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Historical Coastwide IPHC Stock Assessments: 2012 to 2015 – *Compendium of documents*

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INTERNATIONAL PACIFIC
HALIBUT COMMISSION

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LIST OF DOCUMENTS FOR THE 2012 TO 2015 HISTORICAL COASTWIDE IPHC STOCK ASSESSMENTS

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Stewart, I.J., and Martell, S.J.D. 2016. Appendix: Development of the 2015 stock assessment. IPHC Report of Assessment and Research Activities 2015. p. A1-A145.	4
Stewart, I.J., and Martell, S. 2015. Assessment of the Pacific halibut stock at the end of 2014. IPHC Report of Assessment and Research Activities 2014. p. 161-180.	149
Stewart, I.J. 2015. Overview of data sources for the Pacific halibut stock assessment and related analyses. IPHC Report of Assessment and Research Activities 2014. p. 87-160.	169
Stewart, I.J., and Martell, S. 2014. Assessment of the Pacific halibut stock at the end of 2013. IPHC Report of Assessment and Research Activities 2013. p. 169-196.	243
Stewart, I.J. 2014. Overview of data sources for the Pacific halibut stock assessment and related analyses. IPHC Report of Assessment and Research Activities 2013. p. 95-168.	271
Stewart, I.J., Leaman, B.M., Martell, S., and Webster, R.A. 2013. Assessment of the Pacific halibut stock at the end of 2012. IPHC Report of Assessment and Research Activities 2012. p. 93-186.	344

Appendix: Development of the 2015 stock assessment

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This document was developed as a detailed description of the data sources, assessment model development, diagnostics, and sensitivity analyses for the 2015 assessment of the Pacific halibut stock. It also outlines future development of assessments as well as research priorities over 2016-2017 period. It was presented to and reviewed by the Commission's Scientific Review Board in June 2015. This document is best viewed online due to the use of colors in many of the figures.

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Summary

Creating robust, stable, and well-performing stock assessment models for the Pacific halibut stock has historically proven to be problematic due to the highly dynamic nature of the biology, distribution, and fisheries (Stewart and Martell 2014). Although recent modelling efforts have created some new alternatives, no single model yet evaluated satisfactorily approximates all aspects of the available data and scientific understanding. In 2014, an ensemble of four stock assessment models representing a two-way cross of short vs. long time-series', and aggregated coastwide vs. Areas-As-Fleets (AAF) models was used to describe the range of plausible current stock estimates. Each of these models (and many alternatives explored during development) has shown a similar historical pattern: a stock declining from the late 1990s, with several years of relative stability at the end of the time-series.

For 2015, an extensive effort was made to address many previously identified shortcomings in the input data. This included of a complete reprocessing of all inputs, and the addition of several new sources of information. Important improvements included: generating weight-at-age by geographic area (Areas 2, 3, 4, and 4B separated; Fig. 1) for the AAF models, improving the weight-at-age calculations for young halibut (< age-7) rarely encountered in the setline survey using data from NMFS trawl surveys, summarizing index variances and age composition sample sizes, particularly by area for the AAF models, adding age-information to directly inform the selectivity curves for bycatch, sport, and sublegal discard removals, and extending all age-data arrays to include ages 2-25 (instead of 6-25, used in historical analyses).

Although the basic approach to each of the four assessment models used in 2014 remains unchanged, several modeling aspects were explored more deeply than in previous analyses and improved where necessary. These improvements included: updating the constraint on recruitment deviations (σ_r) for consistency with stock-recruitment assumptions, updating relative data weighting to reduce the potential influence of outliers and strong residual patterns, and updating the constraints on time-varying parameters to better reflect degree of estimated variability. In addition, a much greater number of sensitivity analyses, alternate model configurations, and diagnostic evaluations were completed than in previous assessments. The 2014 assessment highlighted a difference in trend for the most recent years between the two aggregated coastwide models (the long and short time-series), and the two AAF models for the last several years. For this preliminary analysis, all models were extended to 2016 (using the projected removals for 2015, but no new observed data from that year) in order to better evaluate the recent differences among the four models in both estimated scale and trend.

Preliminary results were very consistent with projections from the 2014 assessment and indicate relatively flat trends in the coastwide models and slightly increasing trends in the AAF models. The terminal (2016) biomass estimate is uncertain both within each model and among models based on the integrated distribution. Looking forward, it is not clear whether addition of the 2015 data for the final assessment will begin to reconcile the differences in recent trend between the coastwide and AAF models. Several recent studies (e.g., Hurtado et al. 2014, Punt et al. 2015, Li et al. 2015, McGilliard et al. 2014) have evaluated the performance of aggregated vs. disaggregated approaches to catch-at-age modelling in the presence and absence of variability among fisheries and movement among areas within the stock. In some cases the AAF approach appears to be an improvement over aggregated methods, and in others (particularly Punt et al. 2015) it does not. The primary conclusion from simulation-based studies is that if the true underlying process is well-

represented, then models tend to perform well. In the halibut assessment, it is likely that none of these models accurately represents the complex spatial dynamics. In light of this uncertainty, the same equal weighting among models is retained for this analysis, and the preliminary integrated results provided for quantities of management interest.

Two primary uncertainties continue hinder our current understanding of the Pacific halibut resource: 1) the sex-ratio of the commercial catch (not sampled due to the dressing of fish at sea), which serves to set the scale of the estimated abundance (identified in the 2013 assessment; Stewart and Martell 2014b) in tandem with assumptions regarding natural mortality, and 2) the treatment of spatial dynamics and movement rates among regulatory areas, which are represented via the coastwide and AAF approaches, have very strong implications for the current stock trend. In addition, movement rates for adult and juvenile halibut (roughly ages 0-6, which were not well-represented in the PIT-tagging study), particularly to and from Area 4, are necessary for parameterizing a spatially explicit stock assessment. Ongoing research on these topics may help to inform our understanding of these processes in the long-term, but in the near-future it appears likely that a high degree of uncertainty in both stock scale and trend will continue to be an integral part of the annual management process.

Data sources

This section is not intended to duplicate the more detailed summary of data sources provided in Stewart (2015), but instead focuses on the improvements that have been made specifically for the 2015 assessment. Development and refinement of methods for aggregating raw data collected by individual regulatory area (Fig. 1) into larger areas that can be treated as separate fleets, as well as coastwide values, has been an ongoing effort over the last several years. Much progress was made during 2015 with remaining data processing challenges summarized below (see research priorities). This description is divided into two sections, the first dealing with the improvements to the treatment of weight-at-age, and the second with improvements to the index and age data used in the development of 2015 assessment models.

Weight-at-age

Historical halibut assessments have used various extrapolation and smoothing methods to assign weight-at-age to fish that are younger than those observed in the setline survey, which provides the most detailed source of sex-length-age information. These calculations are not critically important to the treatment of commercial fishery or survey information, as few very young fish are observed in those data sets; however, accurate depiction of the removals from other sources, such as recreational fisheries and bycatch in non-target fisheries requires representative weight-at-age for all fish captured, particularly ages 2-6. For 2015, average weight-at-age by year and sex was summarized from the NMFS trawl surveys in Alaska. Age and length data were available for all years since 1998, although mean values were somewhat variable due to limited sample sizes (Fig. 2). To reduce the effect of sampling variability (there is no easy way to account for observation error in the treatment of weight-at-age), raw values were smoothed across years within age (Fig. 3). Only a small subset of the 2014 trawl survey ages had been entered into the IPHC's databases at the time of this analysis, so values for that year are more variable at present, but will be revised to include the full datasets for the final 2015 assessment. These data were used to augment the weight-at-age inputs calculated from ages 7+ in the setline survey and commercial fishery (as described in Stewart, 2015).

A second important improvement to the treatment of weight-at-age, separating the trends by geographic areas (2, 3, 4, and 4B) was explored for use specifically in the AAF models. Due to the unknown sex-ratio of the commercial data, and the lack of comprehensive historical survey observations, a method was developed during 2013 to use the relative trends in weight-at-age observed for ages 8-16 in the commercial fishery, to scale the recent observations of sex-specific weight-at-age for fish collected by the setline survey. When the method was developed, it was applied only to data aggregated at the coastwide level. The coastwide trends among ages 8-16 in those data showed very similar historical patterns, despite differences on an absolute scale (Fig. 4), suggesting that temporal changes in relative weight-at-age have been relatively conserved across different ages. When this approach was duplicated for data by geographic area, the patterns for Areas 2 and 3 were quite similar to those observed at the coastwide level (Fig. 5), and appeared coherent enough to warrant summary into area-specific trends. When rescaled (relative to the value observed in 1997, the first year of comprehensive survey data), it is more obvious that the coastwide and Area 2 trends have been less pronounced than the very large increase in fish size observed for Area 3 from the 1950s through the 1990s (Figs. 6-7).

Summarized fishery data for Area 4 (including regulatory areas 4A and 4CDE) were available only beginning in 1945. The estimated trends for ages 8-16 in Area 4 showed a markedly different historical trend than for Areas 2 and 3, with fish not much larger during the historical period than in the early 1990s (Fig. 8). The relative scalar for Area 4 is therefore only slightly above a value of one for most of the historical period, and the smallest values occur in the most recent years (Fig. 9).

No historical data predating the setline survey were available from the commercial fishery in Area 4B. The Area 4 weight-at-age arrays were therefore used as model input for both Area 4 and Area 4B. All final input weight-at-age values used in each model can be found in the supplementary background material included with this document.

Index and age data

When the AAF models were assembled in 2014, data sets were parsed out into separate fleets, but not all fleet-specific index variances and samples sizes were derived. For the indices of abundance, current variance estimates are based on the among-sample variability within each regulatory area. In the case of survey data from Area 4CDE, this includes variability in both setline survey and NMFS trawl survey observations, but currently not the uncertainty in the calibration of the two series (Webster 2014). Combined index values by geographic area are weighted by the relative spatial bottom area in each regulatory area, and variances were summed, accounting for the square of the weights. For each geographic area, the annual index variance (σ^2) was converted to log Standard Error (SE) for model input via the relationship with each annual index value ():

$$\log(SE) = \sqrt{log\left(1 + \left(\frac{\sigma}{\bar{x}}\right)^2\right)}$$

Prior to 2001, there were individual regulatory areas and portions of regulatory areas missing from the coastwide and geographic area indices from the setline survey (Soderlund et al. 2012). To account for the associated missing variance components, the average log(*SE*) from the time-series with complete coverage was doubled (survey indices from 1997-2000 include a variety of calibrations for the index, but not the variance; Webster et al. 2015). For years prior to 1997 (except Area 3 in 1996) the coastwide log(*SE*) was doubled again to reflect the increasingly poor spatial coverage relative to that scale (both catchability and selectivity were also configured in the models to allow for the spatial changes).

Final input setline survey indices (numbers-per-unit-effort), coastwide and by geographic area, all showed a very clear increase in catch-rates associated with the switch from "J" to circle hooks in 1984 (Table 1). Surveys have been very precise, based on the limited variance components included in the estimates, with precision decreasing from Area 3 (log(SE) values around 0.03), to Area 2, and Area 4; Area 4B had the least precise survey with log(SE)s around 0.1 (Table 1).

Commercial fishery catch rates were aggregated from 1984 to the present using methods analogous to the survey data. For years prior to 1984, a log(SE) of 0.10 was assumed for all geographic areas, and the coastwide index, due to incomplete coverage of individual regulatory areas, lack of raw data (only historical summaries available), or both. As has been the case in recent analyses, unverified fishery data in the terminal year (in this case 2015) was assigned twice the observed log(*SE*) (Stewart 2015; this has been done to account for the use of unverified and incomplete logbook information during the preparation of the input data each fall, the data are complete in time for the subsequent year's assessment). In recent years the precision of the fishery index is estimated to be similar to, or slightly better than that of the setline survey, as a function of the extensive reporting and correspondingly large sample sizes. All fishery indices showed a large increase in 1984, similar to the setline survey. Trends in recent years have been much more pronounced in the fishery indices of weight-per-unit-effort (compared to survey indices of numbers-per-unit-effort), because these include the effects of both the numbers of halibut, as well as those of trending size-at-age (Table 2).

Examination of the number of survey stations contributing age data reveals that Area 3 is sampled much more heavily than Area 2; this is expected, and approximately in proportion to the spatial extent of the each due to the uniform 10 nautical mile grid design. Area 4 generally contributes around half as many samples as Area 2, and Area 4B less than 10% of the total (Table 3). A similar situation is present for the number of fishing trips sampled for age data, with the exception that Area 2 comprises more than half of the total samples in recent years (Table 4). Prior to 1964, only summarized age data are currently available, and samples sizes are assumed to be roughly half of those in later years. There are no age data available for Area 4 prior to 1945 and for Area 4B prior to 1991.

Historical halibut assessments have included age-data delineated only for fish age-6 and greater. For 2015, the age-arrays for all input data were extended to include ages 2-25, with age-2 including all observations age-2 and below (a 'minus group') and age-25 including all observations age-25 and greater (a 'plus group'). This change was necessary to accommodate several data sources (description below) with appreciable numbers of age-5 and younger fish as well as to provide more detailed information from existing data sets, such as the setline survey and commercial fishery. As an example of this additional information, coastwide fishery age data contain appreciable numbers of age-4 and age-5 halibut from the 1930s through the introduction of the current 32-inch minimum size-limit in 1973 (Fig. 10). As in past assessments, age-data were still been aggregated at age-20+ for years where only surface ages are available: prior to 2002, except for the 1998 setline survey data, which was re-aged in 2013.

In historical assessment models, there have been no data representing the age-structure of the discards from the commercial fishery, bycatch in non-target fisheries, or the sport and personal use removals. In the absence of direct data, selectivity curves were assumed for each of these sources of removals. In 2015, each of these sources was re-examined, and methods for including more representative selectivity estimates were developed. This effort began with the processing of relevant data for each, as outlined below.

The calculation of wastage, or halibut captured as part of the commercial fishery, discarded, and assumed to subsequently die, has historically been performed as an external analysis to the stock assessment (Gilroy and Stewart 2015). The magnitude of the wastage estimates has been based on the rate of sublegal to legal catch rates in the setline survey. This calculation has been made independent from the fixed selectivity curve assumed in the stock assessment. For 2015, the age-distributions of sublegal female and male halibut captured in the setline survey were compiled for evaluation in the stock assessment directly. These data showed a remarkably protracted age-distribution, with both male and female halibut age-10 and greater making appreciable contributions to the total (Fig. 11). The age-distribution for the two sexes also differed importantly, with sublegal females present in appreciable numbers from roughly age 7 to 11, and sublegal males from 7 to well beyond age 15 in some years (Fig. 11). The protracted age structure of fish below the 32” minimum size-limit illustrates the recent variability in size-at-age: some fish from each cohort reaching the minimum size limit by age-6, and others (particularly males) many years later. Although the distributions derived from survey data may not be strictly representative of the age-structure of the discards in the commercial fishery, they are consistent with the calculation of wastage outside the assessment model, and allow for the direct estimation of selectivity rather than simply the assumption of a fixed curve. Summary of these data also allows for comparison, and potentially replacement with direct fishery data collected by the various observer programs when and where it becomes available.

The length-distribution of halibut caught as bycatch in fisheries targeting other species is reported to the IPHC each year by the National Marine Fisheries Service (NMFS; for Alaska and Washington-Oregon-California) and Fisheries and Oceans Canada (DFO; for British Columbia). The historical time-series of these lengths has been summarized each year by regulatory area, and also aggregated to the coastwide level (weighting by the total estimated number of halibut) for use in the annual harvest policy calculations and catch tables. In order to evaluate these data directly in the context of the stock assessment, they first needed to be converted to age-distributions. Due to the large frequency of very small (and young) halibut observed in the bycatch removals, the length-to-age relationships from neither the setline survey, nor the directed halibut fishery were applicable. Halibut of all ages are routinely sampled for length and age by IPHC samplers on the NMFS trawl surveys conducted in the Bering Sea, Gulf of Alaska, and Aleutian Islands (Sadorus and Palsson 2014, Sadorus et al. 2015, Sadorus et al. 2015b). These data contain halibut of roughly the same size-range as have been observed in the bycatch data. Annual age-length keys were produced from the NMFS survey data for the years 1997-2014. Relatively few fish greater than age-15 were present in these data; therefore, to avoid extensive smoothing or extrapolation across years, the keys were aggregated at age-15. Without earlier data available, the key for 1997 was used for all prior years. Exploration of the average length-at-age didn’t show particularly strong trends for this age range; however, it would be preferable to have year-specific key information. Coastwide aggregate bycatch lengths were summarized into predicted ages via the annual age-length keys. Estimated bycatch ages showed a mode (or modes) between age-3 and age-10, with up to one-third of the total age distributions represented by halibut age-4 or less in some years (Fig. 12).

