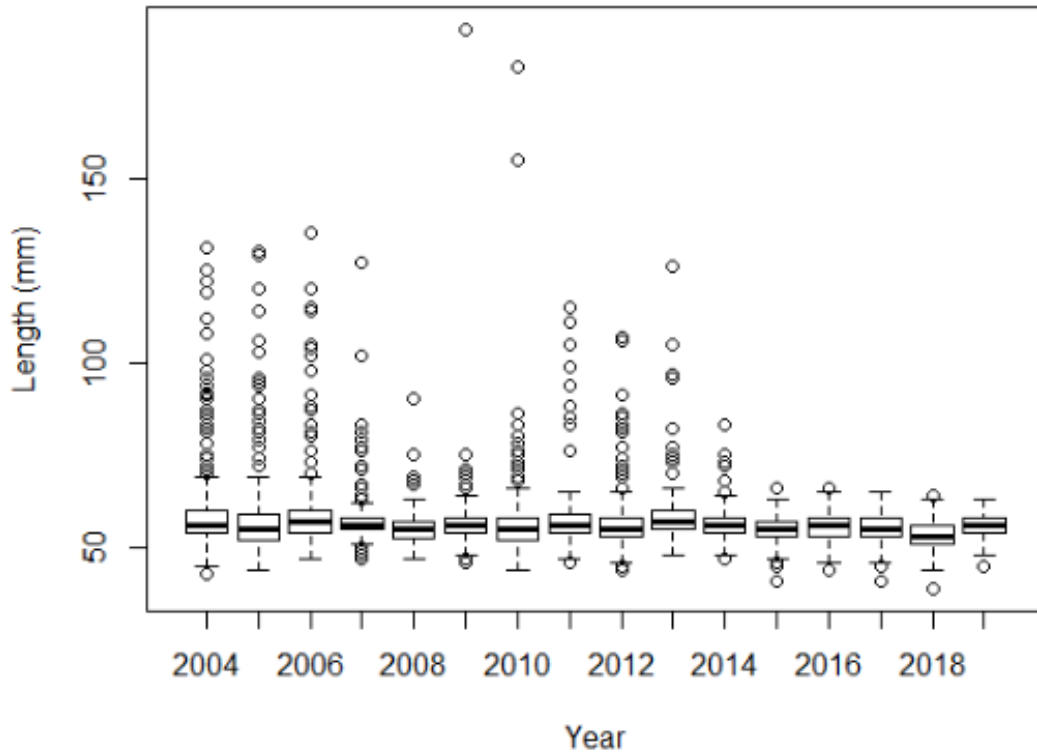


Figure 47. Boxplot of American eel YOY lengths recorded in the Rhode Island Hamilton Fish Ladder Survey.

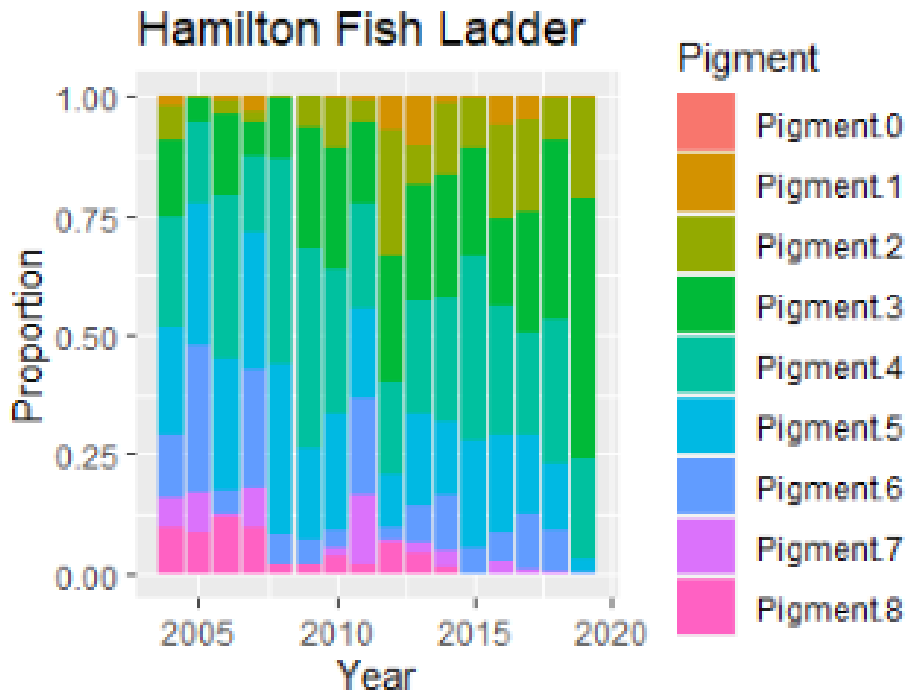


Figure 48. Distribution of pigment stages in the Hamilton Fish Ladder YOY American eel survey.

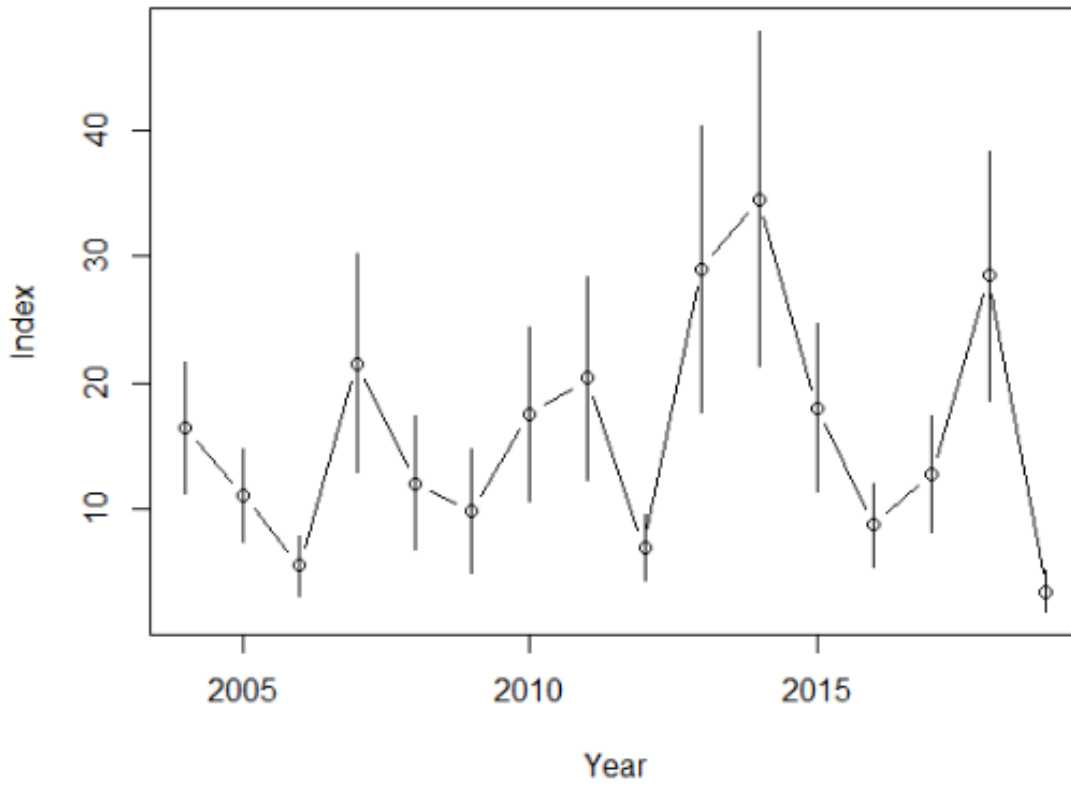


Figure 49. Standardized index of relative YOY abundance developed from Rhode Island’s Hamilton Fish Ladder survey with 95% confidence intervals.



Figure 50. Map of the YOY Ingham Hill/Fishing Brook Eel Ramp as provided by CT DEEP.

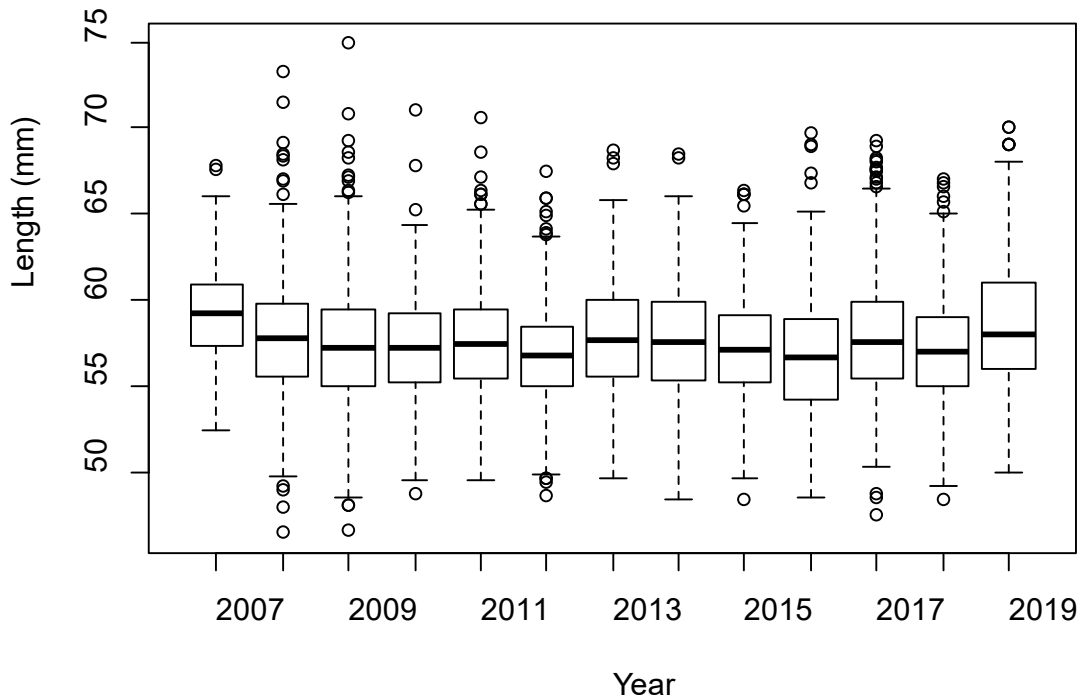


Figure 51. Boxplot of American eel YOY lengths recorded in the Connecticut Ingham Hill Survey.

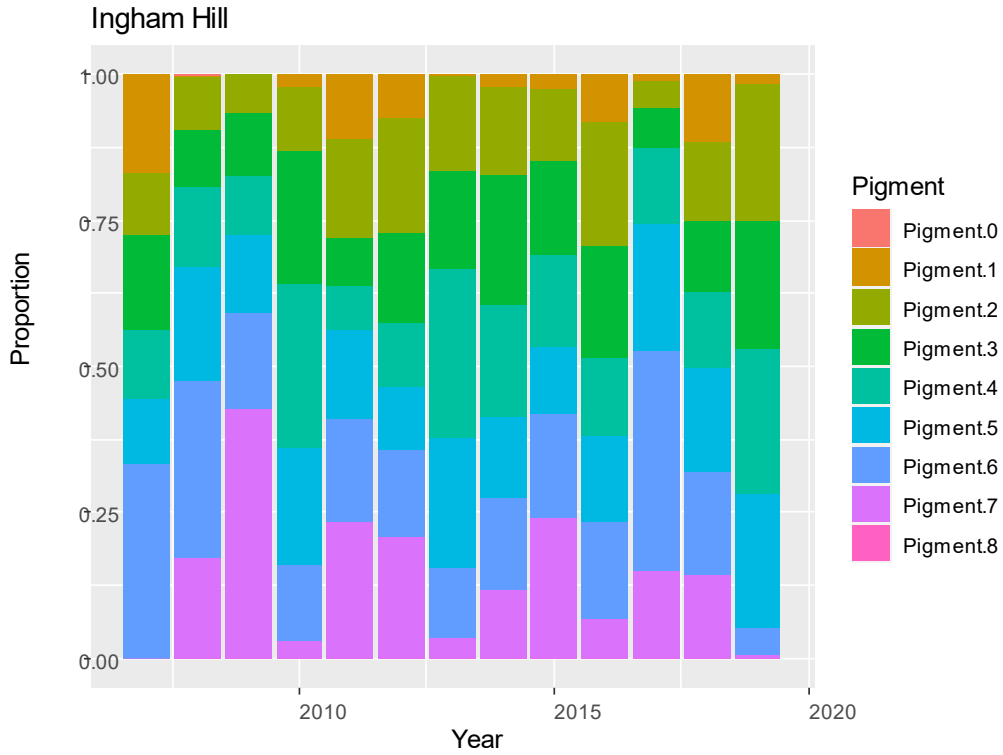


Figure 52. Distribution of pigment stages in the Ingham Hill YOY American eel survey.

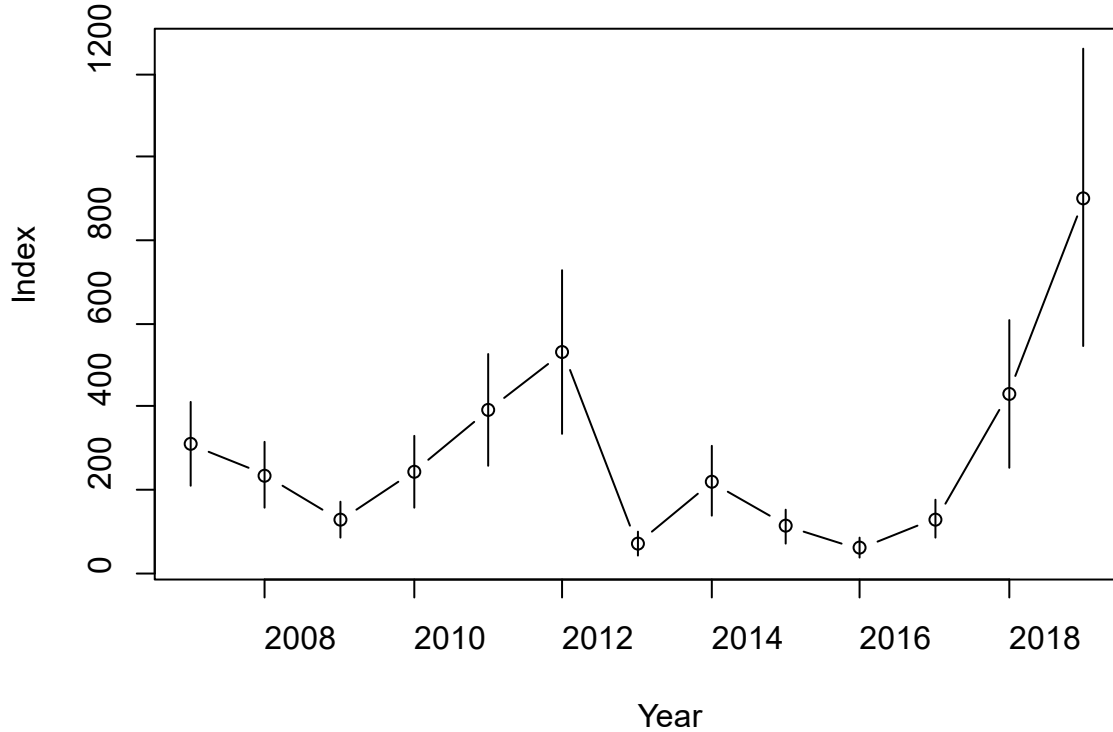


Figure 53. Standardized index of relative YOY abundance developed from Connecticut's Ingham Hill Survey with 95% confidence intervals.

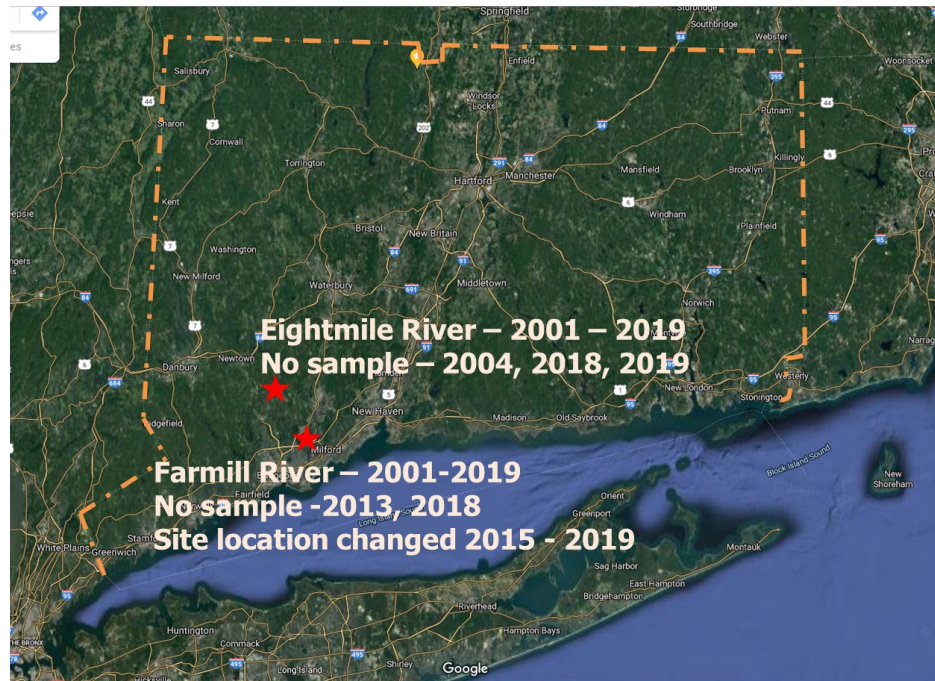


Figure 54. Map of the Connecticut electrofishing surveys used in this assessment as provided by CT DEEP.

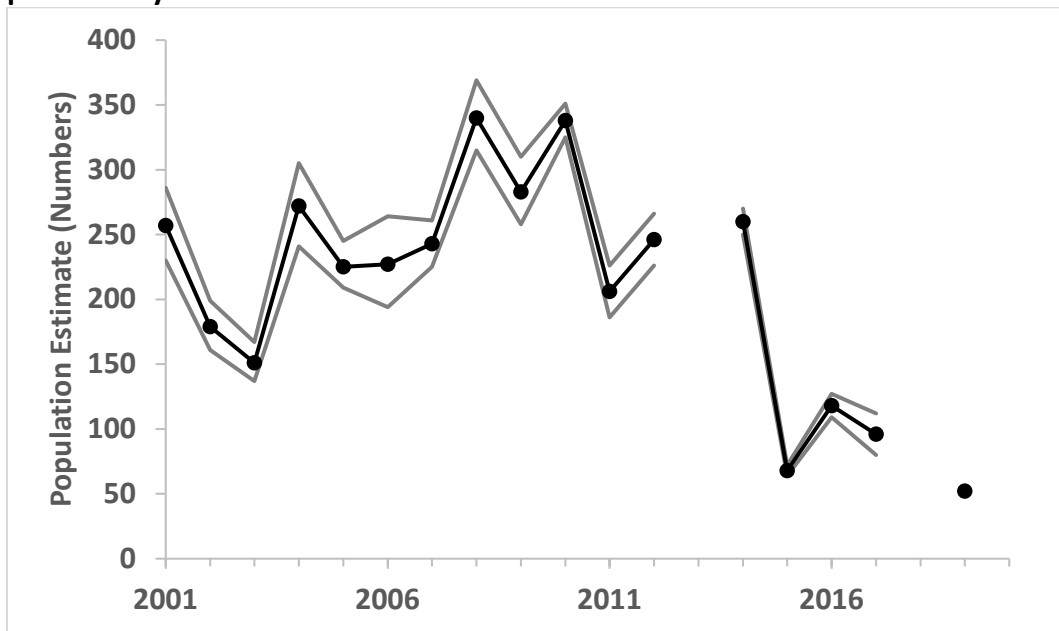


Figure 55. Population estimate for American eels caught by the CT DEEP Electrofishing Survey in the Farmill River. The grey lines represent 95% confidence intervals. The survey did not collect data in 2013 and 2018 and the survey changed sites in 2015.

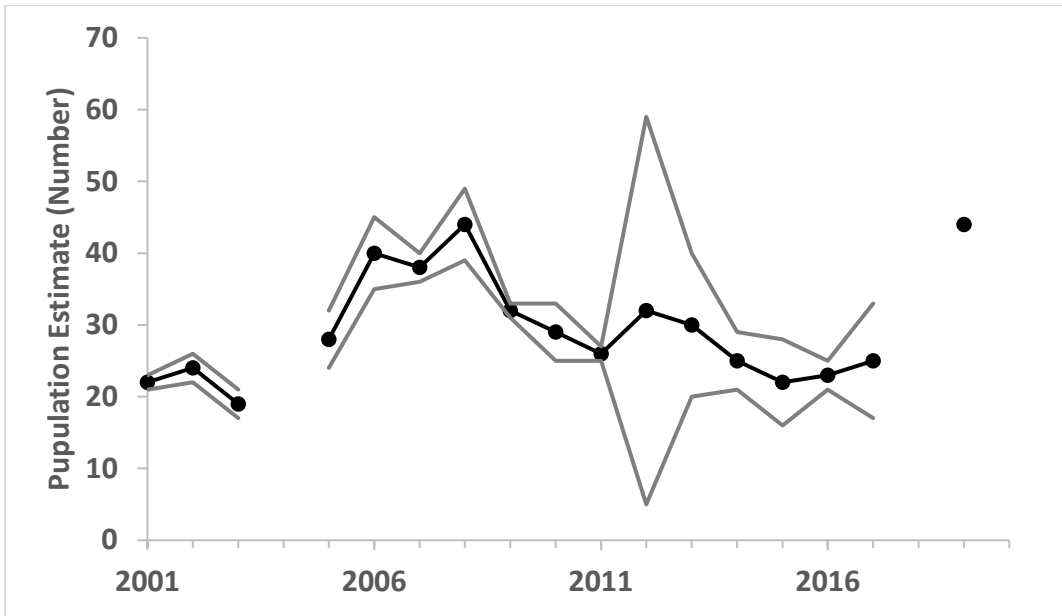


Figure 56. Population estimate for American eels caught by the CT DEEP Electrofishing Survey in the Eightmile River. The grey lines represent 95% confidence intervals.

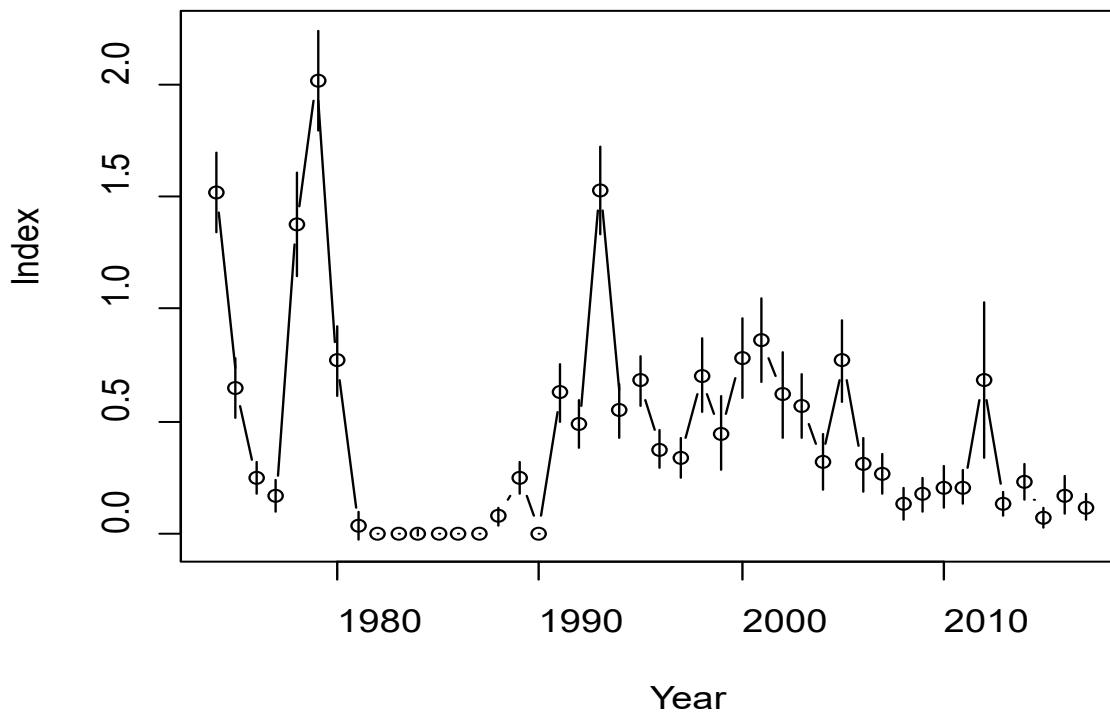


Figure 57. Standardized index of relative abundance of YOY eel developed from the Hudson River Estuary Monitoring Program with 95% confidence intervals.

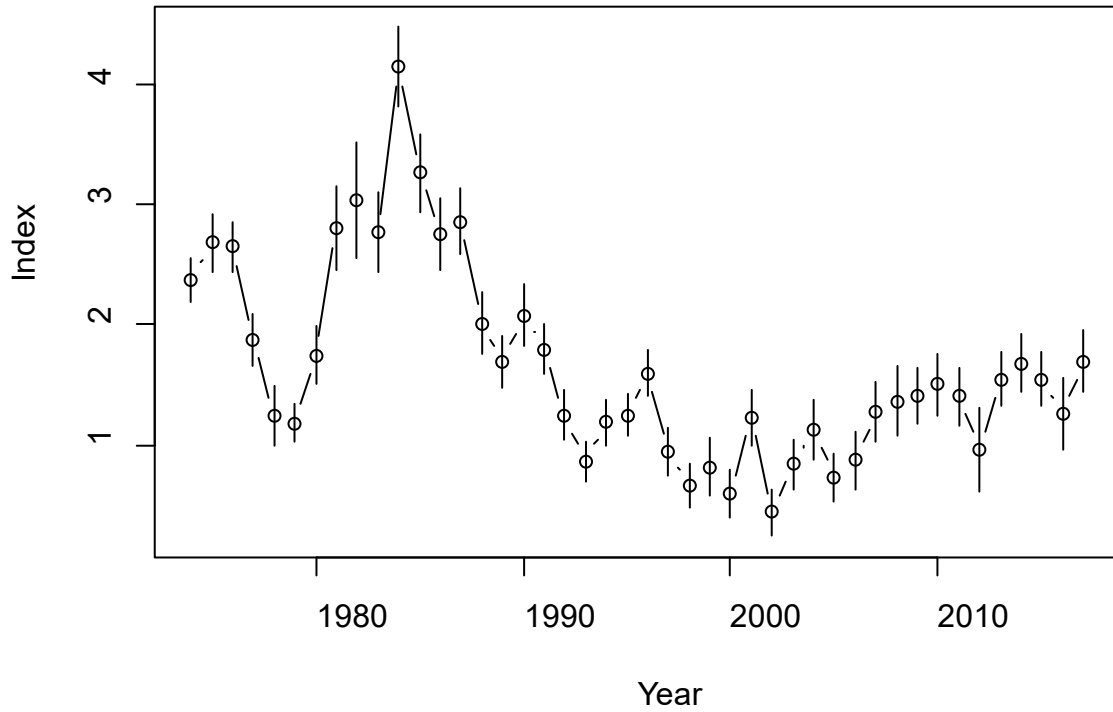


Figure 58. Standardized index of relative abundance of yellow eel developed from the Hudson River Estuary Monitoring Program with 95% confidence intervals.

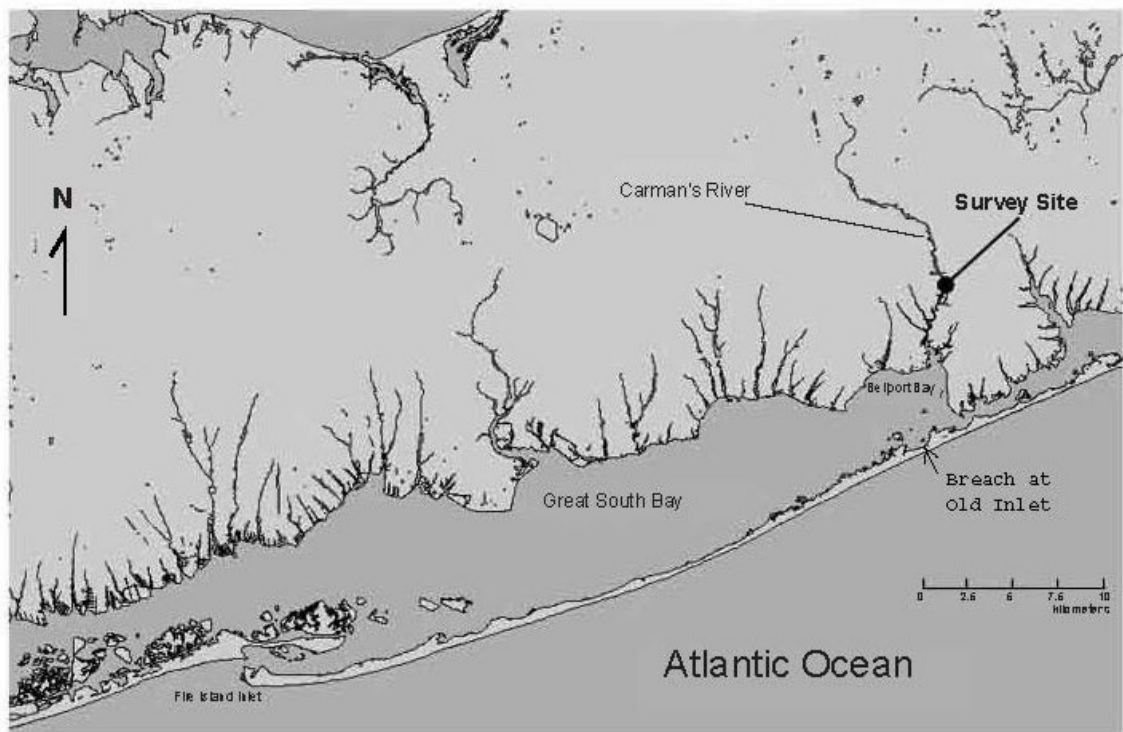


Figure 59. Map of Long Island showing the location of the Carman’s River American eel YOY fyke net sampling site.

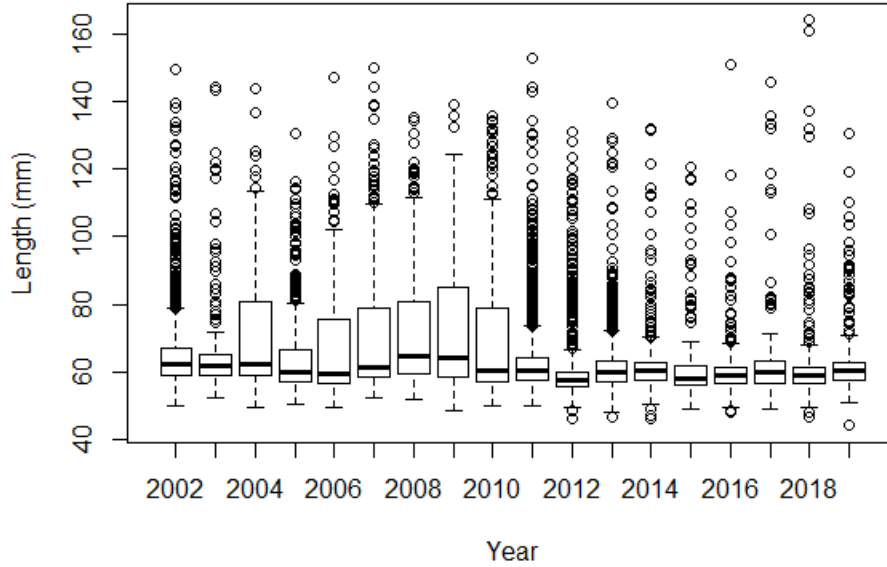


Figure 60. Boxplot of American eel lengths recorded in the Carman’s River YOY American eel survey.

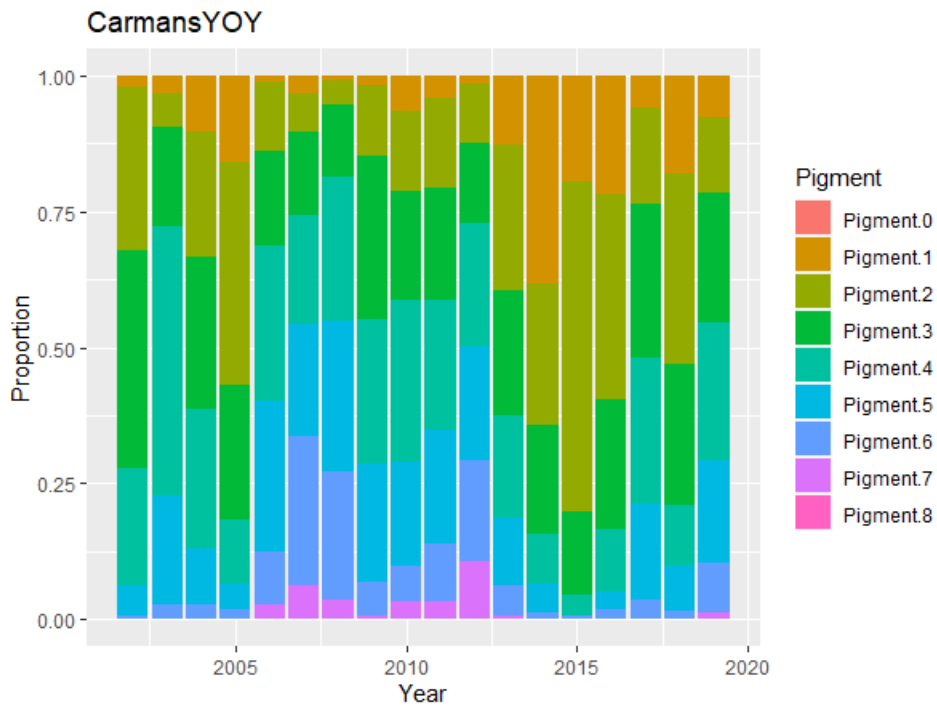


Figure 61. Distribution of pigment stages in the Carman’s River YOY American eel survey.

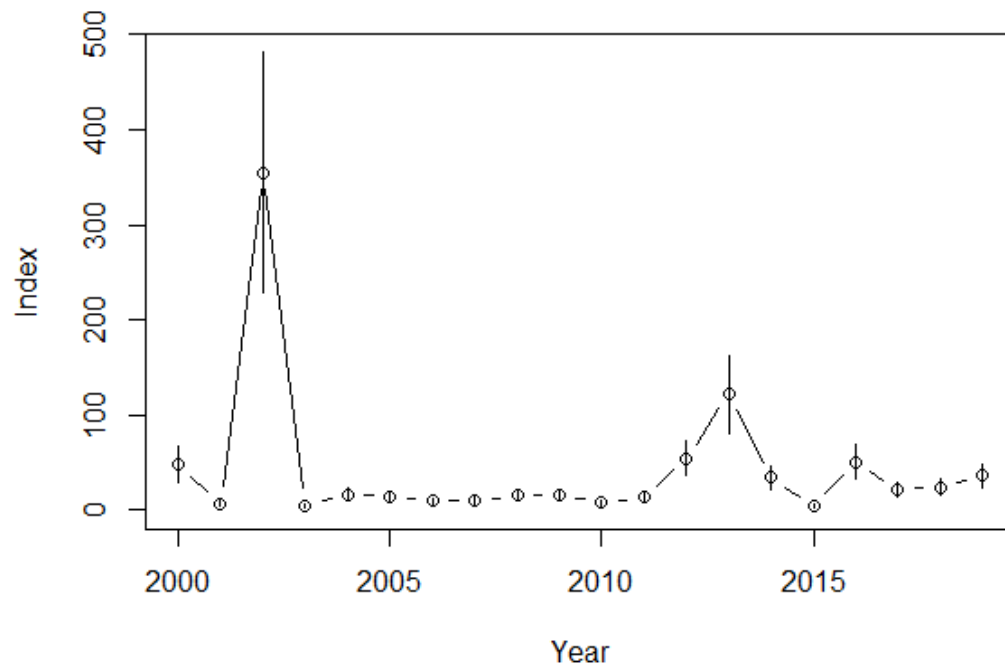


Figure 62. Standardized index of relative abundance of YOY eel developed from the NYSDEC Carman’s River survey with 95% confidence intervals.

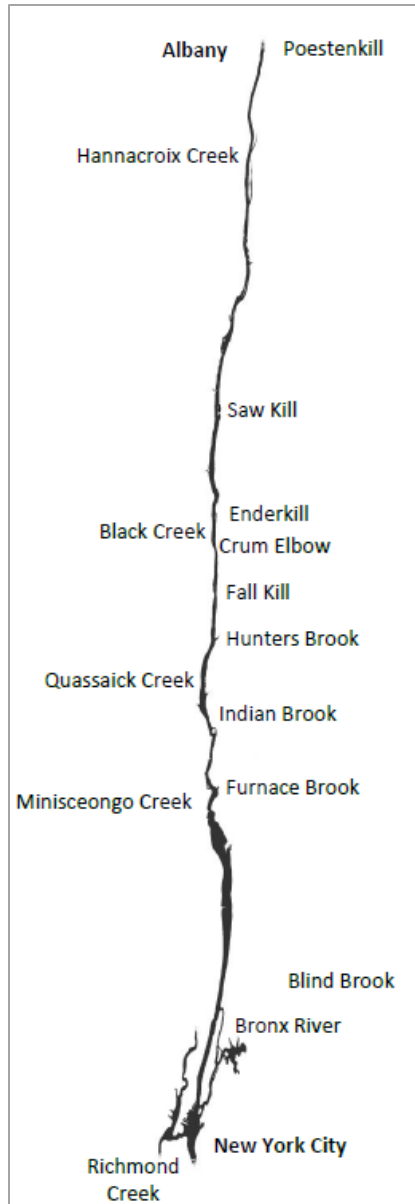


Figure 63. Map of the NYSDEC Hudson River citizen science survey sampling sites.

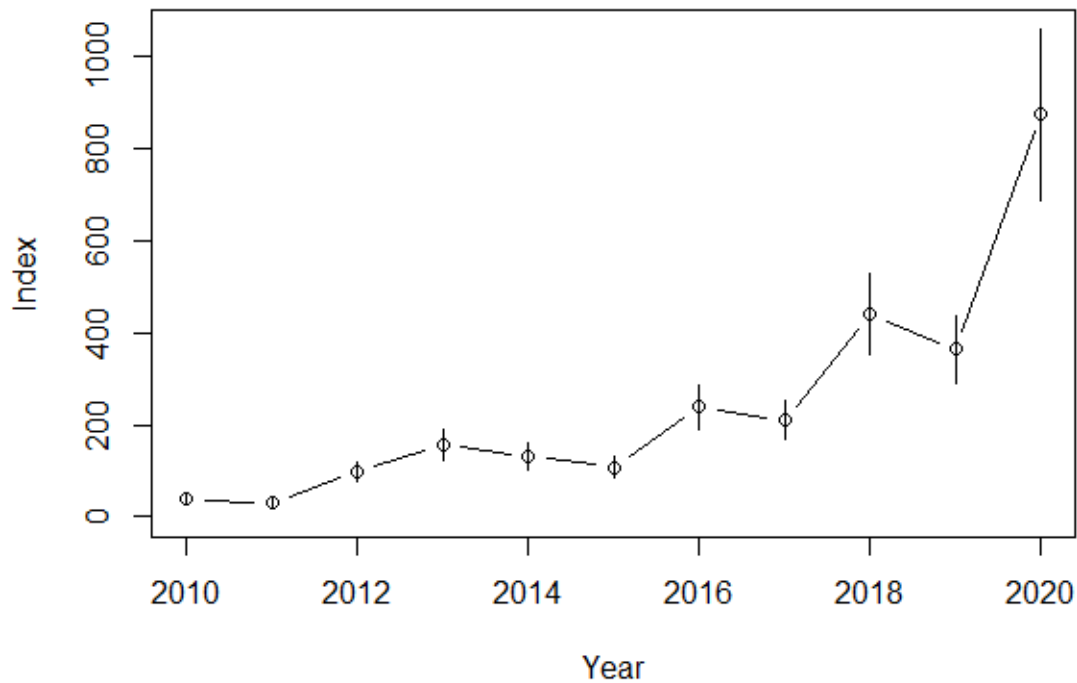


Figure 64. Standardized index of relative abundance of YOY eel developed from the NYSDEC Hudson River citizen science survey with 95% confidence intervals.

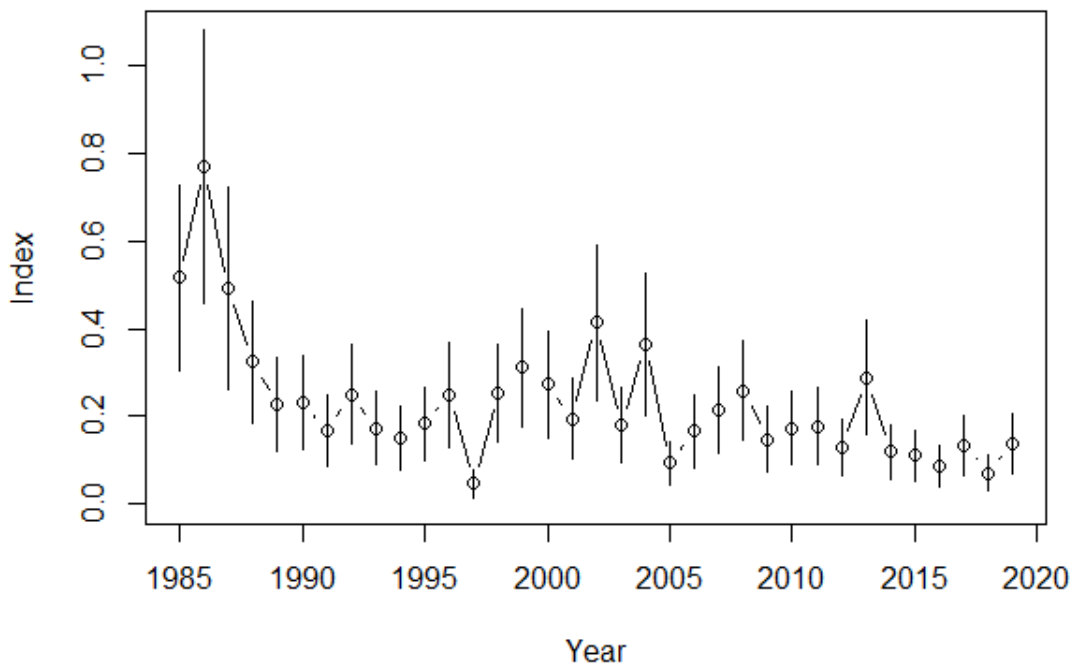


Figure 65. Standardized index of relative abundance of yellow eel developed from the NYSDEC Hudson River Juvenile Alosine Seine survey with 95% confidence intervals.

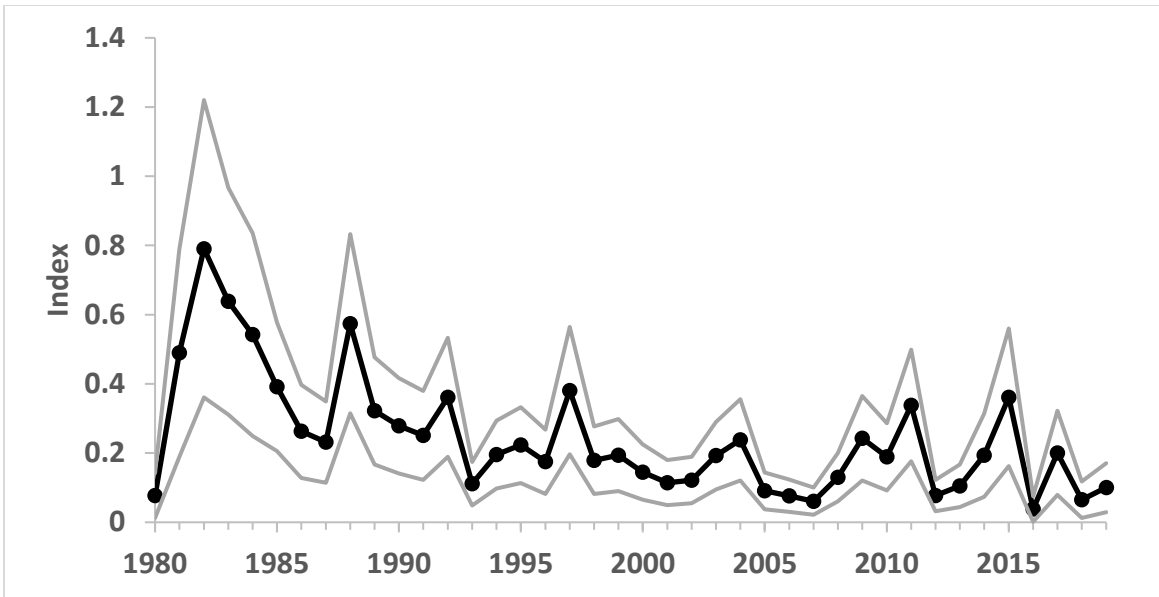


Figure 66. Standardized index of relative abundance of yellow eel developed from the NYSDEC Hudson River Juvenile Striped Bass Seine survey with 95% confidence intervals.