The length data currently available for bycatch and used in this analysis is in the form of summaries, for which the methods and original data sources are unknown. It is clear from several of the year-specific age-distributions that some of the historical data must be duplicated among years (e.g., 1974-1976 in Fig. 12). Ongoing efforts by the IPHC and the NMFS during 2015 to reconcile bycatch estimates and biological data may be able to provide a more reliable time-series for the 2015 stock assessment or in the near-future. The issues to be addressed include the stratification of estimates by IPHC regulatory area and the appropriate weighting of length data within and among vessels, fisheries, and areas. In the meantime, it may be reasonable to consider these data generally representative of the age structure of the bycatch, but annual observations may not be appropriate for deriving information on cohort strengths.

The final new source of information evaluated during 2015 was from the recreational fishery. Otoliths from recreationally caught halibut in regulatory Area 3A have been routinely collected by ADF&G, and the ages read by IPHC staff. Estimated numbers-at-age for the years 1994-2006 were weighted by port within Area 3A, and summarized by Scott Meyer (ADFG, pers. comm.). These data showed a variable but generally larger proportion at ages younger than age-5, and smaller proportion greater than age-15 (Fig. 13) compared to the coastwide setline survey over a similar time-period (Fig. 14). The recreational data contained a few halibut at ages 2-3, younger than any observed in the setline survey. The observation of extremely young halibut is somewhat surprising, as trends in size-at-age indicate that some of the smallest fish for their age across the coast are currently observed in Area 3A, so that area might be expected to have relatively fewer very young fish in the recreational harvest if selectivity were similar to that of the setline survey. These data are not geographically comprehensive; however, recreational removals from Area 3A represented 52% of the coastwide recreational total in 2014. Additional age data from the 3A recreational fishery collected in 2007-2013 were made available during the completion of this document, and will be analyzed for the final 2015 assessment. Currently, there are no additional age data from the recreational fisheries in other regulatory areas, but such data could be included with those from Area 3A if they become available in the future.

Model development

Structural rationale

The Pacific halibut stock assessment model has evolved through a number of different structural configurations (Clark and Hare 2006, Stewart and Martell 2014). Perhaps the most influential of these changes in recent years was the change from area-specific models to a coastwide model in 2006, as the understanding of adult movement among areas was substantially updated by the results of the IPHC's extensive PIT-tagging experiment in 2003-2009 (Clark and Hare 2006, Webster et al. 2013). A number of simulation studies have found that dividing a migratory population into several discrete assessment units tends to overestimate the total biomass (e.g., McGilliard et al. 2014 and Li et al. 2014 provide recent examples).

A primary structural assessment model choice is whether or not to model growth explicitly (and often parametrically) or empirically. Many U.S. and Canadian groundfish stock assessments assert a growth function of some type. This approach has the benefit of allowing direct fitting to observed length observations, as well as interpolating and/or extrapolating predictions for years where direct observations may be missing, as well as inclusion of the potential effects of selectivity at length on the observed data. The cost of such an approach is that growth can be an extremely complex process, varying over time, space and by cohort (via density dependence). In the face of appreciable growth variability, a great deal of complexity is required to adequately model this population process, even before sampling and selectivity issues have been addressed. Failure to account for this type of variability can lead to poor fits to composition data, potentially biasing the assessment results.

This challenge has resulted in many groundfish stock assessments taking a simpler approach to growth by using empirically derived weights-at-age where there are sufficient data available to do so. An example of this is the Pacific hake stock assessment, where a large amount of historical length data has been omitted from recent analyses, in favor of the use of weight-at-age directly, due to the complexity in observed growth (Taylor, I.G., Stewart, I.J., Hicks, A.C., and Hamel, O.S. *In review*. Drowning in data: empirical vs. parametric growth in an integrated stock assessment model. *Fisheries Research*). The simplicity of the empirical weight-at-age approach has the benefit of reducing complexity with regard to growth modelling, but has several costs in other modelling areas. These include the need for more complexity in modelling selectivity, particularly where some of the selectivity process may be a function of size rather than age alone. This is the case for Pacific halibut, where the interaction of changes in size-at-age, gear selectivity that is likely at least partially a function of fish size, and minimum size limits thus requires the treatment of selectivity-at-age as a time-varying process (Stewart and Martell 2014). However, the treatment of selectivity as time-varying appears to be a necessity for Pacific halibut even if treated as a function of size; static selectivity for a spatially aggregated model in the face of changes in availability was identified as a primary contributor to severe historical retrospective patterns (Stewart and Martell 2014).

There are relatively few examples of stock assessments used for management purposes that are explicitly spatial: modelling movement among areas, distributing recruitment events, and tracking spatial variability in biological characteristics. Most assessments either aggregate the available data across spatial heterogeneity (preferably weighting appropriately such that the aggregate information reflects the underlying distribution), or retain separate data series representing spatial areas, but fit to them in the context of a single instantaneously-mixing population model (the AAF approach). These methods for dealing implicitly with spatial dynamics are by necessity gross approximations, with performance properties that are unknown, and almost certainly depend on the true underlying processes. Simulation studies have shown that fisheries operating in different areas with differing selectivity schedules can be reasonably approximated by an AAF approach (e.g., Waterhouse 2014). Other studies have found acceptable performance of AAFs when simulating actual spatial variability (e.g., Hurtado et al. 2014, McGilliard et al. 2014); however additional studies have found that combining spatial data into weighted-aggregates also performs acceptably, and may be more stable than more complex AAF approaches (Punt et al. 2015, Li et al. 2015). A primary conclusion from simulation-based studies is that if the true underlying process is well-represented, then models reflecting these dynamics tend to perform well. Unfortunately, in the case of Pacific halibut it is not clear whether aggregated or AAF models might be the best choice as neither approach accurately represents the complex spatial dynamics.

The choice of how long a time-series to model generally represents a compromise among: data availability, data quality, model complexity, and technical convenience (e.g., data preparation and model convergence times). As assessment model time series' are extended to include more historical data, commonly the quality of those data becomes increasingly lower as standardization of sampling programs has a greater likelihood of having changed appreciably. In the case of Pacific halibut, fishery-independent survey information has been reasonably comprehensive since approximately 1997, and current fishery sampling approaches have not changed dramatically over the same period. The completeness of this time period with regard to data availability was one of the primary incentives for stock assessment models used by the IPHC since 2006 to begin the modelled period in 1996. Notable differences prior to that period included the transition in the survey and fishery from "J" to circle hooks, variable and much less comprehensive survey coverage, lack of access to raw historical fishery data (ages, catch rates, etc.), and many others. The costs of using only a relatively short time-series include a lack of integration between harvest policy calculations derived from full historical period, a lack of perspective on recent trends, the need for careful treatment of initial model conditions, and increased sensitivity to additional data, as each year represents a greater fraction of the total information available in the model. These trade-offs prompted the development of a long time-series model in 2013, with the recognition that neither the short or long time-series approach was clearly superior, and that differences in the results reflected a meaningful source of uncertainty in the assessment results.

All of the halibut models considered here treated male and female halibut separately. Like many broadcast spawning fishes, there is a basic assumption that spawning is likely to be limited primarily by female spawning output and not by male abundance over a reasonable range of sex-ratios). If the sex-ratio could be expected to be stable over time, it might be reasonable to structure assessment models without regard to sex and/or just assume half of the mature biomass represented females. However, for Pacific halibut, highly dimorphic growth interacting with a fishery in which there are strong incentives to target the larger females (due to the minimum size limit and graduated price structure) results in sex-ratios of the catch (as inferred from the survey catches) skewed largely toward females. Historical modelling suggesting lower natural mortality for males and changing size-at-age all lead to the potential for a static assumption regarding sex-ratio to lead to a highly biased interpretation of stock status unless females and males are modelled separately.

In aggregate, these considerations led to the choice of four stock assessment models during the 2014 assessment process: a two-way cross of: coastwide vs. AAF data structuring, and long vs. short time-series. Each of these models explicitly treated male and female halibut separately and employed empirical weight-at-age rather than an explicit growth function. All models fit to both fishery and survey index trends and age compositions, and allowed for temporal variability in selectivity and catchability. Additional alternative modelling approaches were considered, including a simple surplus production model and a Virtual Population Analysis model. Both of these approaches suggested that recent removals and stock trends were on a similar scale to the four models included in that assessment (Stewart and Martell 2015), but presented sufficiently substantial issues in interpretation or application to the management process that they were not formally included in the final risk-assessment. Including four alternative assessment models in an integrated result should better approximate the uncertainty associated with the many structural choices that must be made in developing these models as well as the estimation uncertainty within each model.

General model configuration

There are a number of basic technical settings and features that are common to all four stock assessment models described here. This section provides an overview, which is supplemented by a description of individual model details (where they differ) below.

All 2015 stock assessment models were constructed using the generalized stock assessment software Stock Synthesis (Methot and Wetzel 2013, Methot and Wetzel 2013b, Methot 2015). The most recent version (3.24U) was used, however there were no changes made in recent versions that had any relevant impact on the Pacific halibut models as they have been developed over the last three years. This software separates the inputs into several files read in prior to estimation including the primary data file, the primary control file (including parameter setup and estimation switches), the weight-at-age file, the forecast file (including settings for reference point calculations), and the starter file (including some general estimation and reporting switches and settings). Each of these input files for each of the four stock assessment models described here are included in the background documents, along with the primary report file of estimated and derived quantities (see Appendix A).

These models were configured to make use of relatively standard population structuring. There were no seasonal dynamics, and catches were assumed to be removed halfway through the year via Pope's approximation. This approach does not require estimation of fleet- and year-specific fishing mortality rate parameters, and should reasonably approximate the dynamics unless fishing mortality rates are extremely high. Catches were input in thousands of pounds (net weight; head-off and gutted, approximately 75% of round weight), so that the weight-at-age inputs were in pounds and the numbers-at-age tracked in thousands of individuals. Population dynamics contain ages 0-30, and female and male halibut are tracked separately in the dynamics.

The input data were partitioned via a fleet structure of: the directed fishery (by area in the AAF models), discards, bycatch, sport, personal use, and survey (by area in the AAF models). Table 5 summarizes the data and key features of each model. Age data were aggregated into bins representing each age from age-2 (which also includes ages 0 and 1) through age 25 (which includes all observations greater than or equal to age 25). Aging bias and imprecision were estimated externally to the stock assessment, based on multiple reads for both surface aging (all years <2002, except the 1998 survey data) and break-and-bake (all years >=2002, as well as the 1998 survey data) methods (Stewart 2015). Break-and-bake ages are assumed to be unbiased (which has been corroborated via radiocarbon methods; Piner and Wischniowski 2004) and estimated to be relatively precise, while the surface ages are increasingly biased and much less precise beyond about age-15 (Fig. 15). Each annual age composition observation was assigned the appropriate ageing method in the data file and age data were partitioned by sex (the vectors for each year contain females, then males), where this information was available. Where few fish contribute to the 'tails' of the age distributions for each fleet and year combination, the model was set to automatically aggregate observations and predictions representing proportions less than 0.1%. The model was also set up to add a very small constant (0.0001) to all age proportions in order to stabilize the computation.

All growth specifications in the control file were bypassed in order to use the empirical weight-at-age approach; therefore the settings in the control file and the results included in model outputs related to these settings are not meaningful (this includes length-at-age, weight-at-length, and maturity-at-length; these are all integrated directly in the weight-at-age inputs). The weight-at-age file also included a matrix of spawning output-at-age representing the product of annual weight-at-age and the vector of maturity-at-age (Stewart 2015).

For all estimated parameters (except temporal deviations), uniform priors were implemented, with bounds sufficiently wide to avoid maximum likelihood estimates falling on or very near a bound, unless the bound was structurally logical. Table 6 summarizes the counts of estimated parameters in each model. Natural mortality was allowed to differ by sex, with the value for male halibut estimated in all four models, and the value for females in the two long time-series models. Treatment of both the stock-recruitment relationship and the initial conditions at the start of the modelled time-series differed among the four models and are described below. However, an important aspect of the treatment of the stock-recruitment relationship for all models is that they were structured to recreate the time-series of recruitments, not to estimate reference points such as *MSY* (this is discussed further in the context of each model below). This means that the output in the report file and automatically generated figures in the background material pertaining to *MSY* are not meaningful. However, this does not apply to the calculation of the Spawning Potential Ratio (*SPR*) as it is calculated on a per-recruit basis.

The double-normal selectivity parameterization (option #20) is used extensively in all four models, as it represents a flexible, but still parametric approach that can easily be made time-varying via just one or two parameters with annual deviations. There are more flexible nonparametric selectivity options, but these generally require all the parameters to vary over time, creating a substantial increase in complexity. The double-normal selectivity can be easily configured to be either asymptotic or dome-shaped, by adjusting the width of the peak and final selectivity parameters. It also includes an option for male selectivity to be offset from female selectivity, based directly on the parameters of the selectivity curve (females from males), such that time-varying selectivity for one sex can be mapped into variability for both sexes without estimating a second set of parameters. The double-normal was implemented for all model fleets, with at least the ascending limb of selectivity (ascending width and peak parameters) allowed to vary over time for all four models (described further below).

As has been the case in all recent halibut models, the catch-per-unit-effort index derived from the directed halibut fishery is included in each of the models, but the catchability is allowed to vary over time. In principle, there are many factors which can create changes in the proportionality of the catch-rate in a fishery with the underlying population. The most obvious of these are abrupt changes in fishing methods, such as the change from “J” to circle-hooks in 1984. This type of change was accommodated (in the long time-series models) via an unconstrained deviation on catchability in that year (effectively a separate q for the two parts of the time series). Beyond abrupt changes, there are many factors that can ‘drift’ over time, but may not be so obvious, including technological improvements, changes in spatial areas or times of year being fished, etc. This type of change suggests a random walk in catchability, which was the approach taken in all four models here. To implement this, a catchability parameter was estimated for the first year for which index data were available, and then a deviation (from the previous year’s value, not the mean) was estimated for each subsequent year of the time-series. The annual deviations were constrained by a single σ for each fleet, which was iteratively adjusted such that the resulting variability in the deviations was similar to, but less than the value for σ (essentially the ‘Thompson and Lauth method’; Annex 2.1.1 in Thompson and Lauth 2012).

In all models, fit to the age data used a multinomial likelihood with initial input sample sizes representing the number of fishery trips or survey stations contributing to that observation, subsequently adjusted down via a multiplicative scalar for each fleet in the control file (more discussion below). Indices of abundance from both the setline survey and commercial fishery (by area in the AAF models) were fit using a log-normal likelihood and input log(*SE*)s. Survey indices were fit in numbers of fish to avoid converting numbers to weights in the data and then weights back to numbers in the model predictions (as recommended by the Scientific Review Board in 2014). Weight-per-unit-effort is the native scale for the fishery indices.

As described above, several new age data sets were available for evaluation in 2015 including the sublegal halibut captured by the setline survey, the estimates from the bycatch length frequencies, and the recreationally caught halibut from Area 3A. Rather than assume a fixed selectivity curve, as has bene done in the past for discard mortality and bycatch, for 2015 these curves were estimated in the assessment models.

There are currently no options for age-based discarding (selectivity plus a retention function) available in Stock Synthesis. Therefore, as has been the case for all historical halibut assessments, discards are treated as a separate fishery. This treatment of discard removals (sublegal wastage) was substantially improved in 2015. First, sex-specific selectivity curves were estimated in each model based on the observations from the sublegal fish captured by the setline survey. The selectivity was configured to be a double normal, with female halibut offset from male halibut to account for the dimorphic growth, and the relative scale of females to males estimated directly. Both sexes were allowed to be allowed to be dome-shaped, with differing descending limbs. Because the sublegal survey age data were already included in the likelihood as part of the survey age compositions, it would be a misrepresentation of the uncertainty to naively fit them again equally as part of the discard data set. Instead, preliminary analyses showed that down-weighting these data such that they had a very small input sample size had no appreciable effect on the model results but still allowed for the direct estimation of selectivity. This approach propagates uncertainty in the estimated selectivity, and lends itself to direct inclusion of observer data on discarded halibut when it becomes available.

The second improvement related to modelling discarded halibut in the directed fishery was to implement a way to quickly and easily evaluate the assumed 16% Discard Mortality Rate (DMR). Using the features readily available in Stock Synthesis, the approach was based on the existing length-based implementation. Briefly, a retention function (constant across all lengths; option #2 in Stock Synthesis) was added, with the retention parameter (ρ) set to 0.0016. Input removals in the data file were divided by 100, and the DMR parameter (ψ) was set to 0.15864, the result being an identical quantity of dead discards to the previously assumed value, but with a mortality parameter could be adjusted to correspond to different hypotheses. For example, 1,000 pounds of handled halibut, with an assumed DMR of 16% would result in an estimated 160 pounds of wastage. As implemented: 1.6 pounds of input catch, implies 1,000 pounds handled , 158.4 pounds of additional handling mortality , for a total of 160 pounds of wastage, or an implied discard mortality of 16% (160/1,000). This approximation, where a DMR parameter value of 15.9% approximates an actual value of 16% is effectively linear (to less than 0.2%) across a range of relevant DMRs.

Sensitivity analyses could be performed on the assumed DMR parameter directly (rather than simply adjusting the wastage calculated outside the model as was done in 2013), or uncertainty could be integrated directly into the model results via an informative prior. This particular configuration of settings (interacting with empirical weight-at-age) had apparently not yet been closely evaluated in Stock Synthesis, and a minor reporting error was discovered in the code, such that the report file contains accurate numbers but inaccurate biomass values for discarded fish. The Synthesis code was updated to fix this issue (R. Methot, personal communication) and the updated code was subsequently tested on the halibut files to verify that the dynamics were being correctly calculated; estimates of discards in the report files provided in the background material contain this reporting discrepancy. A similar approach could be taken for bycatch DMRs, however identification of a single DMR and the range of factors contributing to uncertainty in bycatch are far more complex (see discussion of uncertainty below).

Due to the unknown origin and quality of the bycatch length frequencies, and the additional uncertainty associated with using the NMFS trawl survey-based age-length key to convert those lengths to ages, it did not seem reasonable to take these data as informative about the population dynamics. However, they should contain some information about the shape of the selectivity curve, potentially more reasonable than the fixed curve assumed in previous assessments. As with the sublegal discard data, down-weighting to a very small input sample size eliminated appreciable effects on model results, but still allowed for a sex-aggregated (and time-invariant) selectivity curve to be estimated. Also like the treatment of discards, in all models this curve was allowed to be dome-shaped given the relative frequency of younger halibut in the distributions, and the general observation that large halibut are not efficiently captured by trawl gear, which comprises the majority of the bycatch removals.

Where historical assessments assumed that recreational removals were subject to the same selectivity as the setline survey, age data collected from Area 3A suggested a greater proportion of young and fewer old halibut (see above). These data were introduced to all four models, and down-weighted such that selectivity parameters could be estimated (with a commensurate contribution to uncertainty), but little signal would be imparted to the modelled dynamics. Because of this down-weighting, and the unknown or potentially poorly spatially representative nature of the data themselves, no attempt was made to allow these selectivity curves to vary over time.

The presence of both observation error (in the indices and age composition data) and process error (in fishery catchability and selectivity for the survey and fishery) creates a challenge for standard weighting and tuning practices employed in many assessment models. Specifically, if process error is not modelled (and/or a fixed value is asserted), the input sample sizes (and sometimes index variances) can be iteratively tuned or estimated (Maunder 2011). This approach is useful for reducing the potential effects of outliers, lack-of-fit, or model misspecification with regard to composition data (Francis 2011). At the other extreme, if the observation error is assumed to be known (and assigned a fixed value), then the degree process error can be estimated via random effects, or iteratively tuned using a maximum likelihood-based approximation (the 'Thompson and Lauth method'; Annex 2.1.1 in Thompson and Lauth 2012). Where both sources of error are accounted for but unknown, they cannot be freely estimated simultaneously.

In all four models developed here, the initial input sample sizes, derived from the number of survey sets and fishery trips (and not the number of individual fish measured, which would be much larger), were considerably larger than commonly applied weighting for stock assessment models would suggest (Tables 3 and 4). These values were iteratively reduced based on evaluation of three considerations: the relative magnitude of the standardized residuals, comparison of the input value for each fleet with the harmonic mean effective sample size (which is an unbiased estimator for a set of independent multinomial samples, Stewart and Hamel 2014), and the scaling suggested by the Francis (2011) method (as implemented in the r4ss package). For almost all fleets and all models, this approach led to a substantial reduction from initial sample sizes (the fishery ages from Area 4B in the AAF short model were the sole exception, and these already represented one of the smallest values). In no cases were the input values increased from those derived from the number of trips or stations represented in the data.

The degree of process error had been evaluated in the 2012 and 2013 stock assessments, where the σ parameters (defining the random walk in selectivity parameters) were adjusted such that the change in model results using larger values was not appreciable. Specifically, the 2012 assessment found that retrospective bias was substantially reduced by allowing selectivity to vary over time for both the fishery and survey (the survey was particularly sensitive), and that this bias decreased as the temporal variability in selectivity increased. Those analyses also suggested that model estimates of stock size and trend responded to changes in the σ parameters, when the input values were small, but as they were increased little additional change was observed. When the models were extended in 2014, the σ parameters for each fleet in each model were not revisited.

Evaluation during 2015 revealed that in some cases the σ parameters were appreciably larger than the variability in the resulting estimated deviations.

As a general rule, a logical approach to the treatment of observation and process error would be to adjust model structure to fit the data as well as possible, increasing or decreasing the constraint on time-varying processes (e.g., the σ values for each fleets selectivity or catchability) to be consistent with the resulting variability, then adjust the observation error to be roughly consistent with the resulting lack-of-fit. For the coastwide models, repeating this process one to two times resulted in a reasonable balance between process and observation error that minimized residual and diagnostic patterns and did not appear to re-introduce dramatic retrospective patterns. However, for the AAF models, this process did not rapidly reach a stable solution: the trade-off among fleets might lead to more processes or observation error in one iteration and less in the next. However, the trend and scale of the solutions tended to be reasonably robust to the adjustment of process and observation error for particular fleets, once both were within a reasonable range. Specific diagnostics are provided for each model below.

For model integration and calculation of decision table metrics, three-year projections were needed from each assessment model. Projected catches were assumed to be known, and treated as inputs to the forecast file. Projected selectivity for each fleet was assigned the average of the most recent three years of estimated values. This is accomplished dynamically in the model code, which serves to propagate some uncertainty (about the mean), but not all of the uncertainty associated with a future year's selectivity. Weight-at-age is projected using the most recent year's observed values, as this was found to have little effect in previous comparisons.

Coastwide Short

The initial conditions for a model starting after an extensive historical fishery and appreciable recruitment variability must be structured to avoid simple assumptions that may have strong effects on the subsequent time-series. For the coastwide short model the initial conditions included estimating the population numbers at age 1-19 in the first year of the model (1996). Since the age data available for the initial year were aggregated at age-20 (due to the historical use of the surface ageing method), there was no specific information on additional individual year-classes. To accommodate a non-equilibrium value in the plus group, an offset to initial equilibrium recruitment (R_1) was also estimated. The effect of these two approaches was to essentially decouple the numbers-at-age in 1996 from any equilibrium assumptions.

Due to the short time-series, and for consistency with previous halibut assessments, there was no explicit stock-recruitment function imposed on the coastwide short model. To achieve this, the equilibrium recruitment level (R_0) parameter was estimated setting the scale of the stock-recruit relationship. Steepness (h) was fixed at a value of 0.75; however, recruitment deviations were implemented with no zero-centering constraint (simple deviations in ADMB, option #2 for the type of deviation in Stock Synthesis), which means that the central tendency of the stock-recruit function is unimportant (and uninterpretable) because the deviations are not necessarily centered on the curve. Without zero-centered deviations, calculation of equilibrium based reference points (i.e. *MSY*) cannot be performed internally with this model. In evaluating the 2014 model configuration, the degree of recruitment variability (σ_r) was found to be mildly constraining to the estimated deviations, so it was increased to a value of 0.9, appreciably above the resulting level of variability (the RMSE of the maximum likelihood estimates for constrained deviations will always have a negative bias relative to the appropriate σ, as the deviations are not being integrated as they should be in a Bayesian or random effects context). A summary of the number of estimated parameters contributing to each aspect of the model is provided in Table 6.

Age-based selectivity for female halibut in both the setline survey and commercial fishery was estimated using the double normal, forced to be asymptotic once it reached peak selectivity. This required two parameters: the ascending width of the curve and the age at which the peak selectivity is reached. Both parameters are allowed to vary over time with a random walk of annual deviations. These deviations were initiated in the first year for which age composition data were available, 1996 for the fishery, and 1997 for the survey. No deviation was estimated for the terminal year (2015), because the data were not yet available (this means that the catches in 2015 may have a different effect on the projections when they are removed via an informed selectivity schedule in the final assessment). Male selectivity for the survey was estimated via offsets to the female ascending width and peak parameters, and a third parameter defining the scale of male selectivity relative to that for females. In the coastwide short model, with fixed female natural mortality and direct overlap between all years of fishery and survey age data, the male offset parameters for the fishery have been estimated in recent assessments. These parameters are informed by the diffuse information on sex-ratio included the sex-aggregated age data. In aggregate, there were five estimated base parameters each for the survey and fishery and annual deviations on the ascending limb parameters (Table 6).

Based on exploration in 2015, the scale of male selectivity for both the survey and fishery were made more flexible by allowing it to also vary over time as a random walk. With only sex-aggregated commercial fishery age compositions, it is not clear how strongly the temporal variability in the scale of male selectivity is informed (and potentially how correlated it would be with female natural mortality, which is fixed in this model). However, the addition of time-varying deviations on the scale parameters was found to improve the residual patterns in the fit to the fishery age-data, and did not show signs of erratic estimation over sensitivity and alternative model runs. A specific sensitivity test of this change was explored and is reported below.

Coastwide Long

Initial conditions for the coastwide long time-series model were represented simply as the equilibrium stock condition, as the model period began well before the first age data were available (1935), and therefore there was a substantial 'burn in' for recruitment variability. The treatment of the stock-recruitment function in the coastwide long model was substantially different from that of the coastwide short model. Consistent with historical IPHC analyses, and the current harvest policy (Clark and Hare 2002 and 2006), the coastwide long model allowed for the possibility that recruitment variability is correlated with the regimes of the Pacific Decadal Oscillation (PDO). To implement this approach, a Beverton-Holt relationship, parameterized with an estimated value for the equilibrium recruitment level (R_0) parameter, and a fixed value of steepness (h) of 0.75. The annual average of the PDO index was converted to a binary indicator (PDO_{regime}) where productive regimes (e.g., 1977-2006) were assigned a value of 1.0, and poor regimes a value of 0.0. These regimes were linked to the scale of the stock-recruit function via an adjusted equilibrium level of recruits (R_0') based on an estimated coefficient (β) creating an offset to the unadjusted value:

$$R_0' = R_0 * e^{\beta * PDO_{regime}}$$

The adjusted equilibrium recruitment value was then used in the stock-recruit function with bias-corrected annual deviations:

$$R_y = f(SB_y, R_0', SB_0, h) * e^{r_y - \frac{\sigma^2}{2}}$$

This parameterization allows for the β parameter to be estimated at a value of 0.0 if there is no correlation between the putative environmental index and underlying mean recruitment. In that case R_0' is simply equal to R_0. As was the case for the coastwide short time-series model, fixing steepness precludes the use of *MSY* estimates that might be used for informing the harvest policy; however, the calculation of *SPR* is independent of steepness and can be compared to harvest-policy based estimates.

The approach to selectivity in the coastwide long model was identical to that in the coastwide short model, except that the scale of male selectivity was highly unstable (when allowed to be freely estimated, the value often went to 1.0, inconsistent with available information about likely sex-ratios in the fishery), and was therefore fixed at the estimated offset for the setline survey. When this behavior was first identified in the 2013 stock assessment, the sensitivity in the scale of the estimated stock size was highlighted and reported as a major source of uncertainty. This continues to be the case, and is re-illustrated in the sensitivity analyses reported below. Assigning the survey value for the scale of male selectivity from the survey to the fishery does not imply the same sex ratio in the catch for all ages, only those beyond the peaks of both female and male selectivity which represent only a subset of the total removals. Selectivity deviations on the ascending limb parameters of the fishery and survey series were initiated in the first year for which age composition data were available for both the fishery (1935) and the survey (1963).

Areas-As-Fleets Short

The AAF short model was configured very similarly to the coastwide short model. The most notable difference was in the treatment of selectivity for the survey and fishery in Area 2 and Area 3: these were allowed to be dome-shaped relative to the coastwide population dynamics. Implementing dome-shaped selectivity for these four model fleets requires the addition of a third selectivity parameter defining the width of the descending limb. This additional parameter was not allowed to vary over time, although this could be investigated in future modelling efforts.

The second difference between the short time-series models was in the treatment of the scale of male selectivity for the fishing fleets in each of the four areas. Similar to the coastwide long model, the three parameters defining the male offset to female selectivity for the commercial fishery in each area were set equal to the analogous estimated parameters for the setline survey in that area. This was an iterative process, as changes in the fishery selectivity influenced the estimated survey selectivity; however, the values usually converged to within one or two model runs. Estimation of some or all of these male scale parameters could be evaluated in future efforts. Temporal variability in selectivity parameters occurred over a slightly longer range of years in the AAF short model, as there were area-specific survey data available for the entire time-series from Areas 2 and 3.

Areas-As-Fleets Long

The only structural differences between the AAF long and AAF short models were the years over which deviations in recruitment, selectivity and catchability are estimated. The AAF long model treated the stock-recruitment function in the same manner as the coastwide long model.

Coastwide short model

Diagnostics

Predictions of both the fishery and survey indices of abundance fit the observed data very well in the coastwide short model (Fig. 16). The predicted aggregate age distributions also matched the observed distributions quite well, indicating that the selectivity approach was generally capturing differences in both the age-structure and sex-ratio among the model fleets (Fig. 17). Average input sample size by fleet (after adjustments) was substantially below the harmonic mean effective sample sizes for both the survey and fishery and the multiplier estimated via the Francis method did not suggest further reductions (Table 7).

Fit to the annual setline survey age compositions were good, although some patterning was visible in the standardized residuals (Fig. 18). Specifically, there was a pattern of negative residuals in the plus group for male halibut; however, this was almost imperceptible in the fits themselves. The fits to the annual fishery data were also acceptable (Fig. 19). Additional diagnostics and diagnostic figures (such as fits to the down-weighted annual compositions for the discard, bycatch, and recreational fleets) are included in the in the background materials.

Results

Estimated selectivity for the discard fleet differed appreciably for males and females, with females less selected than males overall and declining beyond about age-11, where males were fully selected until about age-16 before becoming highly domed (Fig. 20). These estimates are very consistent with the observed dimorphic growth and its likely interaction with the 32-inch minimum size-limit in the commercial fishery. Estimated selectivity for the bycatch fleet was quite similar to the fixed curve used in historical assessments, (suggesting that fitting to the length data may have been the method used to generate the original). Halibut of ages 2-7 were much more strongly selected by the bycatch fleet than any other in the coastwide short model, with full selectivity occurring at ages 4-5 (Fig. 20). Estimated selectivity for the recreational fishery was shifted to the left of the commercial fishery discards (and therefore the survey), reflecting the increased numbers of halibut age-7 and younger in the data from the Gulf of Alaska. Neither the survey nor the fishery selectivity was estimated to have a highly variable ascending limb over the short time-series (Figs. 21 and 22). The fishery selectivity estimated a trend toward increasing selection of males in recent years, perhaps a function of the catch distribution shifting toward the Eastern side of the stock where fast-growing males are much more common, as well as the decline in the strong cohorts from the 1980s which produced an abundance of older females. Because the addition of temporal variability in the scale of male selectivity was new for 2015, an alternate model with time-invariant male scaling was also investigated (see sensitivity results below).

The degree of variability in fishery catchability was much smaller than that implied by the input σ over a broad range of starting values. Reducing this sigma until it was commensurate with the observed variability in the deviations resulted in little model change. Fishery catchability showed a trend toward increasing values in the more recent years, however the scale of this change was trivially small (Fig. 23). The sensitivity to assuming strictly constant catchability was explored, and is reported below.

Male natural mortality was estimated to be slightly less (0.138) than the fixed value assumed for females of 0.15 (Table 8, Fig. 24). The difference in natural mortality, combined with lower overall selectivity for male halibut, suggests highly skewed sex ratios that are increasing somewhat as the larger cohorts of the 1980s leave the population (Fig. 25).