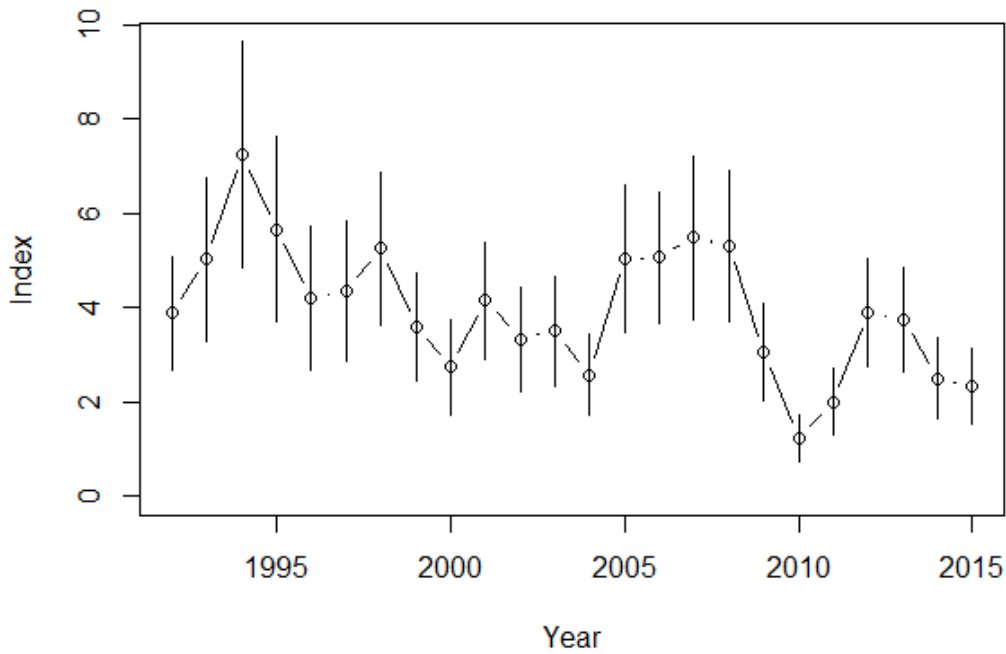


Figure 67. Standardized index of relative abundance of YOY eel developed from the Little Egg Inlet Ichthyoplankton survey with 95% confidence intervals.

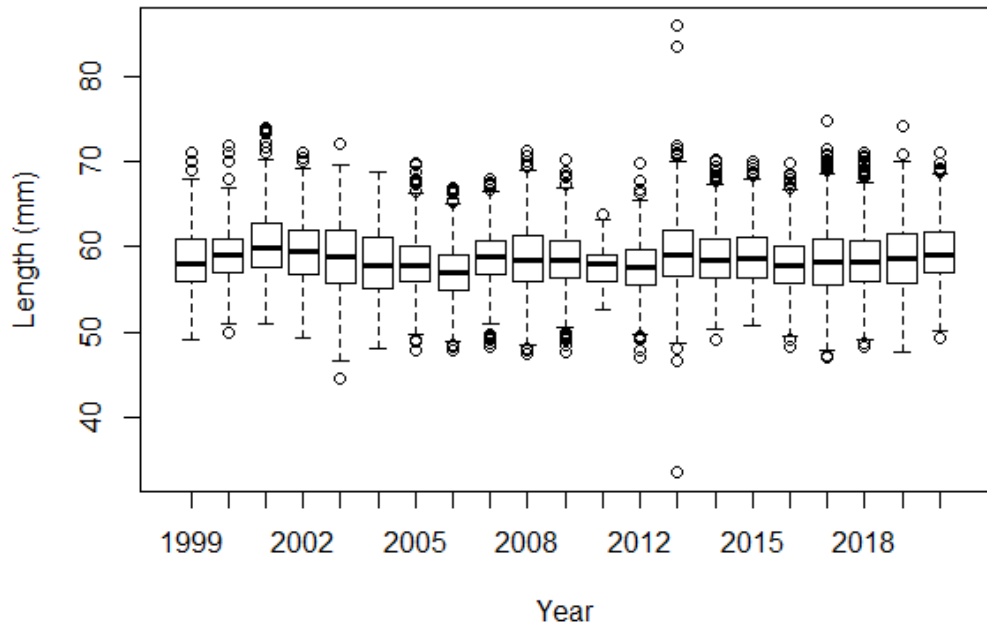


Figure 68. Boxplot of American eel lengths recorded in the Patcong Creek YOY American eel survey.

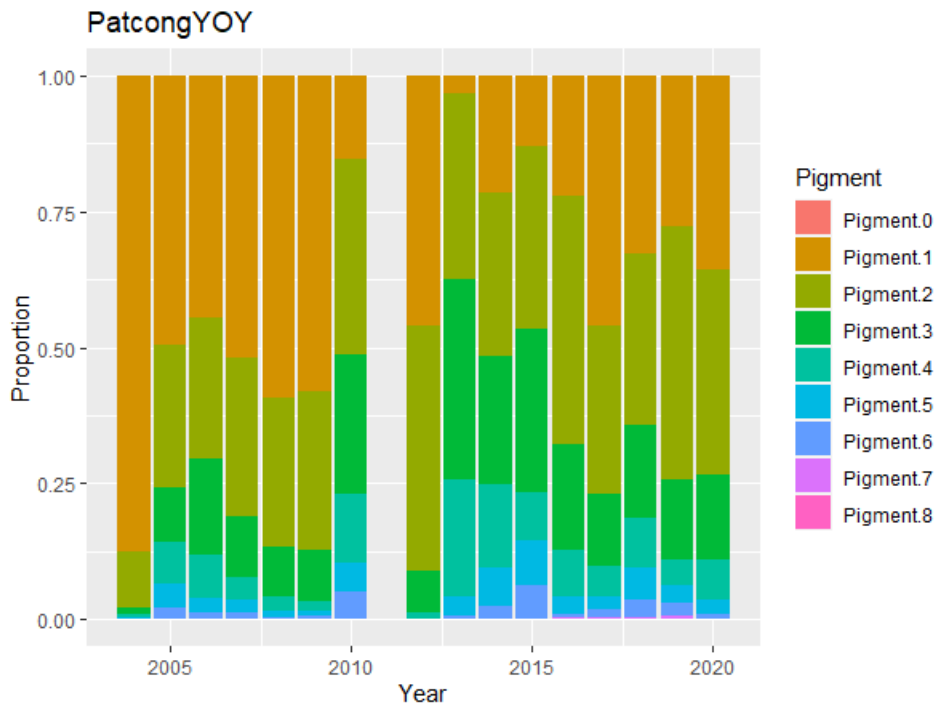


Figure 69. Distribution of pigment stages in the Patcong Creek YOY American eel survey.

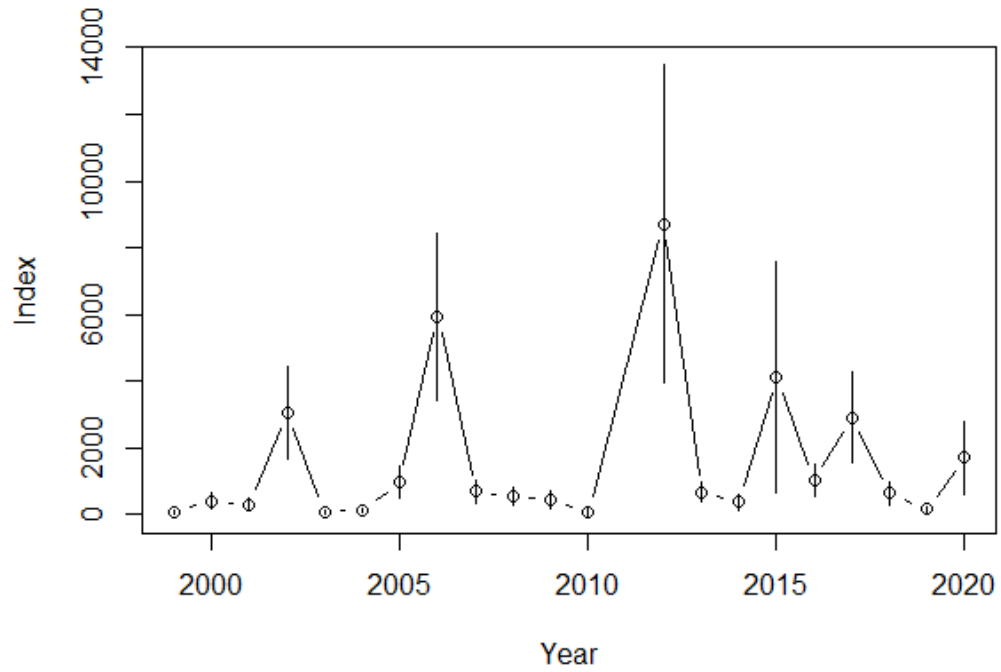


Figure 70. Standardized index of relative abundance of YOY eel developed from the Patcong Creek survey with 95% confidence intervals.

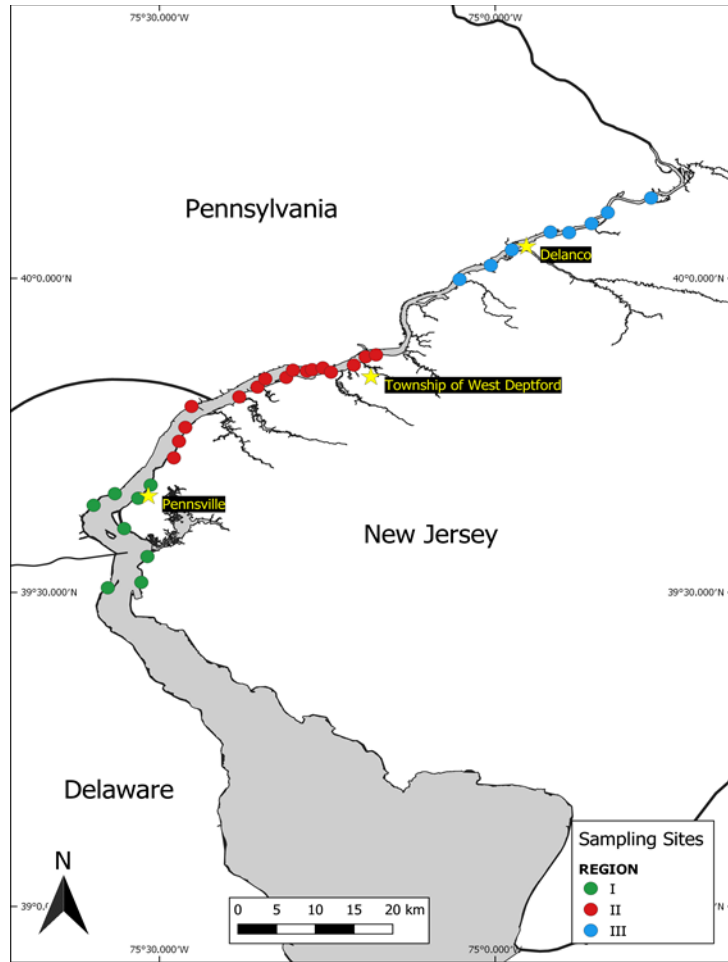


Figure 71. Map of sampling stations for the Delaware River seine survey.

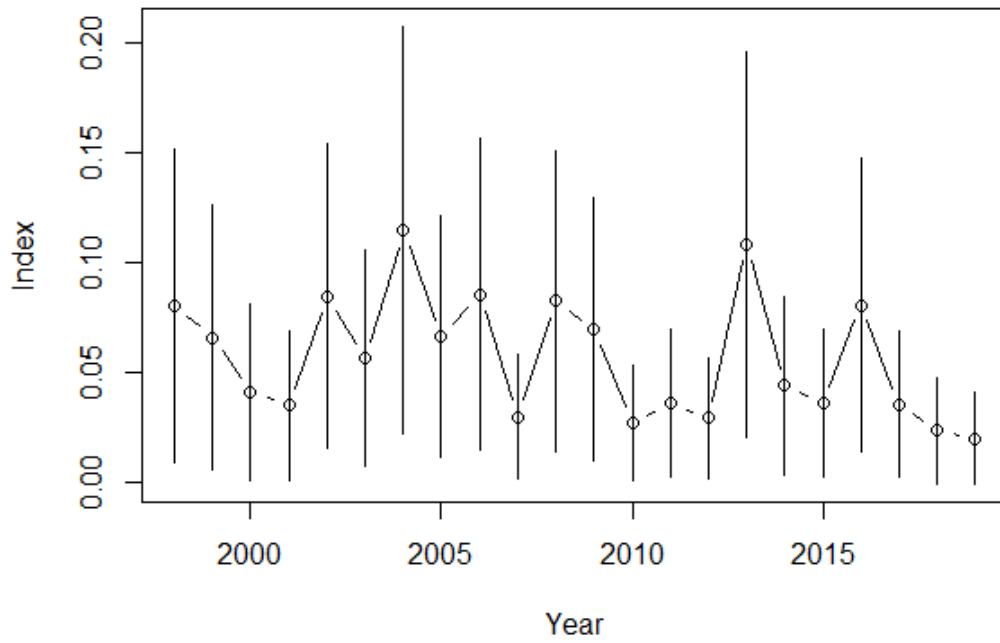


Figure 72. Standardized index of relative abundance of yellow eel developed from the Delaware River seine survey with 95% confidence intervals.

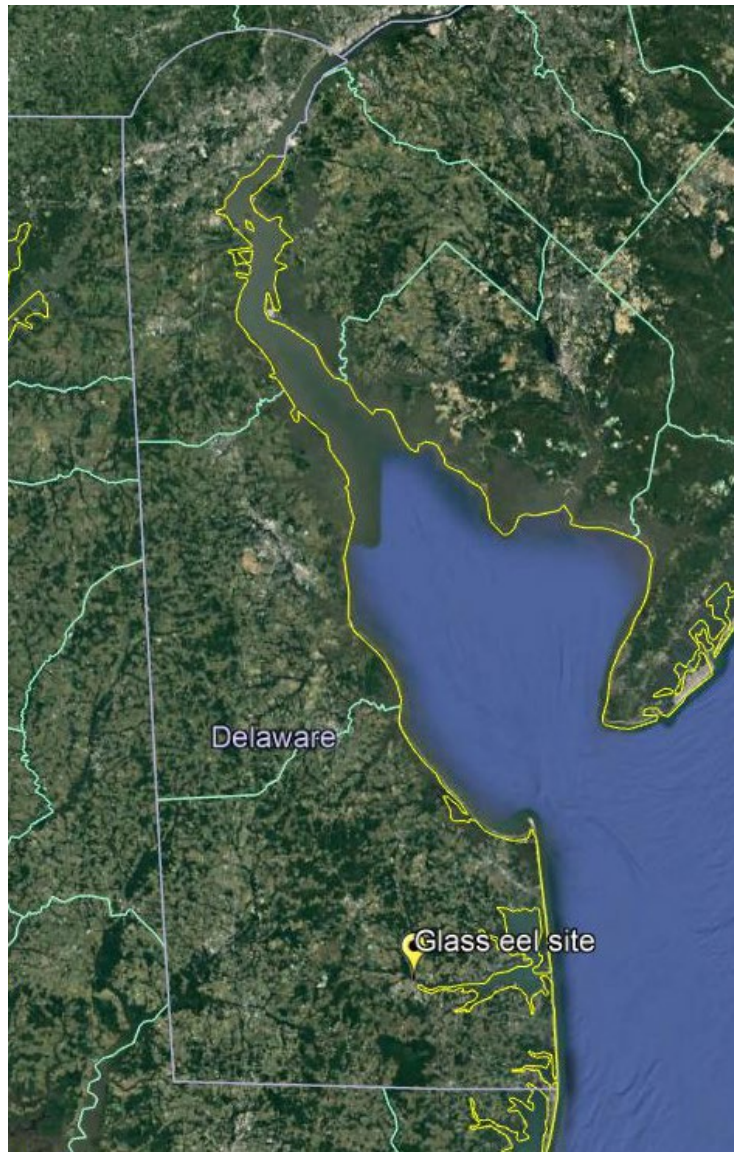


Figure 73. Delaware Millsboro Dam Survey fixed station sampling location.

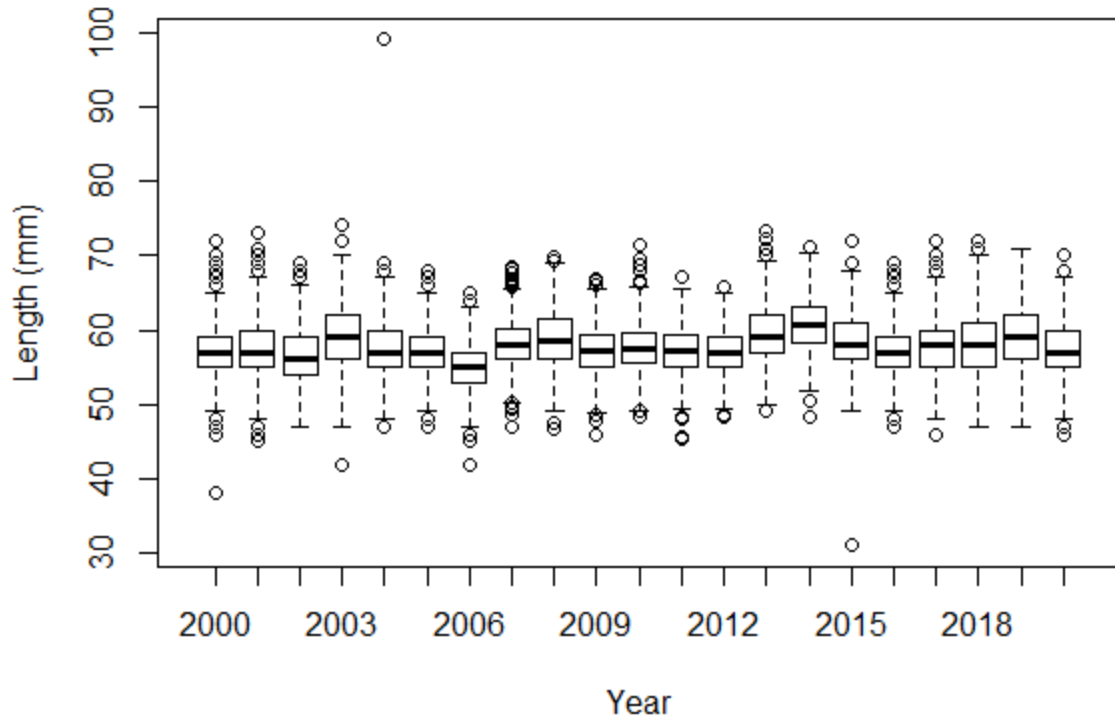


Figure 74. Boxplot of American eel lengths recorded in the Delaware Millsboro Dam Survey.

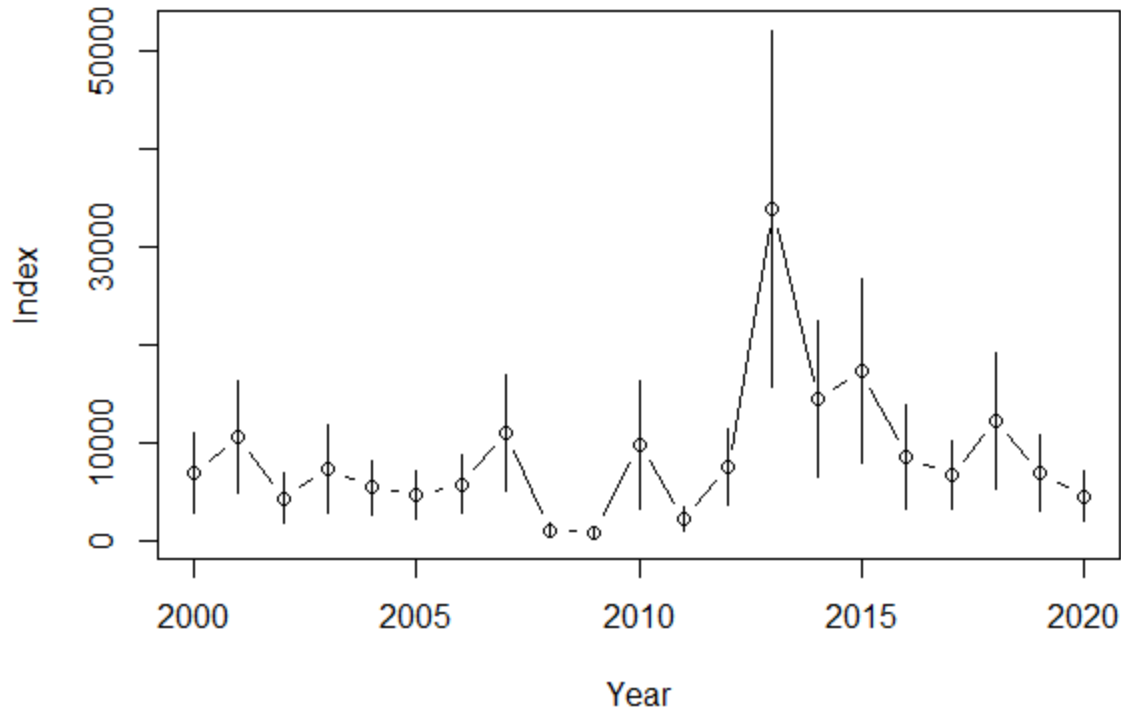


Figure 75. Standardized index of relative abundance of YOY eel developed from the Delaware Millsboro Dam Survey with 95% confidence intervals.

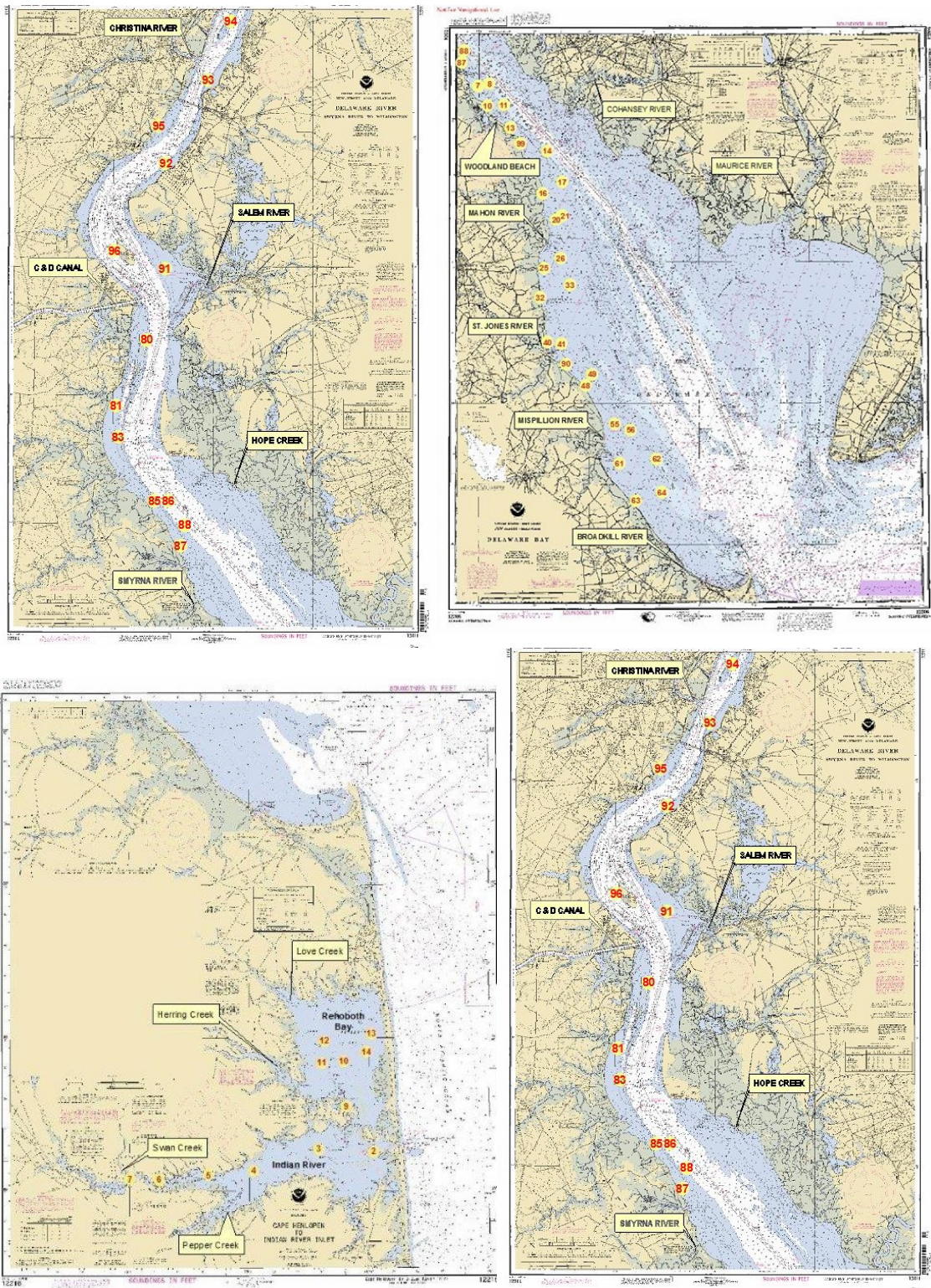


Figure 76. Delaware Juvenile Trawl Survey fixed station sampling locations.

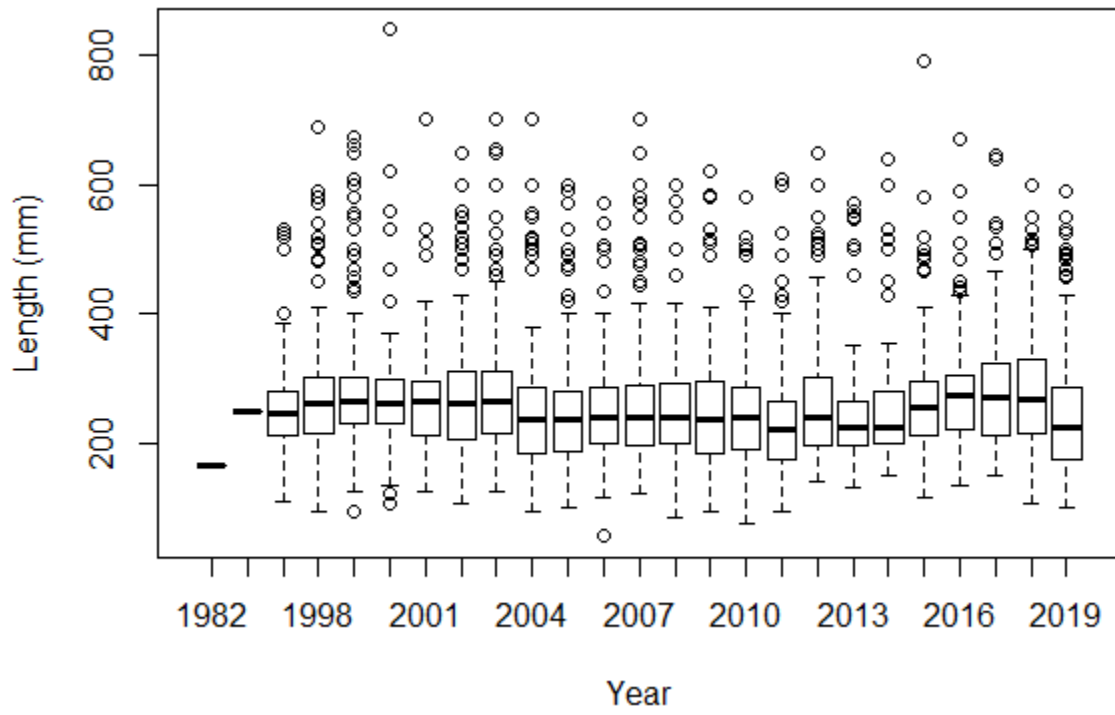


Figure 77. Boxplot of American eel lengths recorded in the Delaware Juvenile Trawl Survey.

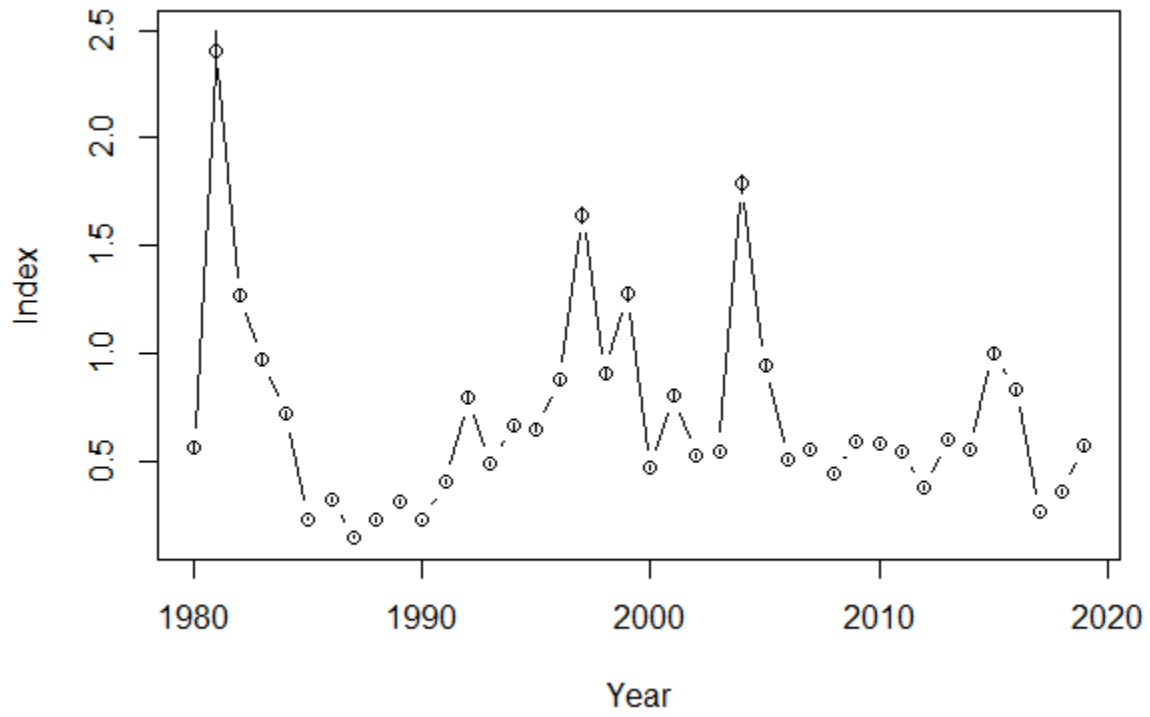


Figure 78. Index of relative abundance of yellow eel developed from the Delaware Juvenile Trawl Survey with 95% confidence intervals.



Figure 79. Pennsylvania Delaware River Area 6 Survey sampling locations.

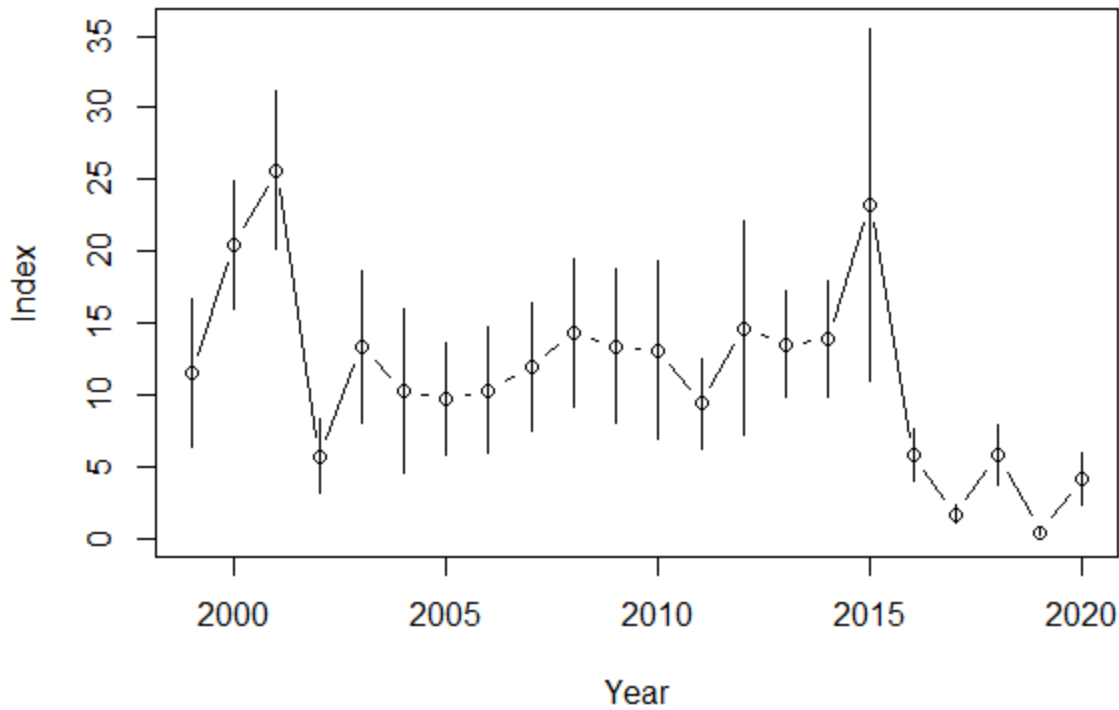


Figure 80. Index of relative abundance of elver eels developed from the Pennsylvania Delaware River Area 6 Survey with 95% confidence intervals.

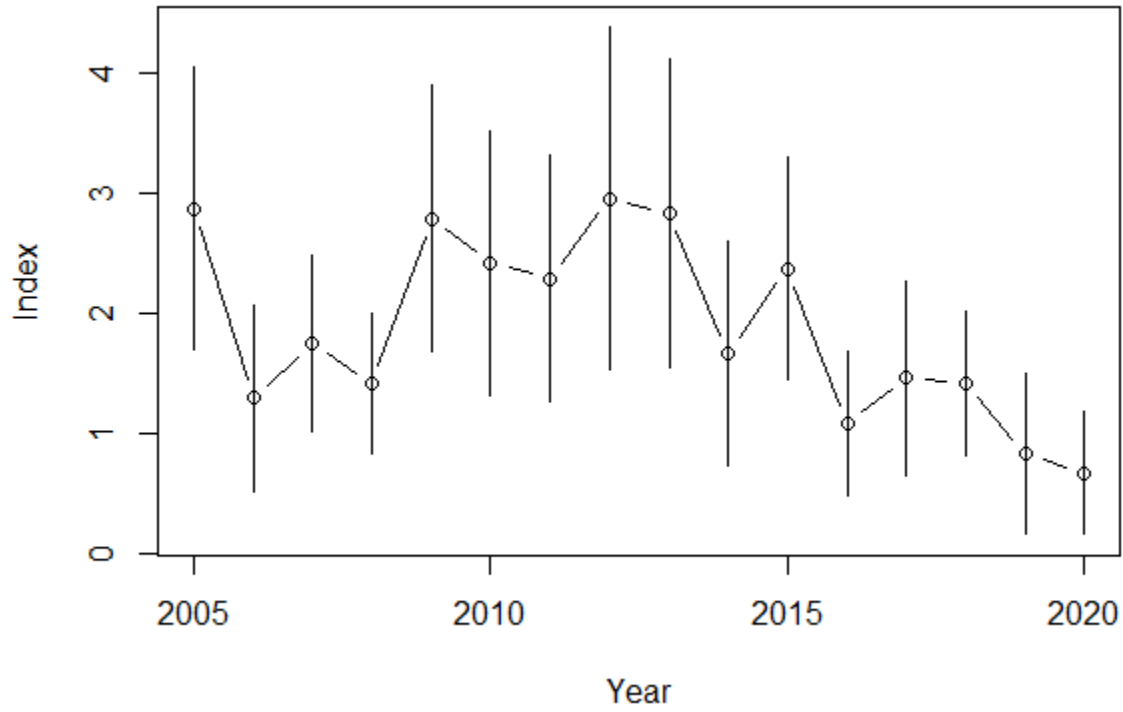


Figure 81. Index of relative abundance of yellow eels developed from the Pennsylvania Delaware River Area 6 Survey with 95% confidence intervals.

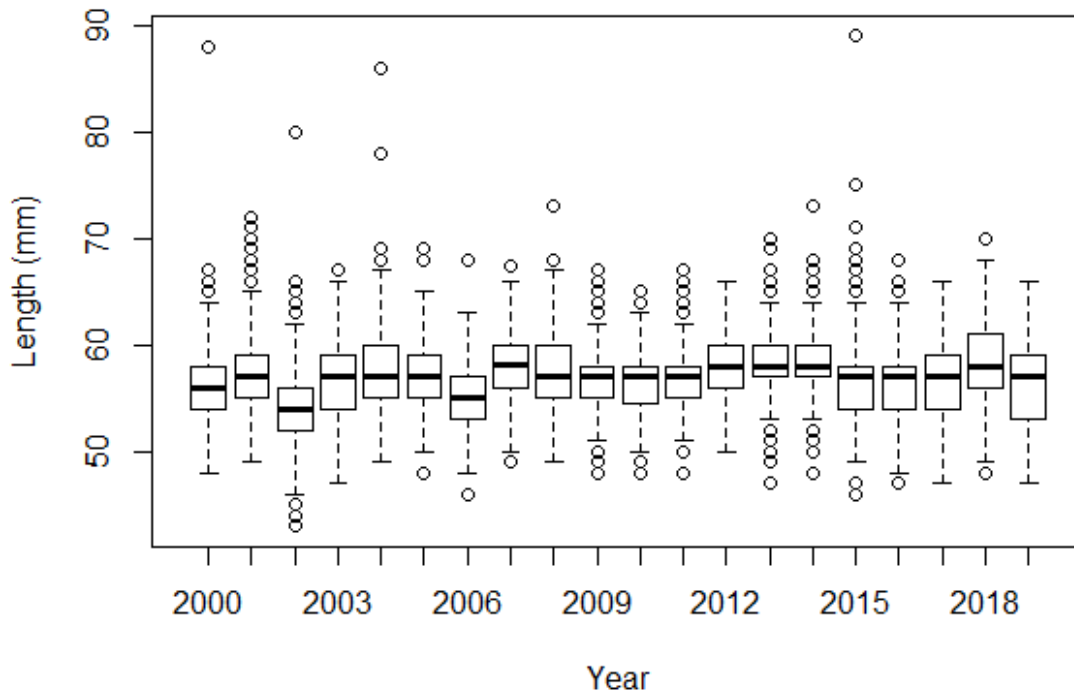


Figure 82. Glass eel total length measurements from Turville Creek, 2000 – 2019.

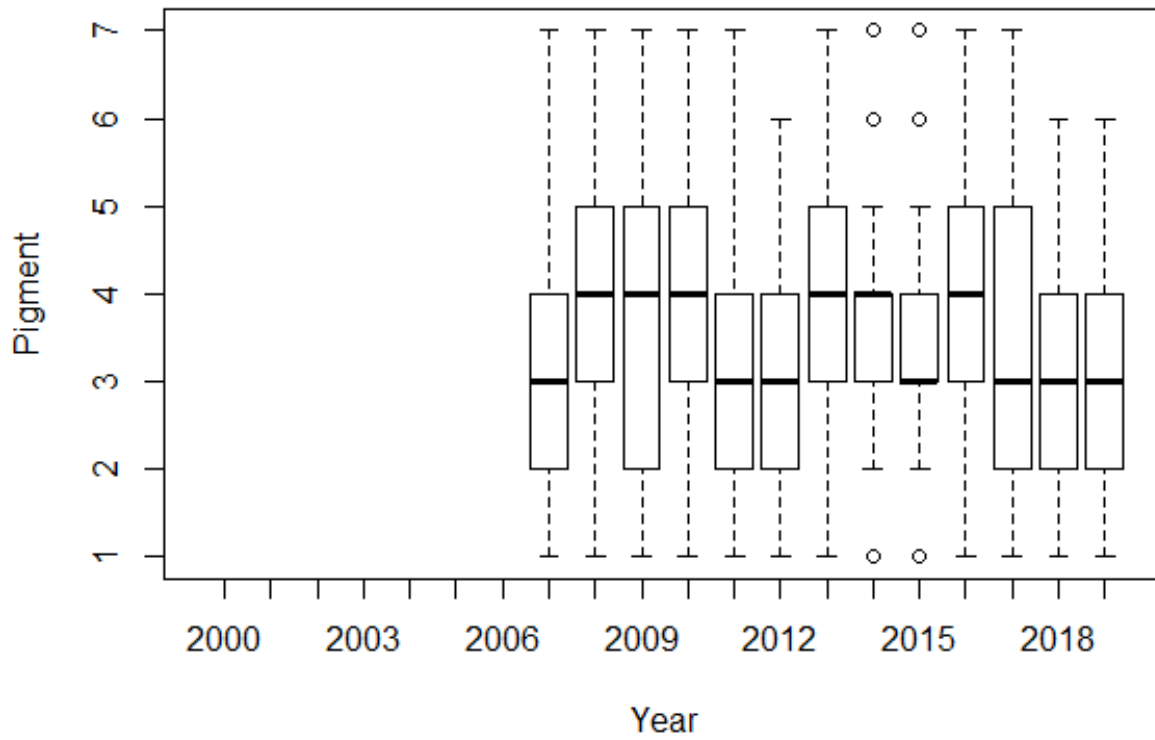


Figure 83. Glass eel pigment stage from Turville Creek, 2007 – 2019. Pigment stage was not assessed prior to 2007.

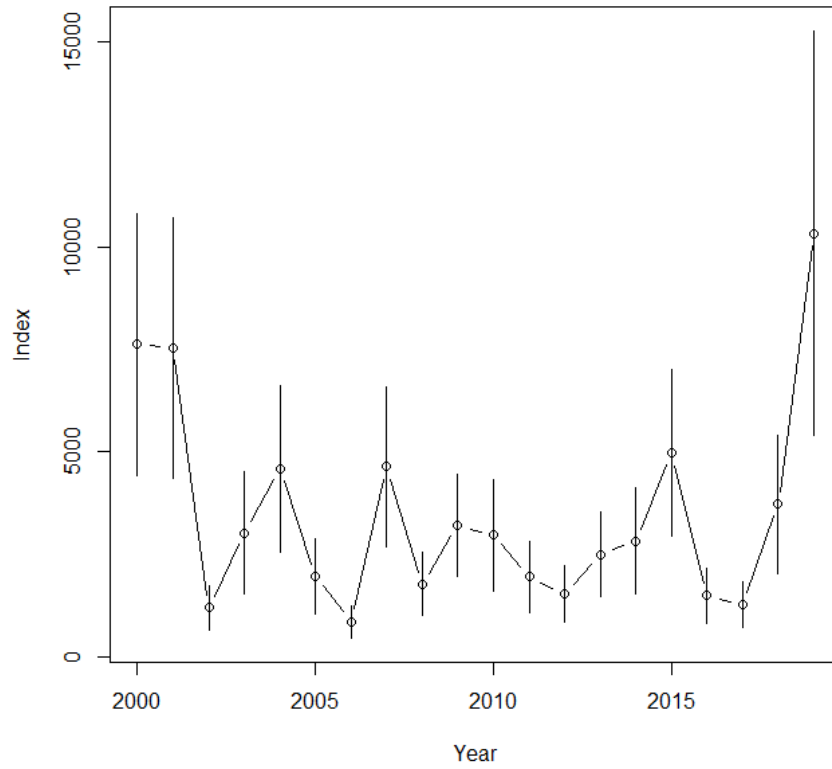


Figure 84. Standardized index of YOY relative abundance developed from Maryland’s Turville Creek YOY Survey with 95% confidence intervals.

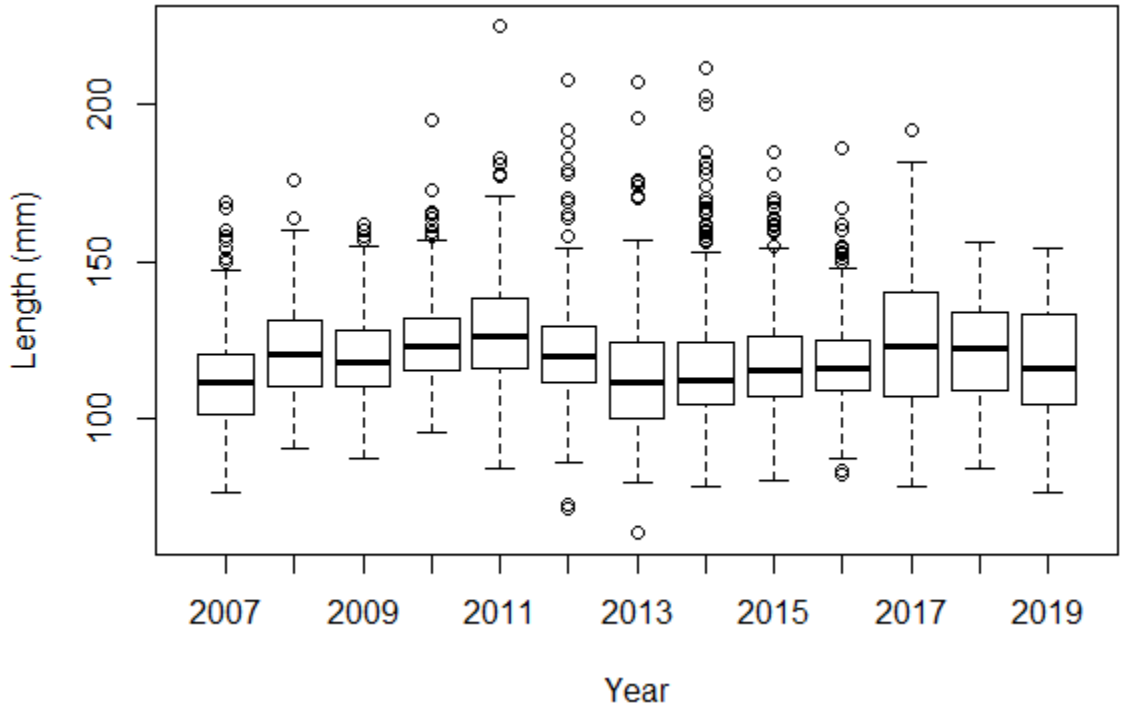


Figure 85. Elver total length measurements from the Maryland Susquehanna River Conowingo Dam Ramp Survey.

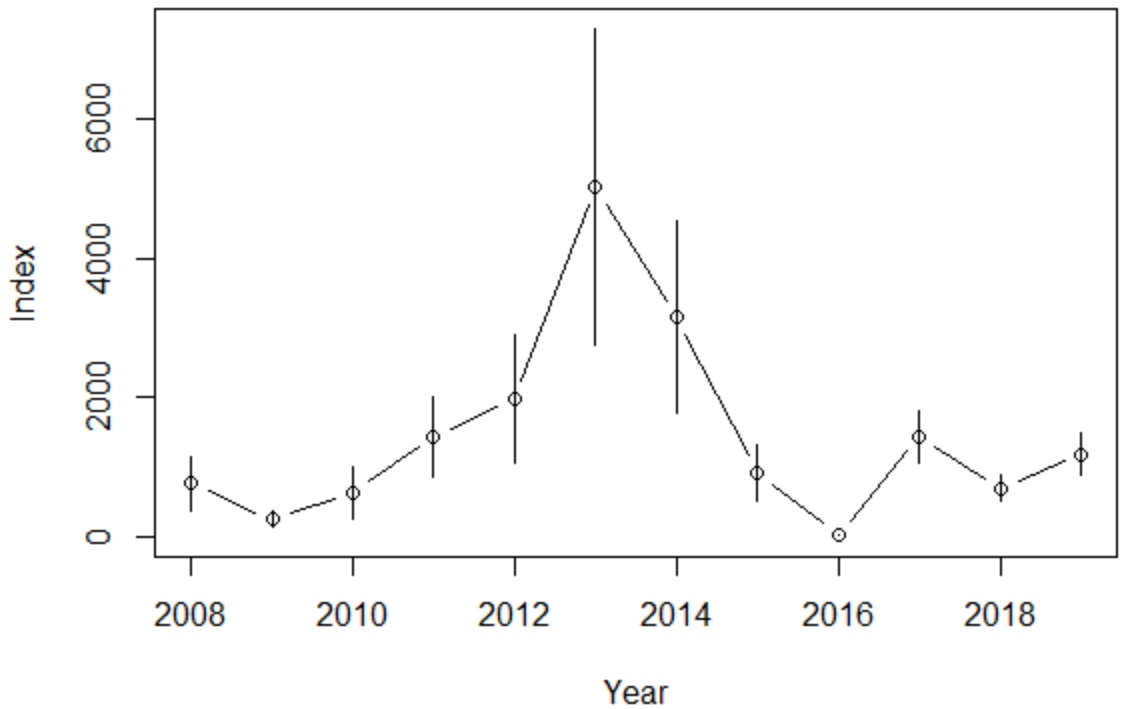


Figure 86. Index of relative abundance of elvers developed from the Maryland Susquehanna River Conowingo Dam Ramp Survey with 95% confidence intervals.

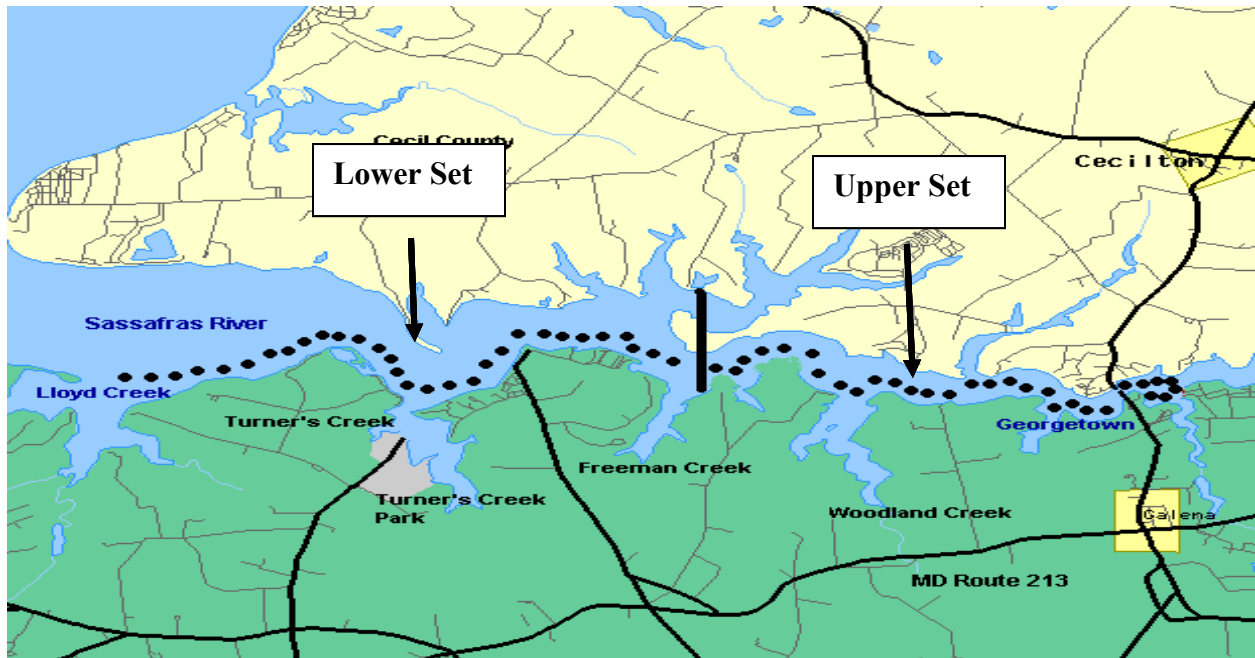


Figure 87. Location of fixed sites in Maryland's Sassafras River eel pot survey targeting yellow eels.

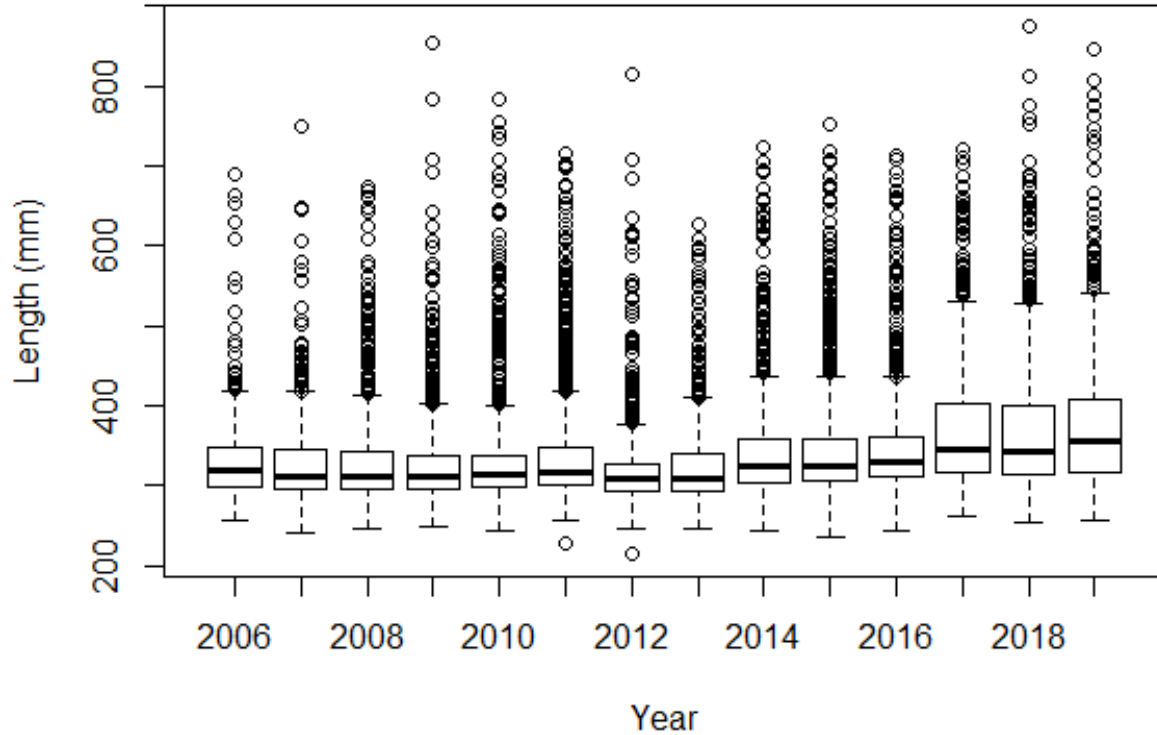


Figure 88. Yellow eel lengths from the Sassafras River Eel Pot Survey, 2006 - 2019.

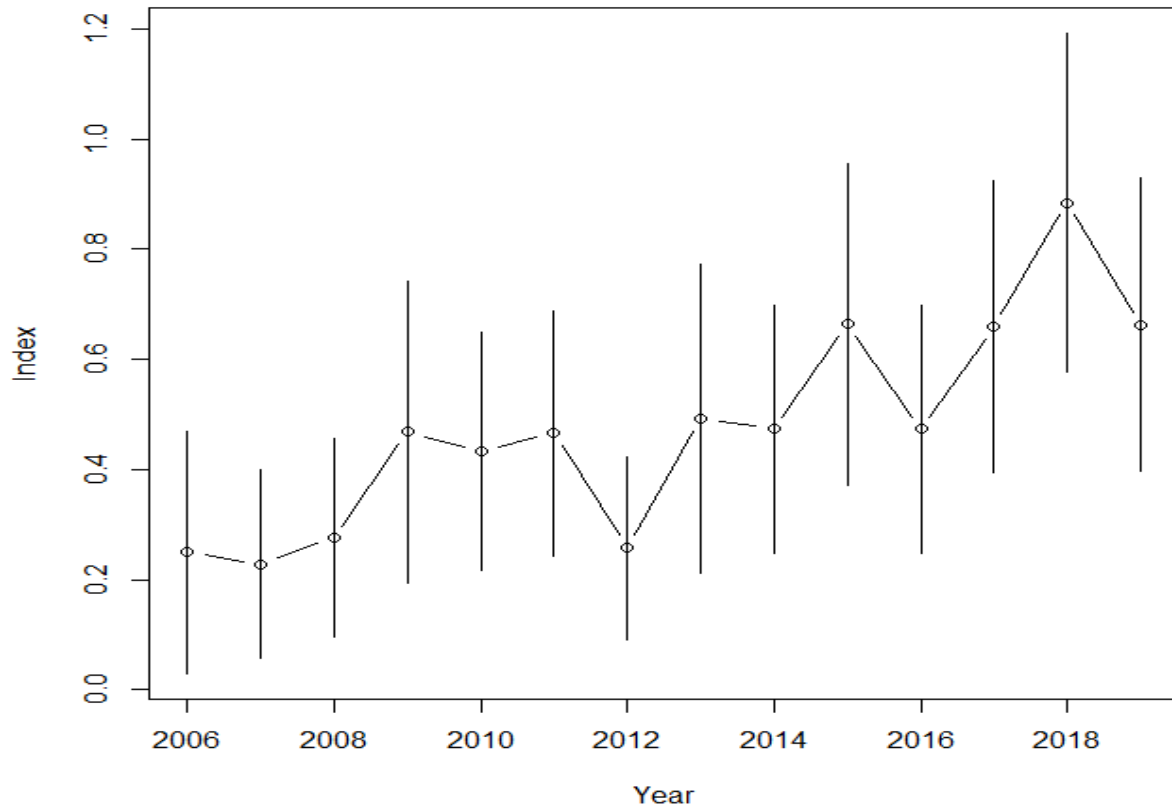


Figure 89. Index of relative biomass of yellow eels developed from the Sassafra River Eel Pot Survey with 95% confidence intervals.

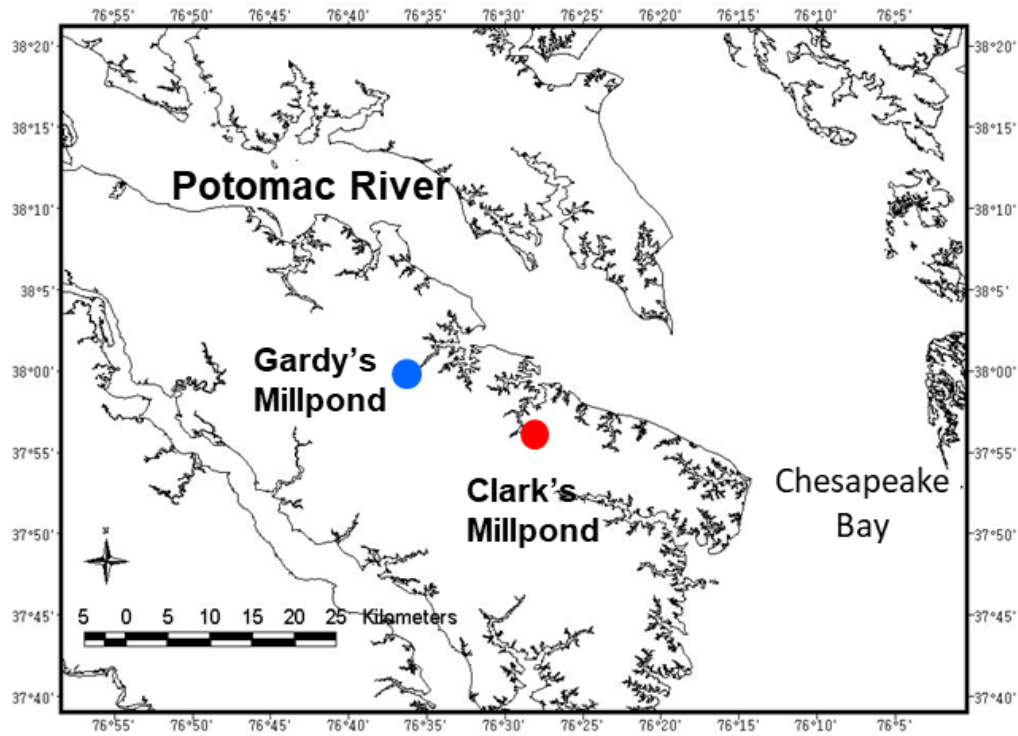


Figure 90. Location of the Gardy's Millpond and Clark's Millpond YOY surveys on the Potomac River.

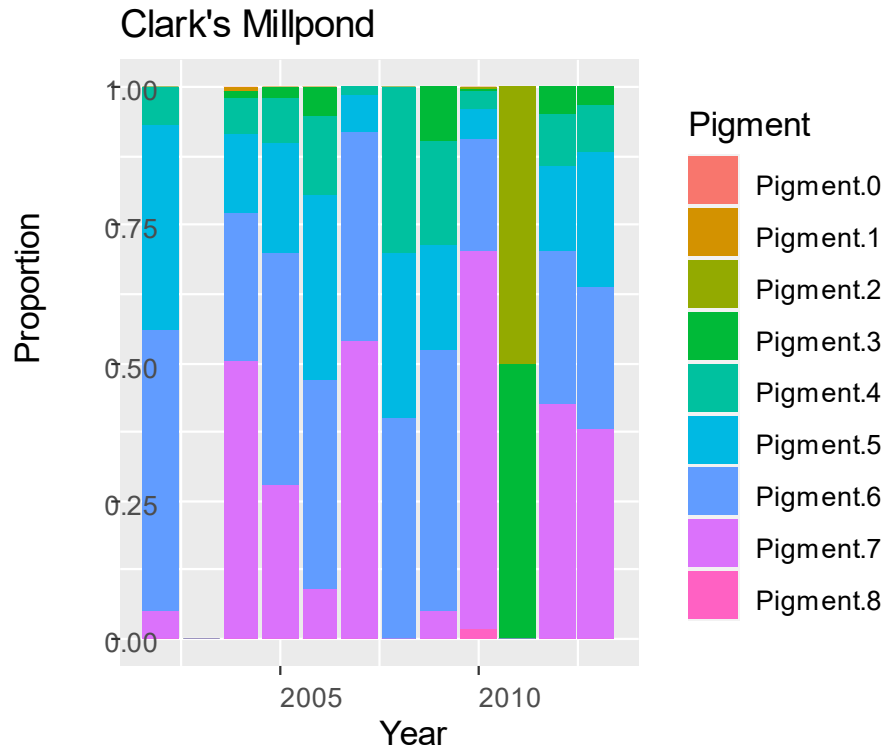


Figure 91. Distribution of pigment stages in the Clark's Millpond YOY American eel survey

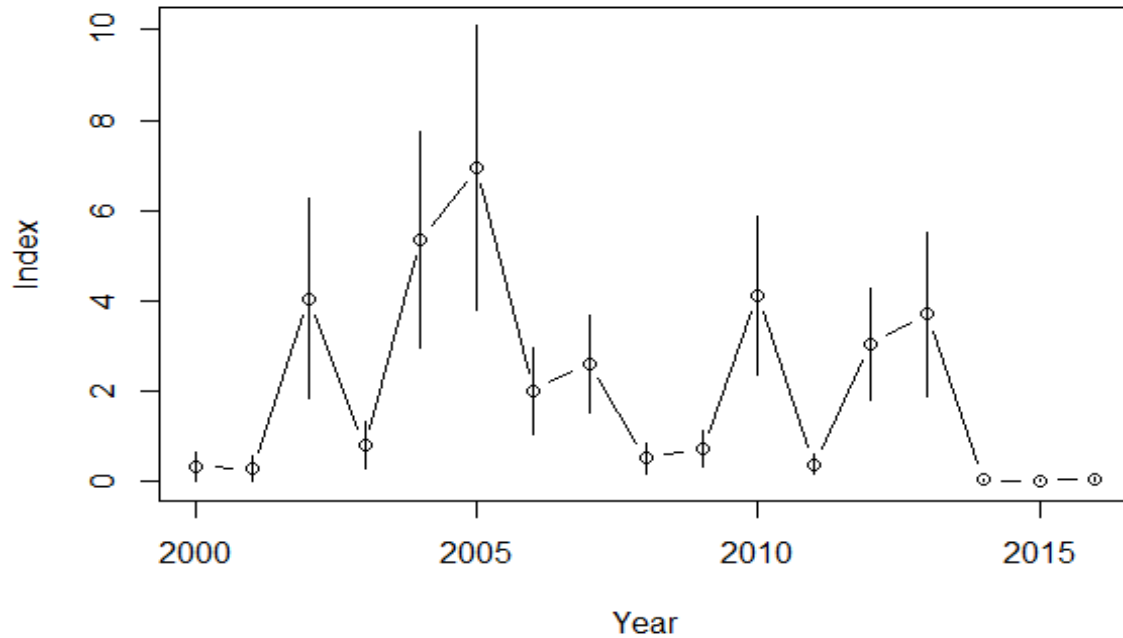


Figure 92. Relative abundance index for YOY glass-stage American eel from Clark's Millpond. Characteristics at the site changed in 2014 and was no longer attractive to glass eels. Therefore, this site was terminated in 2016.

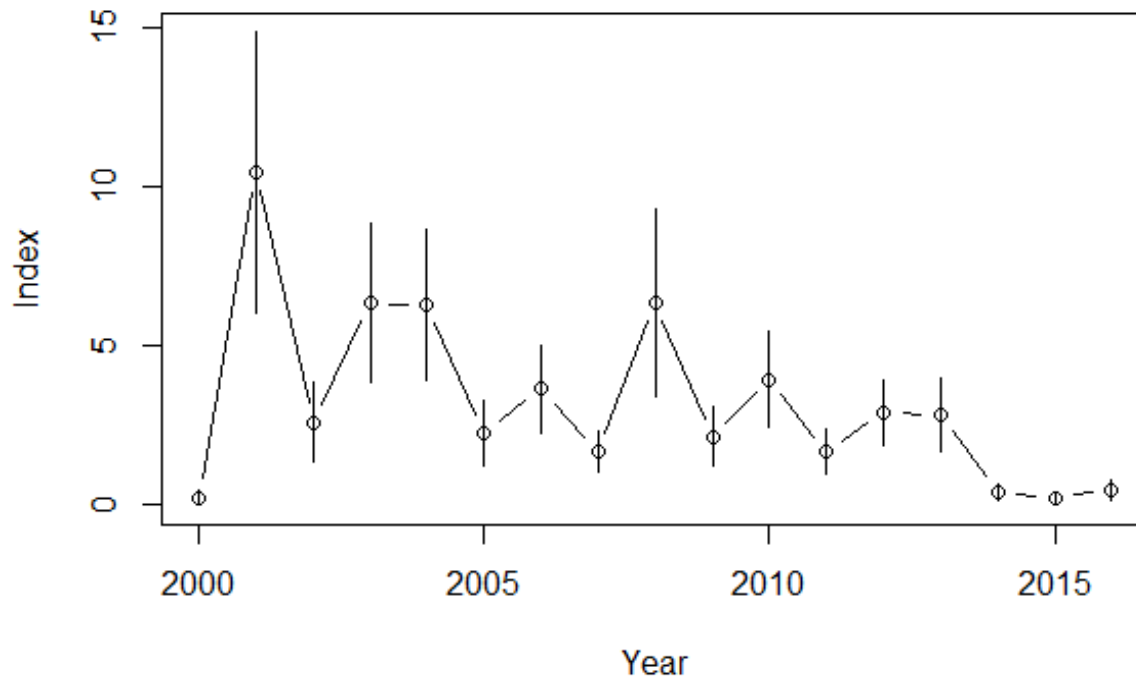


Figure 93. Relative abundance index for elver American eel from Clark's Millpond. Characteristics at the site changed in 2014 and was no longer attractive to eels. Therefore, this site was terminated in 2016.

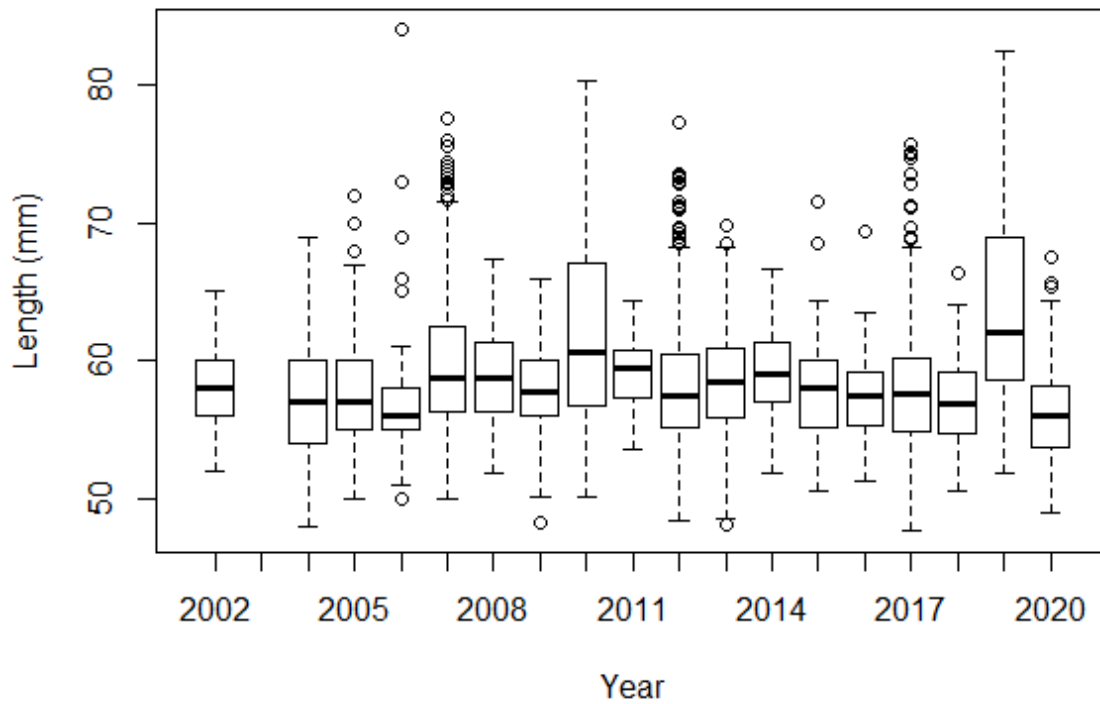


Figure 94. Glass eel total length measurements from Gardy's Millpond, 2002 – 2020.

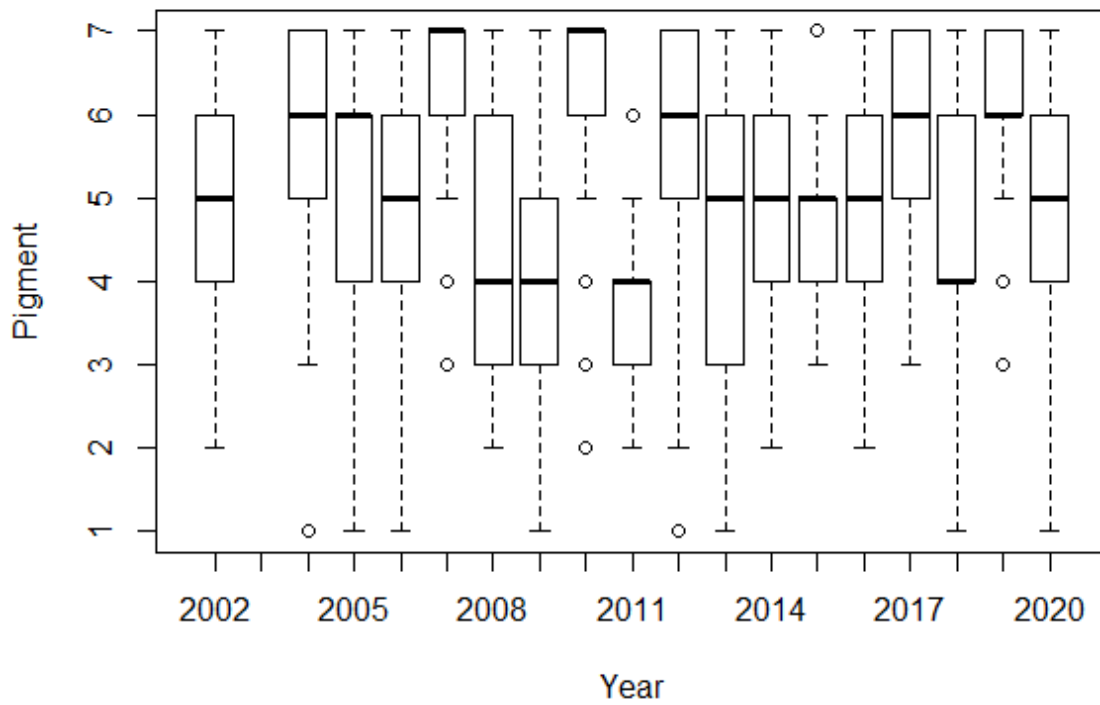


Figure 95. Glass eel pigment stage from Gardy's Millpond, 2002 – 2020.

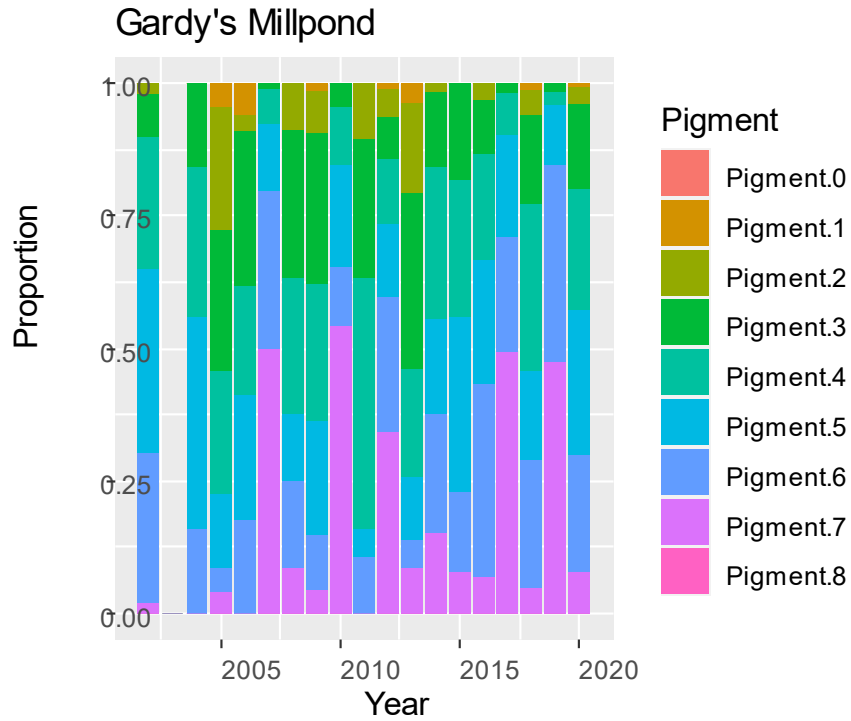


Figure 96. Distribution of pigment stages in the Gardy's Millpond YOY American eel survey.

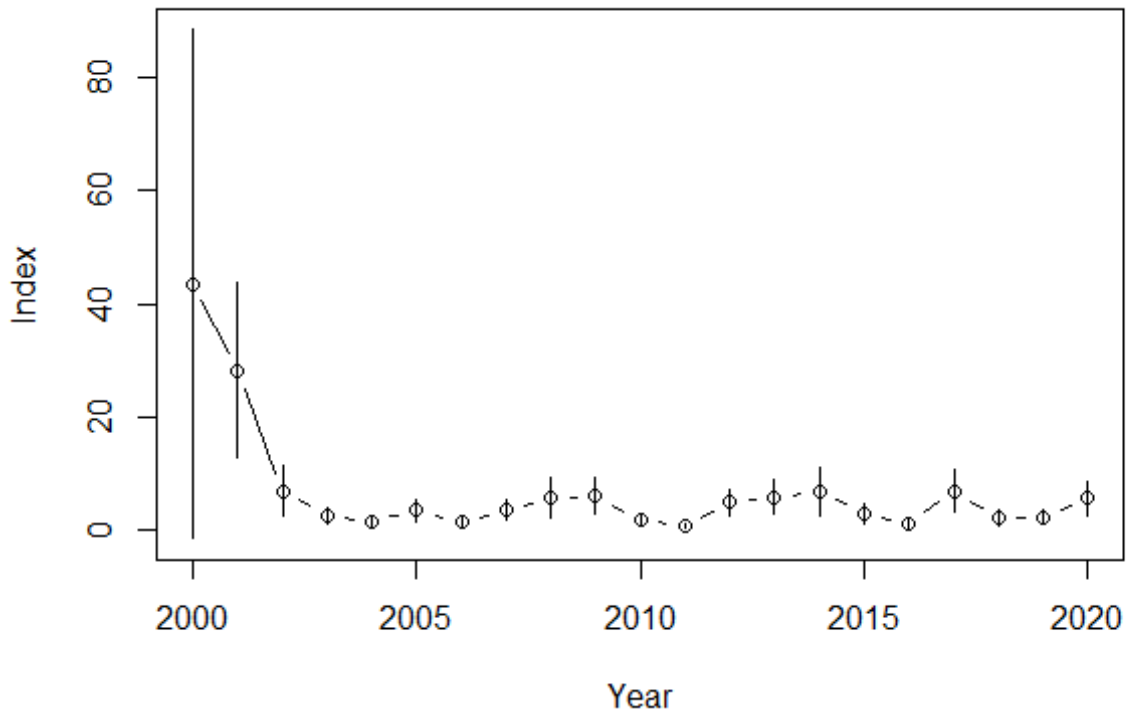


Figure 97. Relative abundance index for YOY glass-stage American eel from Gardy's Millpond.

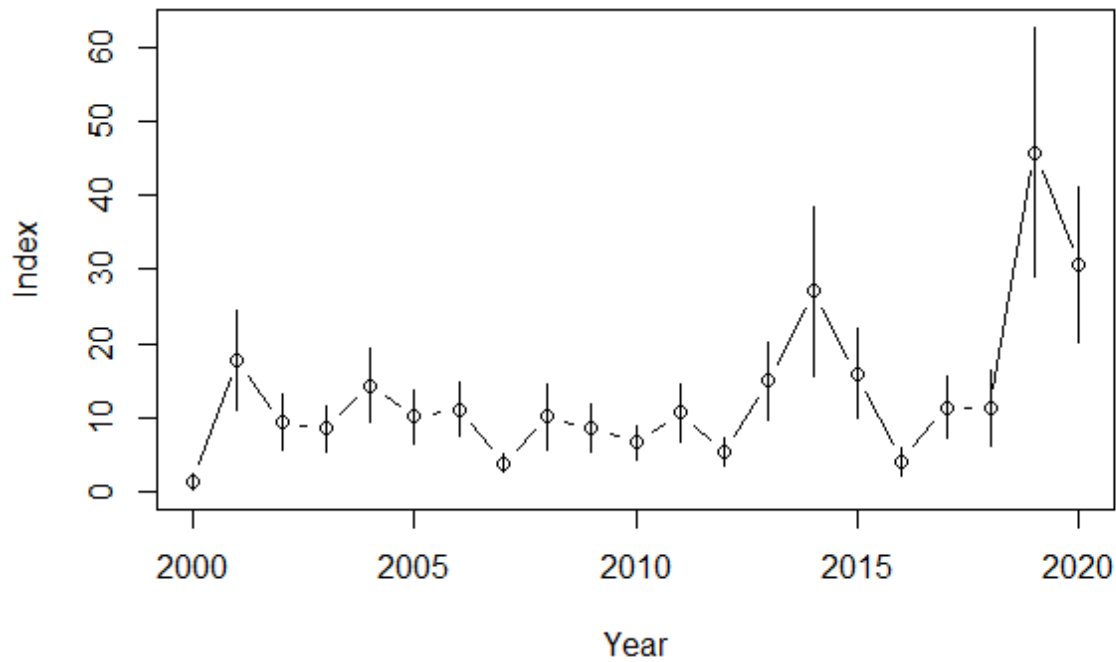


Figure 98. Relative abundance index for elver American eel from Gardy's Millpond.

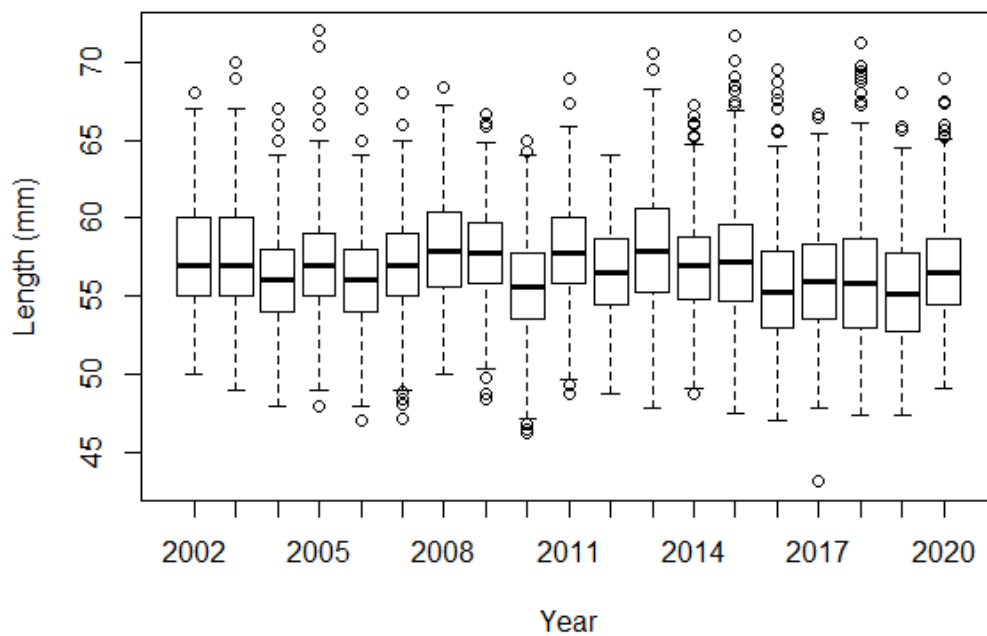


Figure 99. Glass eel total length measurements from Wormley Creek, 2002 – 2020.

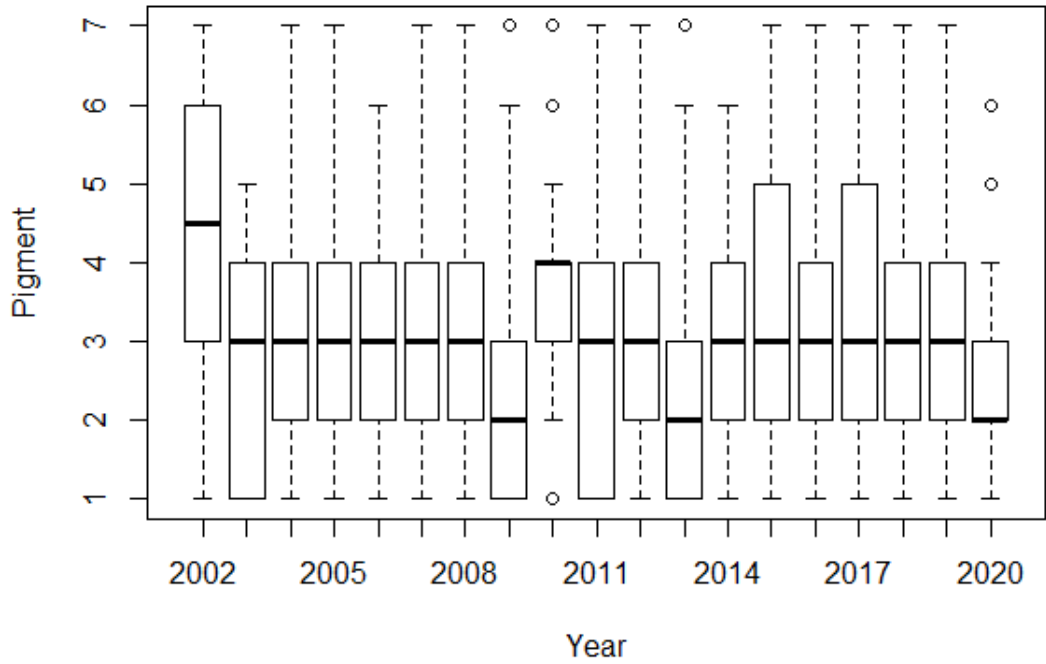


Figure 100. Glass eel pigment stage from Wormley Creek, 2002 – 2020.

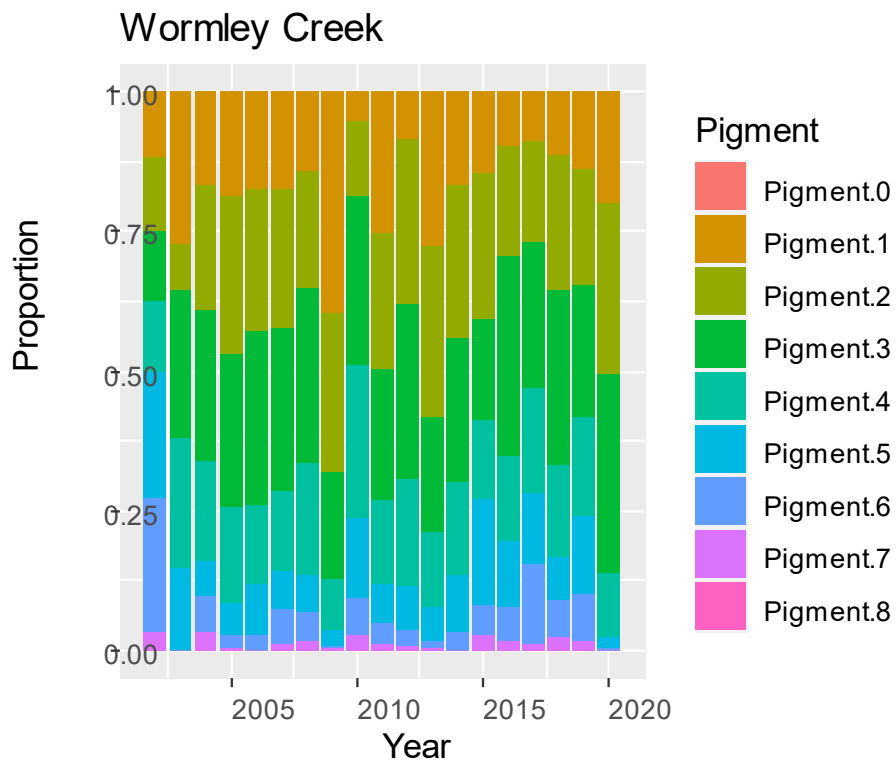


Figure 101. Distribution of pigment stages in the Wormley Creek YOY American eel survey.

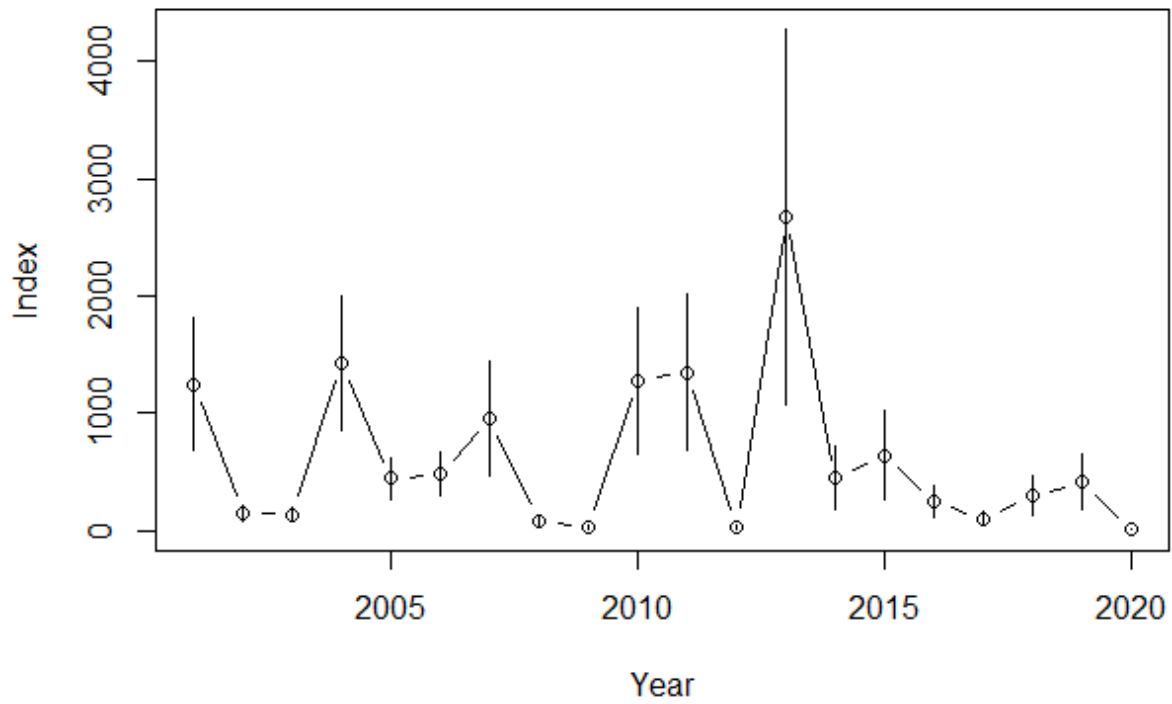


Figure 102. Relative abundance index for YOY glass-stage American eel from Wormley Creek.

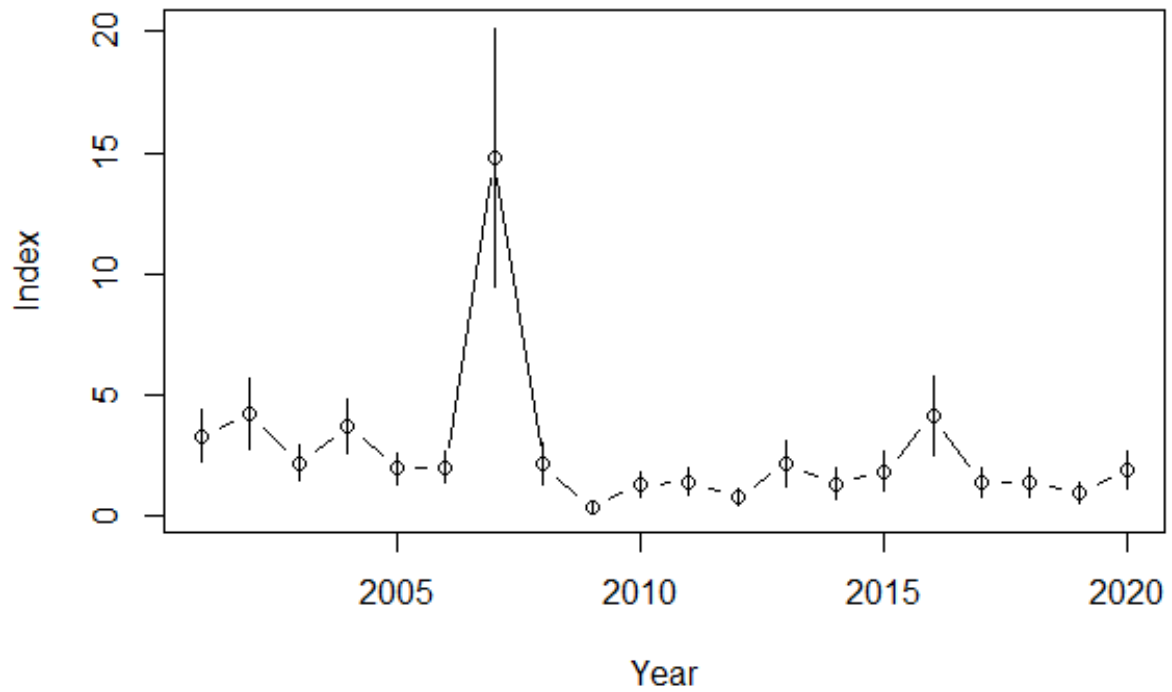


Figure 103. Relative abundance index for elver American eel from Wormley Creek.

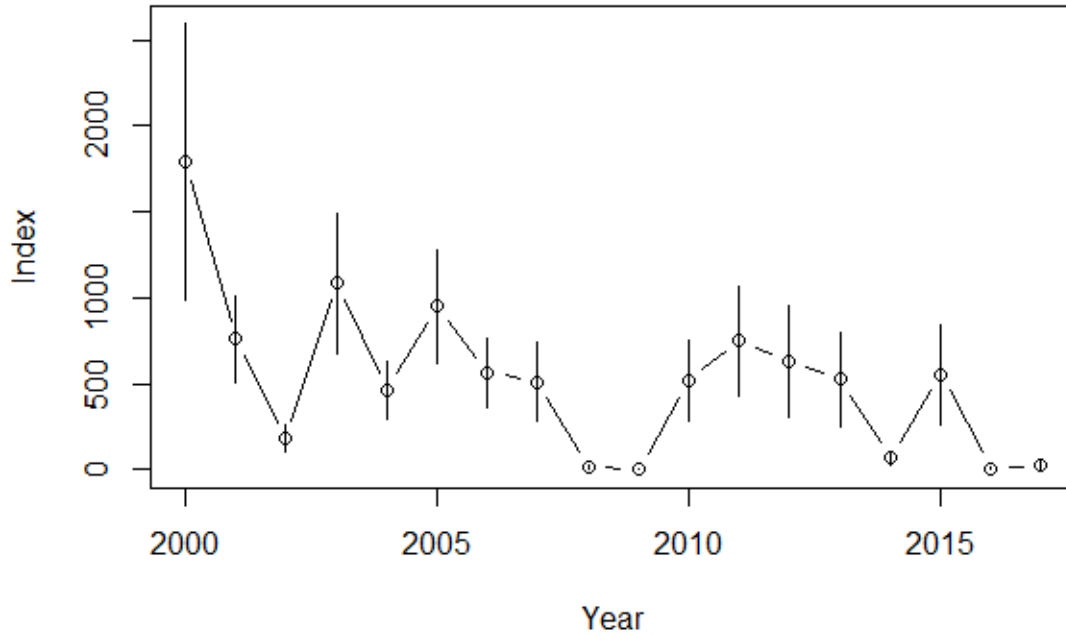


Figure 104. Relative abundance index for YOY glass-stage American eel from Bracken's Pond.