In aggregate, all the updates and improvements made to the coastwide short model in 2015 had the largest influence on the spawning biomass estimated for the early portion of the time-series (Fig. 26). Additional figures of the coastwide short model results, in addition to the entire report file containing all parameter estimates, are included in the background materials. However, note that many of the plots produced automatically are not relevant to the specific model configurations used here (e.g., biology plots, stock-recruit plots for the short time-series models, etc.).

Coastwide long model

Diagnostics

Both the fishery and survey indices were fit well, with breaks in catchability to accommodate the change from "J" to circle hooks very conspicuous in both series (Table 8, Fig. 27). In aggregate, the predicted age compositions matched the observed data well (Fig. 28); however there were notable differences among years within the time-series. Fits to the setline survey were quite poor in the early portion of the time series, improving where the data became more comprehensive in the mid-1990s, and quite good in the most recent years (Figs. 29 and 30). Fishery data fit reasonably well for the entire time-series, with patterns in the residuals corresponding to relatively small differences with observed distributions (Figs. 31 and 32). Harmonic mean effective sample sizes were much larger than adjusted inputs (Table 7). The Francis multipliers suggested slightly more weight to the fishery data, and less to the survey, but this seemed to be inconsistent with the residual patterns and scale in the recent part of these time-series.

Results

Older halibut were more represented in the bycatch age data prior to 1996, and therefore the estimated selectivity had a higher selectivity asymptote than was estimated in the coastwide short model (Fig. 33). Due to the unknown quality of the currently available bycatch age distributions, not attempt was made to allow the bycatch selectivity to change over time, although this could be explored if and when data thought to be more reliable can be included. Recreational and discard selectivity estimates were relatively similar to those from the coastwide short model. Estimated survey selectivity showed a pattern of decreasing relative values for younger halibut through the mid-2000s and then an increase at the end of the time series (Fig. 34). This may be consistent with changes in both the age-structure of the stock and the spatial distribution. Fishery selectivity generally showed a pattern toward selecting fewer younger fish over a longer historical period, but a similar trend to the setline survey in the most recent years (Fig. 35). Fishery catchability showed a very large (unconstrained) increase associated with the change from "J" to circle hooks, and a similar trend from the late-1990s through the end of the time series as was estimated in the coastwide short model (Table 8, Fig. 36).

Female natural mortality in the coastwide long model was estimated to be higher (0.202) than for males (0.156; Table 8, Fig. 37). The environmental link parameter (β) was estimated to be positive (0.308), with very little density below a value of 0.0 (Table 8, Fig. 37). However, the time series of estimated recruitment deviations suggested that some residual effect and/or mismatch in the relationship might still be present, as the poor PDO period from 1947-1977 and the positive phase from 1978-2006 generally correspond to negative and positive residuals, respectively (Fig. 38).

The net change to the time-series estimates from all the updates and changes made for 2015 was minor and had the largest influence on the peak biomass values (Fig. 39).

Areas-As-Fleets short model

Diagnostics

The AAF short model fit the observed trends in Areas 3, 4, and 4B relatively well, but not the trend observed in Area 2 (Fig. 40). None of the configurations evaluated for either AAF model were able to capture the full extent of the recent increase in Area 2, and the continued decline in Area 3 at the same time. If the mismatch in trends for Area 3 and Area 2 are actually spatial in nature (halibut with similar demographics are moving from Area 3 to Area 2), then there is little chance of capturing both trends simultaneously with any approach that is not explicitly spatial, even using separate fleets as in the AAF models. Trends in the fishery catch-rate indices were also fit reasonably well, including in Area 2 (Fig. 41); this was achieved via changes in catchability (see AAF short model results below).

Fit to the aggregate age data for each model fleet clearly illustrated the differences in age structure among them (Fig. 42). The biggest differences between female and male halibut occurred in the Area 3 survey, and generally Areas 4 and 4B were predicted (and observed) to have the greatest fraction of older halibut, particularly males. The fit to the annual setline survey data generally captured these patterns (Figs. 43 and 44); however, there were some relatively strong patterns in the residuals and the fits to the data from Area 4B were noisy (Figs. 45 and 46). Although the input sample sizes were substantially below the harmonic mean effective sample sizes by fleet, the Francis multipliers suggested further reduced emphasis on the survey age data (or perhaps increased process error in the selectivity deviations; Table 7). The AAF models, due to the complexity of tuning constraints on the deviations of selectivity and catchability, as well as the scale of the male selectivity were not tuned extensively, but rather a few iterations were made to bring the scale of residuals and σ parameters generally in line with the diagnostics. Fits to the fishery age data (Figs. 47 and 48) were somewhat better, however there were still clear residual patterns (Figs. 49 and 50). Perhaps the most clear of these patterns was the lack of fit to the very strong 1987 cohort apparent in the Area 4 fishery data (Fig. 50, upper panel). No model configurations evaluated during model development were able to fit the peak observations of this cohort observed in Area 4 (and to a lesser extent in Area 4B), which may be a reflection of the spatial nature of the dynamics not well approximated by an AAF approach.

Results

Male survey selectivity was estimated to be shifted much more strongly to the right relative to females, in Area 3 compared to Area 2 (Figs. 51 and 52). The surveys in both Area 4 and Area 4B were assumed to have asymptotic selectivity, with Area 4B showing a greater amount of temporal variation in the estimated ascending limb, and much younger males selected than in Area 4 (Figs. 53 and 54). Estimated fishery selectivity showed generally similar patterns, but with somewhat less temporal variation (Figs. 55-58). Bycatch, sport and discard selectivity estimates were similar to those from the coastwide short model.

Estimated fishery catchability showed differing temporal patterns and scale by Area (relative to the coastwide population dynamics), with the observed increasing trend in Area 2 corresponding to increasing catchability for the fishery in that area (Fig. 59). Temporal change estimated for Areas 4 and 4B were much smaller than in Areas 2 and 3, and this was also the case in preliminary analyses where even weaker constraints were placed on the deviations.

The estimate of male natural mortality in the AAF short model (0.129) was slightly lower than in the coastwide short model (Table 8, Fig. 22).

In aggregate, the result of all the changes and improvements to the AAF short model led to a small increase in the scale of the spawning biomass estimate which was observed across the scale of the whole period (Fig. 60).

Areas-As-Fleets long model

Diagnostics

Like the AAF short model, the AAF long model fit the survey trends relatively well, with the exception of Area 2 (Fig. 61). The fishery index in Area 3 (also similar to the fit in the AAF short model) predicted an increase at the end of the time-series despite continued decline in the observations (Fig. 62). If this pattern represents a spatial trend, then fishery catchability would appear to be the only way for a non-spatial model to begin to fit these trends.

Aggregate fits to the survey age composition data showed similar patterns to those observed in the AAF short model (Fig. 63). Generally, the fit to the survey data improved over the time series the poorest fit to the age data occurring in Area 4B (but that Area also had considerably lower average sample size; Table 7, Figs. 64-66). Residual patterns appeared to indicate temporal changes in the sex ratio, especially in Area 2 and Area 3, that were not fit by the time-invariant parameterization employed in this model (Figs 67 and 68). These patterns might be explored further in the AAF models by allowing the scale of male selectivity to vary over time on a fleet-by-fleet basis. Fits to the sexes-aggregated fishery data were reasonably good for Areas 2 and 3 (Figs. 69 and 70), although some patterns were still apparent in the residuals (Fig. 71). As was observed in the AAF short model, the fits to the Area 4 and 4B age data failed to capture the peaks of dominant cohorts (Fig. 72a, and 72b) leading to strong diagonals in the residuals (Fig. 73).

Results

Bycatch, discard and recreational selectivity estimates were similar in the AAF long model to those estimated in the coastwide long model. For each survey fleet, the temporal pattern of selectivity is shown (Figs. 74-77). Because the changes in selectivity for the Area 4 and 4B surveys only occurred at the end of the time-series, cropped contour plots are also presented (Figs. 78 and 79). Fishery selectivity is shown in Figures 80-83; for Area 4 and 4Bcontours are also shown to make the trends more visible (Figs. 84 and 85). Generally the estimated fishery selectivity shows a gradual pattern toward older fish in all areas, somewhat different than the variable temporal trends estimated for the survey data. Fishery catchability was estimated to be strongly increasing in Area 2 and decreasing in Area 3 at the end of the time series (Fig. 86). There was little change estimated for Areas 4 and 4B, but all areas showed a large offset associated with the change from "J" to circle hooks, as was estimated in all four models (Table 8, Fig. 86).

Female natural mortality was estimated to be only slightly less than 0.15 (0.148) and higher than the estimated value for males (0.129) in the AF long model (Table 8, Fig. 87). The environmental link coefficient was estimated to be somewhat stronger (0.522) than in the coastwide long model. Investigation of the predicted sex-ratio over time suggested that the ratio of males to females is highly dynamic, responding to both exploitation and year class strengths (Fig. 88).

The net change from the 2014 to preliminary 2015 model results were less pronounced for the AAF long model than any of the other three models (Fig. 89), with most of the change occurring in the early time-series.

Sources of uncertainty

The four models evaluated here represent significant sources of uncertainty in how to treat the data (partitioning by fleets or aggregating to a single series), as well as how to treat the time-series (emphasizing the recent dynamics or including more historical information). Further, the differing assumptions of fixed vs. estimated female natural mortality rate is also embedded in the differences observed among the model results. These factors lead to differences in both scale and trend. Comparison of the two short-time-series models illustrated that the uncertainty intervals from either of one these models alone would be grossly insufficient to represent a reasonable risk assessment (Fig. 90). Comparison of the two long time-series models illustrated the effects of differing assumptions about domed vs. asymptotic selectivity for the early portion of the time period where the fishery was focused primarily in Areas 2 and 3 (Fig. 91). This aspect of the two long time series models was explored further as a sensitivity analysis (reported below). Although the recruitment time series for the two long models was similar in trend (Fig. 92), the scale, especially of the larger recruitments, reflects the large difference in estimated natural mortality rate between the two models. In aggregate, the four models together reflected much more uncertainty than any single model, while still showing a similar basic trend over the recent time-series' of both spawning biomass and recruitment (Fig. 93). It is not clear how additional data may or may not help to reconcile the divergence in trends in spawning biomass in the terminal years.

Convergence diagnostics

Many models were run with alternative phasing and starting values and there was no evidence that the MLE solutions were particularly sensitive to these choices. All four of these models returned a positive definite Hessian for all alternatives explored during development. Pairwise among parameter correlations were generally less than 90%. Maximum gradient components were generally less than 0.001 among alternative models explored, although the long AAF model varied between 0.001 and 1. The implementation of temporal deviations in selectivity includes a parameter for all years in the series, even when some years have no observed data. These parameters have no contribution to the dynamics (other than the indirect effect of additional change in the series) and frequently result in a value estimated to be very close to zero based solely on the constraint provided by sigma. It is unclear how or whether these parameters may influence the gradient structure.

The convergence of the coastwide short model was explored via a set of 100 sets of alternate initial parameter values created by adjusting each by a random addition of 10% of the range of the parameter bounds (from lower to upper). The goal of this type of exercise is to discover whether a very different path to convergence might identify a more global minimum in the likelihood surface.

It that regard, this represents a one-sided test, capably only of proving lack-of-convergence, and it is desirable to have a high convergence failure rate in the test, which is indicative of a strong exploration. Of the 100 alternate sets of starting values, 47 produced models converged to the maximum likelihood estimate previously identified, 16 were nearly converged to that value, but had a slightly larger negative log-likelihood (these produced very similar results with regard to stock size), and 37 sets that failed to converge to a meaningful result. This suggests that the level of dispersion was sufficient to produce a reasonable test for convergence, and that the model is unlikely to be converging to a local minimum. Other models could not be run from automatically adjusted starting points due to the manual assignment of male selectivity offset parameters for the fishery fleets from the values estimated for the setline survey.

Retrospective analyses

The halibut model used from 2006 until 2011 was plagued by a very strong retrospective pattern, both in the scale of the most recent stock size estimates as well as the trend in those estimates. Both the coastwide and AAF short models showed a small retrospective trend in the scale of the spawning biomass estimates but not the trend, becoming more pronounced after five years of data had been removed (representing six model years, since there were no data yet available for 2015; Figs 94 and 95). These patterns appeared to be slightly stronger in 2015 after increasing the constraint on temporal variation (decreasing the σ parameters) to be more consistent with the level of variation estimated in the models. Original investigation of this using the 2011 model revealed the least amount of retrospective pattern both when the survey index was very strongly emphasized (effectively down-weighting the age data), and when the constraint on selectivity variation was reduced. A few alternate model configurations with substantially reduced temporal variability were explored during 2015 model development, and these suggested similar behavior. It is not clear exactly what the appropriate trade-off between flexibility in the deviations and retrospective behavior might be, but the terminal estimates from each of the recent 'peels' all fall within even the within-model uncertainty intervals, suggesting this is a smaller factor than others explored in the full suite of models. The two long time series models showed somewhat differing retrospective patterns, with no clear trend observed for the coastwide long model (Fig. 96) and only a slightly increasing trend as data were removed from the AAF long model (Fig. 97).

Although the coastwide short model was made more flexible in order to estimate the temporal trends in the scale of male selectivity for both the survey and the fishery, this did not improve the mild retrospective trends. However, none of these models contain data to strongly and directly inform changes in the sex-ratio of male and female halibut over time and these are changes are highly relevant to the degree of temporal variability that should be modelled, as well as to the resulting population estimates from each model.

Sensitivity analyses

Many alternative model configurations were evaluated during model development, but only a subset of these is reported here. These results were selected to try to highlight the features of each of the four models to which there appeared to be the strongest response in stock size and trend estimates, or to illustrate the effect of specific model features of specific interest.

Assuming strictly proportional fishery catchability for the coastwide short time-series did not appreciably change the results (Fig. 98). Forcing the scale of the male selectivity to be time-invariant for both the fishery and survey in the coastwide short model also had little effect on the estimated time-series (Fig. 99). The scale of the estimated stock size was directly proportional and highly sensitive to the fixed value for female natural mortality (Fig. 100). The same degree of sensitivity to the fixed value for female natural mortality was also observed in the AAF short model (Fig. 101).

The fixed value of steepness (0.75) used in the coastwide long model, while extremely important for estimation of *MSY* and similar recruitment-based reference points, had a relatively minor effect on the scale of the stock size estimates compared to other sources of uncertainty. When estimated freely, the parameter estimate went to a value of 1.0 (although the model did not fit the data appreciably better), with the biggest difference in the estimated time-series occurring at the peak biomass levels at the beginning of the time-series and in the early 2000s (Fig. 102).

As was first identified in 2013, forcing the scale of male selectivity in the fishery to differ from that of the survey by +/-10% had a very strong effect on the scale of the biomass estimate (Fig. 103). This result applies to the AAF models as well, where the scale of the male selectivity is also assumed to match that of the survey on an area-by-area basis. In the absence of direct information on the scale of male selectivity in the commercial fishery there is no easy solution to this issue. It may be possible to estimate the scale parameter (and therefore propagate the uncertainty) as these models are more fully developed, however the historical period, lacking commensurate observations in the survey to balance the estimation is likely to remain problematic. Using an aggregated-sex model, such as the VPA developed in 2014 still requires an assumption of the sex-ratio to estimate female spawning biomass. The skewed and variable sex-ratios estimated in these models (Figs. 25 and 88) suggest that an aggregate approach could become highly biased if a simple assumption regarding the ratio of males to females was imposed.

Based on the differing historical trends observed in the 2014 coastwide and AAF long time-series model, an exploration of potential causes was made for 2015. Much of the historical fishery occurred in Areas 2 and 3 over the period when the two model's estimate diverged (before 1980, Fig. 91). To mimic the dome-shaped selectivity estimated for these areas in the AAF model, dome-shaped selectivity was allowed during the time-periods prior to 1958, 1959-1980, and 1981-1996 for an alternate configuration of the coastwide long model. This resulted in a substantial increase in the estimated stock size during much of the historical period (Fig. 104), and brought the results of the coastwide long model much closer to those of the AAF long model (Fig. 105). This alternate model essentially represents a hypothesis that older halibut in Areas 4 and 4B were relatively unavailable to the historical fishery. However, with domed fishery selectivity the coastwide long model also estimated a very high rate of female natural mortality (0.24), perhaps outside the plausible range for a species that is routinely observed to greater than 30 plus years, and to age-55 at the extreme. In addition, there was a substantial and abrupt change between the later domed periods and the selectivity after 1997 (Fig. 106). Conceptually, the degree of migratory connectivity among the areas should determine just how domed the early, and especially intermediate years, were as the fishery progressed to the north. The AAF long model captures this progression more naturally, but a continuously time-varying approach to the degree of domed selectivity might achieve a similar effect at the coastwide level. Further work could investigate the specific implementation of domed selectivity in the coastwide long model; refining this approach could also have implications for estimation of the scale of recent male fishery selectivity.