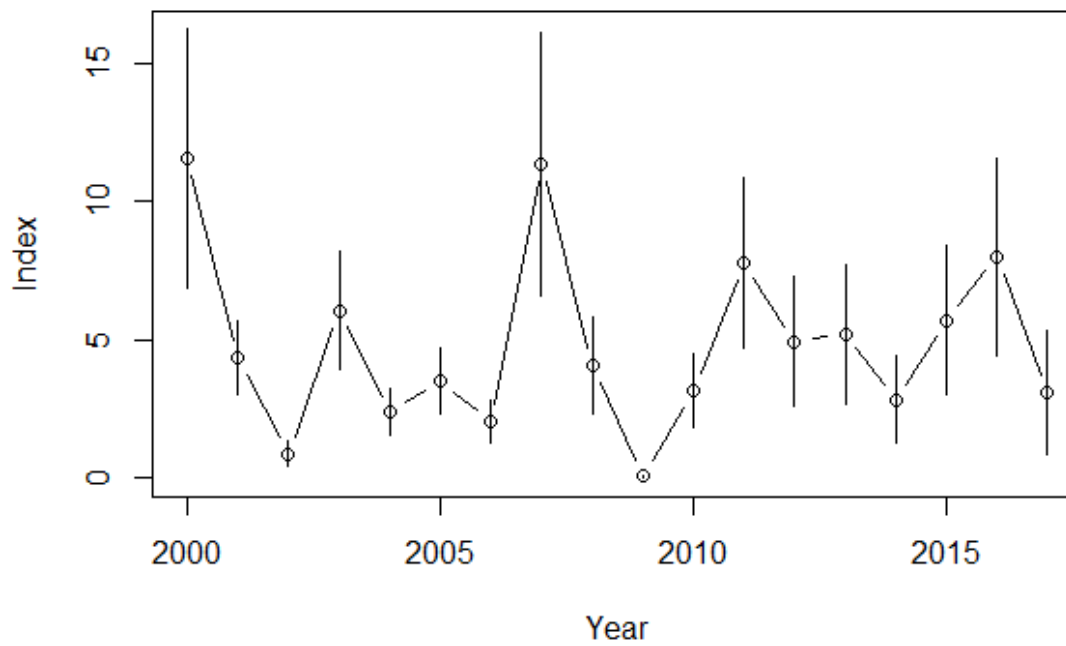


Figure 105. Relative abundance index for elver American eel from Bracken's Pond.

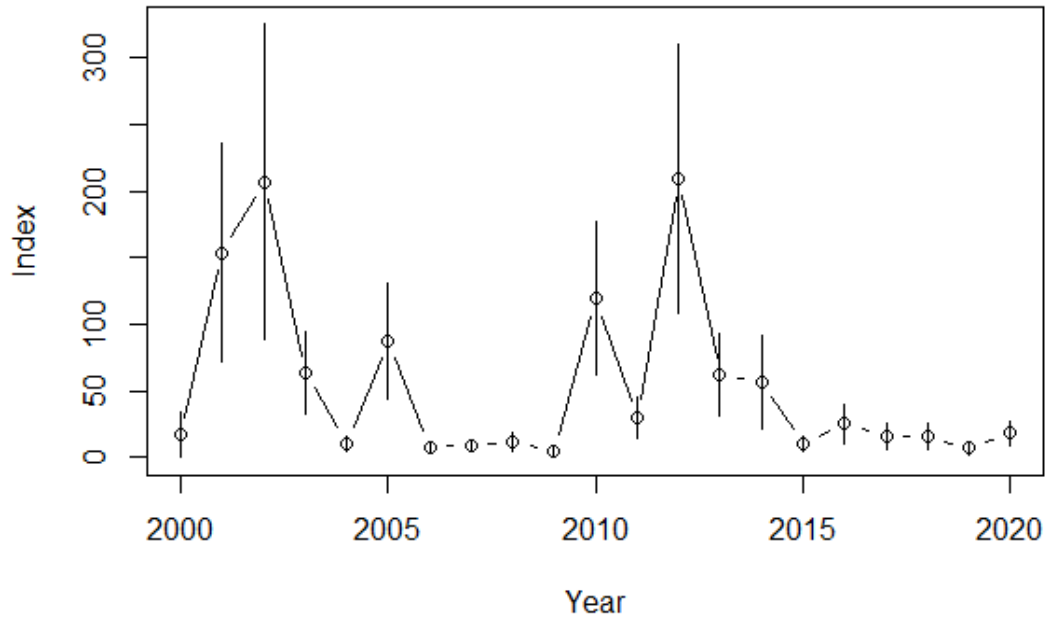


Figure 106. Relative abundance index for YOY glass-stage American eel from Kamp’s Millpond.

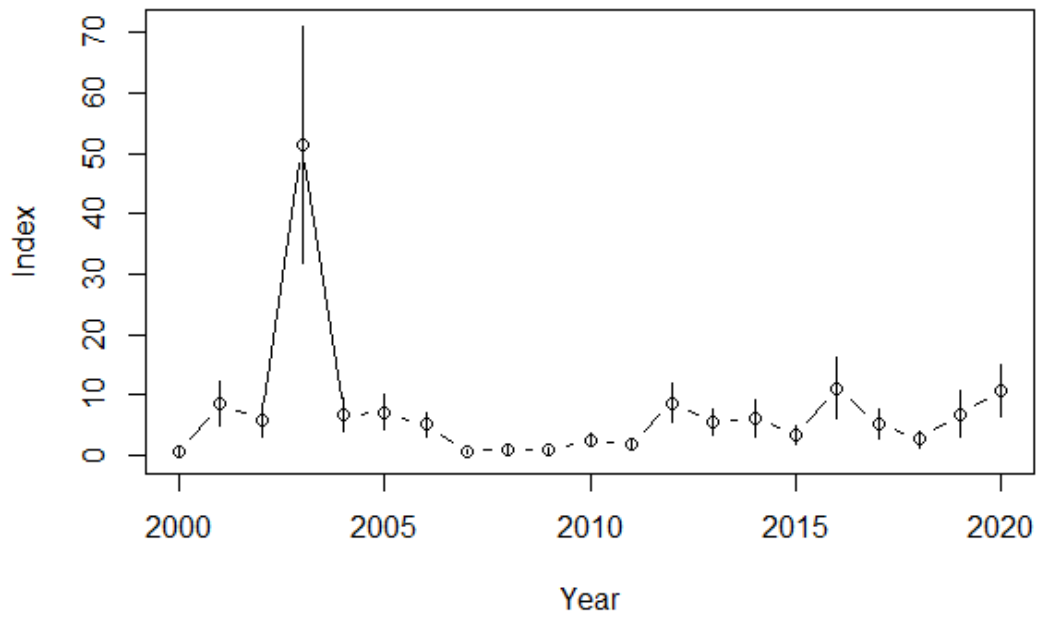


Figure 107. Relative abundance index for elver American eel from Kamp’s Millpond.

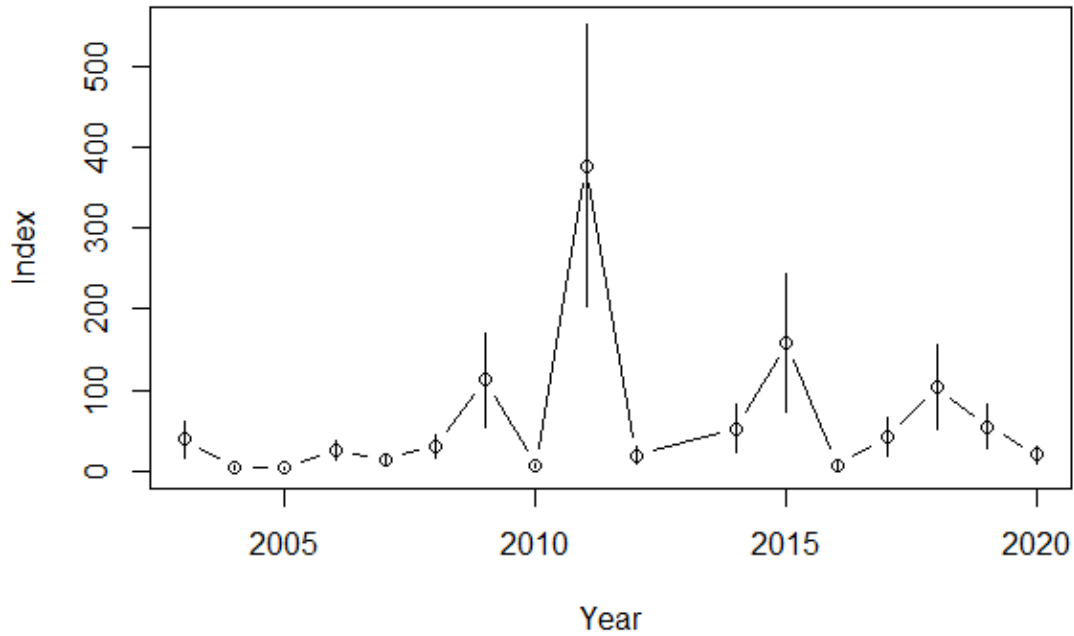


Figure 108. Relative abundance index for YOY glass-stage American eel from Wareham's Pond.

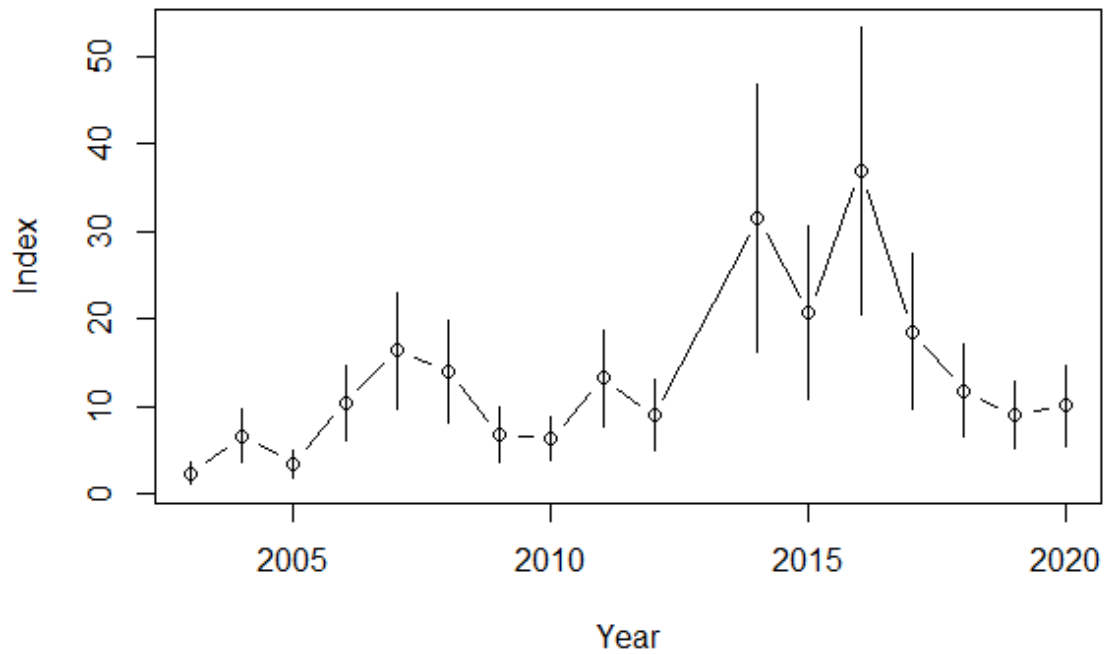


Figure 109. Relative abundance index for elver American eel from Wareham's Pond.

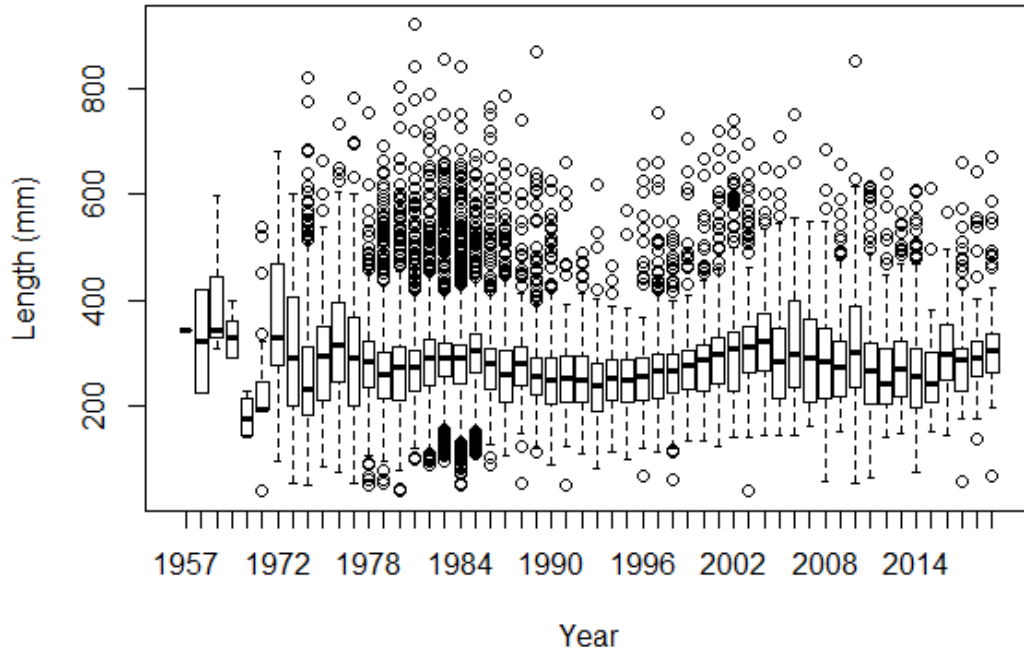


Figure 110. VIMS Trawl Survey yellow eel total lengths from 1955 to 2019.

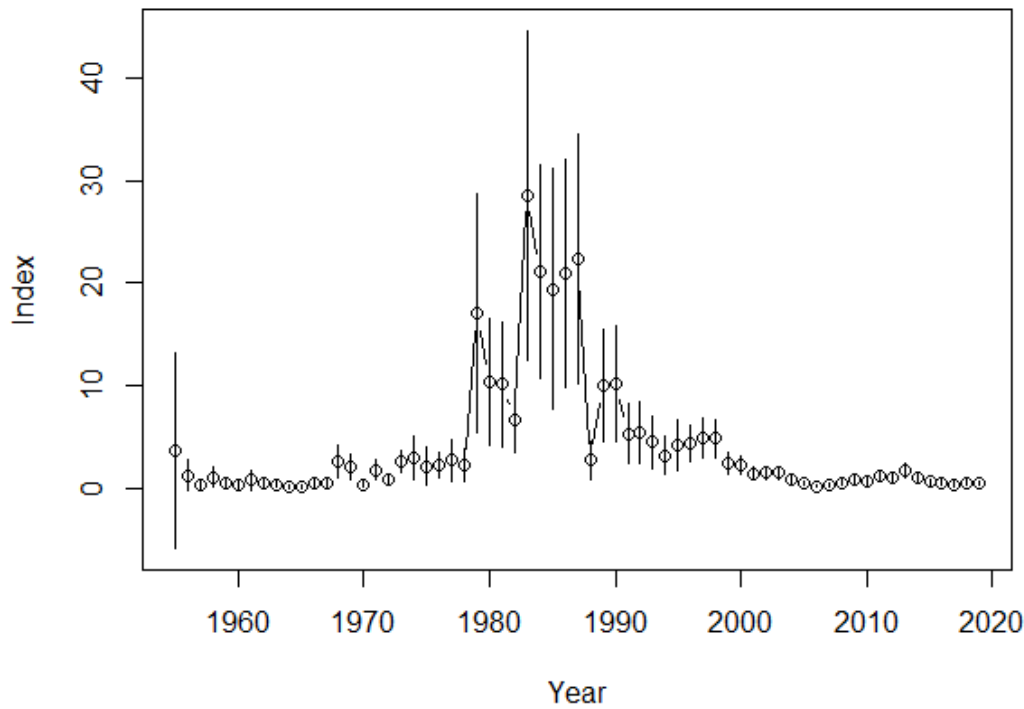


Figure 111. VIMS Trawl Survey yellow American eel index from 1955 to 2019.

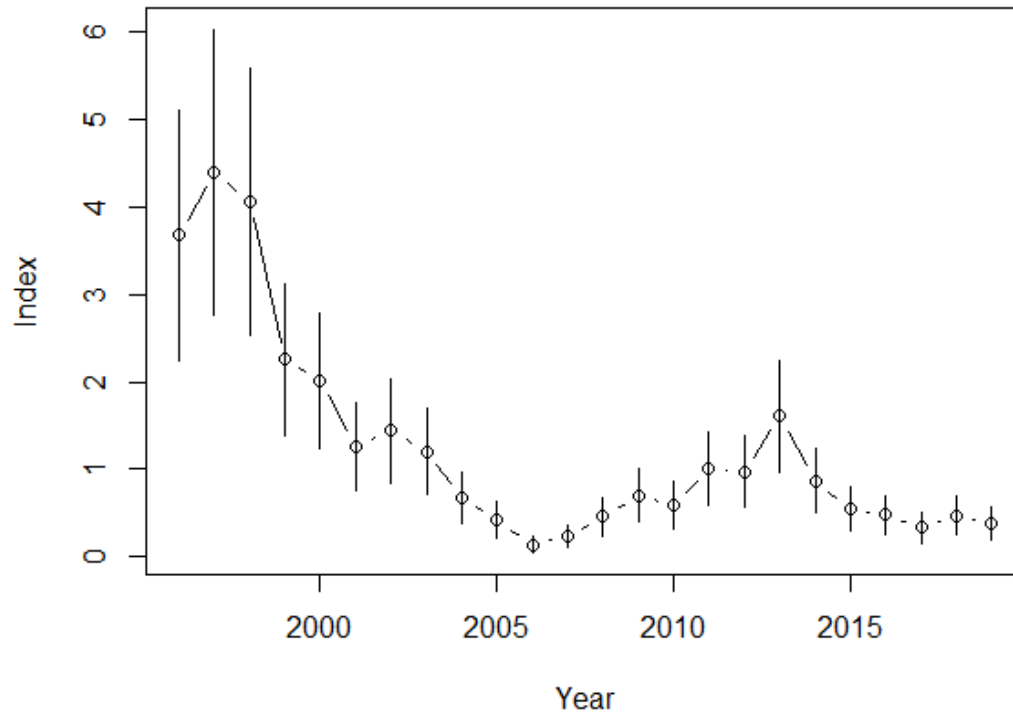


Figure 112. VIMS Trawl Survey short time series for yellow American eel from 1996 to 2019.

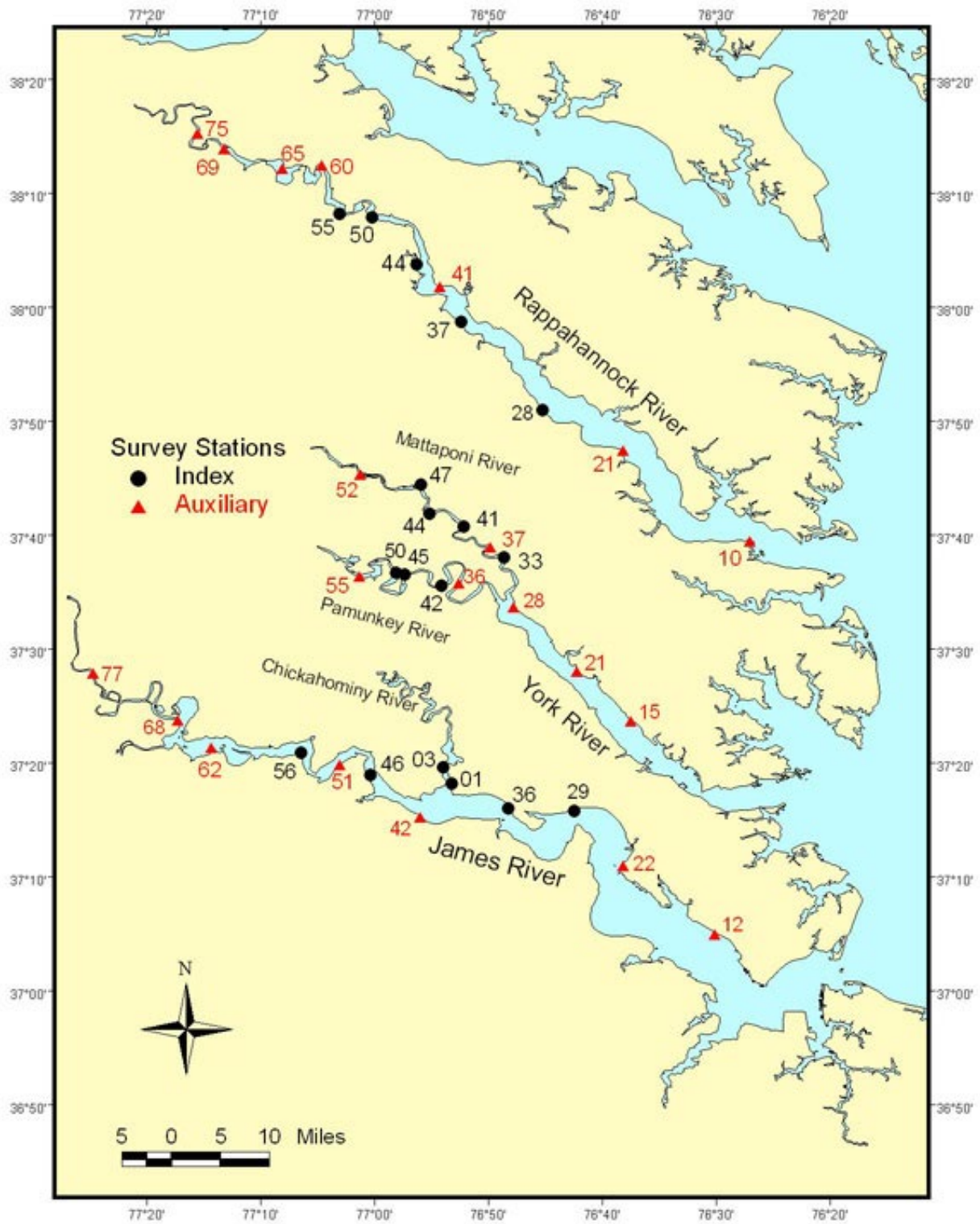


Figure 113. VIMS Striped Bass Seine Survey sites.

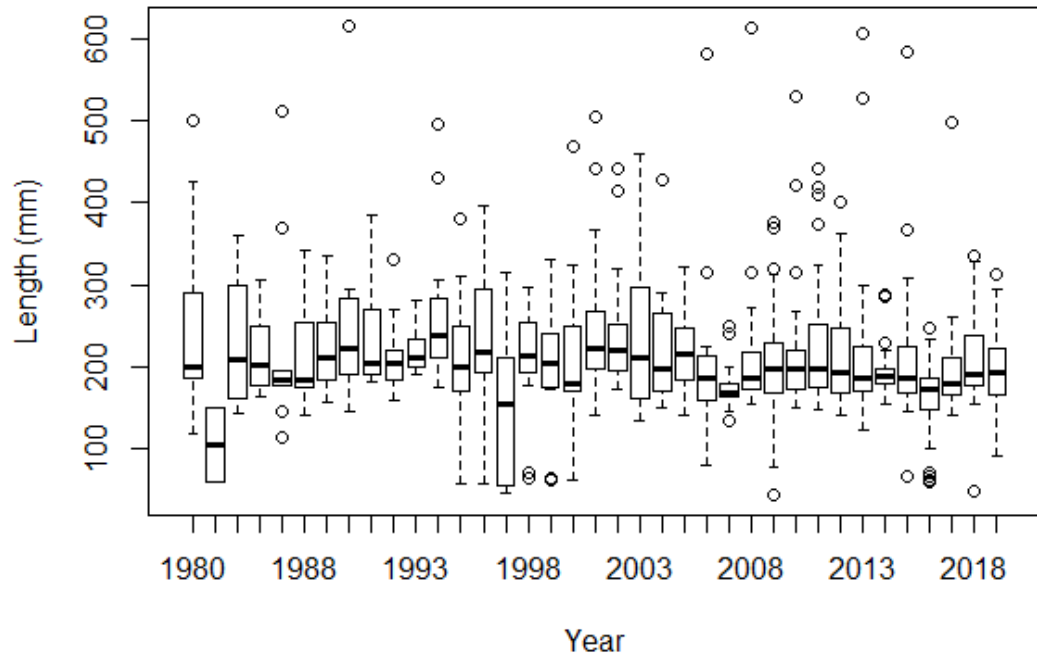


Figure 114. VIMS Striped Bass Seine Survey yellow eel lengths from 1980 to 2019.

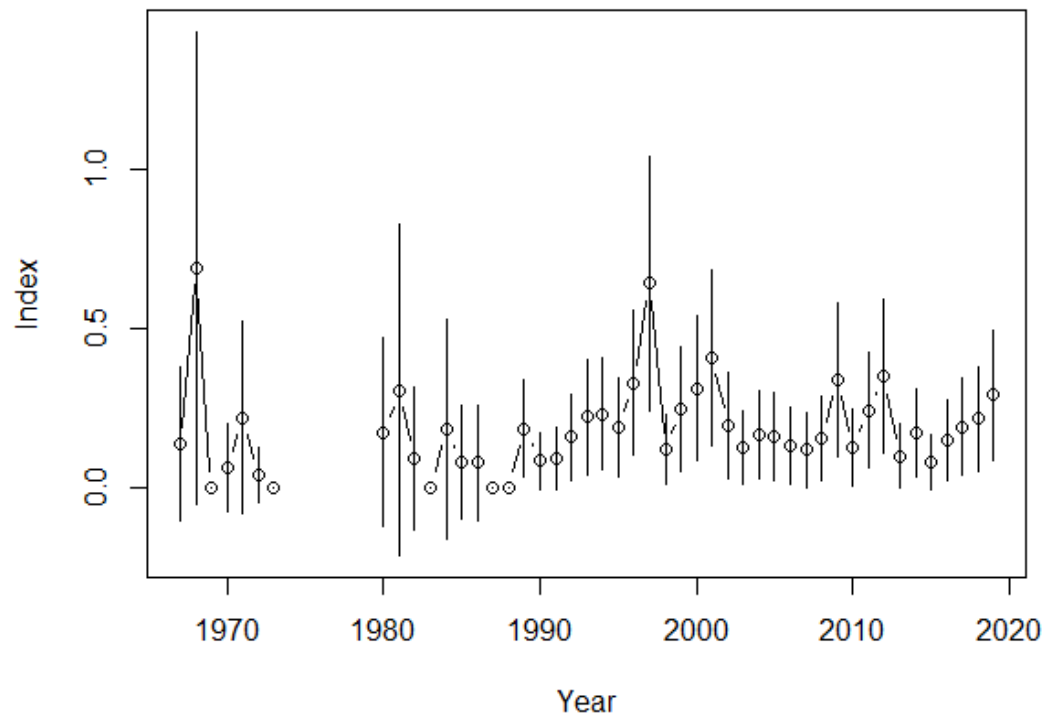


Figure 115. VIMS Striped Bass Seine Survey yellow eel index of abundance for the full time series from 1967 to 1973 and from 1980 to 2019.

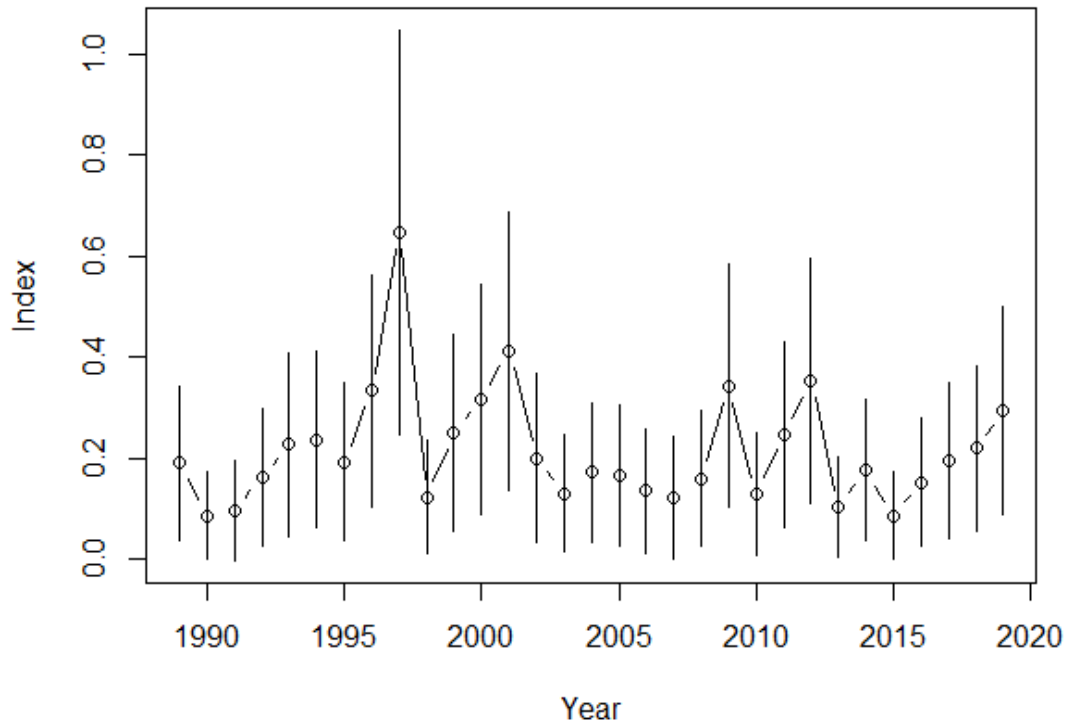


Figure 116. VIMS Striped Bass Seine Survey yellow eel index of abundance for the short time series from 1989 to 2019.

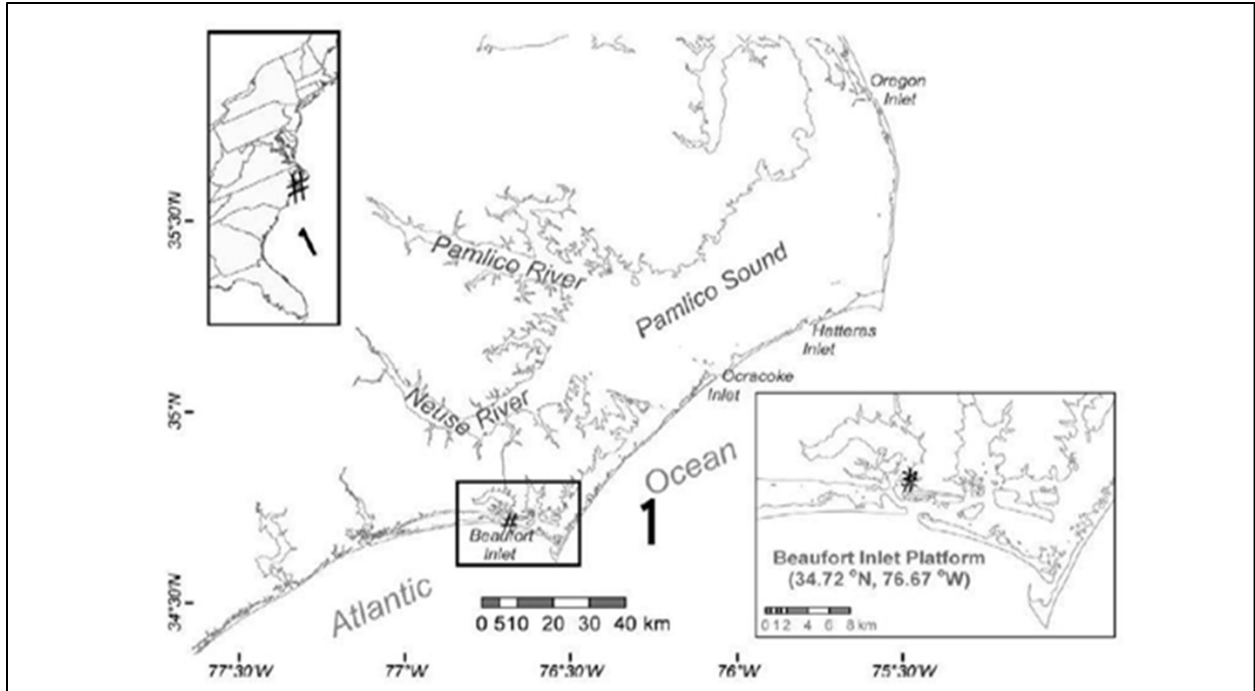


Figure 117. Location of Beaufort Bridgenet Ichthyoplankton Sampling Program observation platform near Beaufort Inlet, North Carolina.

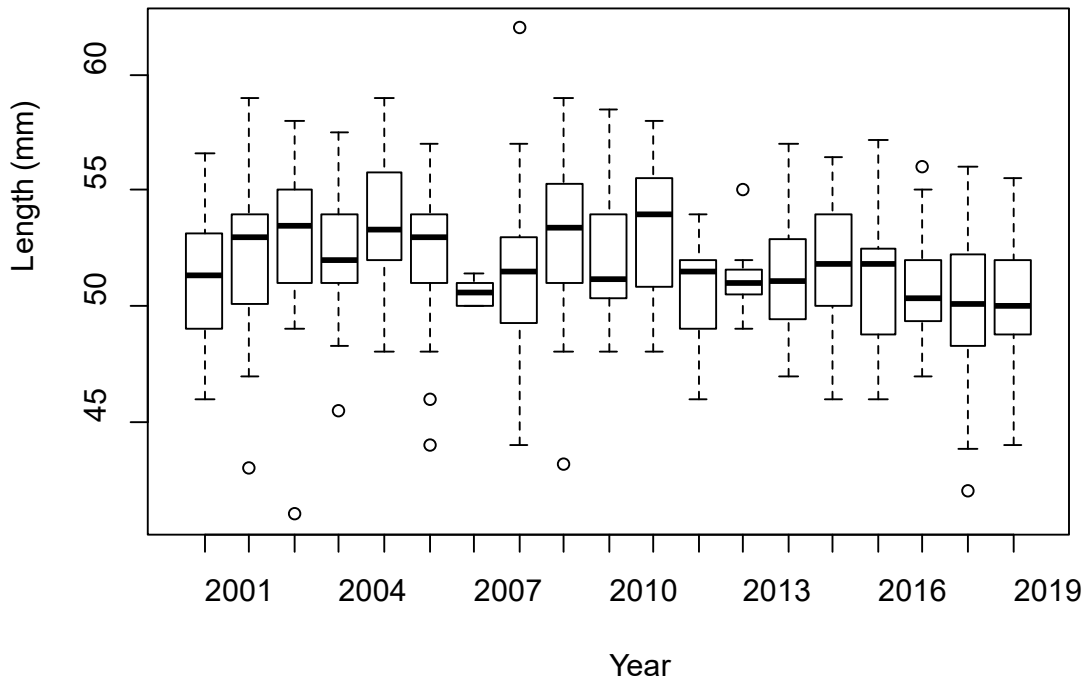


Figure 118. Boxplot of American YOY eel lengths recorded in the Beaufort Bridgenet Ichthyoplankton Sampling Program.

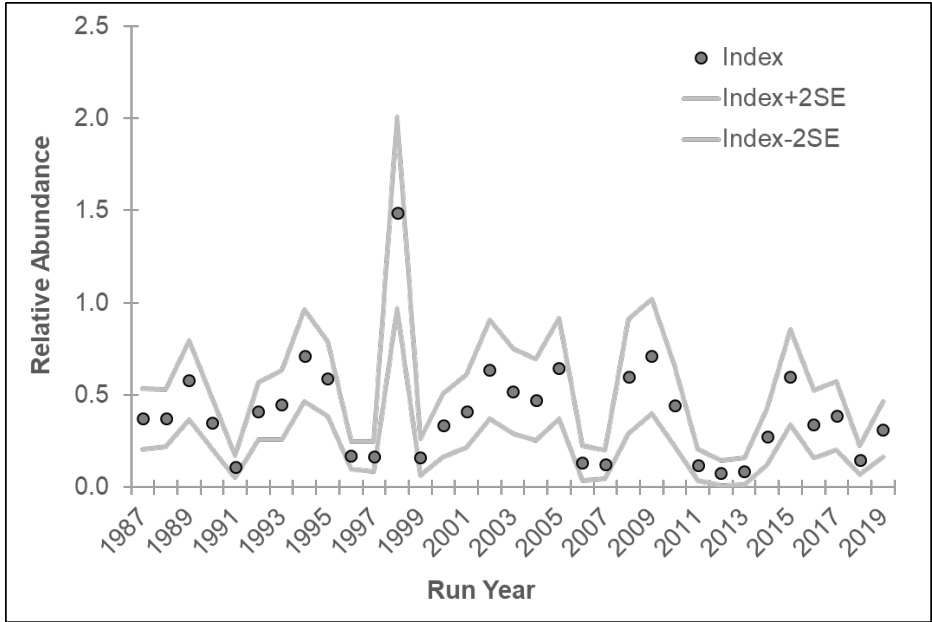


Figure 119. Standardized index of relative abundance of YOY American eel developed from the Beaufort Bridgenet Ichthyoplankton Sampling Program.

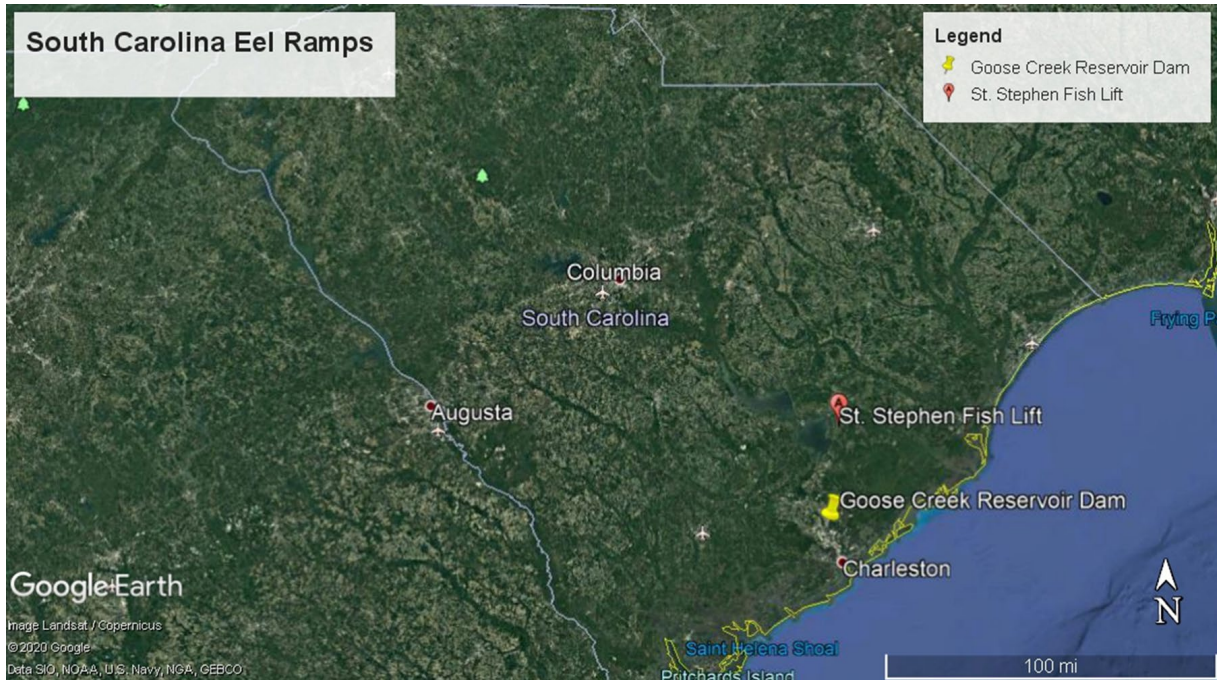


Figure 120. Map of the location of the Goose Creek YOY survey site.

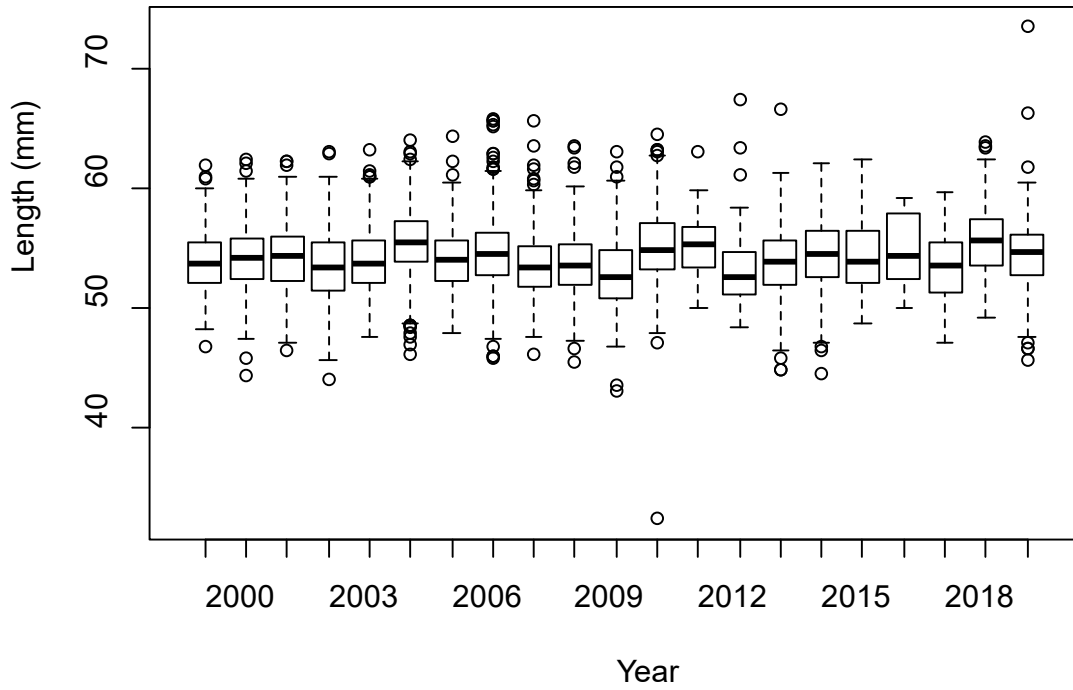


Figure 121. Boxplot of American eel lengths recorded in the South Carolina Goose Creek YOY survey.

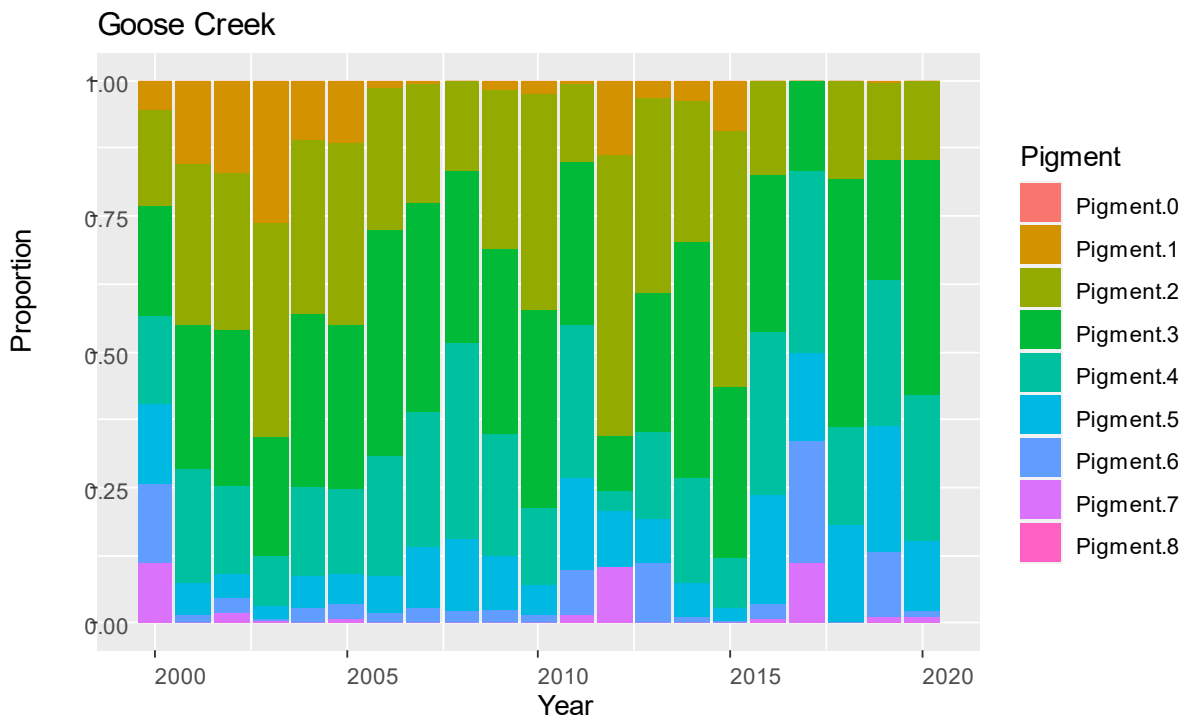


Figure 122. Distribution of pigment stages in the Goose Creek YOY American eel survey.