Other considerations

Uncertainty in the removals for these models is not currently captured, as they are treated as inputs and assumed to be known without error. In previous assessments, sensitivity analyses have been conducted to both the degree of sublegal wastage (mortality) in the commercial fishery as well as to the magnitude of total bycatch. The scale of stock estimates was found to be relatively robust to differing levels of these removals. However, there remains considerable uncertainty in both the wastage and bycatch, although it arises from somewhat different sources in each case. In the case of wastage, the assumed static DMR of 16% could potentially scale the removals up or down, if the actual DMR differed appreciably, due to the relatively large number of halibut handled by the commercial fishery each year. Although it was not specifically investigated in 2015, the improved implementation in these updated models allows for a direct evaluation of the DMR and the potential use of an informative prior rather than a fixed assumption. However, estimation of catch in statistical catch-at-age models generally requires other stabilizing assumptions, so direct integration of this uncertainty may still prove challenging. This is a topic for future exploration.

The relevant uncertainties in both wastage and bycatch have differing components, not all of which are of equal uncertainty or potential magnitude. This is especially the case for bycatch uncertainty, where observer coverage, observer sampling, the total number of fish handled relative to the number assumed to subsequently die and the scale of the various fisheries all contribute. A qualitative comparison reveals that summarizing the uncertainty in the aggregate bycatch from many different fisheries into a single DMR or scalar is not straightforward (Table 9). For example, the major source of uncertainty in the hook-and-line fleets is likely to be the DMRs assigned to those fleets, while the a trawl fleet such as that in the Gulf of Alaska may be more uncertain with regard to the representativeness of the relatively low observer coverage.

During 2014, the uncertainty in the magnitude of bycatch was specifically addressed through the construction of alternative catch tables for the upcoming year. This process allowed for an area-by-area investigation of the sensitivity of the Blue Line (the application of the current harvest policy) to alternative levels of bycatch without the need to postulate a specific probability that alternative levels. Requested levels ranged up to the full PSC limits for Alaska. This appeared to be a helpful way to inform the management process, although it did not represent uncertainty in the historical values.

Generally, each of these models has differing but important sources of uncertainty that have not yet been and may not be easily be resolved. The coastwide short time-series model is highly dependent on the value assumed for female natural mortality. The coastwide long time-series model is sensitive to both the treatment of historical fishery selectivity as well as the scale of male selectivity in the fishery independently, and these may also be confounded given the data available. Both AAF models require a balancing of several confounded factors including: the degree of process error to allow in fishery catchability, fishery selectivity and survey selectivity, the degree of observation error to allow in fishery and survey age composition data and indices of abundance, as well as the scale of male selectivity for fully selected halibut. For the coastwide models there appeared to be more stability in the tuning of each of these factors, the AAF models with multiple fleets were much more sensitive to the allocation among error types by fleet. Heavily weighting toward observation error, led to reduced levels of process error, but tended to generate model results with very strong retrospective patterns, consistent with analyses in 2012 indicating that adding process error in selectivity was an effective tool in reducing retrospective trends. Heavily weighting toward process error did not appear to appreciably improve residual patterns in the data.

It is clear that in this application (and in general), it is not possible to simultaneously estimate (or iterate toward a stable solution for) both process and observation error simultaneously. Continued development of these models may allow for estimation of the scale of male selectivity for one or more areas which would greatly improve the efficiency with which alternative weighting and error assumptions can be evaluated.

Model integration

Model-integrated quantities are used as the primary output for stock assessment results, as well as the basis for decision table probabilities. Quantities have been integrated for the recent time period (1996+, over which all four sets of model results are available) including: spawning biomass, exploitable biomass, and *SPR* (summarized as fishing intensity, $F_{XX\%}$, where the *XX%* represents the *SPR*). Decision table quantities are divided into four categories: stock trend (which is the only set of metrics that are independent of any harvest policy related assumptions), stock status, fishery trend, and fishery status. Integration is performed for all these quantities using the basic approach outlined below.

Methods

Ideally, probability distributions for each model would be obtained through Bayesian integration; however, only maximum likelihood estimates and asymptotic variance estimates are currently available. These approaches may differ importantly in both the estimates of uncertainty as well as the shape of the distributions for management-related quantities (e.g., Stewart et al. 2013). The basic approach to model integration is to create a collection of random draws from each of the four model outputs. For the spawning biomass time-series, the estimates and associated standard deviations for female spawning biomass from each of the four models were extracted from the report file. A vector of length *n* was created for each model (*m*), where the relative weight is simply the relative fraction of the total draws across all models comprised by n_m:

$$w_m = \frac{n_m}{\sum_m n_m}$$

For the results presented below n_m for all models was set equal to one million, this generated equal weight for each model and was found to be sufficient to create extremely smooth distributions, with little to no sign of Monte-Carlo error even in the extreme tails of the distributions. Although this choice could potentially be optimized, current integration code (in R) takes only seconds to run, and does not represent a constraining step in the analysis. For each element in the vector a random normal value with mean and standard deviation equal to the estimates from that model was then created. Summary statistics for the integrated distribution were then saved for reporting and plotting.

Exploitable biomass (*EB*) calculations were more complicated due to the fact that these are a product of the externally derived selectivity schedule (*s*) consistent with the IPHC's existing harvest policy. The exploitable biomass is the product of selectivity, the numbers-at-age estimates (*n*, by sex, *s*, and year, *y*), and the weight-at-age:

$$EB_y = \sum_{sex=m,f} \sum_{age} s_{s,a,y} * w_{s,a,y} * n_{s,a,y}$$

No uncertainty estimate is directly available for these quantities in the model output; therefore the coefficient of variation for the spawning biomass in the same year year was used to approximate the distribution for exploitable biomass. The standard deviation was then calculated from the mean and approximated CV, and a distribution was created as for spawning biomass described above. Exploitable biomass in the IPHC's harvest policy was originally a fixed function of length-based selectivity. This was converted to age-based selectivity in the 2012 model via the mean lengths-at-age observed in the setline survey. This produced a historical trend as size-at-age declined, but had been relatively constant for the terminal several years. Since 2013 the selectivity at age describing the exploitable biomass has been held constant (Fig. 107) as little change had occurred in recent coastwide size-at-age. In order to provide calculations consistent with the policy, if size-at-age changes appreciably in the future this transformation may need to be updated unless revisions to the harvest policy are conducted in the interim.

The calculation of reference points was structured to match the assumptions of the IPHC's current harvest policy as closely as possible, and to use all available information within each stock assessment model. The current harvest policy employs a control rule that reduces the target harvest rate in each regulatory area linearly from the default values (21.5% in Areas 2A, 2B, 2C, and 3A, and 16.125% in Areas 3B, 4A, 4B and 4CDE) at $SB_{30\%}$ to zero at $SB_{20\%}$. In the presence of variable recruitment and size-at-age, these reference points were originally identified with poor environmental conditions for recruitment and relatively good size-at-age (consistent with observations in the 1950s through 1970s; Clark and Hare 2002, Clark and Hare 2006) Since the long time-series models explicitly included more information on these processes than the short models, the calculation of $SB_{30\%}$ and $SB_{20\%}$ differed in the two cases. Two important quantities were not available internally to the short time-series model used in 2006 and were therefore pre-specified when the harvest policy was first applied: the historically estimated ratio of average recruitment during poor and good recruitment regimes was 4.13/13, and the historically estimated spawning biomass per age-6 recruit was 118.491. Using the short time-series models, for the same approach as originally developed, required that the average number of age-0 recruits for the period ending in 2006 (when the PDO reverted to the poor regime) were projected to age-6, accounting for natural mortality (i.e.,), and the initial age structure in 1996 similarly adjusted to age-6. These calculations then produced an estimate of $SB_{x\%}$ for comparison with current and projected future biomass:

$$SB_{x\%} = x * 118.491 * \frac{4.13}{13.0} * \overline{rec}_{age-6}$$

The values for $SB_{20\%}$ and $SB_{30\%}$ were calculated using the same formula. The historically estimated but fixed quantities in these calculations did not have associated uncertainty estimates, and therefore the reference points themselves ($SB_{30\%}$ and $SB_{20\%}$) did not have uncertainty estimates. Because the quantity of interest was the ratio of current to reference point *SB*, and these values must be correlated, it would not be appropriate to add additional uncertainty to the calculation beyond that present in the current biomass estimate without including an appropriate covariance term.

For the long time-series models, this calculation is much simpler. Treatment of the PDO regime was structured such that a value of 0.0 applied to the poor phase, and this is used for the internal calculation of reference points, thus no historically-based adjustment was necessary. Similarly, the average weight-at-age for the period 1950-1980 was assigned to the internal calculation of reference points, consistent with the data available for the historical analysis producing the spawning biomass-per-recruit used in the short time-series models. This means that the ratio of current to unexploited equilibrium *SB* (sometimes confusingly referred to as 'depletion') in the long time-series models was fully internally consistent propagating both the variance and the covariance in each *SB* component.

For all four stock assessment models, current and projected future spawning biomass estimates, conditioned on alternative input projected catch streams, are available directly. The only difference with the similar *SB* calculations described above is that in addition to the asymptotic estimate of the standard deviation for each biomass (e.g., *SB* current vs. *SB* three years in the future), the correlation is also included in the calculation of the ratio defining the probability of stock decrease. Specifically, instead of drawing a vector of independent random normal values for each SB, the draws are multivariate normal, including the covariance.

The decision table also includes a metric reporting the probability that the harvest rate in the upcoming year will exceed to target harvest rate. This calculation creates a distribution of projected harvest rates by dividing the TCEY corresponding to the removals in that row of the decision table by the distribution of exploitable biomass (as described above). The ratio of the projected harvest rate to the target rate (calculated based on apportionment, modified by the median spawning biomass relative to the $SB_{30\%}$ and $SB_{20\%}$ references points via the 30:20 control rule) is then computed. The proportion of values greater than 1.0 thus represents the probability of exceeding the target, accounting for uncertainty in the exploitable biomass, but not the target exploitation rate itself.

The remaining model-integrated results are the fishery trend metrics. These report the probability that applying the current harvest policy in a future year (one and three years hence) would result in a lower fishery CEY than the value specified for that row of the decision table. This calculation first creates a distribution of exploitable biomass values, then finds the target harvest rate accounting for the spawning biomass relative to the harvest control rule and creates a distribution of future TCEYs. To get to the distribution of available FCEY values from the TCEY distribution, the projected removals of halibut greater than 26 inches in length (O26) not included in the FCEY calculations first need to be removed to be consistent with the calculation of catch tables (Stewart 2015b). These include static projections based on the terminal year's data (e.g., recreational removals not included in Catch Sharing Plans, CSPs), as well as O26 removals that scale with the FCEY (e.g., recreational removals included in CSPs).

Results for 2015

For this preliminary analysis, the same equal weighting among models used in 2014 is used to generate integrated results for quantities of management interest. With the additional year of projection to 2016 (and in the absence of additional data) there is considerable uncertainty in the terminal estimates of spawning biomass from each model and among models (Table 10, Fig. 108). This corresponds to a broad cumulative distribution (Fig. 109). The integrated time-series reflects this uncertainty (Fig. 110). Projected median management quantities are generally consistent with the values and trends estimated in the 2014 (Table 11) and recent assessment despite the improvements made in 2015 (Fig. 111)

Future extensions

Continued refinement of the individual models included in the integrated ensemble results could potentially include additional sources of uncertainty. Where specific probabilities can be assigned to alternative values for key inputs, such as female natural mortality, the scale of male selectivity or the magnitude of bycatch removals, these could be used to weight additional models contributing to the ensemble. This would have to be done carefully, to avoid creating too much complexity (particularly the number of different combinations of models) and also to avoid inappropriate weighting. For example, if one of the four existing models was partitioned into three inputs, each representing an alternative level of female natural mortality, those inputs would conceptually be 'nested' and should not be weighted equally to all other models in the ensemble. Specific approaches are likely a useful avenue for future consideration.

Weighting of the four models included in the ensemble could potentially be made less subjective if criteria were developed that represented the relative quality of each model. Such criteria could be based on retrospective and prospective model behavior, fit to summary data common to each (or at least capable of being summarized in each, e.g., the coastwide survey index of abundance), relative behavior in simulation experiments, and other measures of performance. However, none of these approaches is likely to clearly identify a single model (at least over the set that has been examined to date) as far superior to all others and therefore dramatically change the relative weights. Further refinement of the existing models, and continued evaluation of alternative models may be as important as the specific weighting within the ensemble. In addition, periodic comparison of ensemble results with very different approaches, such as the simple surplus production and VPA models developed during 2014 may help to better understand the dynamics in a general sense.

Additional management metrics could be added to the existing decision table (Table 12) as the need arises. Potential candidates could include metrics that are independent of the current harvest policy, such as the probability that the projected future level of fishing intensity ($F_{XX\%}$) is greater than the most recently completed fishing year. Such metrics, similar to those pertaining solely to stock trend, do not rely on the many assumptions embedded in the current harvest policy calculations. Generally, although certain metrics will likely display more or less contrast in a particular year, it may be helpful for all users of the table to continue to report a consistent set of metrics without changing the format of the table dramatically each year. A consistent set of risk metrics will also enable future evaluation of the 'risk profile' for historical decisions. This type of analysis will become more informed as multiple years of decision-making become available and may prove to be a useful input to the Management Strategy Evaluation (MSE) process.

Of current interest, in the interim before more detailed MSE results are available, are the properties of the current harvest policy. The application of this policy and its current results are outlined in Stewart (2015b). The salient result for consideration here is how the Blue Line results in the decision table are calculated. Currently, the median exploitable biomass, target harvest rates (and harvest control rule), as well as the detailed array of O26 removals are used to generate a target level of removals consistent with historical calculations. However, the IPHC's current harvest policy does not explicitly address changes in U26 mortality from those inherently included in the original simulations (Stewart et al. 2015). The implied assumption was that sources of U26 mortality would represent a minor and relatively static component of the Pacific halibut mortality over the long-term. This can introduce a lag in response if, for example, U26 mortality increases, and there is no response in harvest policy calculations until that increase in mortality is observed in subsequent year's surveys and trends. For this reason, in 2014 the projected level of fishing intensity (including all sources of mortality) was included with the decision table. If appreciable trends in the level of fishing intensity associated with the Blue Line are observed, it may be reasonable to consider a constant SPR target as a logical analog to the current Blue Line. Further, ongoing efforts to evaluate Prohibited Species Catch (PSC) in non-target fisheries as well as the effect of shifting allocations among other sectors are not easily tractable in the context of annual harvest targets without a calculation that explicitly includes all sizes and sources of mortality.

Spatially explicit model development

There are several primary motivations for constructing a spatially explicit stock assessment model which include: 1) direct use of the NMFS Bering Sea trawl data which represents a long fishery-independent time-series index and age-distributions for young halibut from Area 4, 2) a better understanding of the historical and current biomass distribution among areas, and 3) direct estimates of potential selectivity and catchability differences among areas. These insights are very relevant to understanding the importance and spatial implications of current levels of directed fishery and bycatch removals, as well as the estimates of apportionment currently based on the setline survey.

Given the development of geographic area-specific weights-at-age during 2015, the extension from the datasets used for the AAF models to a fully spatial model required further partitioning of the bycatch, recreational and wastage removals by geographic area (as they are pooled in the AAF models). These processing steps were also completed during 2015. With the data complete, there are two key processes that must be informed in the parameterization of a spatially explicit assessment model: 1) the distribution of recruitments, and 2) the rates of movement (possibly by age) among regulatory areas. Because of the lag between recruitment and subsequent observation in the setline survey of directed fishery data, it is likely that estimation of juvenile migration vs. recruitment distribution among areas will be highly confounded. Unfortunately, neither of these quantities is well understood.

The NMFS Bering Sea trawl survey data represents a unique source of information on the abundance of halibut (especially those less than age-6) in Area 4, where the setline survey coverage is weakest. The age data from the NMFS trawl survey show a clear diagonal after 2006, apparently corresponding to relatively strong year-classes; the total numbers show a rapid increase in 2006 followed by a slow decline (Fig. 112; note that age data prior to 1998 are inferred from an age-length key from that year). There may be some information in these data (trends in the Bering Sea, as well as trends in the Gulf of Alaska) with which to estimate the rate of movement out of the Bering Sea and/or the fraction of the coastwide recruitment occurring in that area.

Current understanding of adult movement rates for most areas is reasonably well understood, based on extensive historical and more recent PIT tagging studies (Valero and Webster 2012). However, previous summary of these data has been conducted by specific regulatory area, and use in a spatially explicit model structured around geographic areas (2, 3, 4, and 4B) would require re-analysis, because values are not strictly additive from more detailed summary tables (e.g., Table 13). In addition, tag releases and recoveries in Area 4 were highly dominated by Area 4A, and it is unclear how well they might also represent halibut in the Bering Sea. Detailed analysis of these data was originally based on the length of the tagged halibut (Webster et al. 2013). In preliminary re-analyses of the PIT tagging data, Webster (2015) has begun to explore estimation these rates as a function of age. Preliminary results suggest movement-at-age estimates depend on the treatment of missing ages for fish that were measured when tagged but not recaptured. However, appreciable emigration is estimated to occur from areas in the western and central Gulf of Alaska, with the highest rates were observed for young halibut leaving Area 4A (Fig. 113). The PIT tagging data include very few halibut less than age-6.

For halibut less than age-6, most of the available data come from historical studies that used trawl gear (rather than longline gear) to capture fish for tagging (Valero and Webster 2012). Hilborn et al. (1995) used data from studies conducted in the 1980s to estimate movement parameters for juveniles among specific regulatory areas within geographic Areas 2 and 3 (Table 14). These data suggest relatively high rates of 'downstream' movement to the East and South. Similar results are unavailable for Area 4 or 4B, although raw recovery rates from juvenile halibut tagged in the Bering Sea and Aleutians suggest appreciable movement to all other regulatory areas over 5-10 years of life (Webster 2015b). The lack of data from Area 4 is particularly problematic, given that this is the area where the greatest abundance of 2-4 year old halibut are observed (Sadorus et al. 2015c), and therefore assumptions about movement rates will be most important.

Based on preliminary spatial model exploration conducted during 2015, a productive path forward may be to specify a fixed array of movement rates among areas based on re-analysis of tagging data outlined above, and making assumptions about likely values for Area 4 and 4B. This should allow estimation of the annual distribution of recruitment among areas. One impediment to initial development was that Stock Synthesis does not allow for estimated recruitment distribution-by-area (the partitioning of annual recruitment deviations into area-specific components) to extend into the initial age-structure. This requires a longer modelled time-series to achieve relatively unrestricted initial model conditions. Initial set-up of this model was done beginning the time-series in 1996; however, a longer time-series may be necessary. Extending the modelled time-series to include at least the entire NMFS Bering Sea trawl survey (1982-present; the 2014 age data will soon be available), and enough prior years of estimated recruitment distributions to populate the numbers-at age in 1982, would seem to be a reasonable compromise between the complexity required for a full time-series analysis and the potential loss of information and stability associated with a very short time-series.

Although it is possible that the NMFS trawl data as well as differences in trends and age-structure among areas could provide some diffuse information to update movement parameters, a spatially explicit model may ultimately represent a tool for hypothesis exploration, rather than a robust addition to the current ensemble of models used for annual risk-analysis.

Research priorities

Although a number of research tasks have been accomplished for 2015, many of the primary research priorities remain unchanged from previous assessments. These can be divided into three general categories: new information, existing information, modelling work.

Collection of new data:

1) Continued development of methods to estimate the sex-ratio of the commercial catch. Sampling of commercial fishery trips where fish have been voluntarily marked by fishermen at-sea is being undertaken during 2015 in tandem with the development of a genetic assay (based on SNPs) to precisely determine the sex of a dressed fish from a tissue sample. These

may lead to a relatively inexpensive method for collecting data from across the commercial fleet and a validation tool to understand the precision and accuracy of estimates collected in that fashion.

2) Better understanding of movement rates of adults and juveniles between the Bering Sea and other regulatory areas may improve our ability to model the stock in a spatially explicit context. This must be considered as a long-term priority which may require several avenues of research (e.g., potentially tagging, exploration of naturally occurring markers, etc.).
3) During 2015, the calibration study (last performed in 2006) to compare halibut catch rates by length for the NMFS Bering Sea trawl survey and the setline survey will be repeated. This will allow for reanalysis of the survey biomass and apportionment estimates for 2015 and for previous years. Exploration of survey index variance estimates that include calibration uncertainty be possible, although two observations is likely insufficient to develop a reliable variance component from this source.

Analysis and processing of existing data:

1) Planned collaboration between the IPHC, the NMFS North Pacific Observer Program and the North Pacific Region should improve the estimates of bycatch and length-frequency distributions by IPHC regulatory area in Alaskan waters.
2) Re-analysis of survey data prior to 1997 could yield improved variance estimates, especially if based on model-based estimators. Such an approach would also allow for propagation of uncertainty due to missing portions of regulatory areas occurring even in the current design (depth zones and small spatial areas not sampled annually).
3) There is a vast quantity of archived historical data that is currently inaccessible until organized, keypunched and formatted into the IPHC's database with appropriate meta-data. Particularly, the ability to reprocess all historical fishery landings, effort, and age samples would provide a much clearer (and more reproducible) perception of the historical period than current work using summarized information.
4) Reconstruction of historical estimates for discards in the recreational fisheries as well as personal use or subsistence harvest prior to 1991 would make these time-series more accurate, although the changes are likely to be relatively small when compared to the total removals in historical periods.

Modelling:

1) Continued development of alternative models, including an explicitly spatial model that may help to improve process understanding and/or better understand the role of spatial processes contributing to among-model uncertainty. At some point it may also be worthwhile to consider constructing and evaluating an assessment model with explicit time-varying growth and length-based processes for comparison.
2) Continued development and sensitivity testing of existing models to better understand factors such as: the tradeoffs between data-weighting and process error variability in catchability and selectivity, the estimability of the scale of male selectivity in the coastwide long and AAF models, domed-selectivity by area and period, treatment of the stock-recruitment relationship and environmental factors, as well as other technical aspects.

3) Weighting of the individual models included in the ensemble may be of increasing importance if estimated stock trends continue to diverge between coastwide and AAF approaches. Exploration of methods for less subjective weighting could be based on: prospective and retrospective statistics, fit to summary or aggregate data series, simulation performance, and other approaches.
4) Bayesian methods for may provide improved uncertainty estimates within the models contributing to the assessment ensemble.
5) Continue to explore methods for defining and including uncertainty in wastage and bycatch estimates in both the assessment and harvest policy calculations.
6) Continued integration of assessment data and modelling with ongoing development of the harvest policy and Management Strategy Evaluation process.

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Tables

Table 1. Setline survey numbers-per-unit-effort and estimated log(*SE*s); assumed values in italics.

	Area 2		Area 3		Area 4		Area 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1977	0.60	*0.105*	2.00	*0.062*	--	--	--	--	1.47	*0.113*
1978	0.80	*0.105*	1.30	*0.062*	--	--	--	--	1.11	*0.113*
1979	--	--	1.90	*0.062*	--	--	--	--	--	--
1980	1.20	*0.105*	2.50	*0.062*	--	--	--	--	2.01	*0.113*
1981	0.80	*0.105*	3.80	*0.062*	--	--	--	--	2.67	*0.113*
1982	1.84	*0.105*	3.80	*0.062*	--	--	--	--	2.87	*0.113*
1983	2.30	*0.105*	3.40	*0.062*	--	--	--	--	2.88	*0.113*
1984	6.74	*0.105*	11.60	*0.062*	--	--	--	--	9.30	*0.113*
1985	5.65	*0.105*	11.90	*0.062*	--	--	--	--	8.94	*0.113*
1986	4.54	*0.105*	7.80	*0.062*	--	--	--	--	6.26	*0.113*
1993	5.10	*0.105*	14.50	*0.062*	--	--	--	--	--	--
1994	--	--	15.50	*0.062*	--	--	--	--	--	--
1995	5.46	*0.105*	17.74	*0.062*	--	--	--	--	--	--
1996	7.35	*0.105*	17.59	0.035	--	--	--	--	12.89	*0.113*
1997	8.15	0.061	21.72	0.035	2.68	0.088	12.17	0.093	7.78	*0.056*
1998	5.51	*0.105*	19.28	0.029	2.94	0.081	10.68	0.092	6.97	*0.056*
1999	5.43	0.058	17.93	0.026	2.32	0.086	9.59	0.099	6.26	*0.056*
2000	5.58	*0.105*	19.14	0.030	2.47	0.076	9.77	0.075	6.63	*0.056*
2001	6.47	0.063	17.89	0.034	2.39	0.078	8.08	0.101	6.38	0.028
2002	5.79	0.055	19.76	0.031	2.22	0.076	4.75	0.097	6.39	0.026
2003	5.42	0.054	17.89	0.033	1.97	0.079	4.33	0.098	5.79	0.027
2004	5.90	0.053	21.04	0.028	1.99	0.089	3.49	0.098	6.46	0.026
2005	5.61	0.056	19.59	0.033	1.63	0.084	3.78	0.086	5.93	0.027
2006	5.20	0.056	17.38	0.032	1.59	0.082	4.39	0.109	5.43	0.027
2007	5.38	0.054	18.73	0.031	1.55	0.089	4.87	0.114	5.73	0.027
2008	6.12	0.050	16.55	0.031	1.94	0.075	5.16	0.126	5.65	0.026
2009	6.18	0.048	15.07	0.031	2.14	0.083	5.26	0.096	5.50	0.027
2010	6.17	0.055	14.12	0.033	1.95	0.091	3.90	0.109	5.12	0.029
2011	5.44	0.049	14.65	0.030	1.83	0.100	3.94	0.101	5.04	0.029
2012	6.85	0.044	15.26	0.029	2.18	0.099	3.33	0.129	5.56	0.030
2013	6.47	0.044	12.01	0.030	1.86	0.122	4.69	0.109	4.73	0.034
2014	6.90	0.042	13.66	0.026	1.97	0.117	4.07	0.125	5.16	0.032

Table 2. Commercial fishery weight-per-unit-effort and estimated log(*SE*s); assumed values in italics.

	Area 2		Area 3		Area 4		Area 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1907	280.00	*0.100*	--	--	--	--	--	--	280.00	*0.100*
1910	271.00	*0.100*	--	--	--	--	--	--	271.00	*0.100*
1911	237.00	*0.100*	--	--	--	--	--	--	237.00	*0.100*
1912	176.00	*0.100*	--	--	--	--	--	--	176.00	*0.100*
1913	128.94	*0.100*	--	--	--	--	--	--	129.00	*0.100*
1914	124.13	*0.100*	--	--	--	--	--	--	124.00	*0.100*
1915	118.02	*0.100*	266.10	0.100	--	--	--	--	118.00	*0.100*
1916	114.60	*0.100*	202.80	0.100	--	--	--	--	137.00	*0.100*
1917	81.80	*0.100*	157.90	0.100	--	--	--	--	98.00	*0.100*
1918	87.50	*0.100*	125.40	0.100	--	--	--	--	96.00	*0.100*
1919	82.30	*0.100*	129.90	0.100	--	--	--	--	93.00	*0.100*
1920	84.10	*0.100*	147.90	0.100	--	--	--	--	96.00	*0.100*
1921	76.46	*0.100*	141.17	0.100	--	--	--	--	88.00	*0.100*
1922	62.44	*0.100*	133.79	0.100	--	--	--	--	73.00	*0.100*
1923	56.68	*0.100*	149.97	0.100	--	--	--	--	78.00	*0.100*
1924	55.39	*0.100*	109.13	0.100	--	--	--	--	74.00	*0.100*
1925	51.21	*0.100*	94.63	0.100	--	--	--	--	68.00	*0.100*
1926	51.67	*0.100*	93.73	0.100	--	--	--	--	67.00	*0.100*
1927	48.83	*0.100*	86.32	0.100	--	--	--	--	65.00	*0.100*
1928	47.27	*0.100*	72.34	0.100	--	--	--	--	58.00	*0.100*
1929	38.55	*0.100*	70.79	0.100	--	--	--	--	51.00	*0.100*
1930	34.44	*0.100*	65.91	0.100	--	--	--	--	46.00	*0.100*
1931	38.48	*0.100*	76.17	0.100	--	--	--	--	50.00	*0.100*
1932	47.50	*0.100*	83.49	0.100	--	--	--	--	60.00	*0.100*
1933	50.16	*0.100*	83.99	0.100	--	--	--	--	63.00	*0.100*
1934	54.07	*0.100*	74.97	0.100	--	--	--	--	62.00	*0.100*
1935	61.77	*0.100*	97.57	0.100	--	--	--	--	76.00	*0.100*
1936	54.66	*0.100*	96.70	0.100	--	--	--	--	71.00	*0.100*
1937	61.48	*0.100*	109.99	0.100	--	--	--	--	80.00	*0.100*
1938	70.33	*0.100*	114.29	0.100	--	--	--	--	88.00	*0.100*
1939	61.90	*0.100*	112.21	0.100	--	--	--	--	80.00	*0.100*
1940	61.71	*0.100*	116.38	0.100	--	--	--	--	81.00	*0.100*
1941	62.54	*0.100*	122.26	0.100	--	--	--	--	85.00	*0.100*
1942	65.43	*0.100*	132.54	0.100	--	--	--	--	90.00	*0.100*
1943	72.24	*0.100*	131.27	0.100	--	--	--	--	95.00	*0.100*
1944	86.84	*0.100*	149.23	0.100	--	--	--	--	110.00	*0.100*
1945	79.69	*0.100*	130.86	0.100	--	--	--	--	102.00	*0.100*
1946	83.78	*0.100*	123.82	0.100	--	--	--	--	101.00	*0.100*
1947	86.30	*0.100*	114.56	0.100	--	--	--	--	99.00	*0.100*
1948	88.61	*0.100*	112.20	0.100	--	--	--	--	99.00	*0.100*
1949	85.01	*0.100*	105.89	0.100	--	--	--	--	95.00	*0.100*

Table 2 continued. Commercial fishery weight-per-unit-effort and estimated log(*SE*s); assumed values in italics.