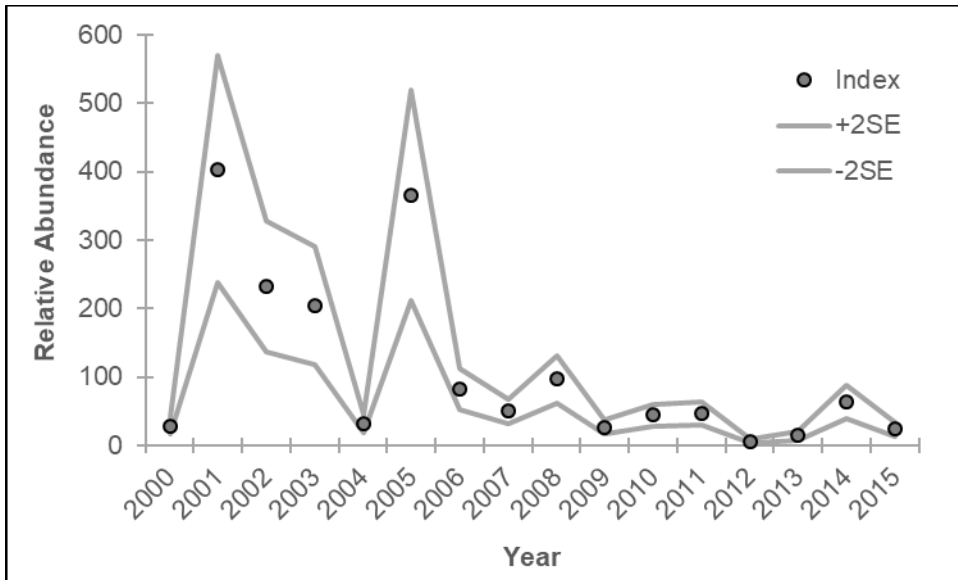


Figure 123. Standardized index of relative abundance of YOY American eel developed from the South Carolina Goose Creek Survey (fyke net).

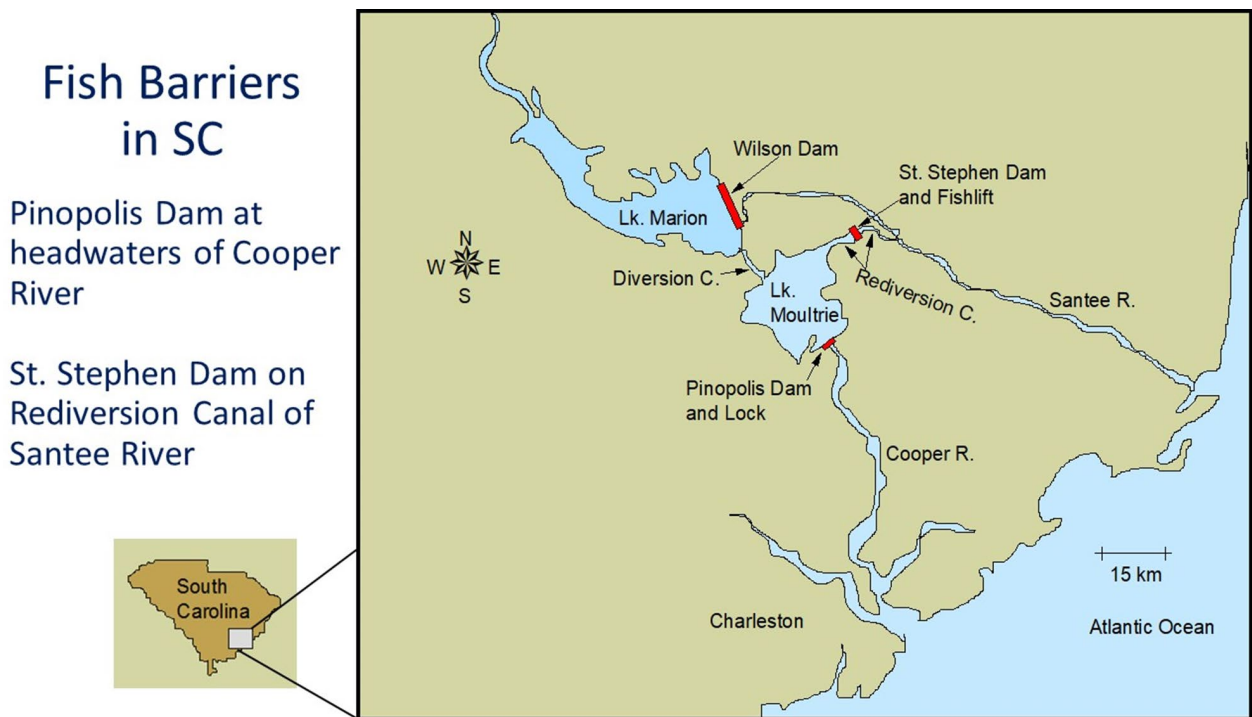


Figure 124. Map of the fish barriers in South Carolina, including the St. Stephen Dam on the Rediversion Canal.

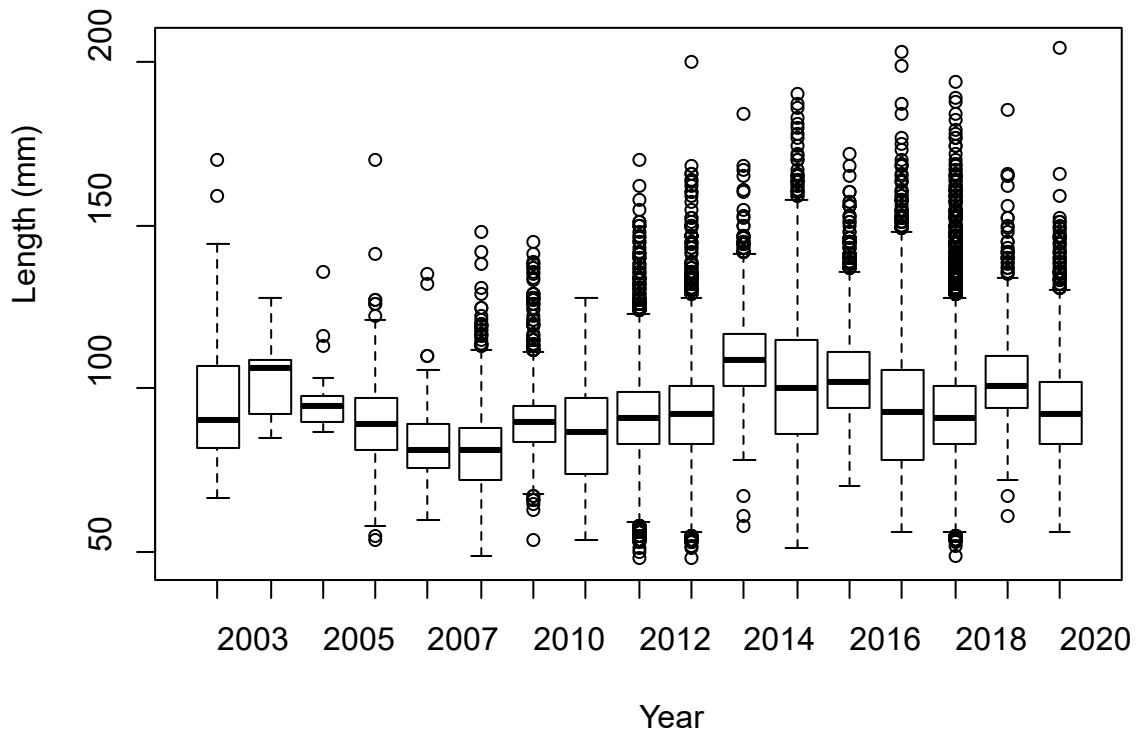


Figure 125. Boxplot of American eel lengths recorded in the South Carolina Rediversion Canal Aluminum Ladder survey.

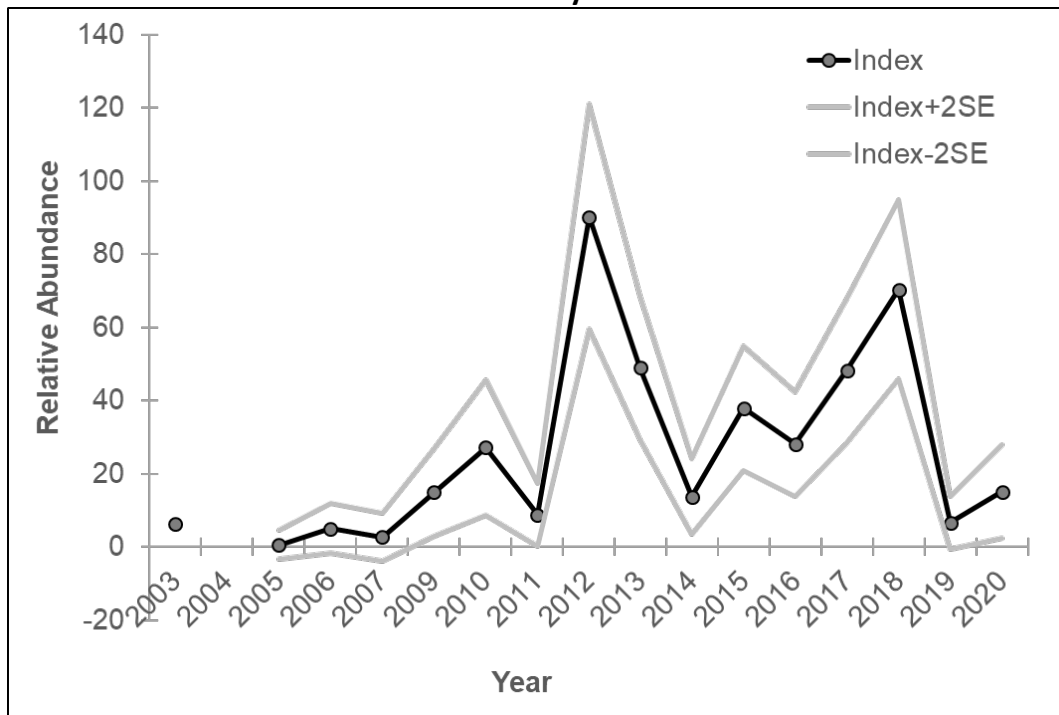


Figure 126. Standardized index of relative yellow eel abundance developed from the South Carolina Rediversion Canal Aluminum Ladder Survey.



Figure 127. Location of American eel sites in Georgia.

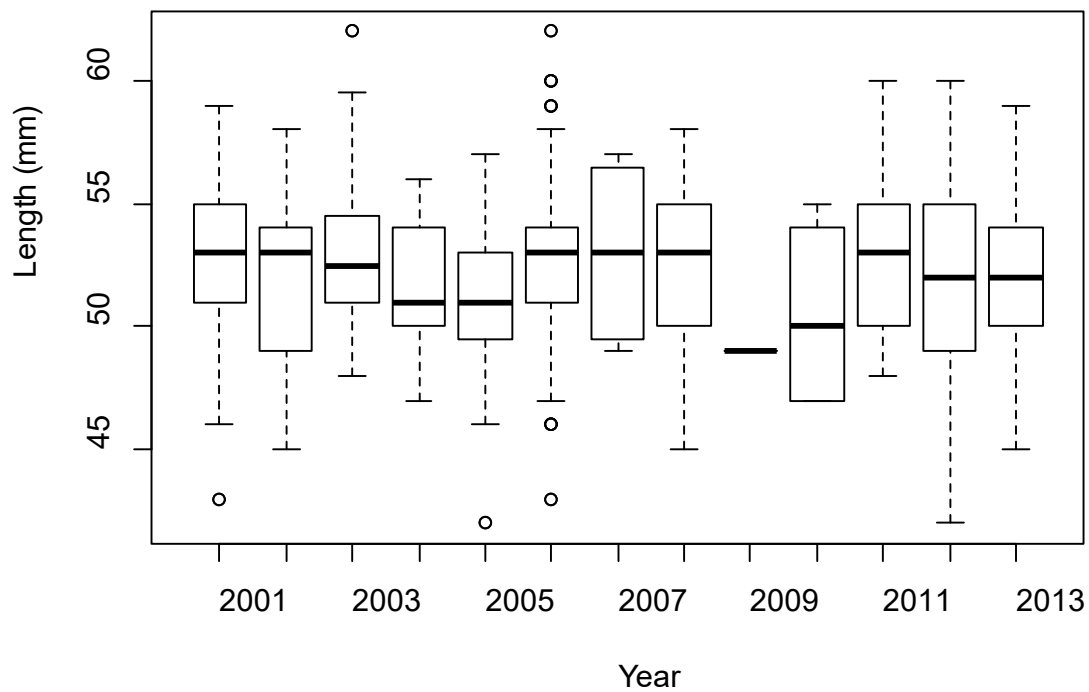


Figure 128. Boxplot of American eel lengths recorded in the Georgia Altamaha Canal YOY survey.

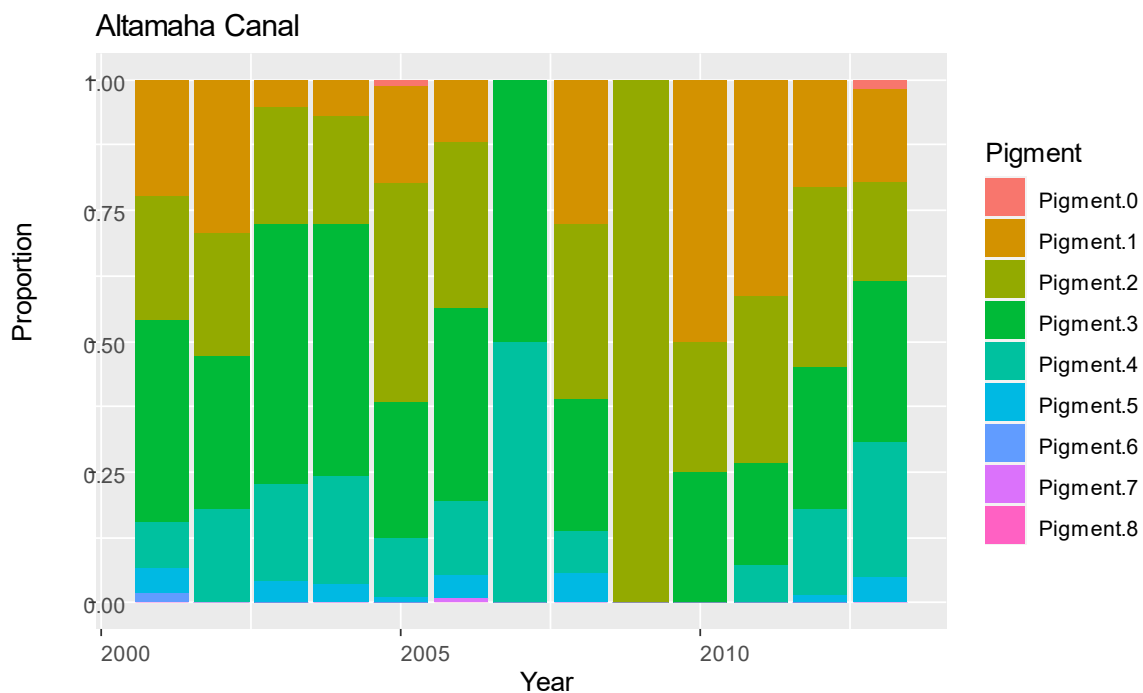


Figure 129. Distribution of pigment stages in the Altamaha Canal YOY American eel survey.

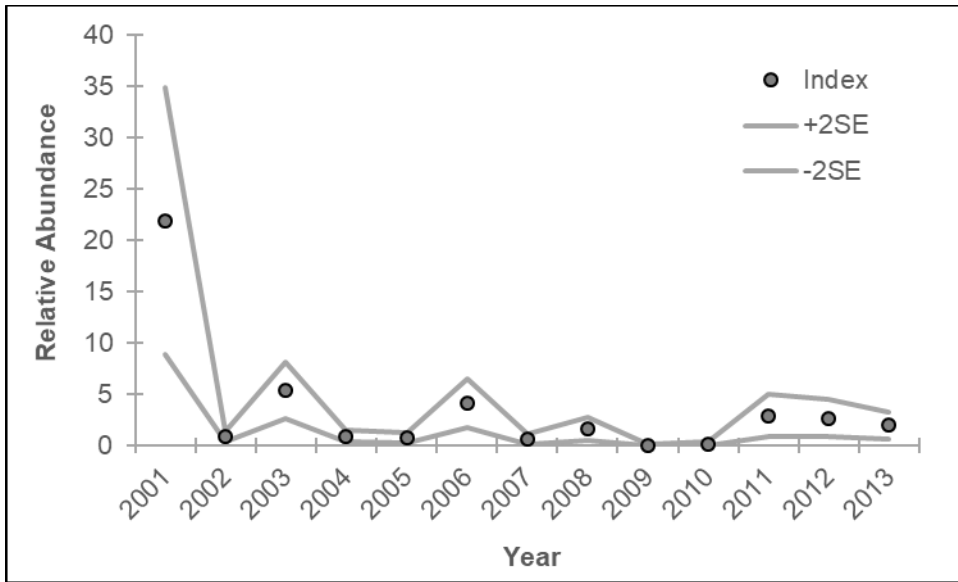


Figure 130. Standardized index of relative abundance of YOY American eel developed from the Georgia Altamaha Canal Survey.

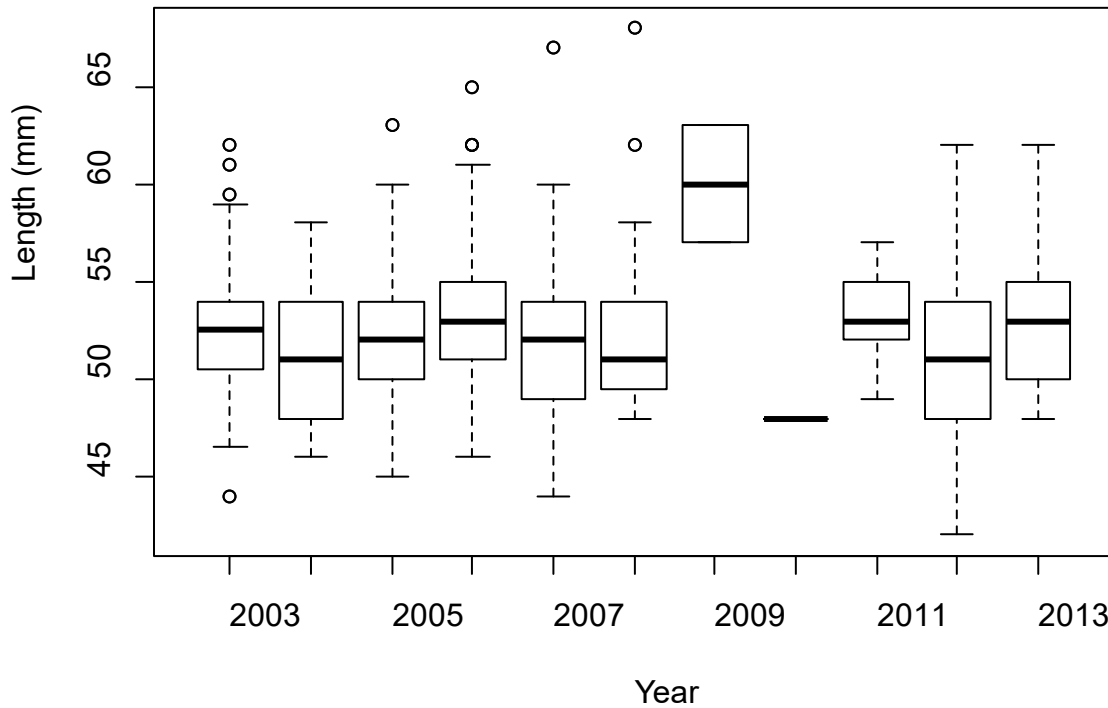


Figure 131. Boxplot of American eel lengths recorded in the Georgia Hudson Creek YOY survey.

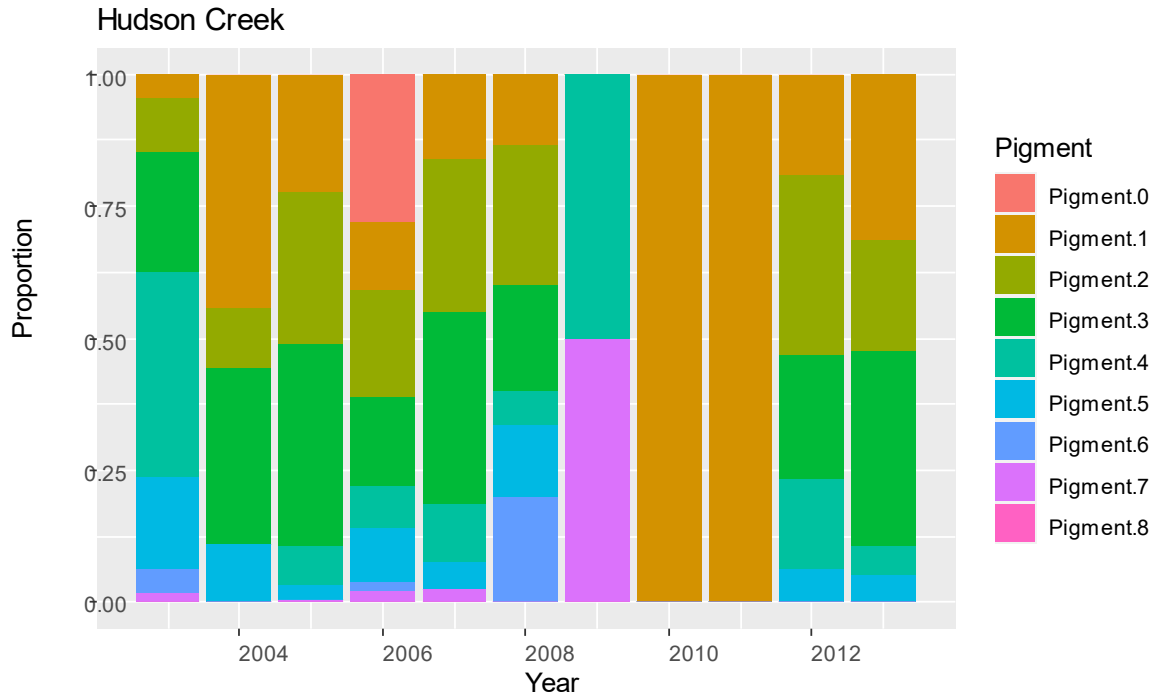


Figure 132. Distribution of pigment stages in the Hudson Creek YOY American eel survey.

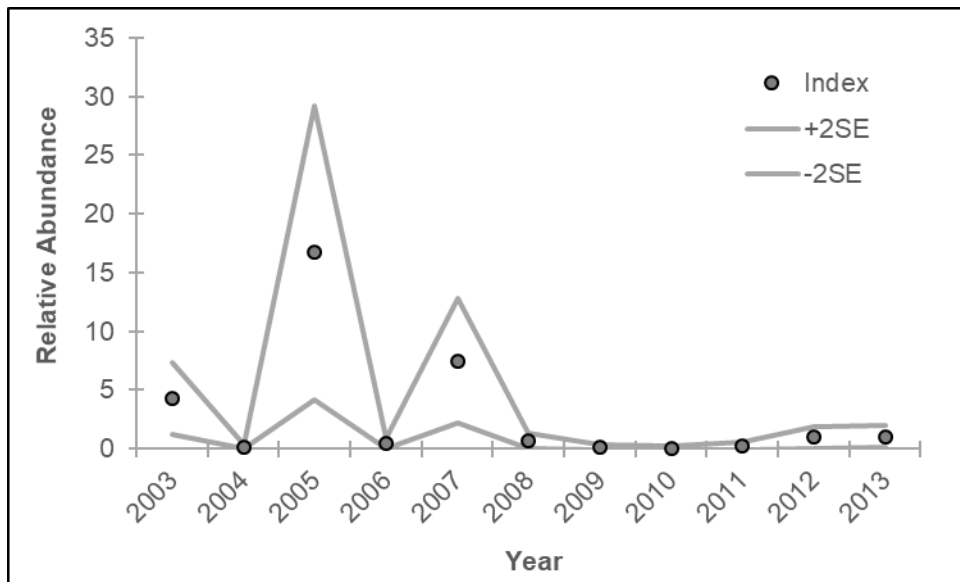


Figure 133. Standardized index of relative abundance of YOY American eel developed from the Georgia Hudson Creek Survey.

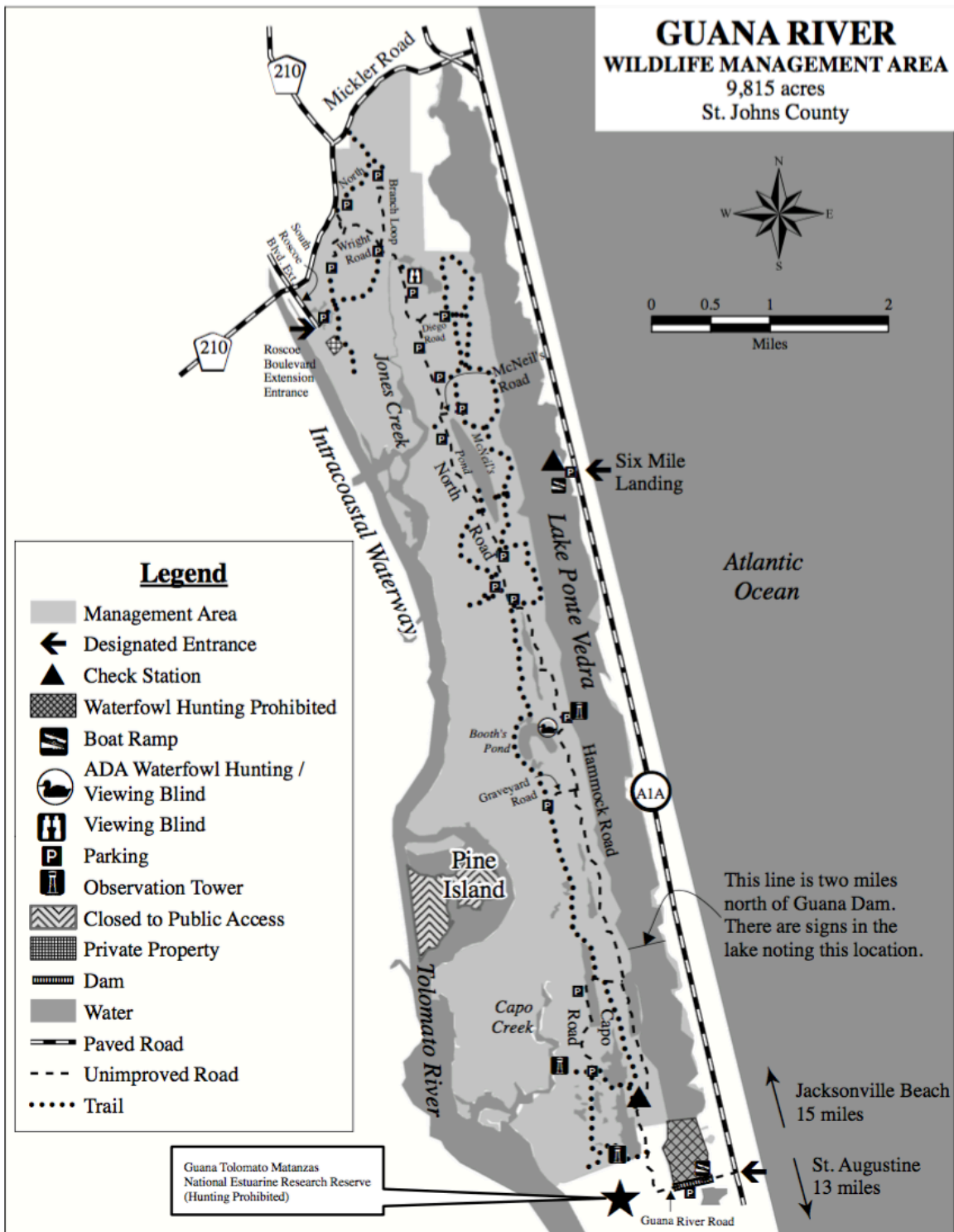


Figure 134. Map of the Guana River Dam in Florida (source: Guana River Wildlife Management Area Trail Meister).

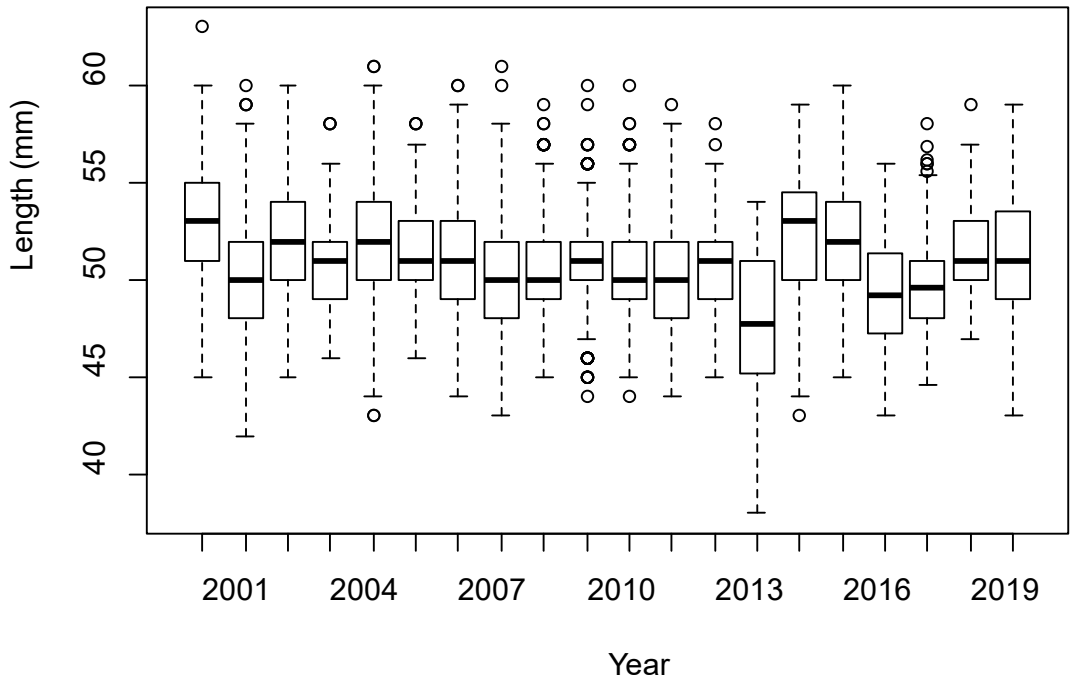


Figure 135. Boxplot of American eel lengths recorded in the Florida Guana River YOY survey.

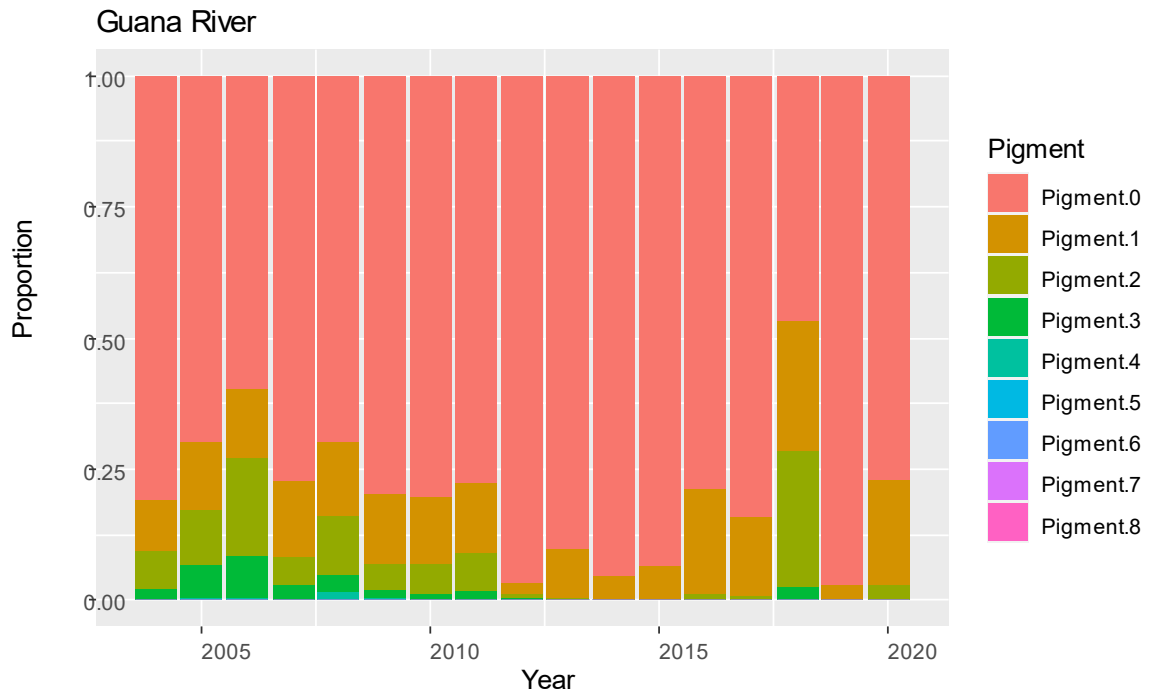


Figure 136. Distribution of pigment stages in the Guana River YOY American eel survey.

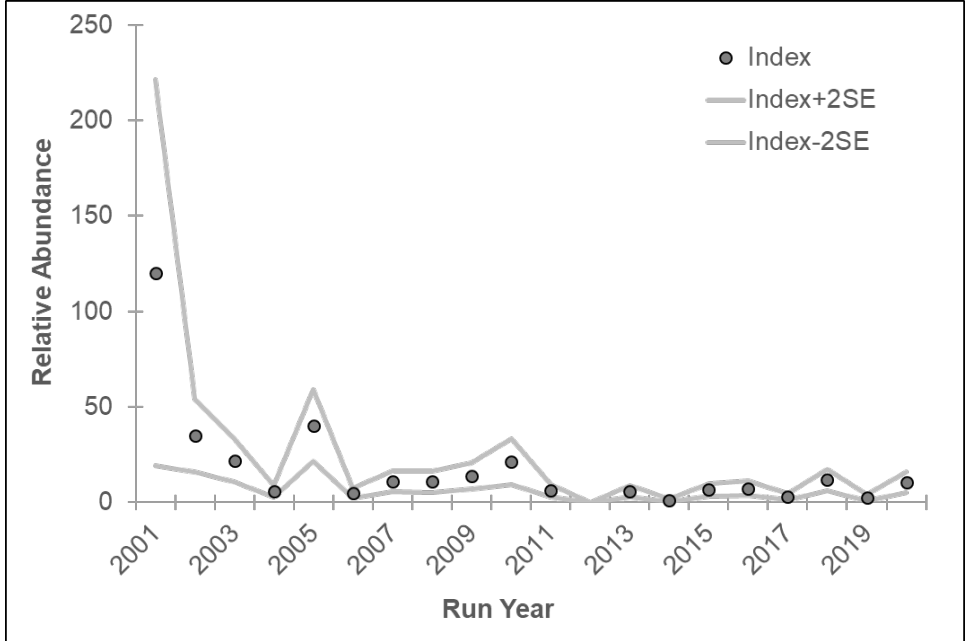


Figure 137. Standardized index of relative abundance of YOY American eel developed from the Florida Guana River Survey.

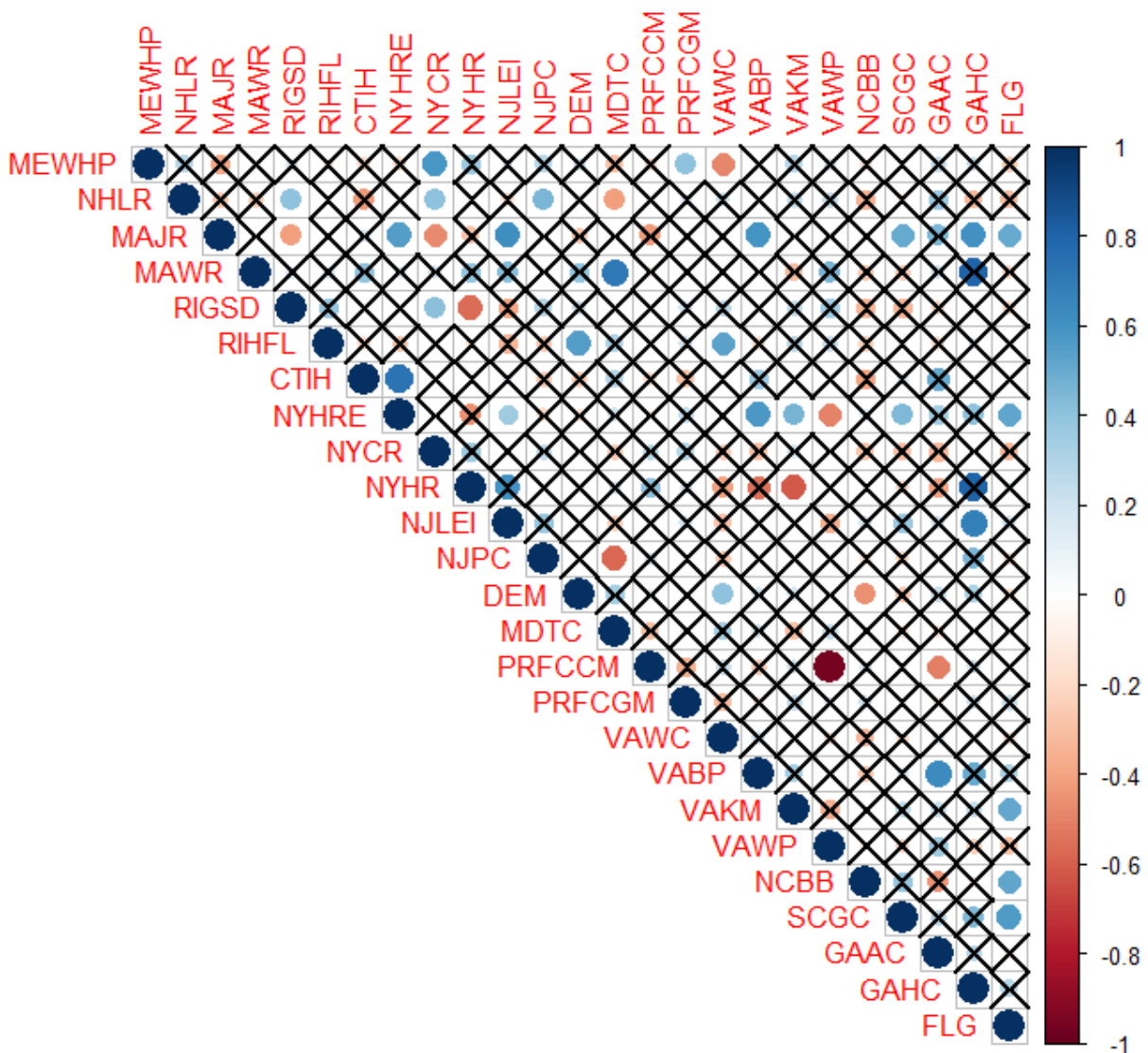


Figure 138. Correlogram of YOY surveys where blue circles indicate positive correlations, red circles indicate negative correlations, the size of the circle and deepness of color indicate the strength of the correlation, and the insignificant coefficients are marked with a black “X”. See Table 11 for survey abbreviations.

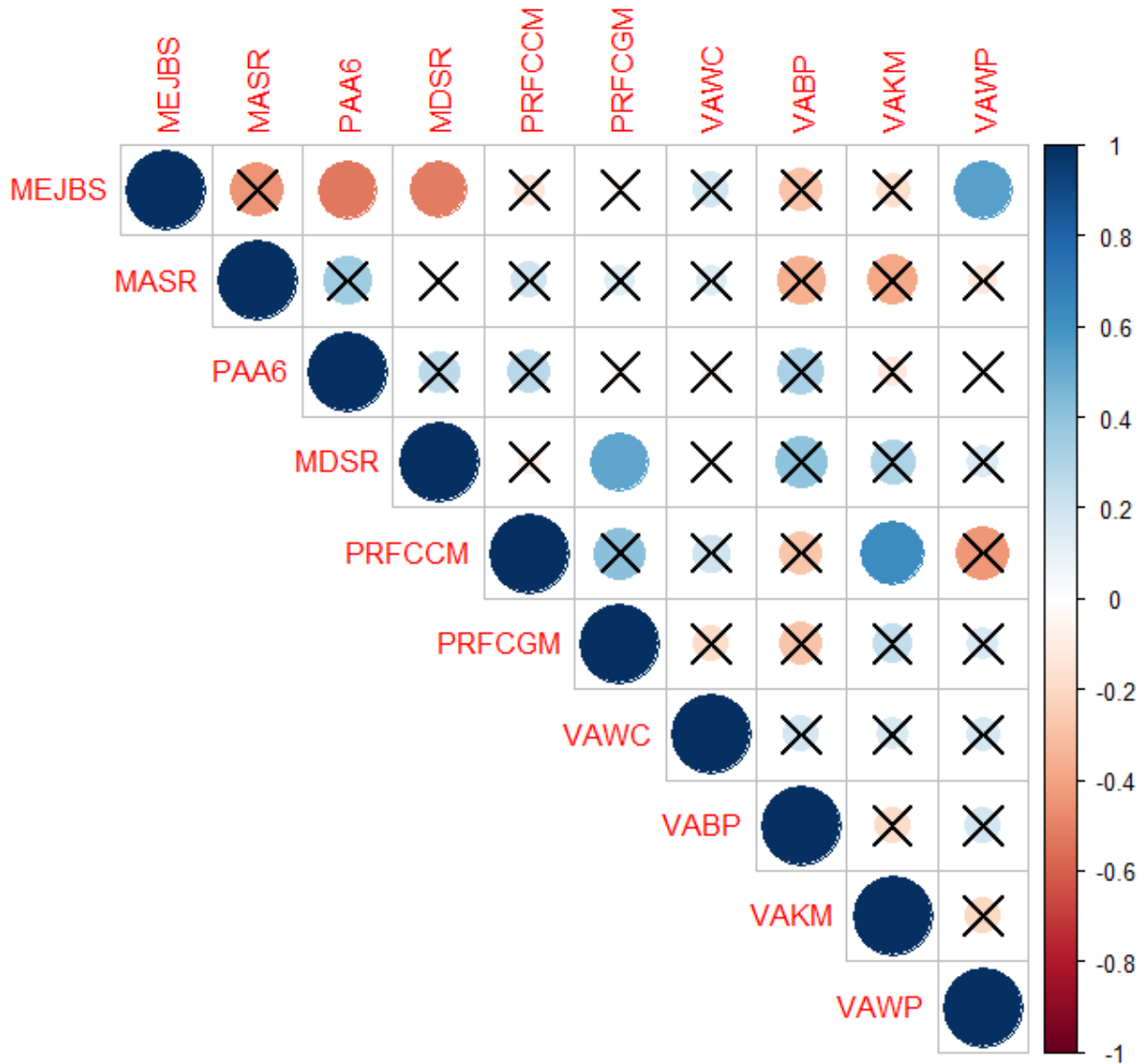


Figure 139. Correlogram of elver surveys where blue circles indicate positive correlations, red circles indicate negative correlations, the size of the circle and deepness of color indicate the strength of the correlation, and the insignificant coefficients are marked with a black “X”. See Table 12 for survey abbreviations.

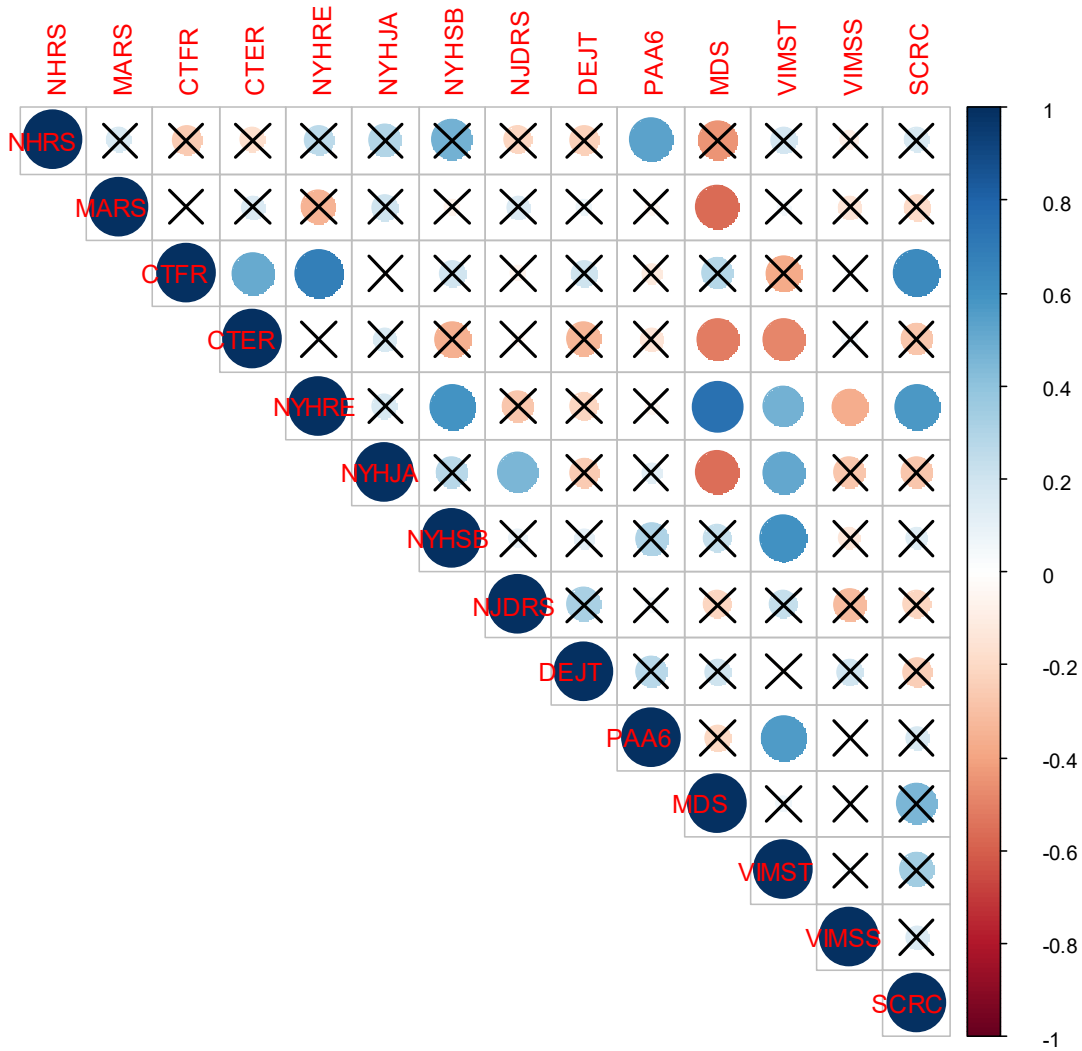


Figure 140. Correlogram of yellow eel surveys where blue circles indicate positive correlations, red circles indicate negative correlations, the size of the circle and deepness of color indicate the strength of the correlation, and the insignificant coefficients are marked with a black "X". See Table 13 for survey abbreviations.

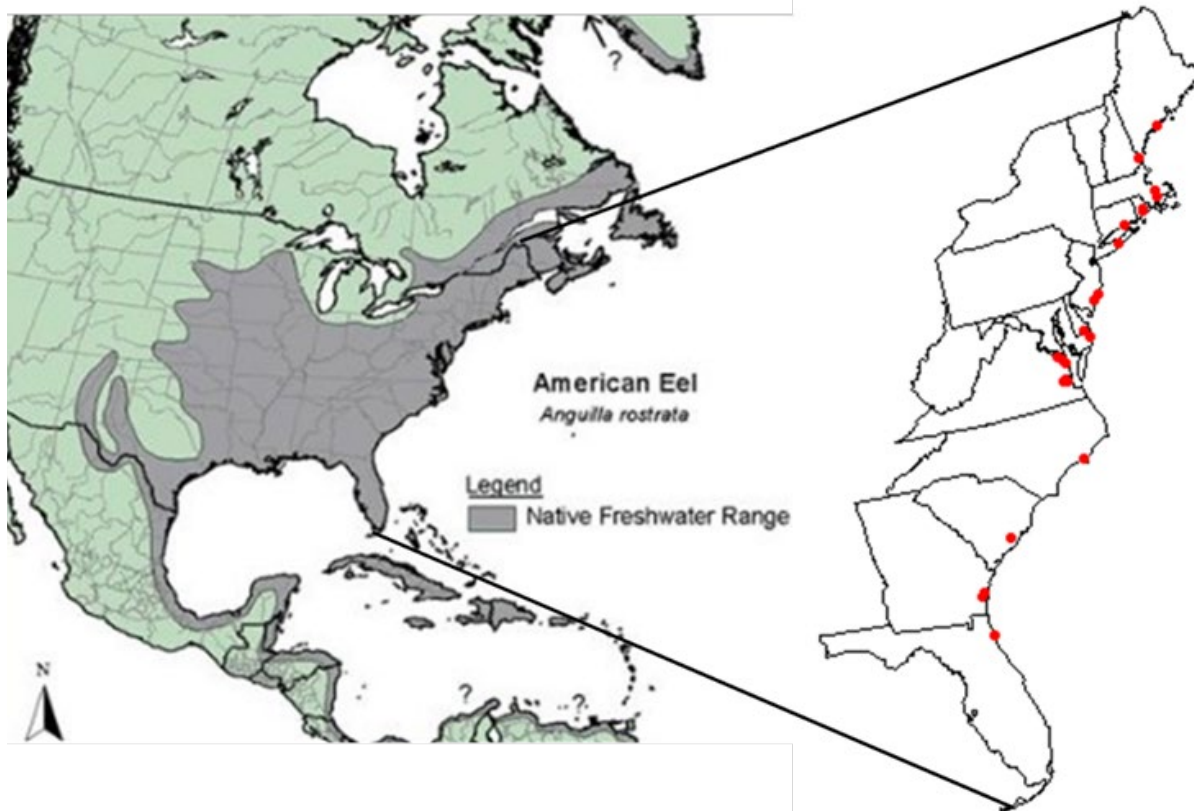
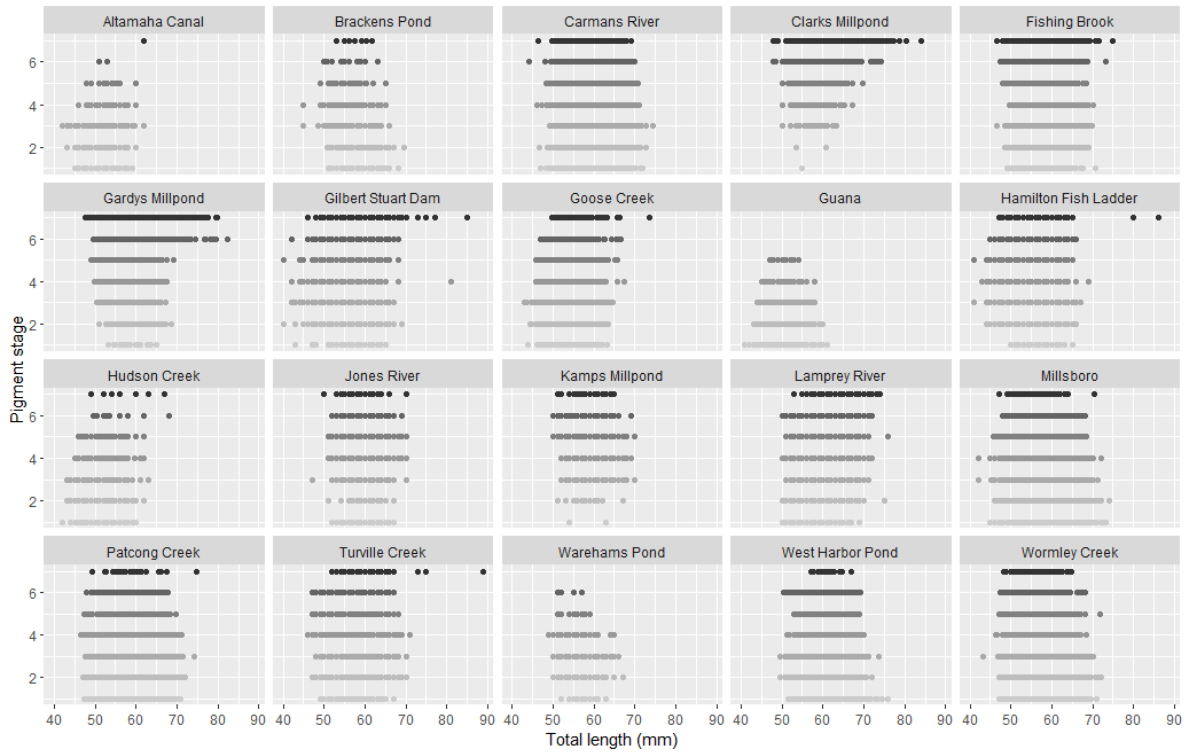
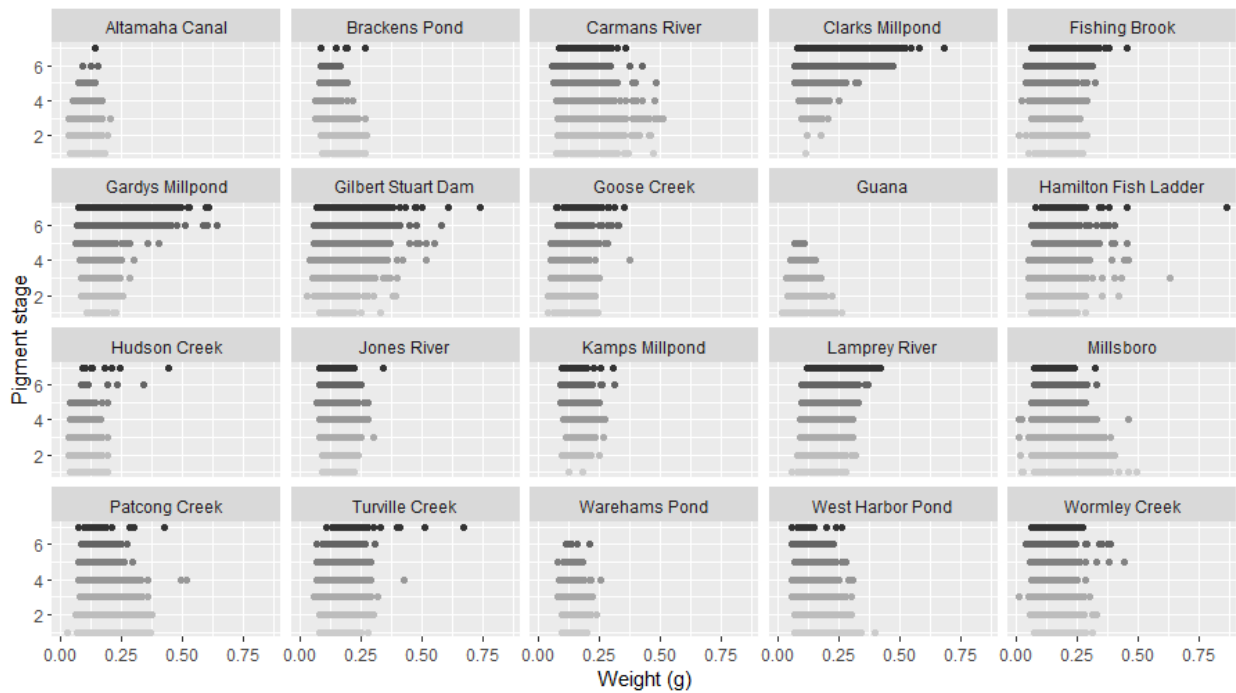


Figure 141. Locations where fixed-site YOY surveys have been or are currently located along the coast. No sites currently exist in the U.S. Gulf of Mexico (source: NatureServe 2006).

a)



b)



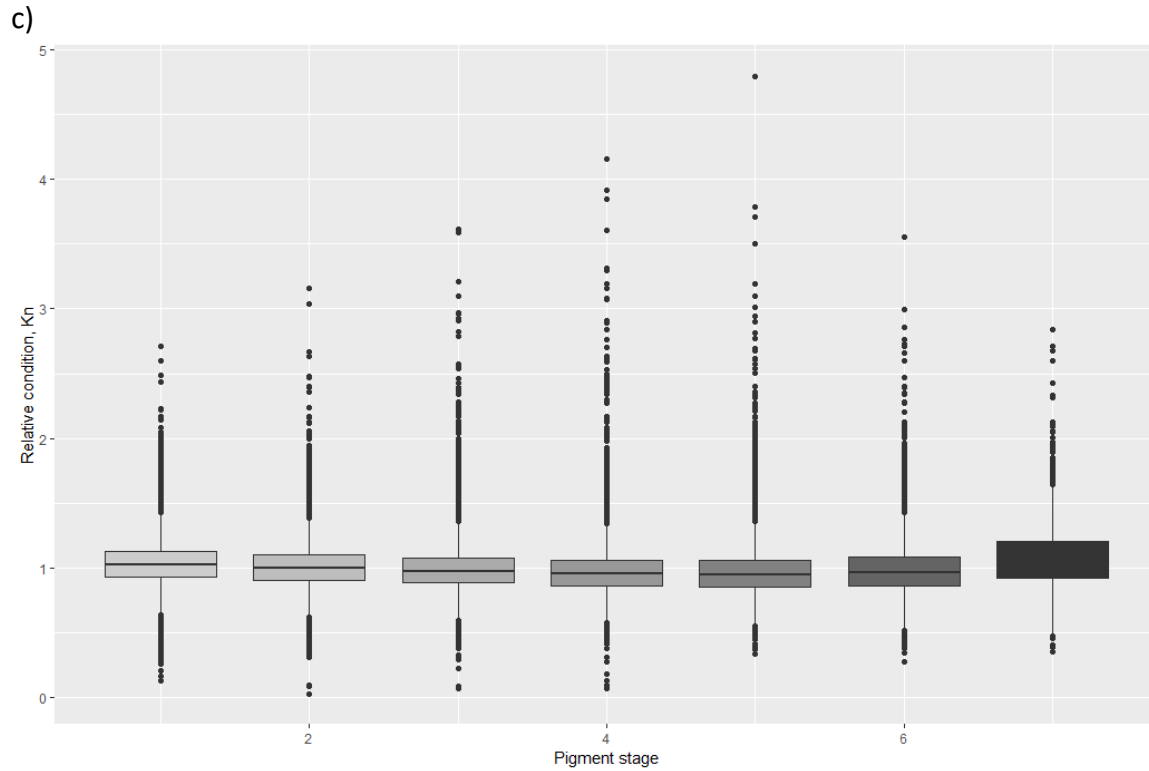


Figure 142. YOY American eel biological data. a) Pigment stage versus total length (mm) of YOY eels, b) Pigment stage versus weight (g) of YOY eels, c) Relative condition of YOY eels versus pigment stage.

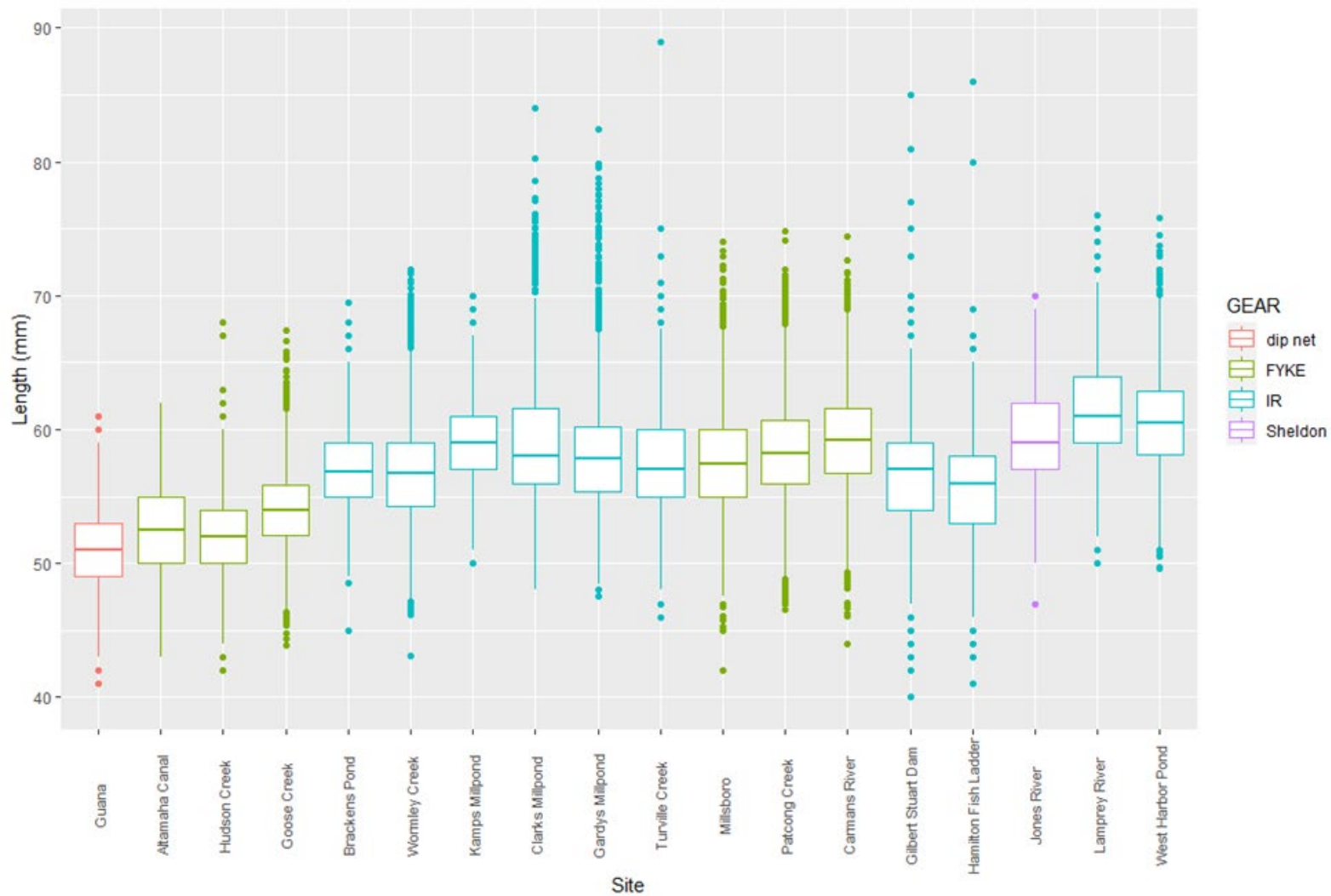


Figure 143. YOY eel length boxplots arranged from south to north along the x-axis. Different gear types are color coded.

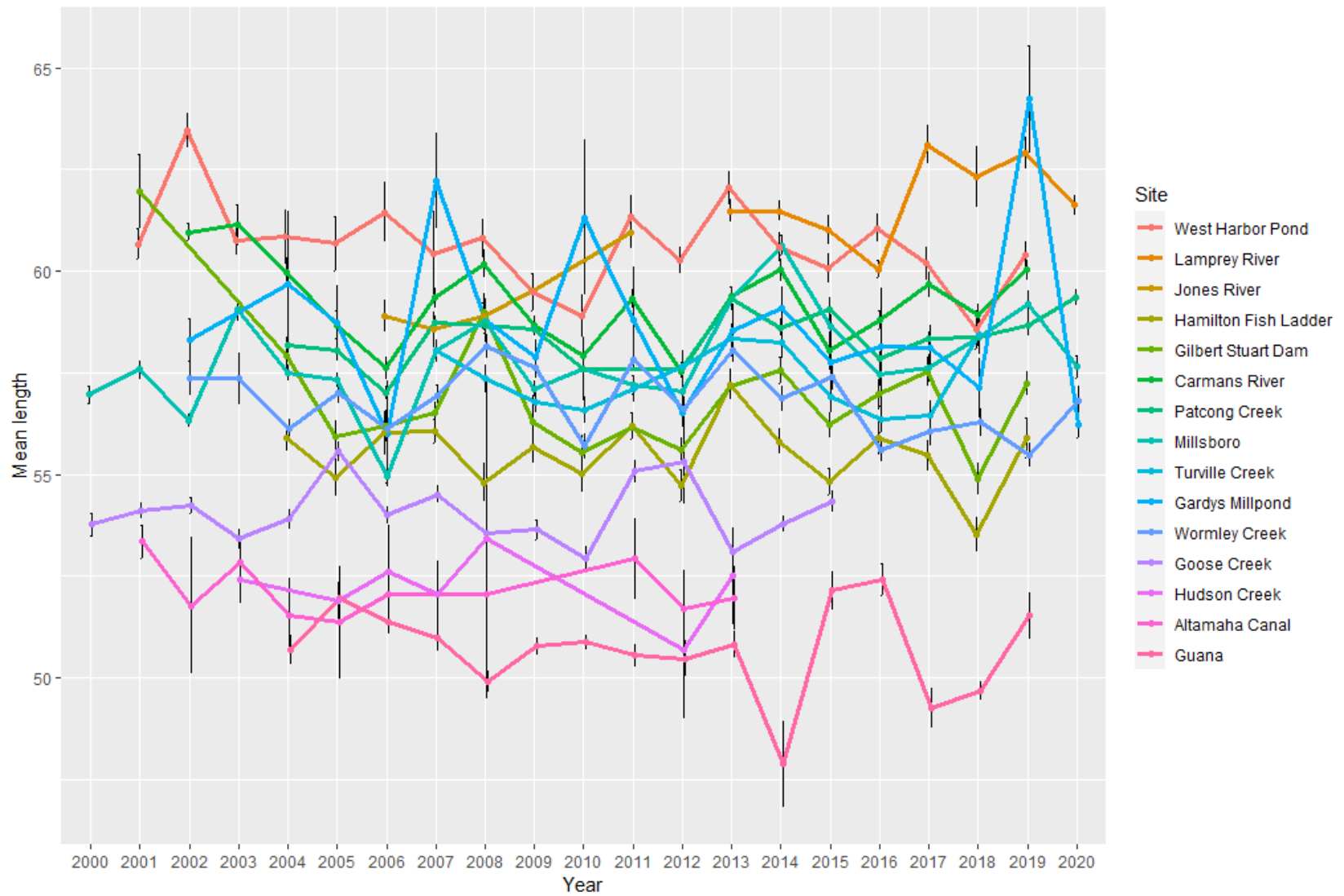


Figure 144. Mean length (95% CI) of YOY eels by year arranged and color-coded by latitude (West Harbor Pond, Massachusetts to Guana, Florida).

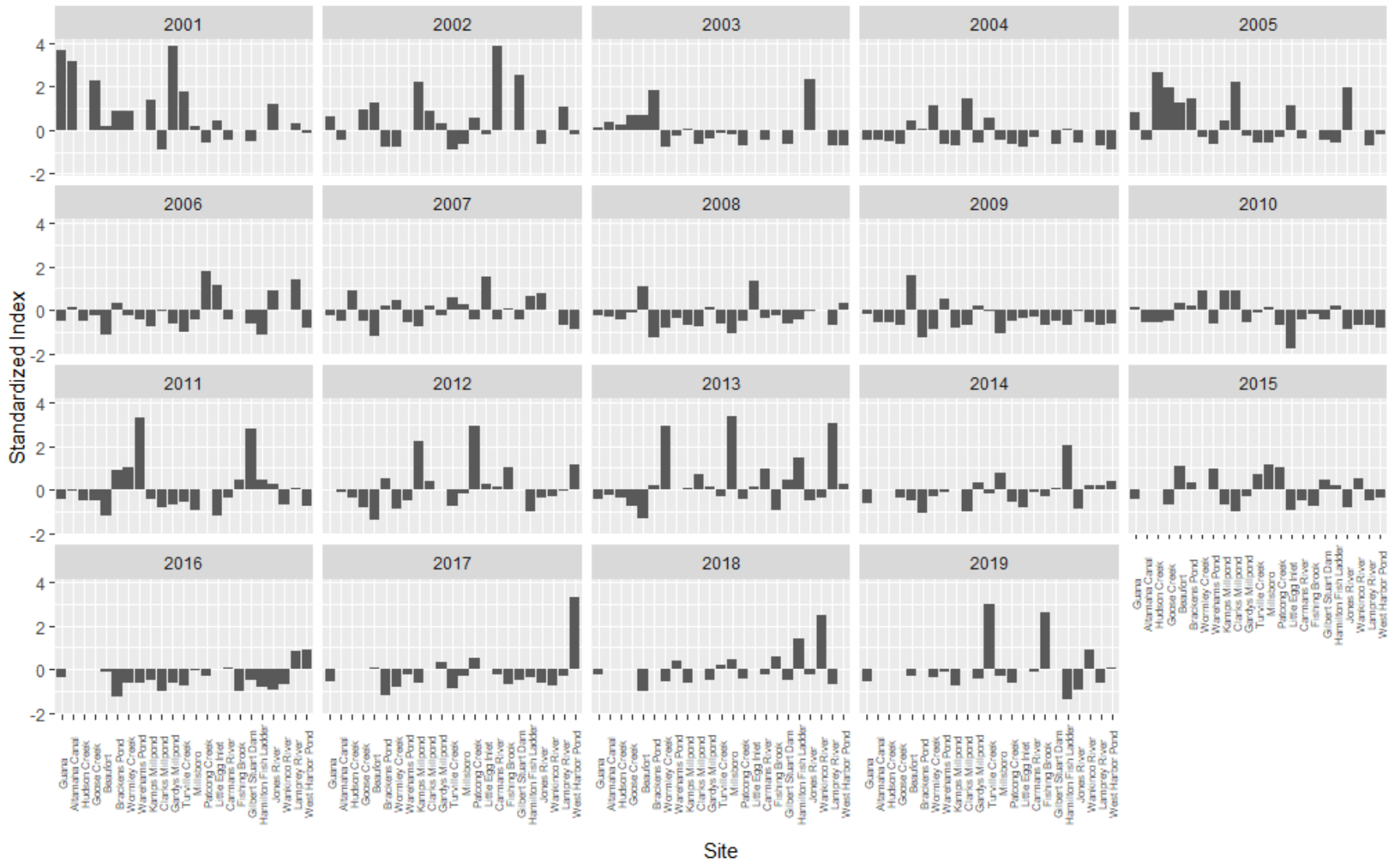


Figure 145. YOY eel indices, standardized within each site, by year. Sites are arranged from south to north along the x-axis in each plot.

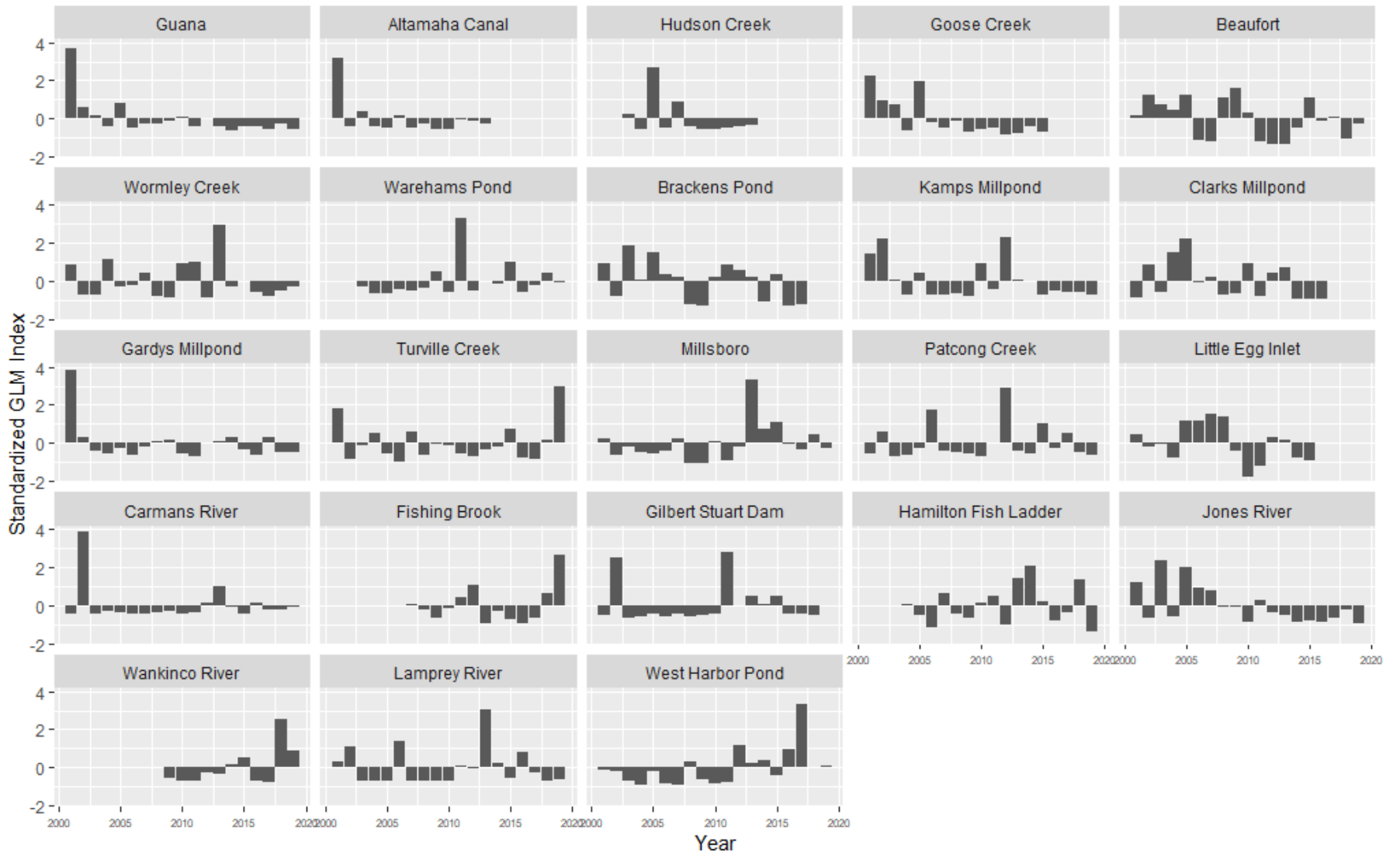


Figure 146. Standardized YOY eel indices (within each site) by year within each site.

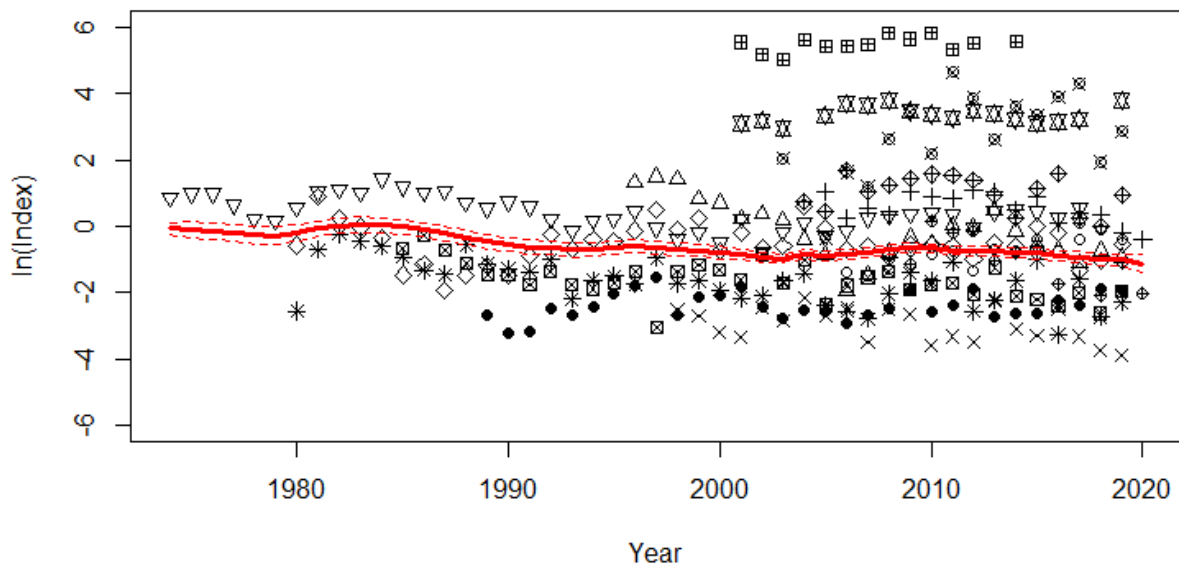


Figure 147. Fit of MARSS model to time series of yellow eel abundance indices along the Atlantic coast. The red solid line represents the true abundance index scaled to the first survey included in the MARSS model fit. Dashed red lines represent 95% confidence intervals. Individual surveys are represented by different symbols in the plot.

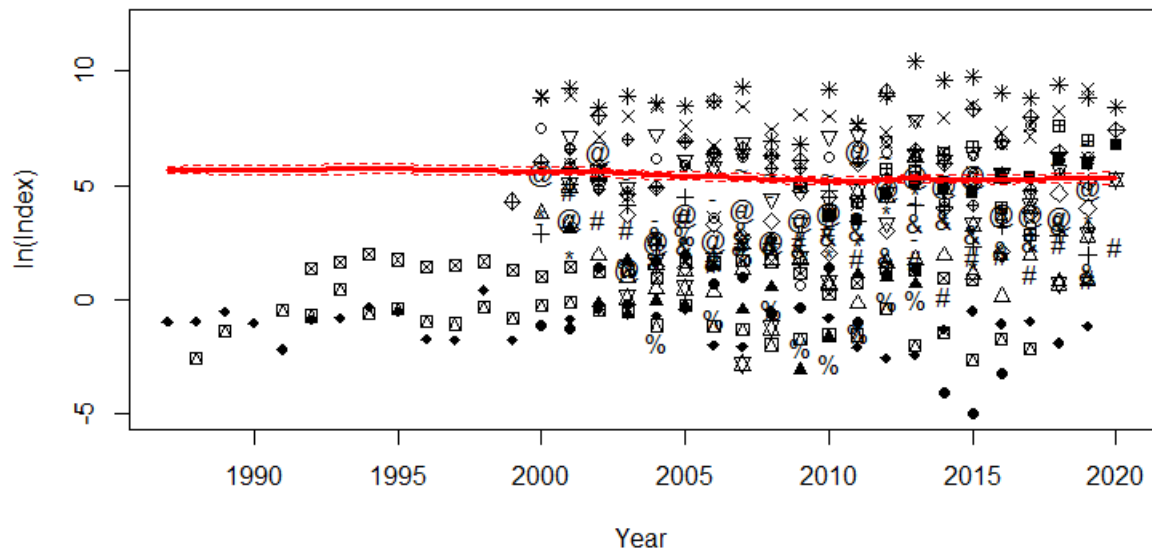


Figure 148. Fit of MARSS model to time series of YOY eel abundance indices along the Atlantic coast. The red solid line represents the true abundance index scaled to the first survey included in the MARSS model fit. Dashed red lines represent 95% confidence intervals. Individual surveys are represented by different symbols in the plot.

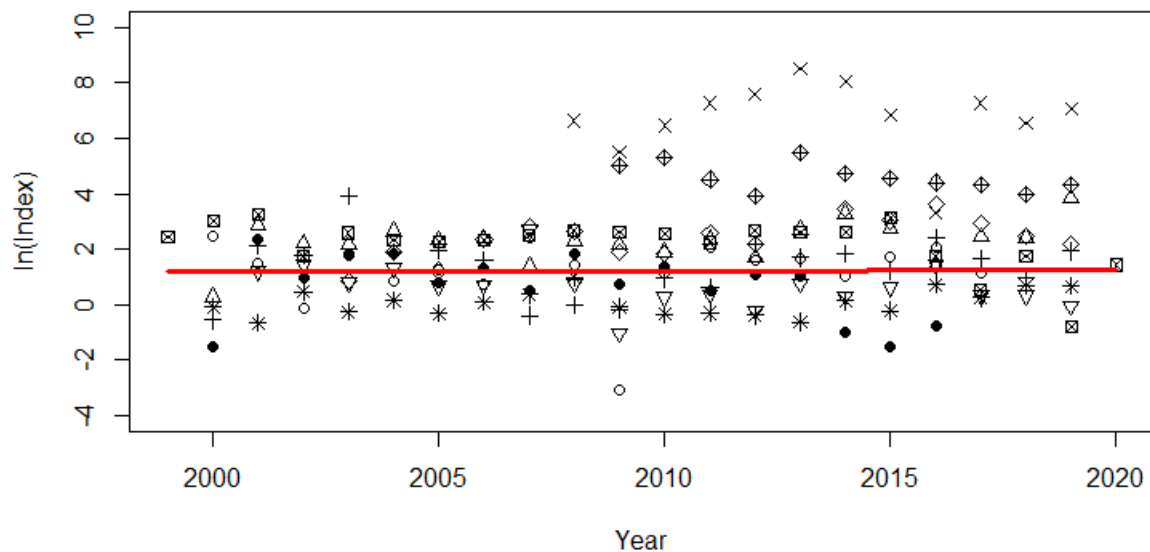


Figure 149. Fit of MARSS model to time series of elver eel abundance indices along the Atlantic coast. The red solid line represents the true abundance index scaled to the first survey included in the MARSS model fit. Confidence intervals (95%) are not shown because there was very little process error among elver surveys which overall showed no trend through time. Individual surveys are represented by different symbols in the plot.

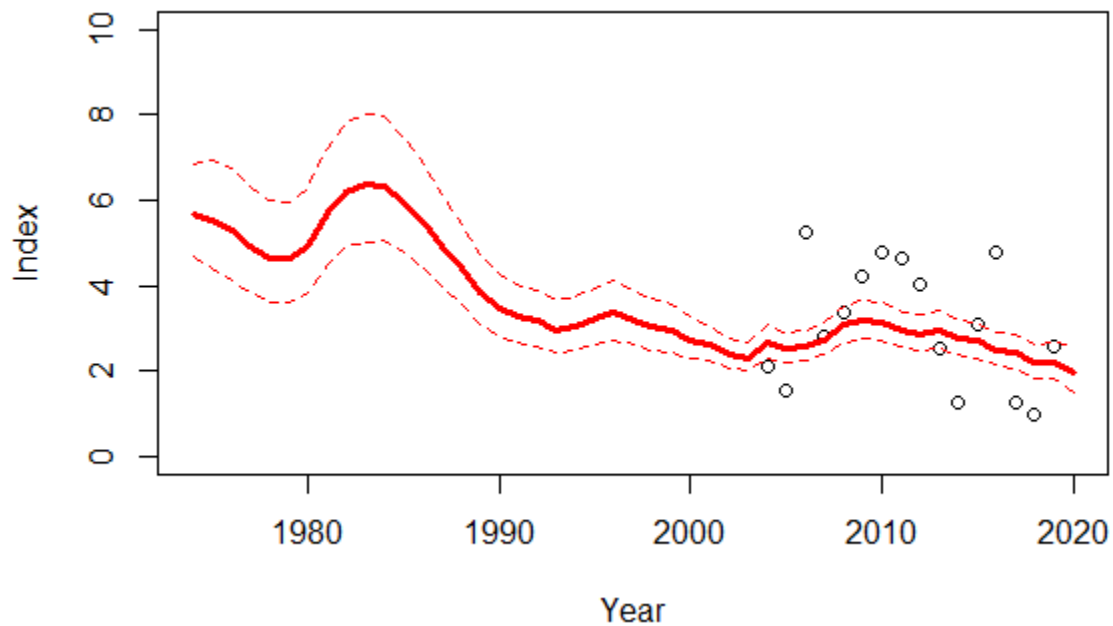


Figure 150. Yellow eel MARSS model fit scaled to the Maine Rainbow Smelt Fyke Net survey.

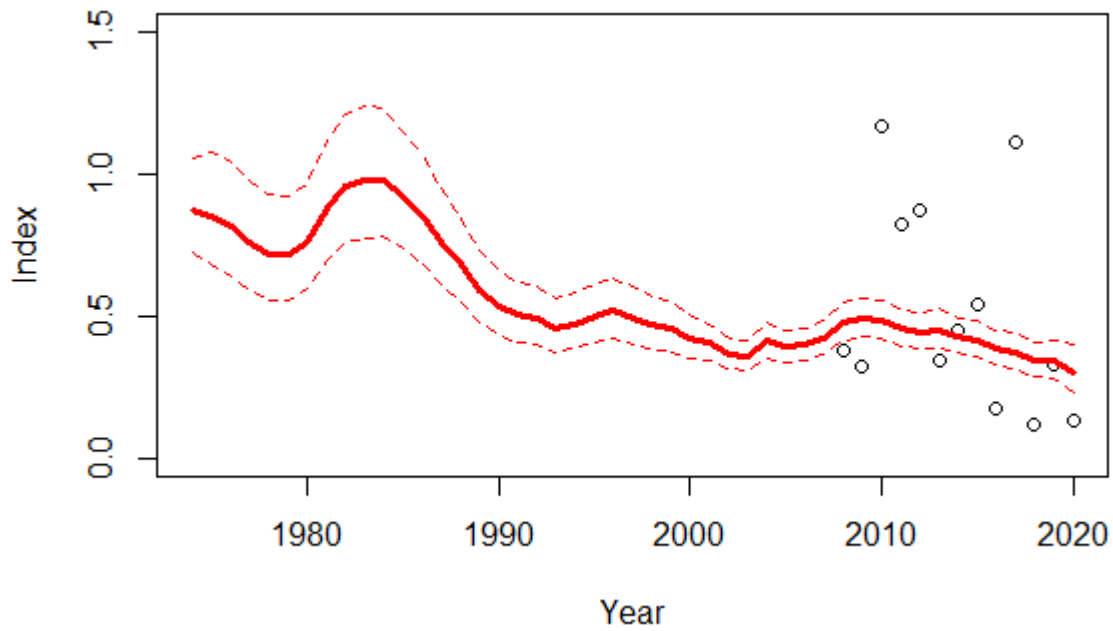


Figure 151. Yellow eel MARSS model fit scaled to the New Hampshire Rainbow Smelt Fyke Net survey.

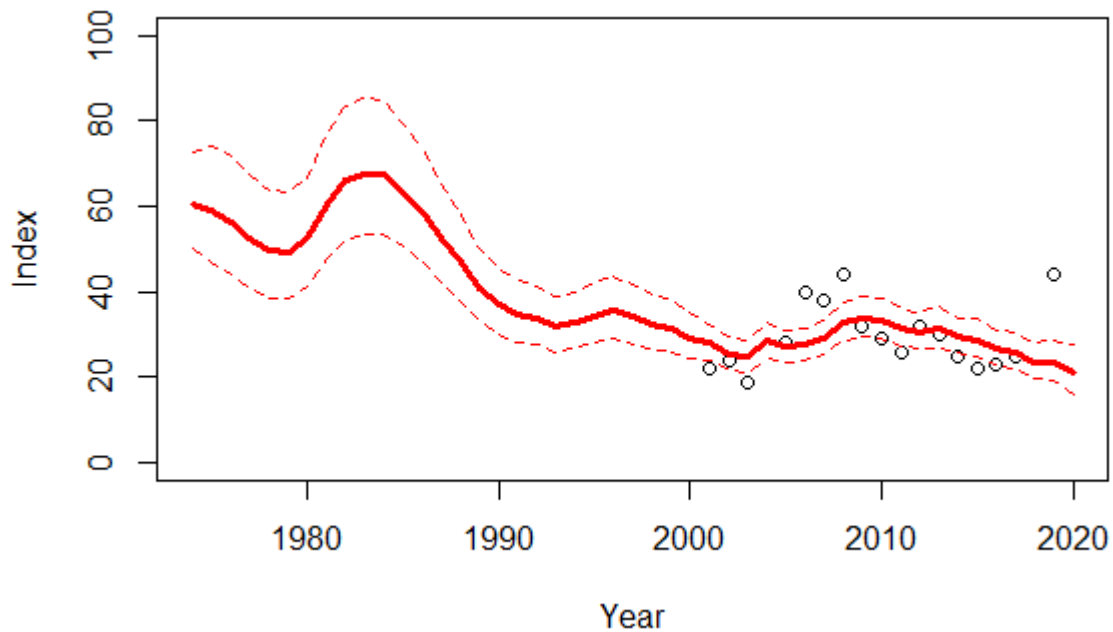


Figure 152. Yellow eel MARSS model fit scaled to the Connecticut Eightmile River electrofishing survey.

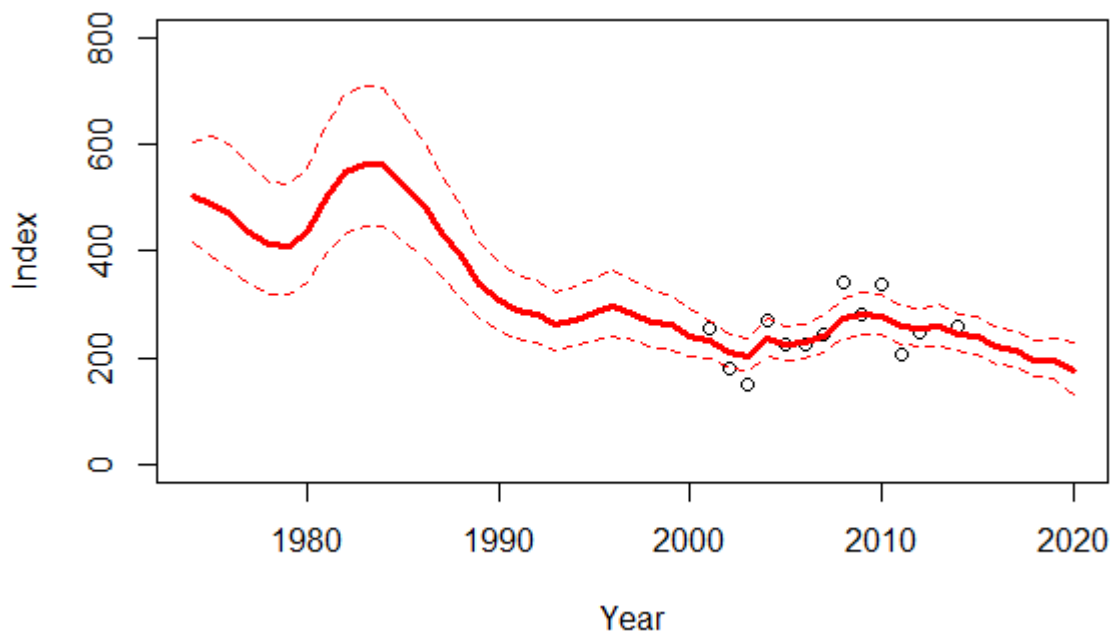


Figure 153. Yellow eel MARSS model fit scaled to the Connecticut Farmill River electrofishing survey.

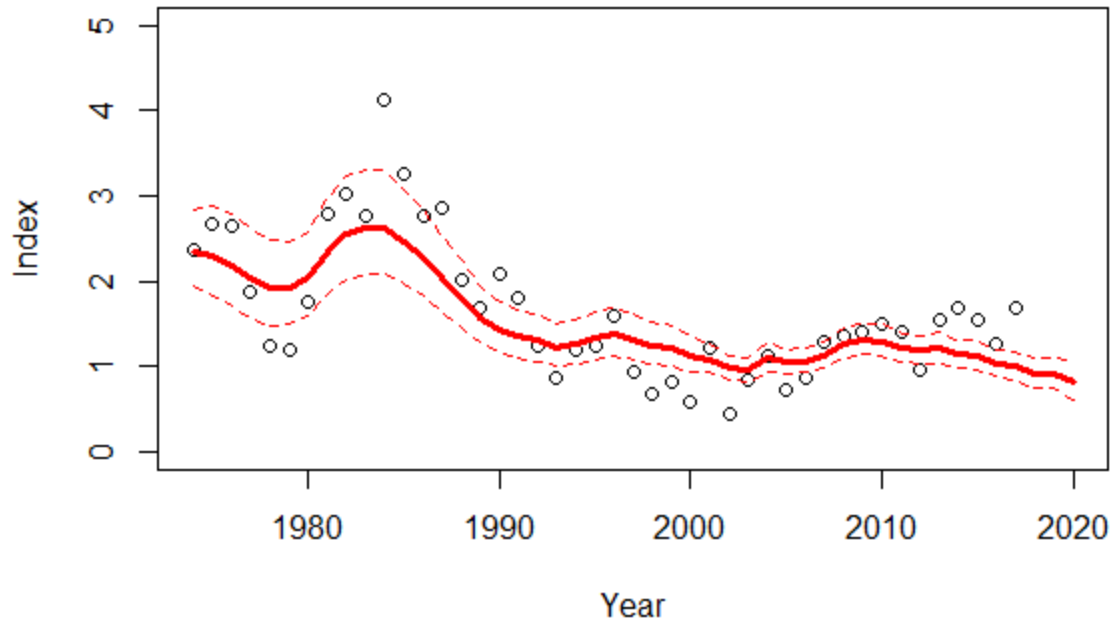


Figure 154. Yellow eel MARSS model fit scaled to the New York Hudson River Estuary (HRE) monitoring program survey.