	Area 2		Area 3		Area 4		Area 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1950	87.66	*0.100*	103.60	*0.100*	--	--	--	--	95.00	*0.100*
1951	87.63	*0.100*	108.93	*0.100*	--	--	--	--	96.00	*0.100*
1952	95.58	*0.100*	128.86	*0.100*	--	--	--	--	110.00	*0.100*
1953	128.65	*0.100*	134.32	*0.100*	--	--	--	--	131.00	*0.100*
1954	137.97	*0.100*	127.43	*0.100*	--	--	--	--	133.00	*0.100*
1955	122.20	*0.100*	116.32	*0.100*	--	--	--	--	119.00	*0.100*
1956	132.02	*0.100*	126.05	*0.100*	--	--	--	--	129.00	*0.100*
1957	100.95	*0.100*	119.84	*0.100*	--	--	--	--	110.00	*0.100*
1958	101.96	*0.100*	139.96	*0.100*	--	--	--	--	121.00	*0.100*
1959	98.67	*0.100*	160.62	*0.100*	--	--	--	--	129.00	*0.100*
1960	105.02	*0.100*	156.08	*0.100*	--	--	--	--	132.00	*0.100*
1961	96.00	*0.100*	159.79	*0.100*	--	--	--	--	127.00	*0.100*
1962	84.76	*0.100*	136.89	*0.100*	--	--	--	--	115.00	*0.100*
1963	77.73	*0.100*	123.89	*0.100*	--	--	--	--	105.00	*0.100*
1964	75.27	*0.100*	120.10	*0.100*	--	--	--	--	100.00	*0.100*
1965	86.47	*0.100*	107.07	*0.100*	--	--	--	--	99.00	*0.100*
1966	82.59	*0.100*	112.72	*0.100*	--	--	--	--	100.00	*0.100*
1967	81.44	*0.100*	113.00	*0.100*	--	--	--	--	101.00	*0.100*
1968	86.58	*0.100*	111.62	*0.100*	--	--	--	--	103.00	*0.100*
1969	81.53	*0.100*	105.07	*0.100*	--	--	--	--	95.00	*0.100*
1970	73.62	*0.100*	103.67	*0.100*	--	--	--	--	91.00	*0.100*
1971	76.05	*0.100*	96.31	*0.100*	--	--	--	--	89.00	*0.100*
1972	69.47	*0.100*	82.87	*0.100*	--	--	--	--	78.00	*0.100*
1973	64.41	*0.100*	62.13	*0.100*	--	--	--	--	63.00	*0.100*
1974	60.96	*0.100*	61.95	*0.100*	--	--	--	--	61.00	*0.100*
1975	61.97	*0.100*	66.76	*0.100*	--	--	--	--	61.00	*0.100*
1976	44.78	*0.100*	61.91	*0.100*	--	--	--	--	55.00	*0.100*
1977	63.52	*0.100*	65.57	*0.100*	--	--	--	--	63.00	*0.100*
1978	54.57	*0.100*	68.47	*0.100*	--	--	--	--	71.00	*0.100*
1979	55.99	*0.100*	67.32	*0.100*	--	--	--	--	75.00	*0.100*
1980	60.31	*0.100*	116.09	*0.100*	--	--	--	--	94.00	*0.100*
1981	75.23	*0.100*	148.86	*0.100*	137.29	*0.100*	99.00	0.078	111.00	*0.100*
1982	73.54	*0.100*	181.34	*0.100*	97.82	*0.100*	--	--	127.00	*0.100*
1984	154.98	0.045	491.33	0.046	350.32	*0.100*	161.00	0.103	291.00	*0.100*
1985	164.97	0.049	535.07	0.039	441.41	0.103	234.00	0.160	355.00	0.034
1986	140.05	0.035	506.00	0.042	325.79	0.059	238.00	0.372	318.00	0.041
1987	138.34	0.027	490.38	0.036	353.58	0.162	220.00	0.111	319.00	0.041
1988	169.56	0.052	560.55	0.042	405.71	0.105	224.00	0.122	367.00	0.035
1989	156.34	0.040	507.69	0.031	379.27	0.080	268.00	0.094	357.00	0.025
1990	195.54	0.041	403.55	0.036	362.96	0.097	209.00	0.103	318.00	0.028
1991	171.04	0.037	375.03	0.041	365.91	0.157	329.00	0.085	317.00	0.038

Table 2 continued. Commercial fishery weight-per-unit-effort and estimated log(*SE*s); assumed values in italics.

	Area 2		Area 3		Area 4		Area 4B		Coastwide	
Year	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)	Index	log(SE)
1992	169.38	0.038	413.39	0.048	324.04	0.117	280.00	0.095	318.00	0.035
1993	201.84	0.029	439.12	0.096	400.32	0.447	218.00	0.220	372.00	0.099
1994	178.56	0.026	362.77	0.049	343.23	0.333	197.00	0.101	305.00	0.072
1995	193.28	0.025	439.49	0.043	330.24	0.100	189.00	0.336	329.00	0.036
1996	210.51	0.039	505.02	0.046	427.64	0.138	269.00	0.185	391.00	0.038
1997	237.91	0.033	498.02	0.026	432.98	0.103	275.00	0.064	403.00	0.025
1998	222.15	0.027	512.60	0.036	433.56	0.084	287.00	0.058	406.00	0.025
1999	246.32	0.074	475.50	0.024	406.93	0.058	310.00	0.045	392.00	0.023
2000	228.89	0.034	494.84	0.026	415.91	0.082	320.00	0.048	401.00	0.022
2001	203.93	0.036	454.52	0.029	365.53	0.212	270.00	0.076	361.00	0.042
2002	215.97	0.030	466.46	0.025	303.98	0.080	245.00	0.081	359.00	0.019
2003	210.18	0.018	439.26	0.024	254.87	0.071	196.00	0.068	328.00	0.018
2004	194.58	0.027	425.78	0.026	242.63	0.070	202.00	0.061	318.00	0.019
2005	180.41	0.022	387.69	0.023	219.65	0.063	238.00	0.093	296.00	0.017
2006	181.05	0.023	360.69	0.022	174.23	0.066	218.00	0.111	269.00	0.019
2007	160.26	0.021	344.26	0.026	150.21	0.057	230.00	0.108	251.00	0.020
2008	141.22	0.019	318.16	0.024	162.58	0.071	193.00	0.069	232.00	0.017
2009	154.83	0.019	277.22	0.020	175.29	0.054	189.00	0.097	222.00	0.018
2010	186.45	0.035	242.31	0.024	141.55	0.081	142.00	0.063	203.00	0.020
2011	182.96	0.019	226.64	0.025	141.25	0.057	165.00	0.103	197.00	0.015
2012	197.09	0.019	213.45	0.032	136.07	0.081	149.00	0.066	194.00	0.021
2013	195.61	0.024	189.98	0.033	117.43	0.075	127.00	0.064	179.00	0.017
2014	222.36	*0.057*	180.07	*0.089*	104.56	*0.183*	168.00	*0.182*	185.00	*0.049*

Table 3. Number of sampling stations contributing to survey age data.

Year	Area 2	Area 3	Area 4	Area 4B	Coastwide
1963	--	236	--	--	236
1964	--	305	--	--	305
1965	121	146	--	--	267
1966	66	--	--	--	66
1977	58	100	--	--	158
1978	62	98	--	--	160
1979	--	104	--	--	104
1980	80	101	--	--	181
1981	72	102	--	--	174
1982	154	148	--	--	302
1983	192	101	--	--	293
1984	241	198	--	--	439
1985	166	103	--	--	269
1986	178	97	--	--	275
1988	72	--	--	--	72
1989	--	33	--	--	33
1993	66	70	--	--	136
1994	--	147	--	--	147
1995	103	120	--	--	223
1996	188	424	--	--	612
1997	200	429	221	74	924
1998	217	507	100	42	866
1999	320	556	61	82	1019
2000	229	553	153	83	1018
2001	322	522	148	83	1075
2002	300	558	154	82	1094
2003	312	518	153	82	1065
2004	319	527	148	71	1065
2005	329	509	152	83	1073
2006	310	529	181	84	1104
2007	317	540	181	74	1112
2008	326	552	184	76	1138
2009	325	559	179	84	1147
2010	324	533	182	78	1117
2011	348	554	172	79	1153
2012	349	524	174	72	1119
2013	357	537	170	80	1144
2014	367	567	241	77	1252

Table 4. Number of sampled trips contributing to fishery age data (inputs assumed for unknown values in italics).

Year	Area 2	Area 3	Area 4	Area 4B	Coastwide
1935	*50*	*50*	--	--	*100*
1936	*50*	*50*	--	--	*100*
1937	*50*	*50*	--	--	*100*
1938	*50*	*50*	--	--	*100*
1939	*50*	*50*	--	--	*100*
1940	*50*	*50*	--	--	*100*
1941	*50*	*50*	--	--	*100*
1942	*50*	*50*	--	--	*100*
1943	*50*	*50*	--	--	*100*
1944	*50*	*50*	--	--	*100*
1945	*50*	*50*	*5*	--	*100*
1946	*50*	*50*	*5*	--	*100*
1947	*50*	*50*	*5*	--	*100*
1948	*50*	*50*	*5*	--	*100*
1949	*50*	*50*	*5*	--	*100*
1950	*50*	*50*	*5*	--	*100*
1951	*50*	*50*	*5*	--	*100*
1952	*50*	*50*	*5*	--	*100*
1953	*50*	*50*	*5*	--	*100*
1954	*50*	*50*	*5*	--	*100*
1955	*50*	*50*	*5*	--	*100*
1956	*50*	*50*	*5*	--	*100*
1957	*50*	*50*	*5*	--	*100*
1958	*50*	*50*	*5*	--	*100*
1959	*50*	*50*	*5*	--	*100*
1960	*50*	*50*	*5*	--	*100*
1961	*50*	*50*	*5*	--	*100*
1962	*50*	*50*	*5*	--	*100*
1963	*50*	*50*	*5*	--	*100*
1964	116	100	14	--	230
1965	118	106	12	--	238
1966	102	113	12	--	228
1967	125	133	20	--	278
1968	135	132	14	--	282
1969	113	102	12	--	227
1970	97	125	18	--	241
1971	82	77	9	--	168
1972	552	196	3	--	752
1973	311	262	5	--	578

Table 4 continued. Number of sampled trips contributing to fishery age data (inputs assumed for unknown values in italics).

Year	Area 2	Area 3	Area 4	Area 4B	Coastwide
1974	153	68	3	--	226
1975	234	76	7	--	320
1976	332	135	7	--	476
1977	247	138	7	--	401
1978	241	120	4	--	377
1979	125	101	6	--	244
1980	140	113	1	--	262
1981	146	90	7	--	248
1982	168	137	11	--	316
1983	133	106	23	--	268
1984	170	90	9	--	282
1985	171	99	14	--	286
1986	158	152	34	--	345
1987	531	498	76	--	1117
1988	278	258	19	--	571
1989	318	371	39	--	752
1990	491	560	50	--	1104
1991	718	496	62	12	1288
1992	1027	478	61	20	1586
1993	959	471	65	11	1506
1994	896	474	89	31	1490
1995	887	468	72	37	1464
1996	859	437	76	27	1399
1997	676	429	183	58	1346
1998	515	277	127	47	966
1999	454	303	118	24	899
2000	512	358	119	27	1016
2001	505	233	117	13	868
2002	561	284	163	53	1061
2003	545	266	118	49	978
2004	491	200	75	9	775
2005	461	193	125	13	792
2006	483	256	81	22	842
2007	429	218	95	12	754
2008	385	221	98	11	715
2009	432	240	68	14	754
2010	354	260	97	25	736
2011	381	224	83	14	702
2012	421	217	81	13	732
2013	459	196	73	14	742
2014	435	221	64	8	728

Table 5. General overview of each assessment model.

	Model			
	Coastwide Short	Coastwide Long	AAF Short	AAF Long
Modelled period*	1996-2015	1888-2015	1996-2015	1888-2015
Data partitions	N/A	N/A	Area 2, 3, 4ACDE, 4B	Area 2, 3, 4ACDE, 4B
Directed Fishery fleets	1	1	4	4
Other fishing fleets	4	4	4	4
Survey fleets	1	1	4	4
Fishery CPUE (weight)	1996+	1907+	1996+	1907+, 1915+, 1981+, 1981+
Fishery age data years	1996+	1935+	1996+	1935+, 1935+, 1945+, 1991+
Survey CPUE (numbers)	1997+	1997+	1996+, 1996+, 1997+, 1997+	1977+, 1977+, 1997+, 1997+
Survey age data years	1997+	1963+	1996+, 1996+, 1997+, 1997+	1965+, 1963+, 1997+, 1997+
Weight-at-age	Aggregate	Aggregate	Areas 2, 3, 4	Areas 2, 3, 4
Female M	Fixed at 0.15	Estimated	Fixed at 0.15	Estimated
Male M	Estimated	Estimated	Estimated	Estimated
Stock-recruit relationship	No	B-H	No	B-H
Initial conditions estimated	R_1, *N*-at-age: 1-19	R_0	R_1, *N*-at-age: 1-19	R_0
Environmental regime effects on recruitment	No	Yes	No	Yes
Steepness (*h*)	0.75	0.75	0.75	0.75
$\sigma_{\text{recruitment deviations}}$	0.9	0.6	0.75	0.55
Selectivity (fishery and survey)	Asymptotic	Asymptotic	Domed (A2, A3), Asymptotic (A4, A4B)	Domed (A2, A3), Asymptotic (A4, A4B)
Scale of male fishery selectivity	Estimated	Fixed = survey	Fixed = survey, by area	Fixed = survey, by area
Bycatch selectivity	Domed	Domed	Domed	Domed
Sport selectivity	Domed	Domed	Domed	Domed
Wastage selectivity	Domed, by sex	Domed, by sex	Domed, by sex	Domed, by sex
Personal use selectivity	Mirrored to sport	Mirrored to sport	Mirrored to sport	Mirrored to sport

*Preliminary removals for 2015 are projected based on the final adopted catch limits.

Table 6. Counts of estimated parameters in each assessment model.

	Model			
	Coastwide Short	Coastwide Long	AAF Short	AAF Long
Static				
Female *M*	--	1	--	1
Male *M*	1	1	1	1
Log(R_0)	1	1	1	1
R_1 offset	1	--	1	--
Environmental link coefficient	--	1	--	1
Fishery catchability	1	2	4	7
Fishery selectivity	5	4	10	10
Wastage selectivity	7	7	7	7
Bycatch selectivity	4	4	4	4
Sport selectivity	4	4	4	4
Survey catchability	--	4	--	4
Survey selectivity	5	5	21	21
Total static	29	34	53	61
Time-varying				
Recruitment deviations[1]	43	161	43	161
Fishery catchability deviations	18	103	72	262
Fishery selectivity deviations	54	158	144	500
Survey selectivity deviations	51	76	140	268
Total deviations	166	498	399	1,191
Total	195	532	452	1,252

[1] Recruitment deviations include estimated numbers-at-ages 1-19 in the first year of the short time-series models, as these are implemented as recruitments depreciated to each age via natural mortality. In addition, recruitment deviations for three projection years are also included in the totals.

Table 7. Sample size diagnostics for age composition data by model and model fleet.

	Average input	Harmonic mean effective	Francis weight (multipier)
Coastwide short			
Fishery	88	403	0.99
Discards	6	274	30.39
Bycatch	5	67	9.79
Sport	5	108	10.80
Survey	325	962	1.20
Coastwide long			
Fishery	95	357	1.58
Discards	6	244	24.83
Bycatch	5	27	1.15
Sport	5	127	6.02
Survey	94	191	0.88
AAF short			
Area 2 Fishery	320	590	1.49
Area 3 Fishery	159	322	0.28
Area 4 Fishery	52	65	1.13
Area 4B Fishery	24	102	2.86
Discards	6	231	20.44
Bycatch	5	48	13.24
Sport	5	116	4.53
Area 2 Survey	242	457	0.49
Area 3 Survey	210	516	0.21
Area 4 Survey	90	192	0.81
Area 4B Survey	31	132	0.64
AAF long			
Area 2 Fishery	145	254	2.07
Area 3 Fishery	83	243	0.64
Area 4 Fishery	16	42	1.73
Area 4B Fishery	19	90	2.55
Discards	6	244	19.38
Bycatch	5	29	1.54
Sport	5	105	4.30
Area 2 Survey	134	221	0.48
Area 3 Survey	102	131	0.28
Area 4 Survey	90	191	0.66
Area 4B Survey	31	131	0.52

Table 8. Select parameter estimates (final value and approximate 95% confidence interval) from each assessment model.

	Model			
	Coastwide Short	Coastwide Long	AAF Short	AAF Long
Biological				
Female M	0.15 (Fixed)	0.202 (0.178-0.225)	0.15 (Fixed)	0.148 (0.126-0.170)
Male M	0.138 (0.126-0.149)	0.156 (0.139-0.173)	0.129 (0.121-0.138)	0.129 (0.114-0.144)
Log(R_0)*	9.42 (9.11-9.74)	10.75 (10.50-11.00)	9.92 (9.65-10.20)	10.11 (9.84-10.39)
R_1 offset	-0.350 (-0.604--0.095)	NA	-0.253 (-0.466--0.040)	NA
Env. Link (β)	NA	0.308 (-0.033-0.649)	NA	0.522 (0.224-0.820)
Survey Log(q) Δ1984	NA	0.85 (0.54-1.15)	NA	*A2:*0.74 (0.56-0.92) *A3:*1.43 (1.25-1.61)
Fishery Log(q) Δ1984	NA	0.52 (0.36-0.68)	NA	*A2:0.50 (0.31-0.68) A3:1.07 (0.94-1.20) A4:0.70 (0.50-0.90)* *A4B:*0.37 (0.18-0.56)

* Log(R_0) values are not comparable for the two short time-series models as there is no constraint that this represent the central tendency of the S-R function at equilibrium. S-R related calculations were performed externally to these models.

Table 9. Qualitative sensitivity ranking of halibut wastage and bycatch estimates to sources of uncertainty, as well as the scale of the removals relative to total removals from the stock (magnitude).

Source	DMR (process)	Observer coverage (sampling)	Potential bias (non-sampling)	Magnitude
Wastage				
Alaska	High	High	High	Moderate
Canada	High	Low	NA	Low
Area 2A	High	NA	High	Low
Bycatch				
Bering Sea trawl	Low	Low	Low	High
Bering Sea H&L	High	Low	Low	Moderate
Gulf of Alaska trawl	Low	High	High	High
Gulf of Alaska H&L	High	High	High	Moderate
Canada trawl	Low	Low	NA	Low
Area 2A trawl	Low	Low	NA	Low
Area 2A H&L	High	Moderate	Moderate	Low

Table 10. Summary of individual model and integrated distributions for 2016 spawning biomass (millions pounds).