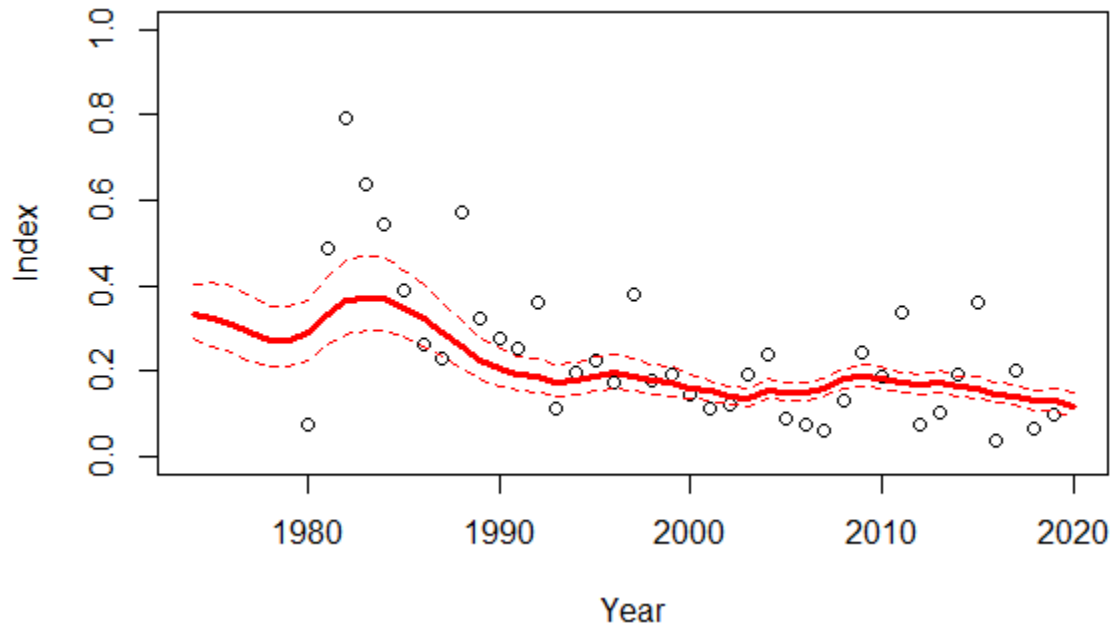


Figure 155. Yellow eel MARSS model fit scaled to the New York Hudson River Juvenile Striped Bass Seine survey.

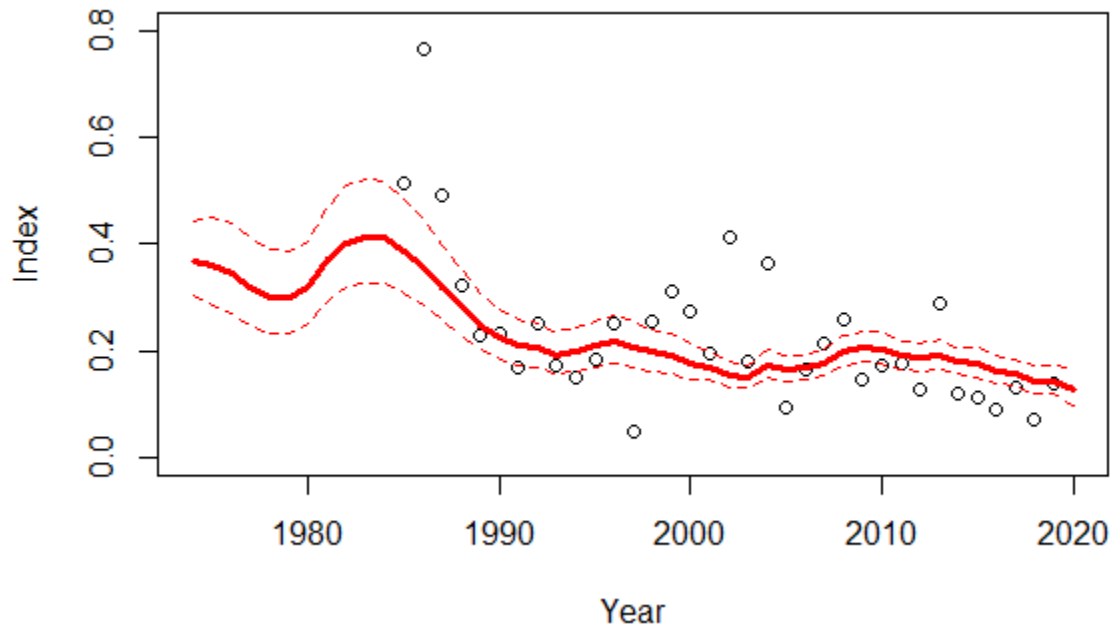


Figure 156. Yellow eel MARSS model fit scaled to the New York Hudson River Juvenile Alosine Seine survey.

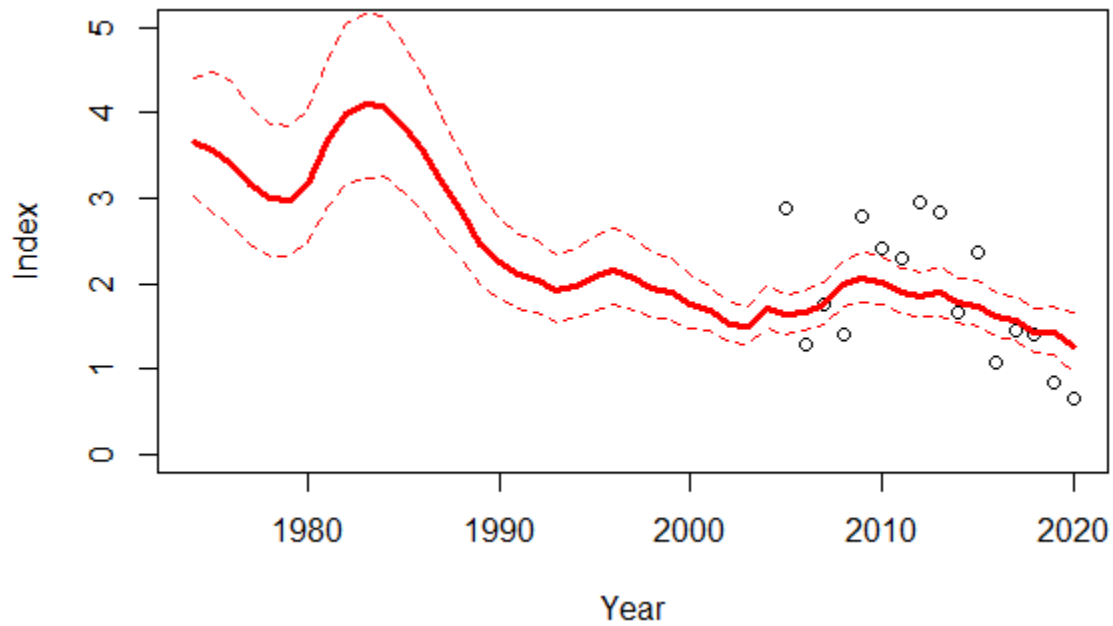


Figure 157. Yellow eel MARSS model fit scaled to the Pennsylvania Delaware River electrofishing survey.

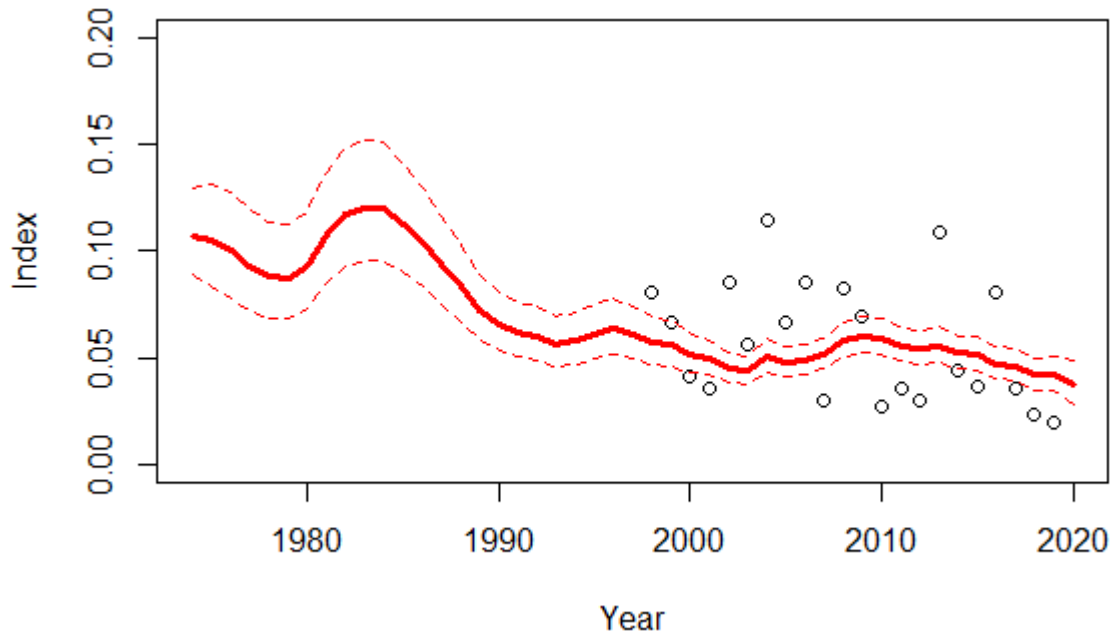


Figure 158. Yellow eel MARSS model fit scaled to the New Jersey Delaware River Seine survey.

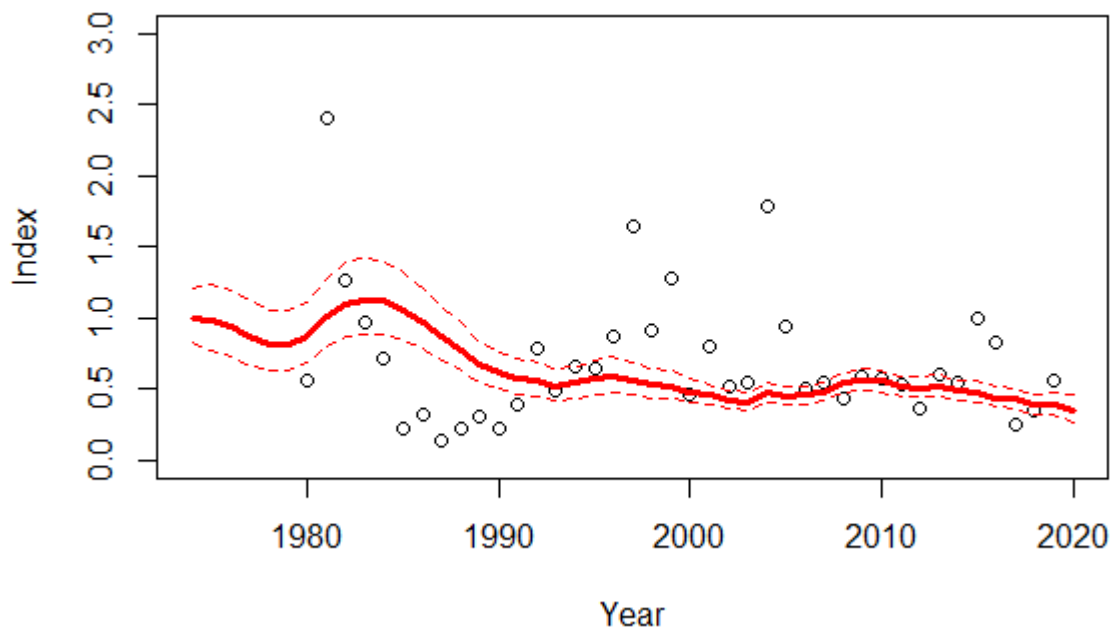


Figure 159. Yellow eel MARSS model fit scaled to the Delaware River Trawl survey.

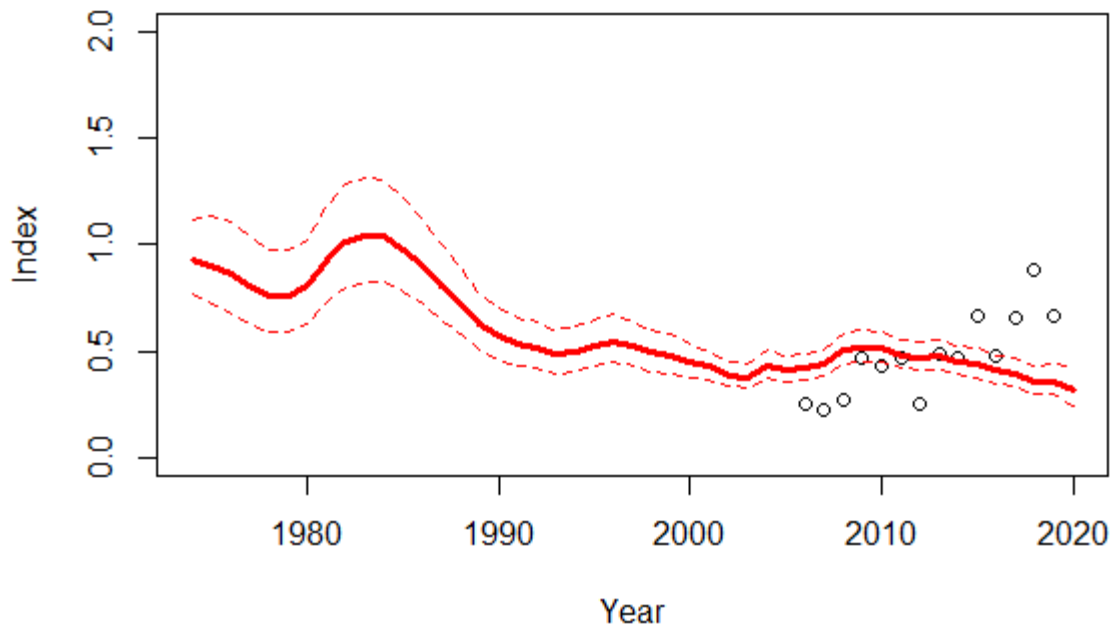


Figure 160. Yellow eel MARSS model fit scaled to the Maryland SassafRAS River Eel Pot survey.

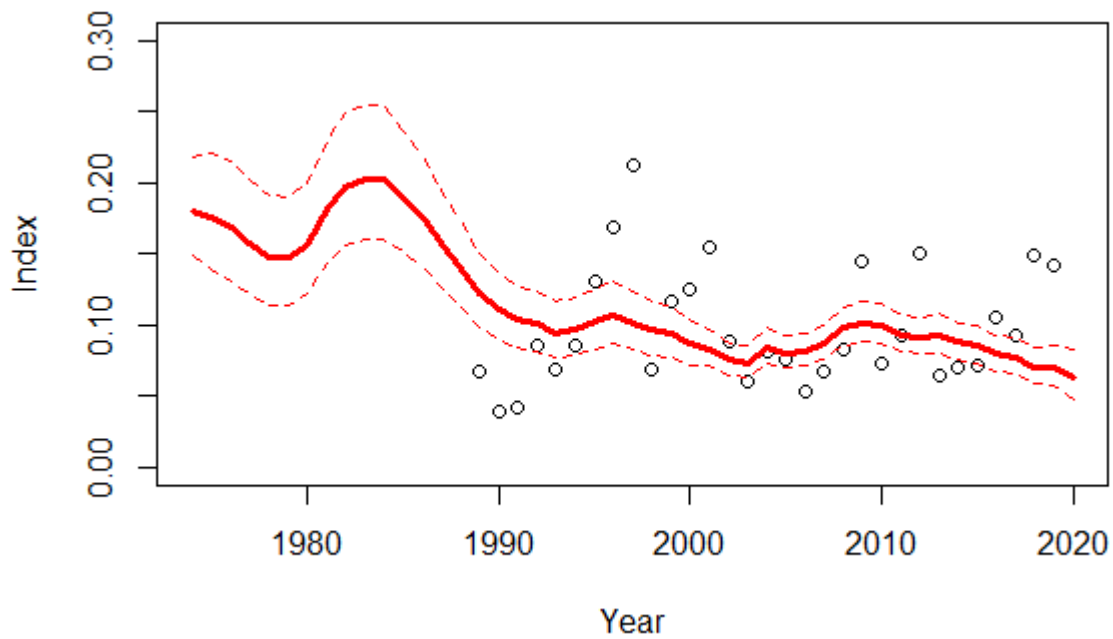


Figure 161. Yellow eel MARSS model fit scaled to the Virginia Institute of Marine Science Seine survey.

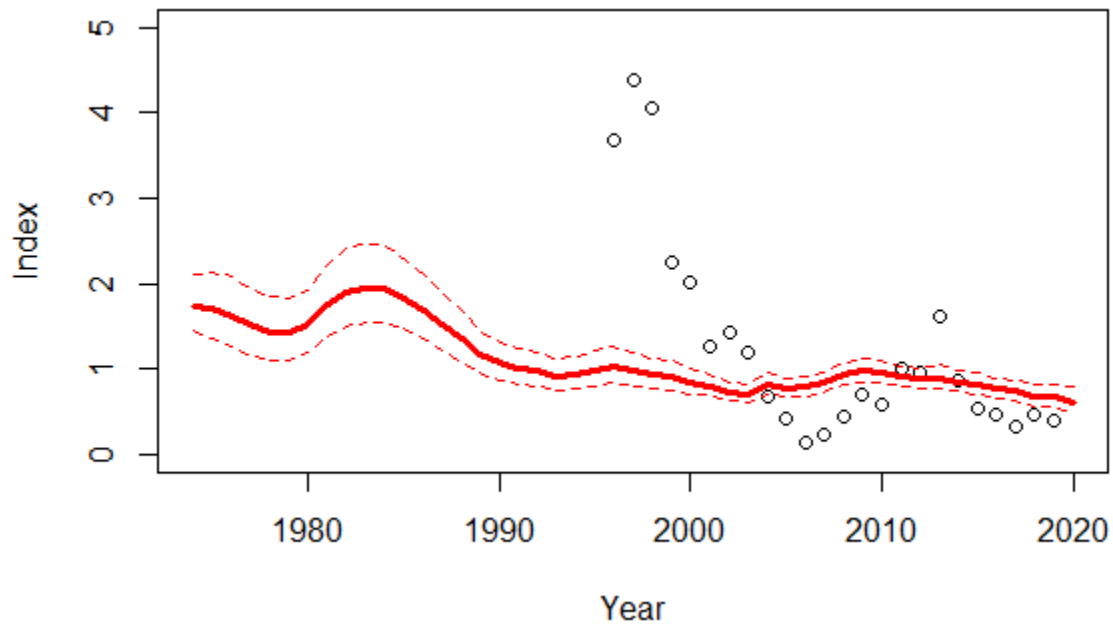


Figure 162. Yellow eel MARSS model fit scaled to the Virginia Institute of Marine Science Trawl survey.

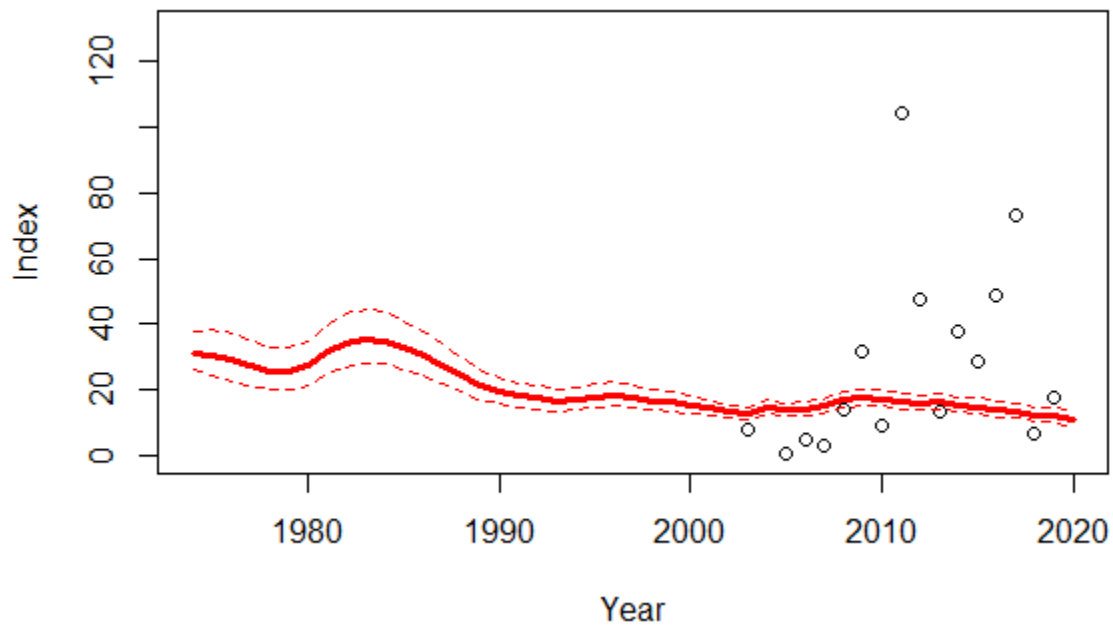


Figure 163. Yellow eel MARSS model fit scaled to the South Carolina Rediversion Canal Ladder survey.

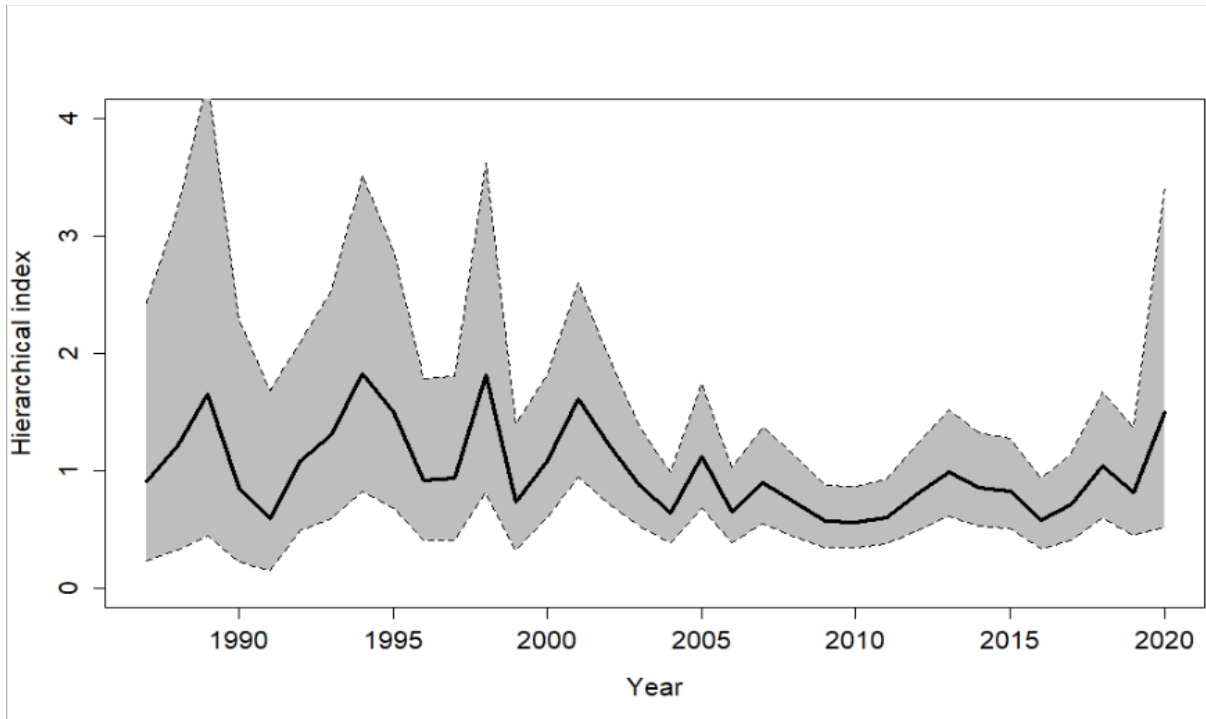


Figure 164. Time series of YOY American eel coastwide abundance as estimated from the Conn method. The black line gives the posterior mean and the grey, shaded area represents a 95% credible interval.

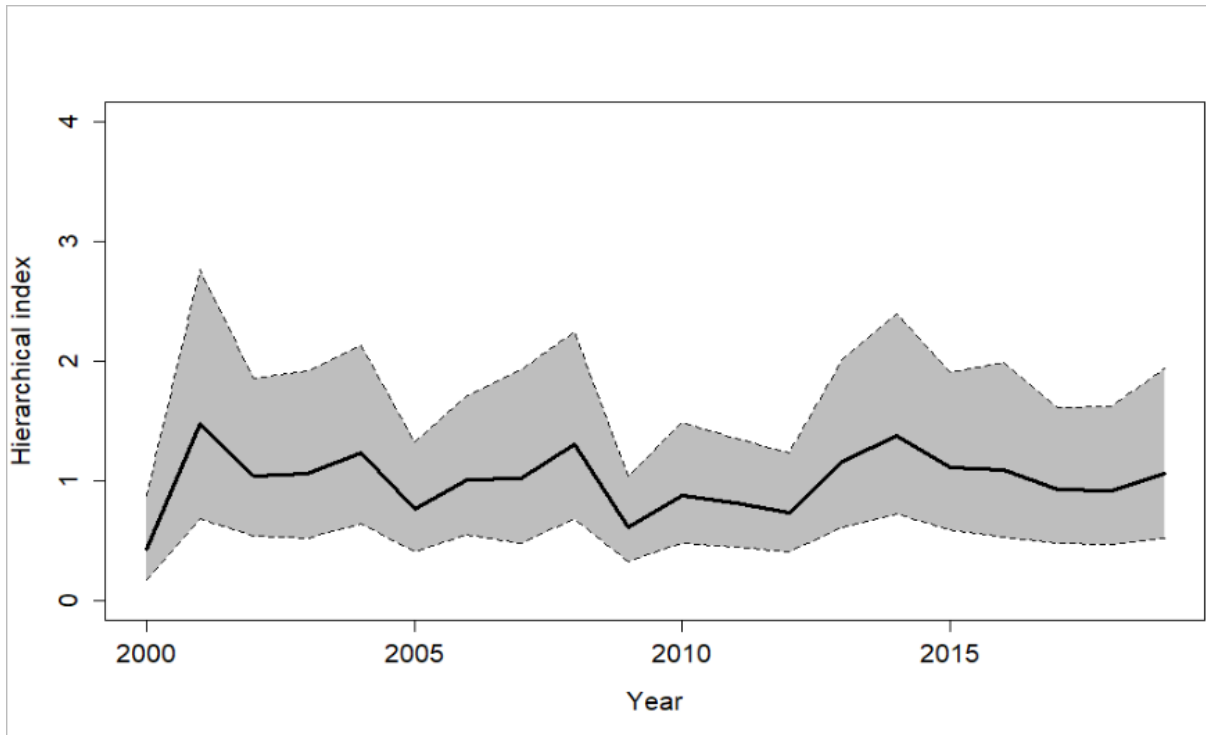


Figure 165. Time series of elver American eel coastwide abundance as estimated from the Conn method. The black line gives the posterior mean and the grey, shaded area represents a 95% credible interval.

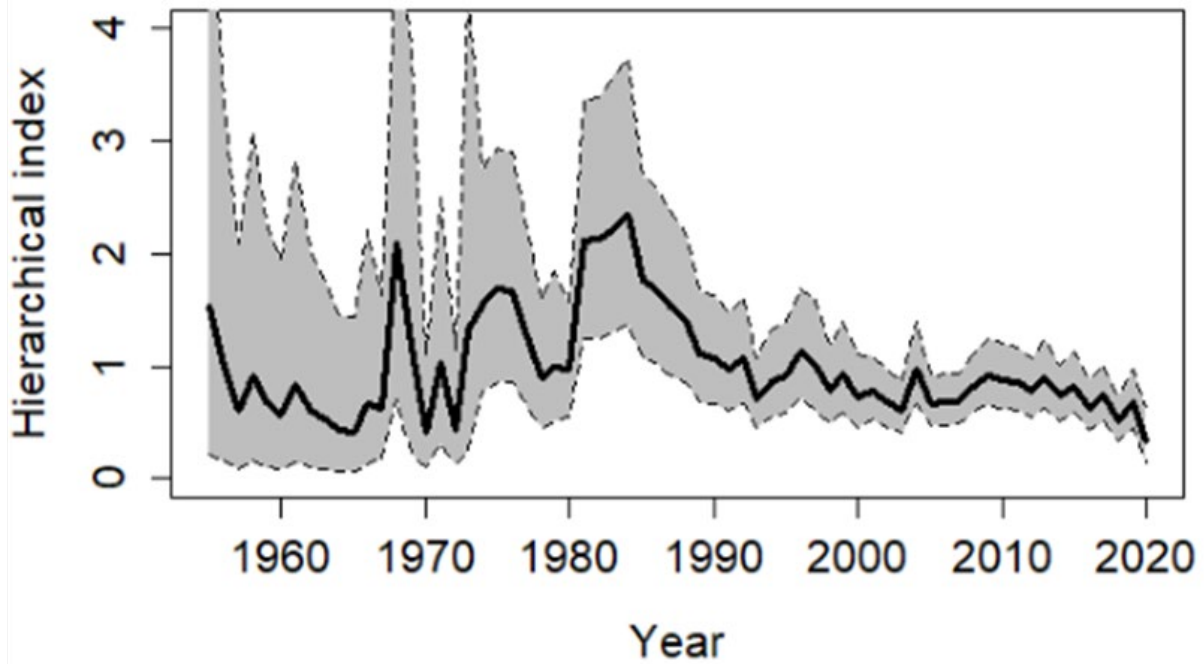


Figure 166. Time series of yellow eel coastwide abundance as estimated from the Conn method. The black line gives the posterior mean and the grey, shaded area represents a 95% credible interval.

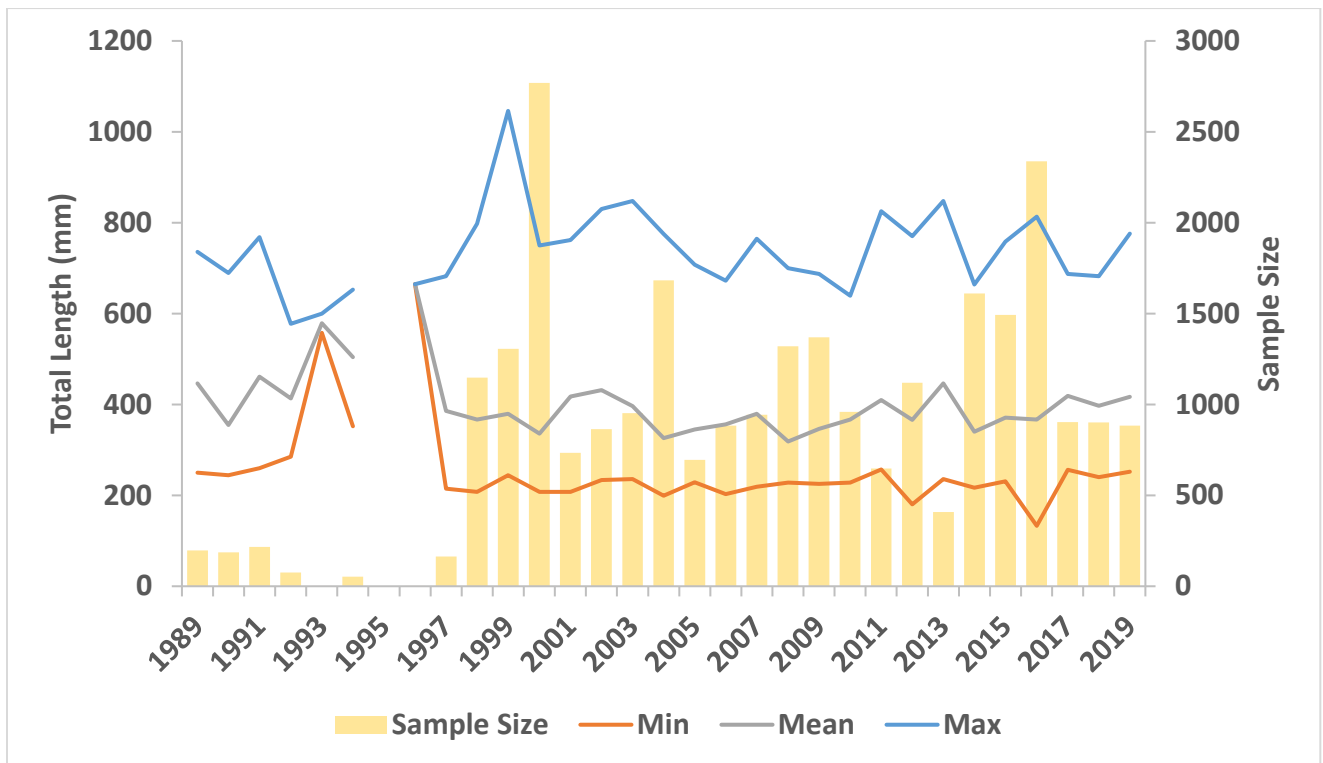


Figure 167. Commercial mean lengths from Chesapeake Bay region states, 1989-2020. Data is from males and females because sex data was not available until 2006. Sample size, minimum length, and maximum length are indicated on the figure.

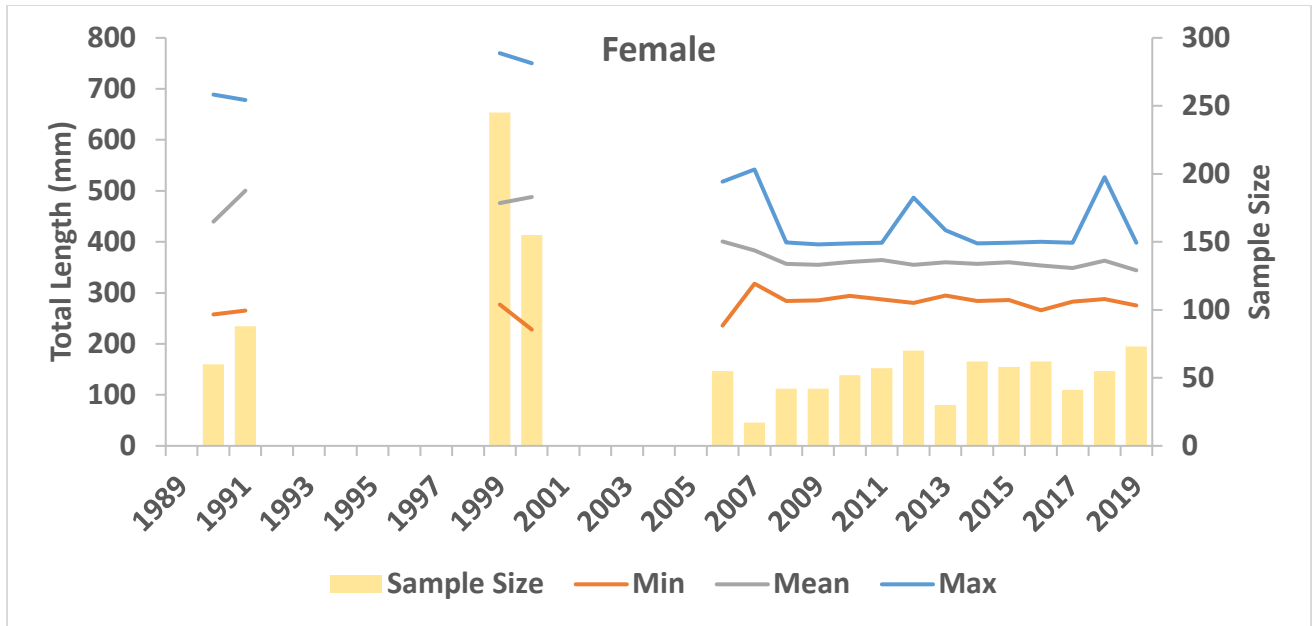


Figure 168. Female commercial mean lengths from Chesapeake Bay region states, 1990-2019. Sample size, minimum length, and maximum length are indicated on the figure. There was no sex data from Delaware and the early 1990s values are from VMRC. The remaining lengths are from Maryland.

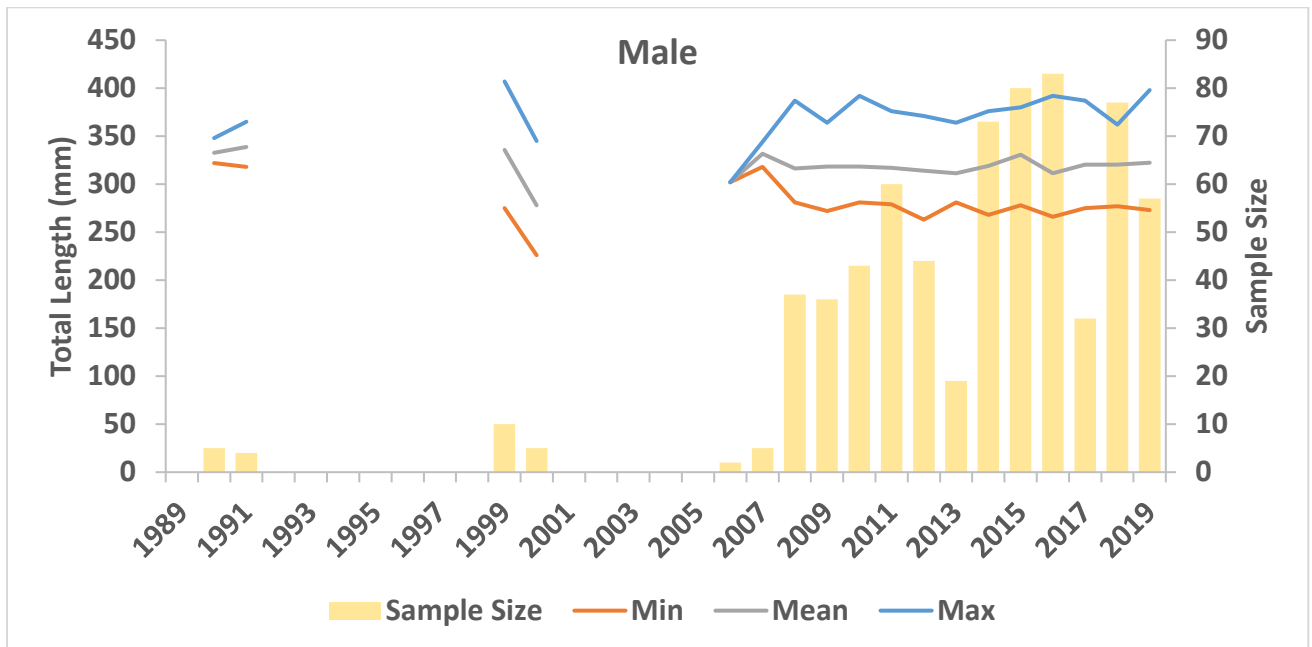


Figure 169. Male commercial mean lengths from Chesapeake Bay region states, 1990-2019. Sample size, minimum length, and maximum length are indicated on the figure. There was no sex data from Delaware and the early 1990s values are from VMRC. The remaining lengths are from Maryland.

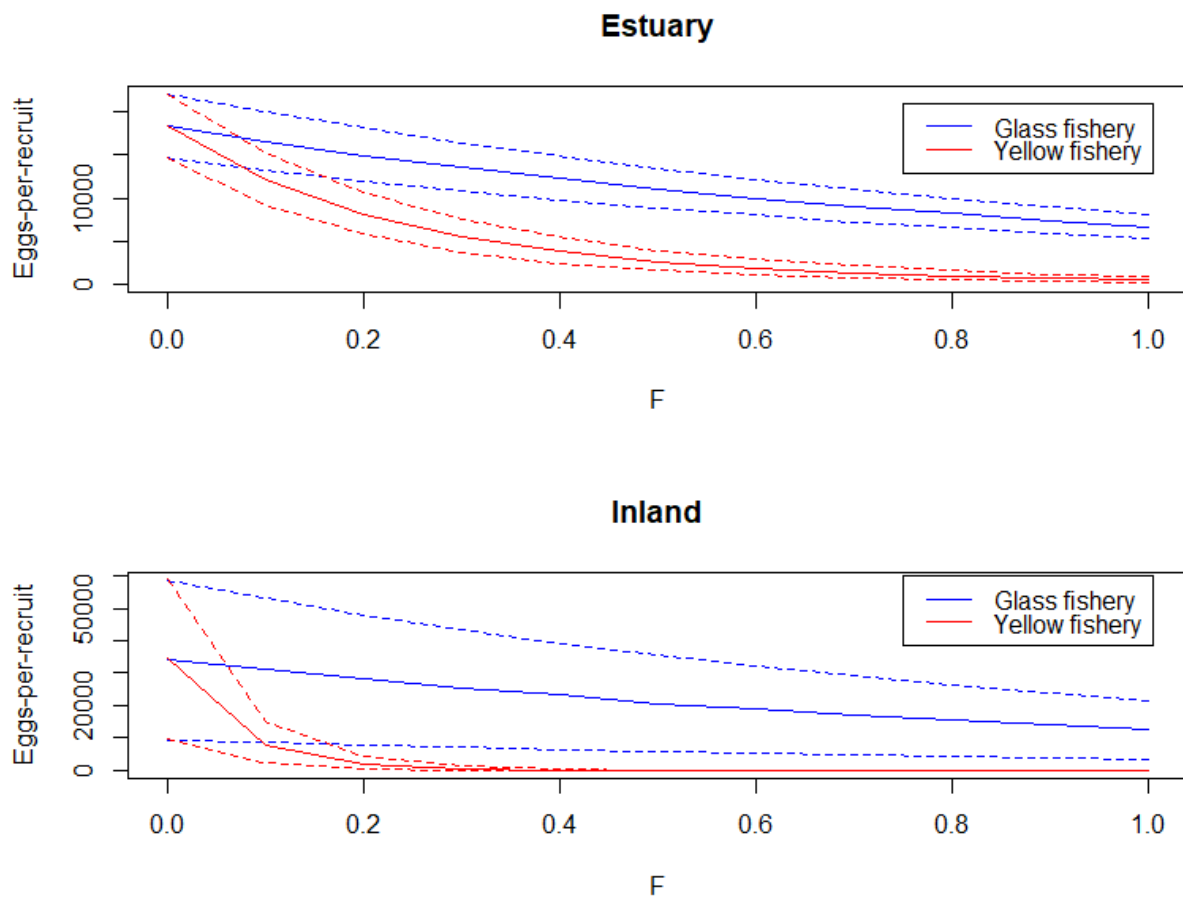


Figure 170. Plots of American eel eggs-per-recruit as a function of fishing mortality (F) for glass and yellow eel fisheries occurring in the estuary and inland waters. Solid lines correspond to medians from simulations and dashed lines correspond to 5th and 95th percentiles.

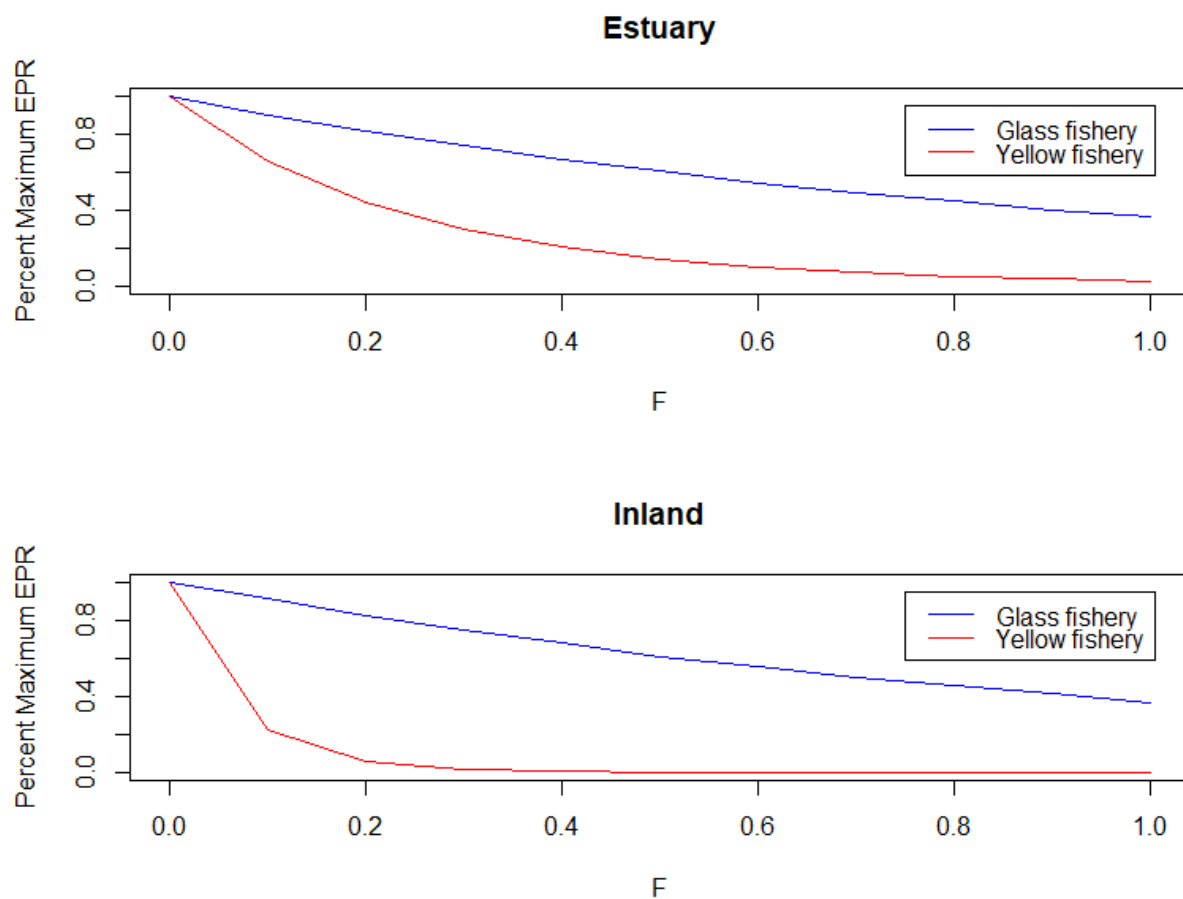


Figure 171. Percent maximum eggs-per-recruit as a function of fishing mortality (F) for glass and yellow eel fisheries occurring in the estuary and inland waters. A potential reference point of F_{40} (fishing mortality that preserves 40% of the unfished EPR) would occur at 0.90 for glass eels in both habitats, 0.23 for yellow eels in the estuary, and 0.06 for yellow eels in inland waters.

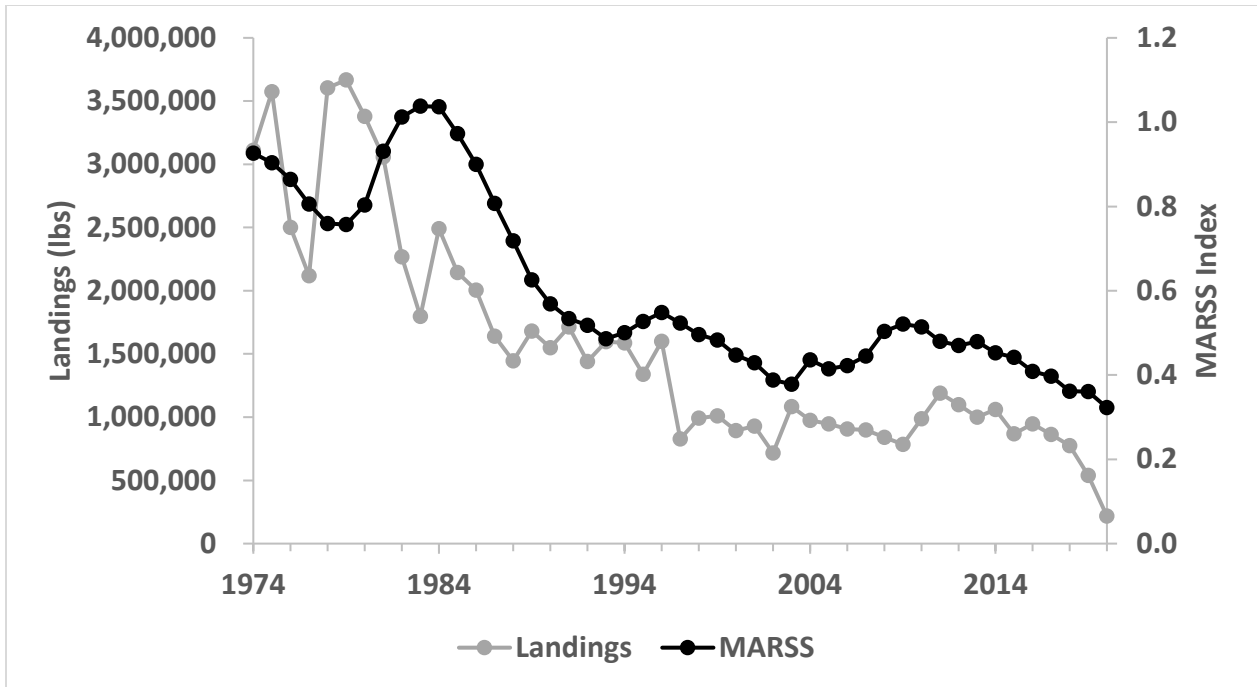


Figure 172. Commercial yellow eel landings and the coastwide MARSS abundance index for use in the surplus production model, 1974-2020.

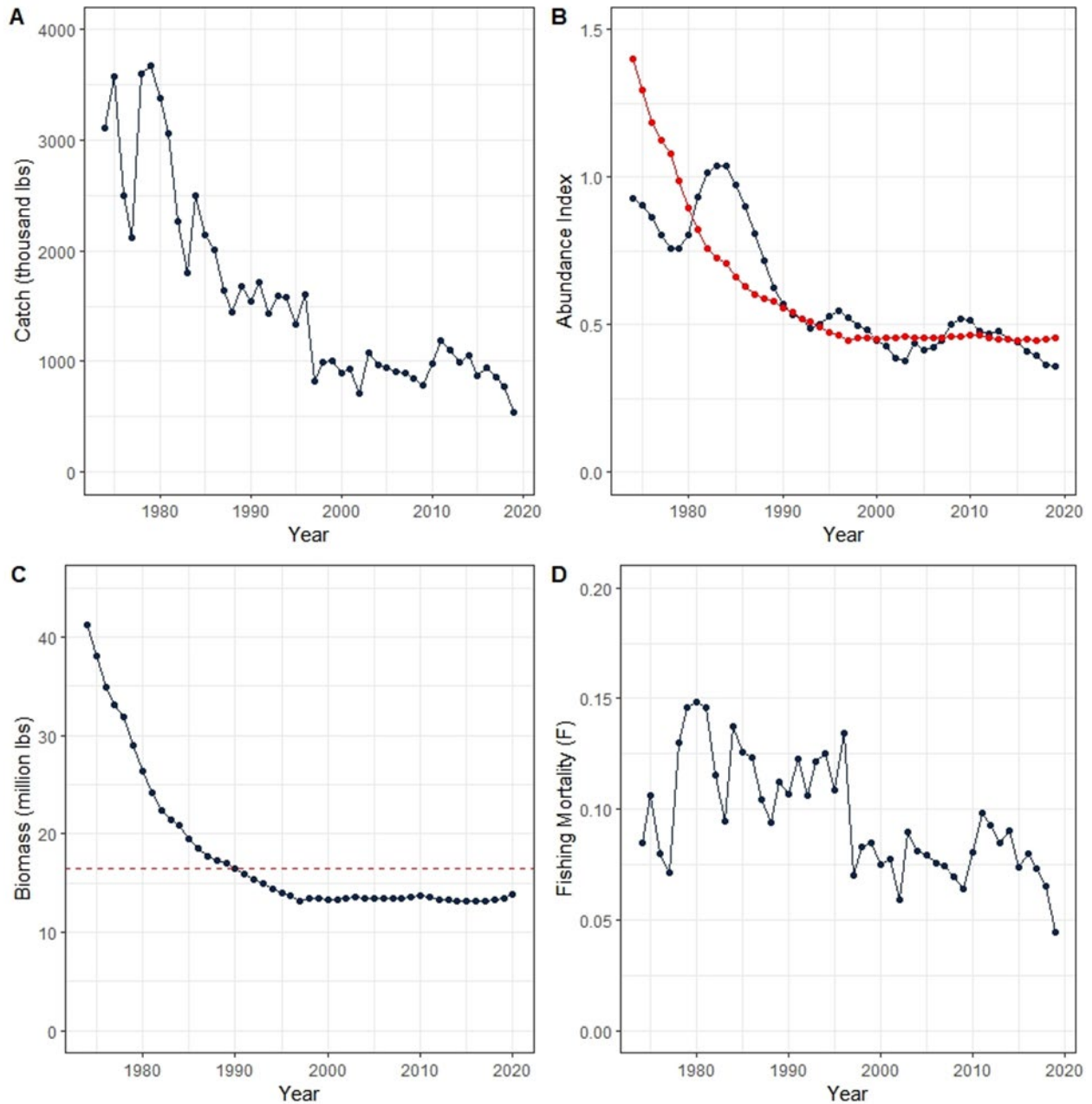


Figure 173. Output of the delay-difference model for the coastwide population of American eel. **A.** Observed commercial yellow eel harvest from 1974 through 2019. **B.** Observed MARSS yellow eel abundance index (black) and model-estimated abundance index (red) from 1974 through 2019. **C.** Model-estimated biomass of the population over time. **D.** Model-estimated fishing mortality over the time series.

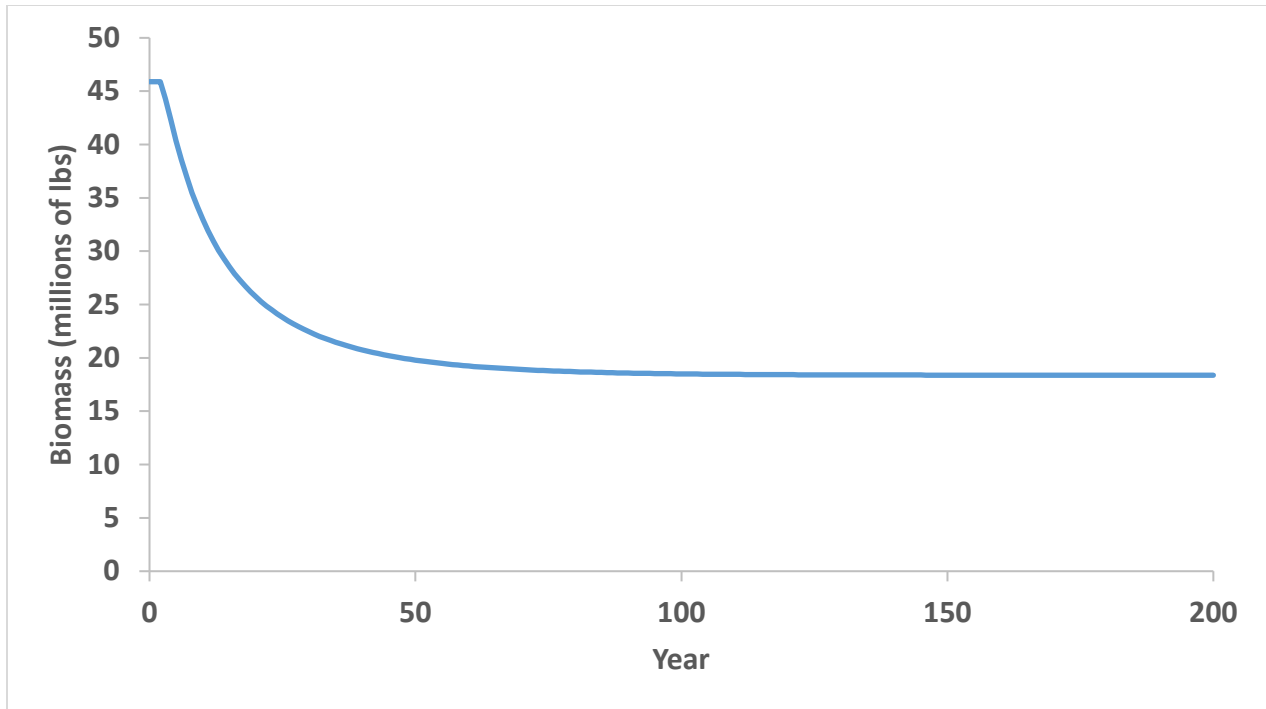


Figure 174. Projection of the delay-difference model starting at $B_0 = 45.89$ million lbs with fishing mortality of $F_{40} = 0.085$.

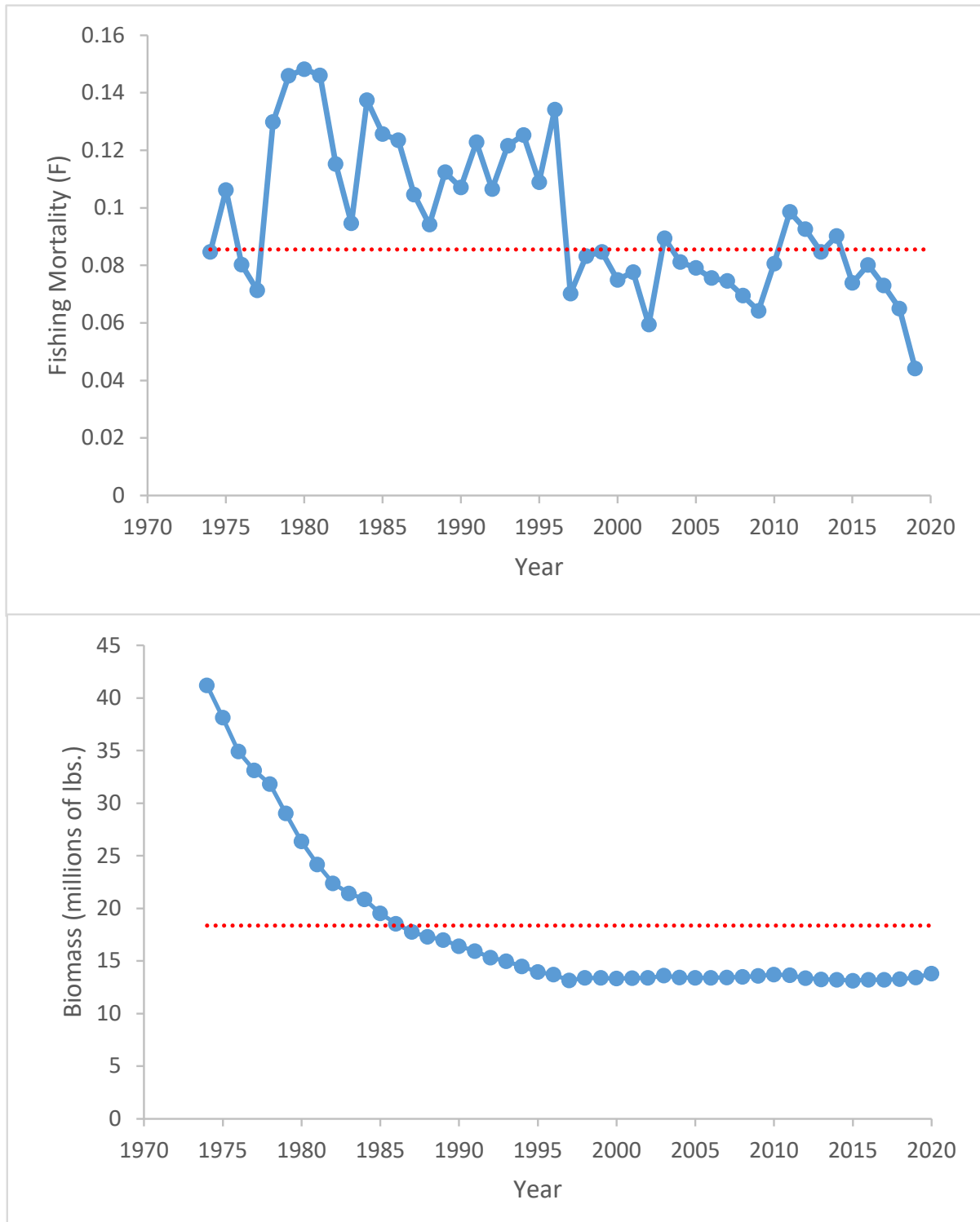


Figure 175. Comparison of estimated fishing mortality and biomass of American eels to reference points of F_{40} (top graph) and B_{40} (bottom graph).

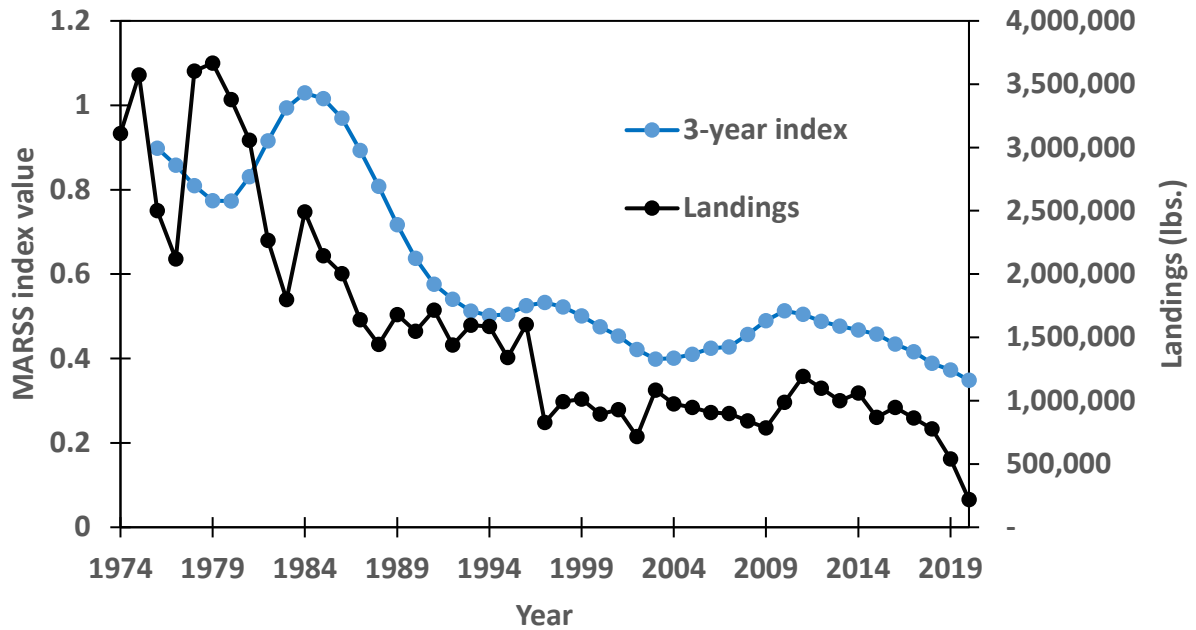


Figure 176. The three-year running average of the MARSS index and coastwide landings.

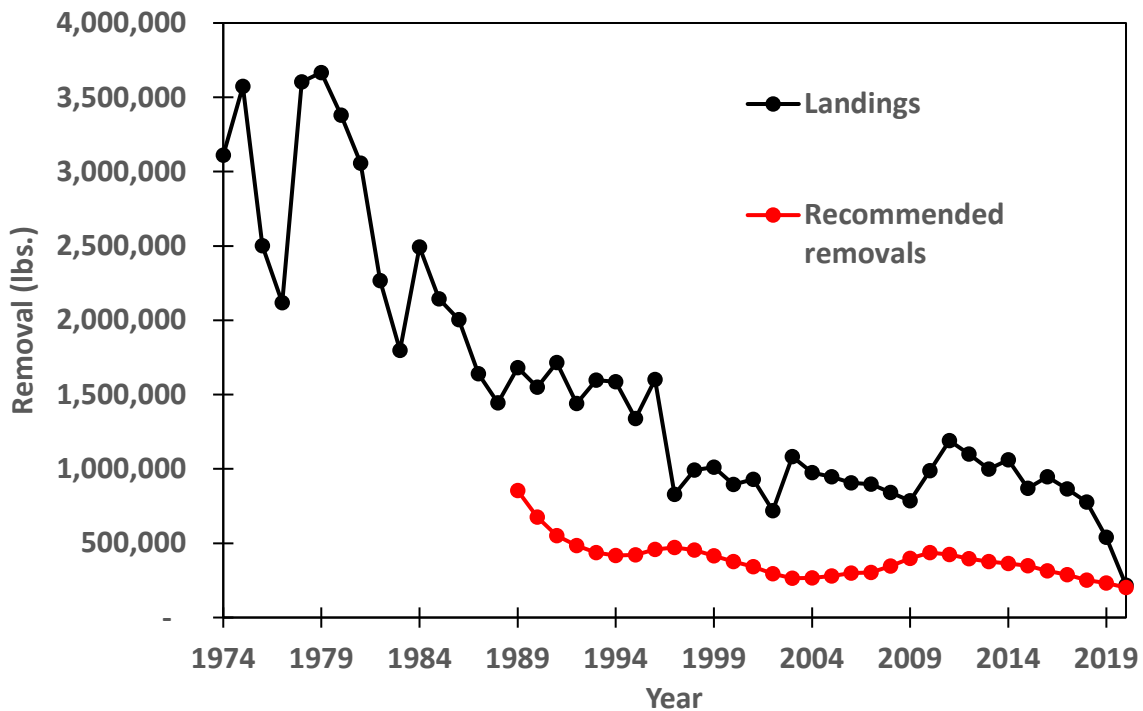


Figure 177. Coastwide landings and recommended removals from the base case using the I_{TARGET} index-based method for catch advice.

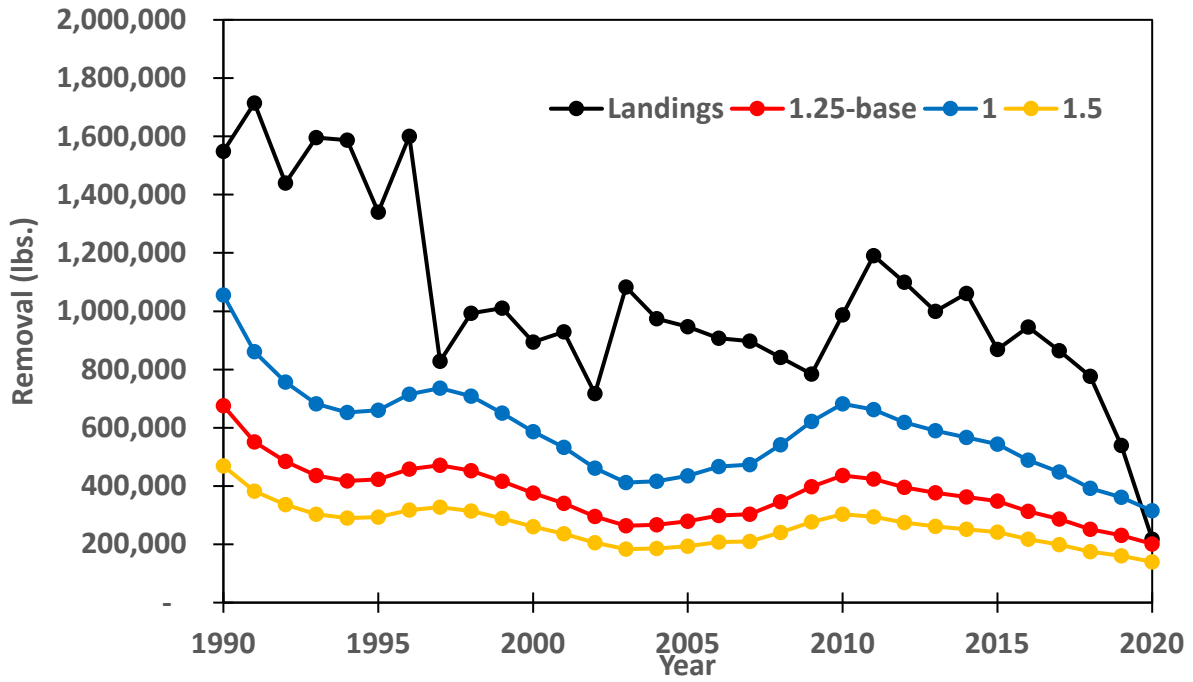


Figure 178. Coastwide landings and recommended catch under three assumptions of $I_{TARG MULT}$. Note X-axis scale change.

14 APPENDIX A: FISHERY-DEPENDENT CPUES

Fishery-dependent catch-per-unit-effort (CPUE) was available in some states, but following review of these data they were not considered indicative of trends in the stock as a whole. Note that fishery-dependent CPUE is almost exclusively composed of positive trips only; trip reports with zero eels caught are rare because most agencies don't require reports of zero catches. Several states provided commercial CPUE time series and the indices are listed here as provided by the state.

14.1 Connecticut

Connecticut Department of Energy and Environmental Protection (CT DEEP) provided a nominal fishery-dependent index for consideration in the assessment (Figure 1A). Commercial fishermen are required to record daily fishing activity in logbooks which are submitted to the department monthly and include information on both effort and landings by species. The commercial CPUE index was calculated for yellow eels from the pot fishery.

14.2 New York

New York Department of Environmental Conservation (NY DEC) provided a nominal fishery-dependent index for consideration in the assessment (Figure 2A). The commercial CPUE is an arithmetic mean of pounds per pot per hour fished. The data was from VTR monthly harvester reports.

14.3 New Jersey

The New Jersey Department of Environmental Protection (NJ DEP) provided a nominal fishery-dependent index for consideration in the assessment (Figure 3A). New Jersey's Harvester Trip Report (Miniature Fyke License) reporting form was redesigned in 2017 and require each fisherman to report the disposition of all American eels caught. New Jersey noted that this may be an overestimate since there were very few trips reported with zero catch and it is possible that the fishermen do not completely understand that daily catch must be reported even if it is zero.

14.4 Delaware

Delaware mandated catch and effort reporting from the American eel fishery in 1999. Delaware considers its American eel catch and effort records since 1999 fairly accurate and has calculated an annual commercial CPUE index from 1999 to the present (Figure 4A). The annual index value for CPUE is expressed as catch per pot-day fished and is the ratio of all eel pounds harvested by eel pots divided by the total number of eel pot-days fished (1 pot-day = 1 eel pot fished for 1 day).

14.5 Maryland

From 1992, mandatory catch and effort reporting was fully adopted by commercial eel fishers in Maryland. A commercial CPUE index was calculated for the pot fishery by Maryland

Department of Natural Resources staff (Figure 5A). Monthly harvester reports with daily information was used, although prior to 2005 only monthly reporting required, so from 2006-present, daily records are converted back to monthly records by area by license number. The annual index value for CPUE is the ratio of the summation of all eel pounds harvested by eel pots and the summation of all eel pots fished. Average annual CPUE has ranged from a low of 0.31 pounds/pot in 1992 to a high of 1.28 pounds/pot in 2019. The CPUE index was relatively flat from 1992–2002 and then generally increased until hitting the time series high CPUE in the terminal year.

14.6 Virginia

Catch rates were calculated for Virginia’s commercial eel pot fishery from daily harvesting reports by dividing the amount of harvest of American eels landed in Virginia (pounds) by the number of eel pot trips (Figure 6A). Only data associated with positive effort are included in the calculations as commercial harvesters only report positive catches to the VMRC. Records where harvest or effort were missing or zero were excluded from the calculations.

14.7 North Carolina

Prior estimates of catch rate, or catch-per-unit-effort (CPUE), for North Carolina were confounded by eel fishermen holding catches from several days of fishing in holding pens and later selling these “accumulated” catches to dealers. In 2007, a new eel pot logbook program was implemented at the individual commercial fisherman level, providing documentation of the number of pots fished, soak time, and landings (pounds) per pot. North Carolina logbook data (which began in 2007) was used for computing fishery-dependent index of abundance (Figure 7A). The index was standardized using a GLM that included year and month with a negative binomial error structure.

14.8 South Carolina

South Carolina Department of Natural Resources did provide data and a calculated CPUE for the commercial fishery using monthly dealer reports but the data is confidential.

14.9 Florida

Commercial catch and effort data collection for American eel began in 2006 in Florida. Data was sourced from trip tickets and a CPUE was provided for the assessment for 2007-2019 (Figure 8A).

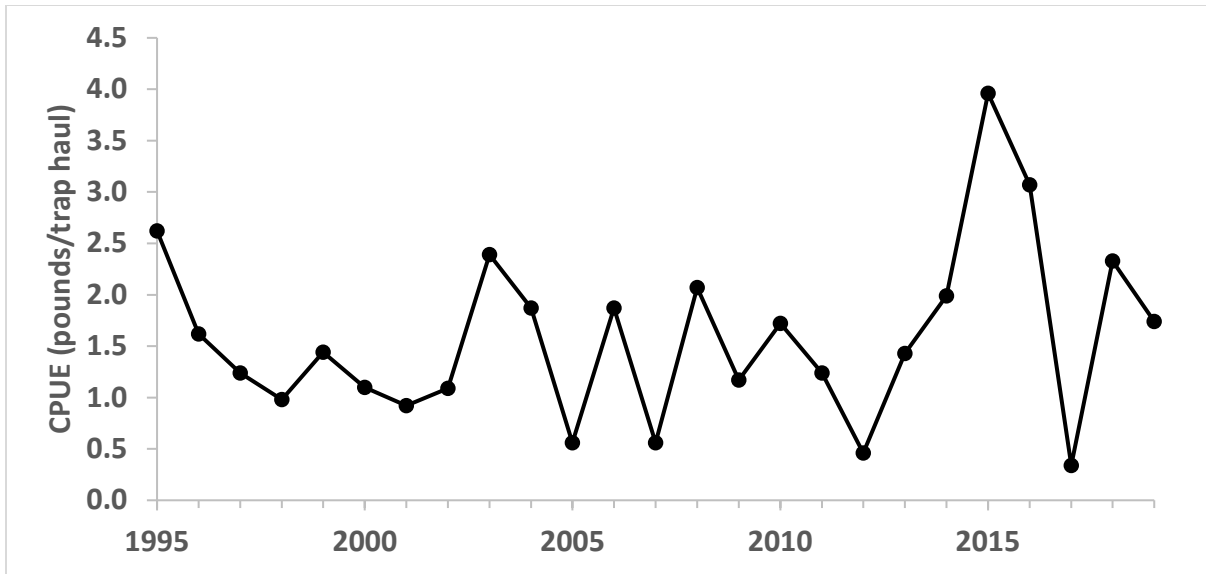


Figure 1A. Fishery-dependent catch-per-unit-effort for Connecticut's yellow eel pot fishery. Estimated errors associated with the index were not provided.

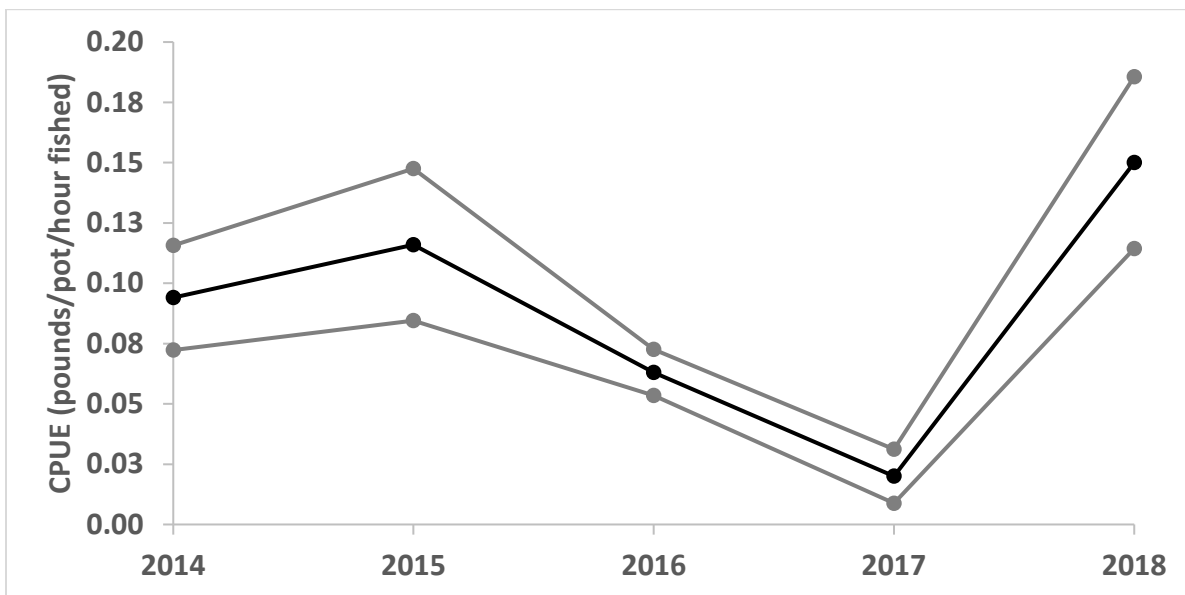


Figure 2A. Fishery-dependent catch-per-unit-effort for New York's yellow eel pot fishery. The black line indicates the CPUE and the grey lines indicate 95% confidence intervals.

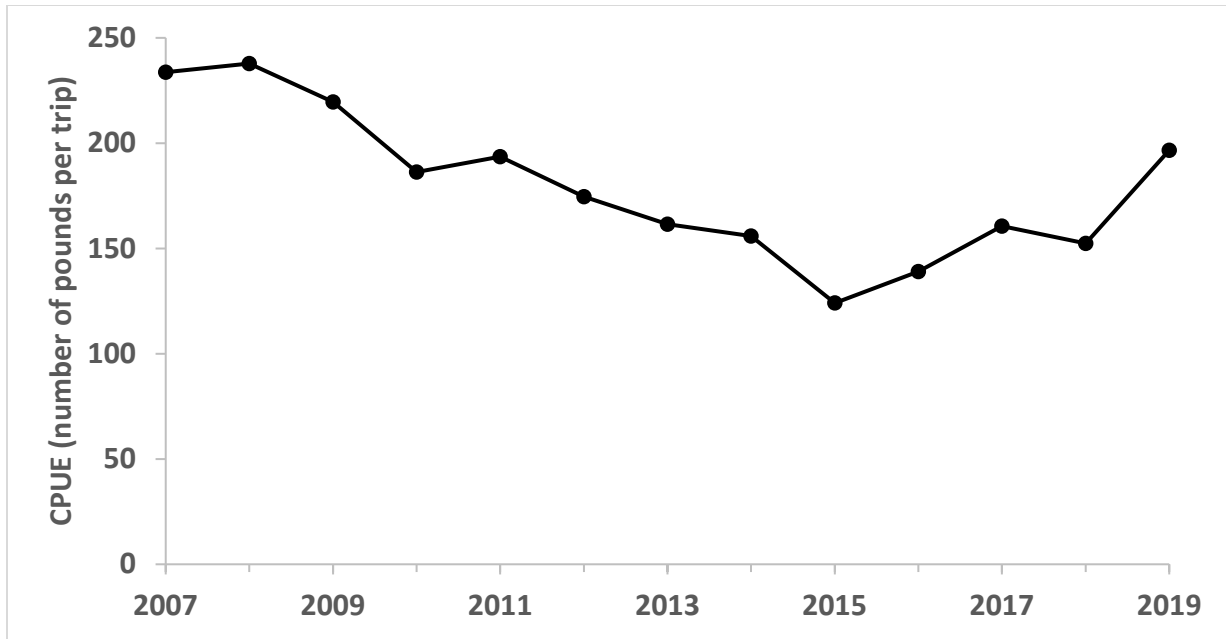


Figure 3A. Fishery-dependent catch-per-unit-effort for New Jersey's yellow eel fyke net fishery. Estimated errors associated with the index were not provided.

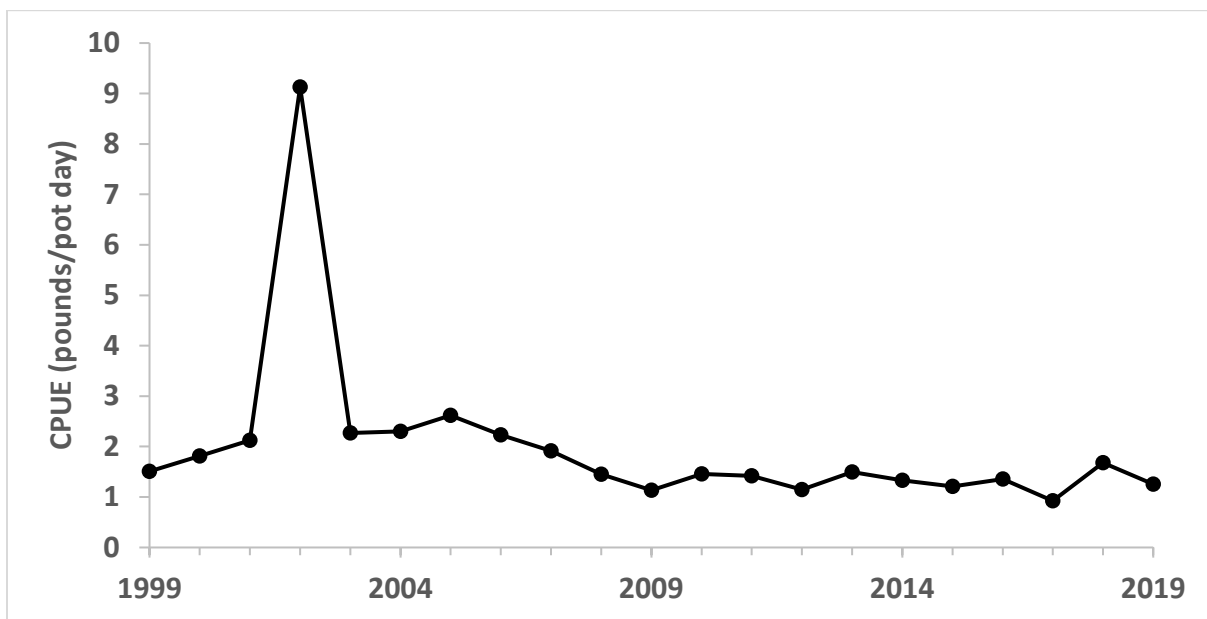


Figure 4A. Fishery-dependent catch-per-unit-effort for Delaware's yellow eel pot fishery. Estimated errors associated with the index were not provided.

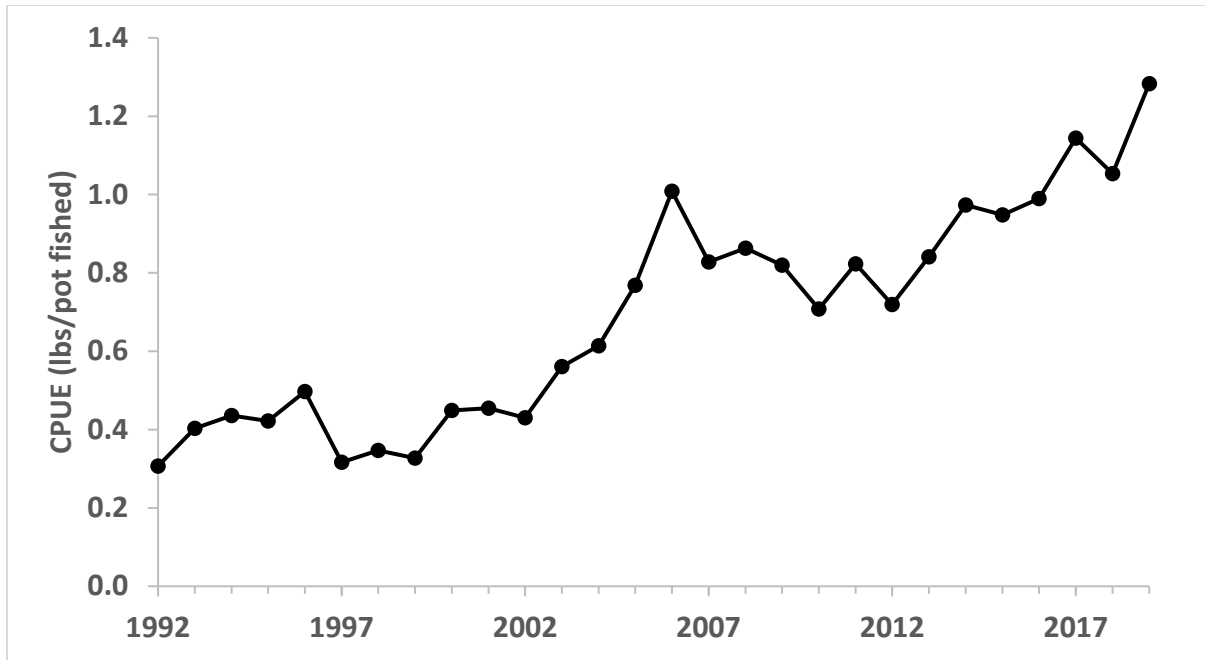


Figure 5A. Fishery-dependent catch-per-unit-effort for Maryland's yellow eel pot fishery. Estimated errors associated with the index were not provided.

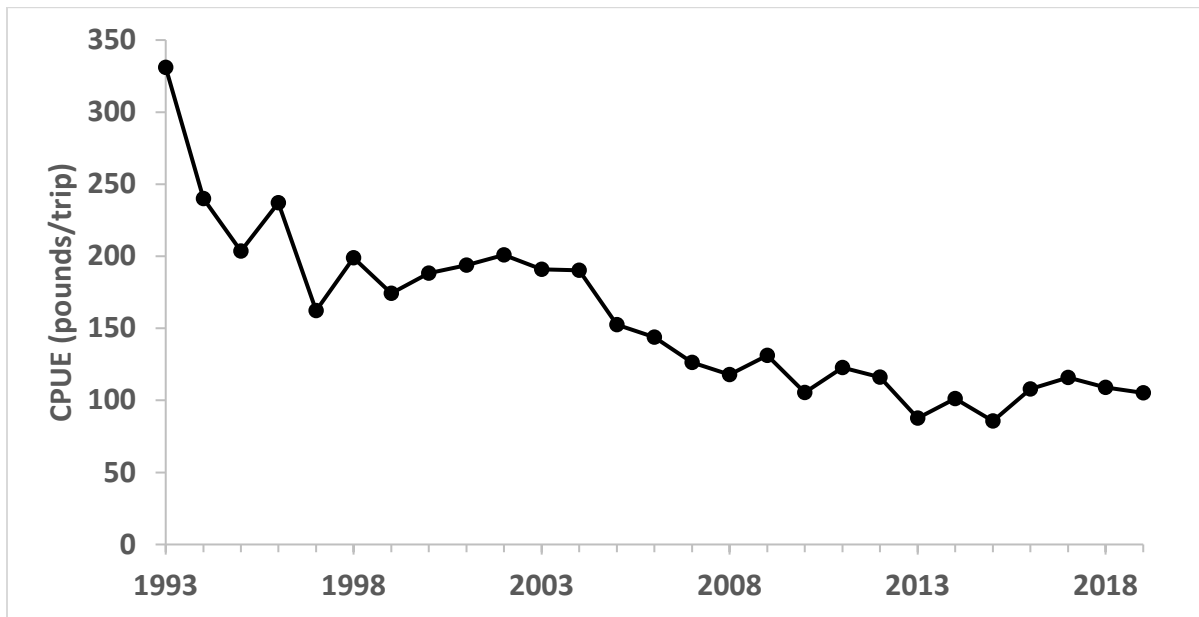


Figure 6A. Fishery-dependent catch-per-unit-effort for Virginia's yellow eel pot fishery. Estimated errors associated with the index were not provided.

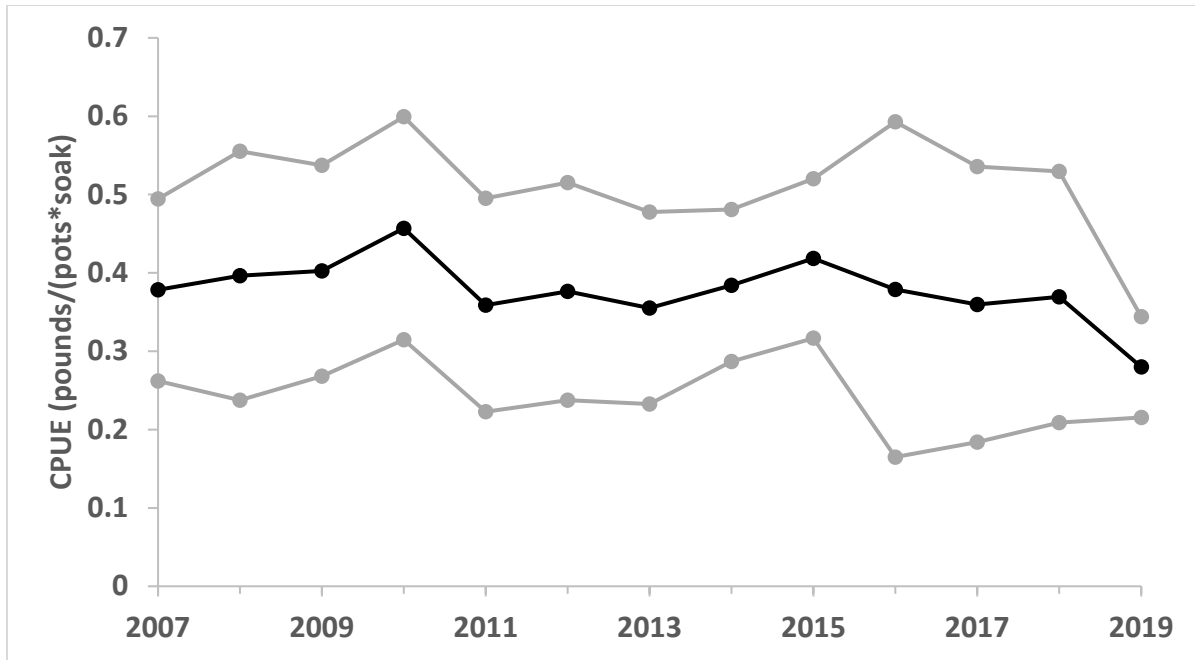


Figure 7A. Fishery-dependent catch-per-unit-effort for North Carolina’s yellow eel pot fishery. The black line indicates the CPUE and the grey lines indicate 95% confidence intervals.

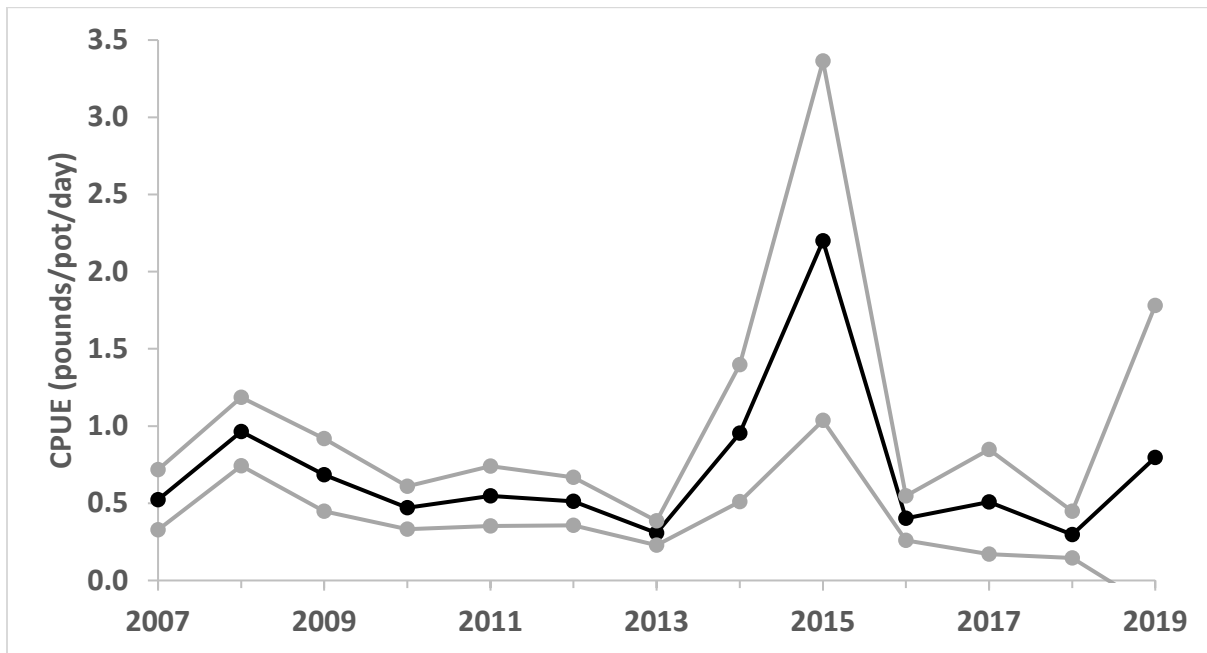


Figure 8A. Fishery-dependent catch-per-unit-effort for Florida’s yellow eel pot fishery. The black line indicates the CPUE and the grey lines indicate 95% confidence intervals.