Models	Percentile 2.5%	50%	97.5%
Coastwide Long	131.2	182.1	233.0
Coastwide Short	145.6	185.3	225.0
AAF Long	198.4	240.8	283.2
AAF Short	231.5	278.0	324.4
Integrated distribution (equal weighting 1:1:1:1)	144.9	217.4	308.5

Table 11. Median integrated population (Mlb) and fishing intensity estimates (based on median Spawning Potential Ratio) from the 2014 and preliminary 2015 assessments.

	2014 results			2015 results		
Year	Spawning biomass	Fishing intensity ($F_{XX\%}$)	Exploitable biomass	Spawning biomass	Fishing intensity ($F_{XX\%}$)	Exploit-able biomass
1996	584.6	49%	779.2	483.8	47%	655.1
1997	605.7	43%	809.6	520.3	42%	708.0
1998	591.8	42%	762.7	512.8	40%	668.1
1999	567.1	40%	746.8	496.9	38%	662.0
2000	529.5	40%	688.3	468.4	37%	614.4
2001	483.9	38%	603.0	432.4	35%	540.7
2002	434.5	34%	532.2	391.4	32%	477.6
2003	382.6	30%	460.5	346.3	29%	415.0
2004	339.5	28%	403.6	309.2	26%	365.3
2005	299.5	26%	352.6	275.4	25%	321.8
2006	266.7	26%	307.9	248.0	25%	283.2
2007	241.5	25%	266.9	227.5	25%	248.3
2008	224.4	25%	236.3	213.9	25%	222.1
2009	204.6	26%	203.9	196.5	26%	193.7
2010	197.8	27%	186.4	190.1	26%	177.8
2011	195.3	31%	175.6	188.2	31%	168.2
2012	197.2	35%	169.2	190.5	36%	163.3
2013	203.9	38%	168.8	197.4	39%	163.9
2014	208.5	43%	169.7	202.7	44%	165.7
2015	215.1	NA	180.6	209.6	51%	176.6
2016	NA	NA	NA	217.4	NA	187.4

Table 12. Decision table framework for the integrated model results.

				Stock Trend				Stock Status				Fishery Trend				Fishery Status
				Spawning biomass				Spawning biomass				Fishery CEY from the harvest policy				Harvest rate
				in 2017		in 2019		in 2017		in 2019		in 2017		in 2019		in 2016
2016	Total removals (M lb)	Fishery CEY (M lb)	Fishing intensity	is less than 2016	is 5% less than 2016	is less than 2016	is 5% less than 2016	is less than 30%	is less than 20%	is less than 30%	is less than 20%	is less than 2016	is 10% less than 2016	is less than 2016	is 10% less than 2016	is above target
No removals	0.0	0.0	0.0%													
FCEY = 0		0.0														
Blue Line																
				a	b	c	d	e	f	g	h	i	j	k	l	m

Table 13. Movement rates for halibut in the IPHC's PIT tagging study; reproduced from Valero and Webster (2012; Table 14).

Area in	Area in year i+1							
year i	4D	4B	4A	3B	3A	2C	2B	2A
4D	**0.924**	0.000	0.062	0.000	0.003	0.001	0.010	0.000
4B	0.002	**0.967**	0.000	0.000	0.021	0.005	0.005	0.000
4A	0.000	0.014	**0.792**	0.053	0.097	0.016	0.025	0.003
3B	0.000	0.000	0.003	**0.887**	0.101	0.005	0.004	0.000
3A	0.000	0.000	0.000	0.046	**0.947**	0.003	0.003	0.000
2C	0.000	0.000	0.000	0.000	0.024	**0.898**	0.067	0.012
2B	0.000	0.000	0.004	0.000	0.004	0.009	**0.970**	0.014
2A	0.000	0.000	0.000	0.000	0.000	0.008	0.110	**0.882**

Table 14. Movement rates estimated for juvenile halibut in Areas 2 and 3; reproduced from Hilborn et al. (1995; Table 14).

Movement parameters(m_{ij}):

	3B	3A	2C	2B	2A
3B	0.708				
3A	0.231	0.894			
2C	0.061	0.080	0.698		
2B		0.026	0.302	0.942	
2A				0.058	1.000

Figures

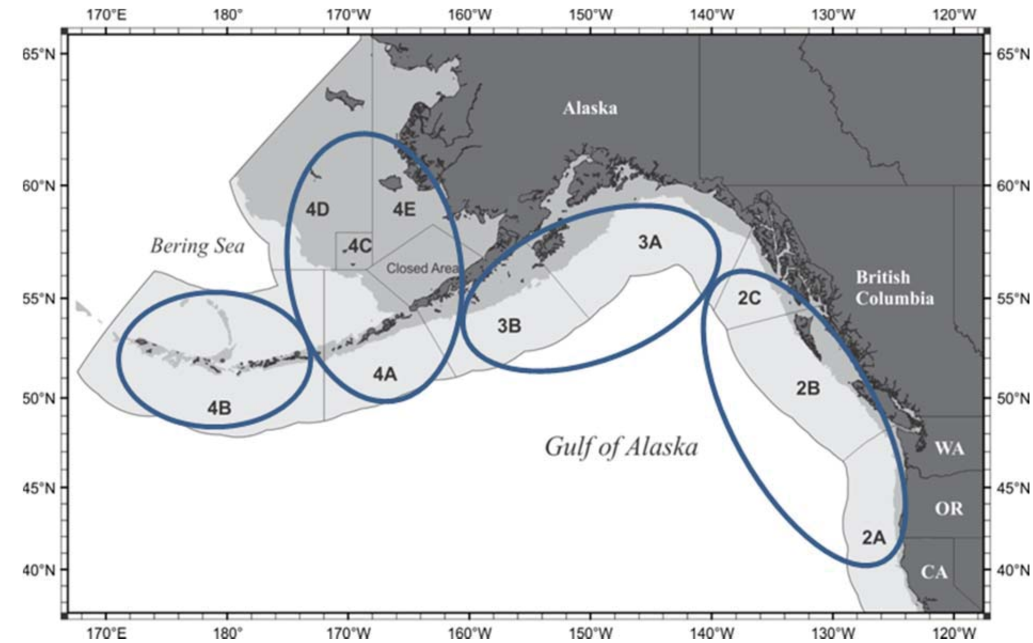


Figure 1. Current IPHC regulatory areas. Shaded region denotes the Exclusive Economic Zones of the U.S. and Canada. Circles denote aggregated geographic areas (2, 3, 4, and 4B) used to partition the data in the AAF models.

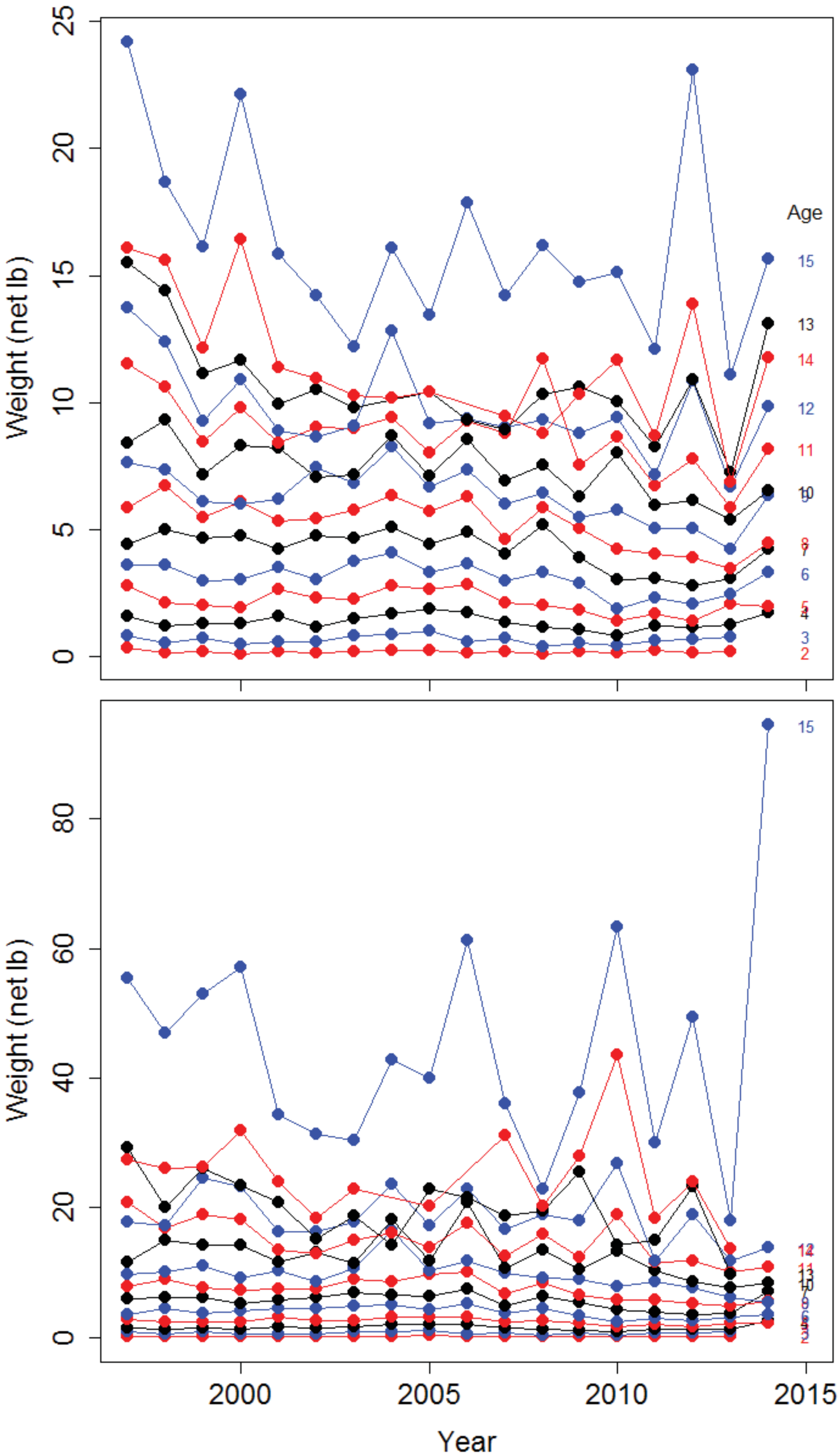


Figure 2. Raw average weight-at-age for male (upper panel) and female (lower panel) halibut, age 2-15+, caught by NMFS trawl surveys from 1997- 2014 (2014 was in the process of being finalized, and contained only a very small number of samples).

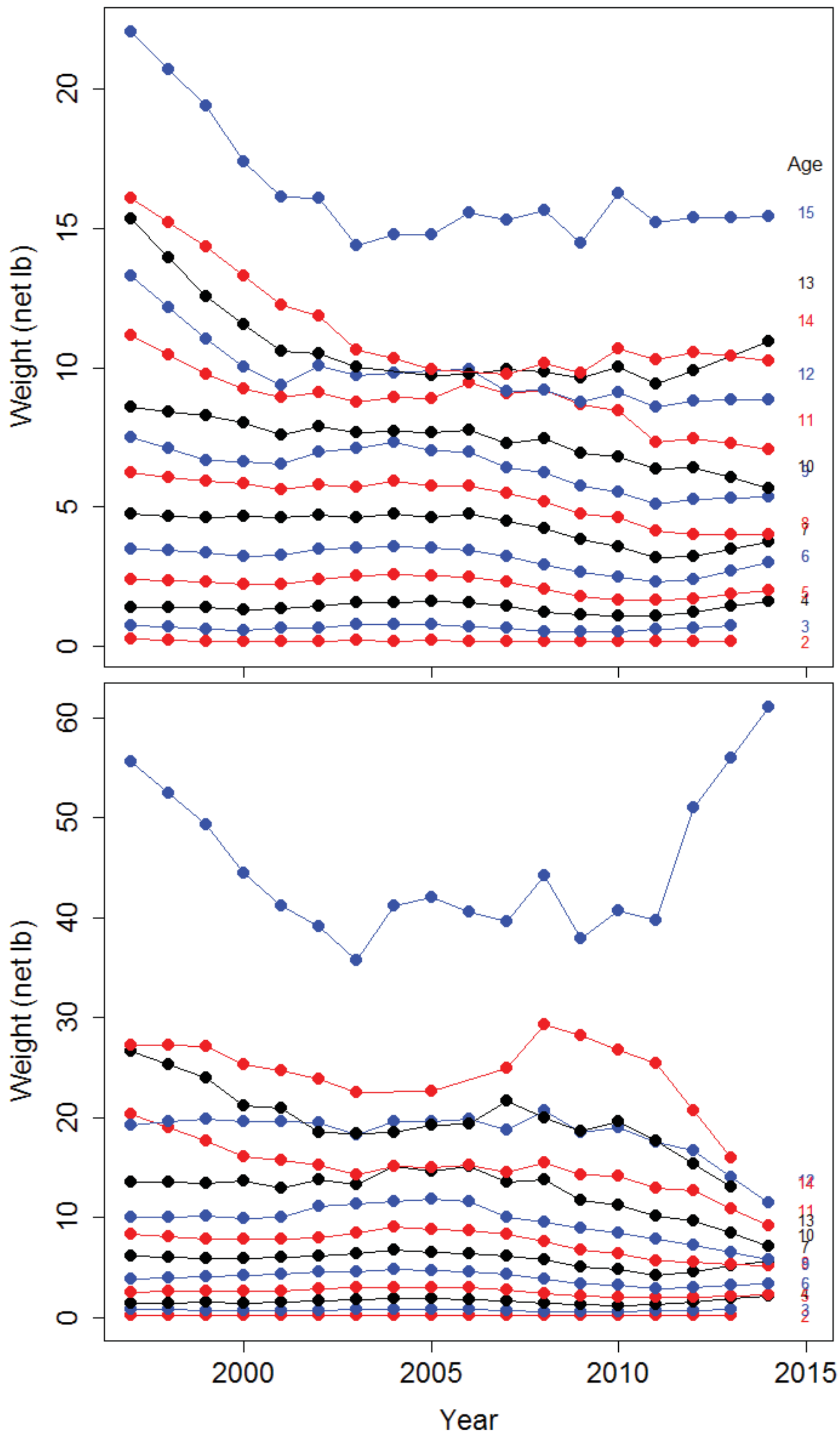


Figure 3. Smoothed average weight-at-age for male (upper panel) and female (lower panel) halibut, age 2-15+, caught by NMFS trawl surveys from 1997- 2014 (2014 was in the process of being finalized, and contained only a very small number of samples).

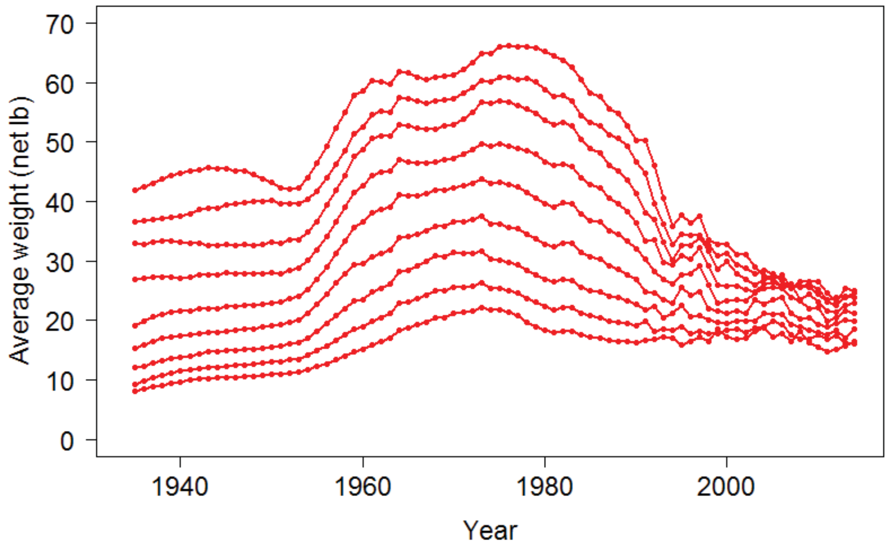


Figure 4. Estimated coastwide trends in weight at age for ages 8-16 from 1935-2014.

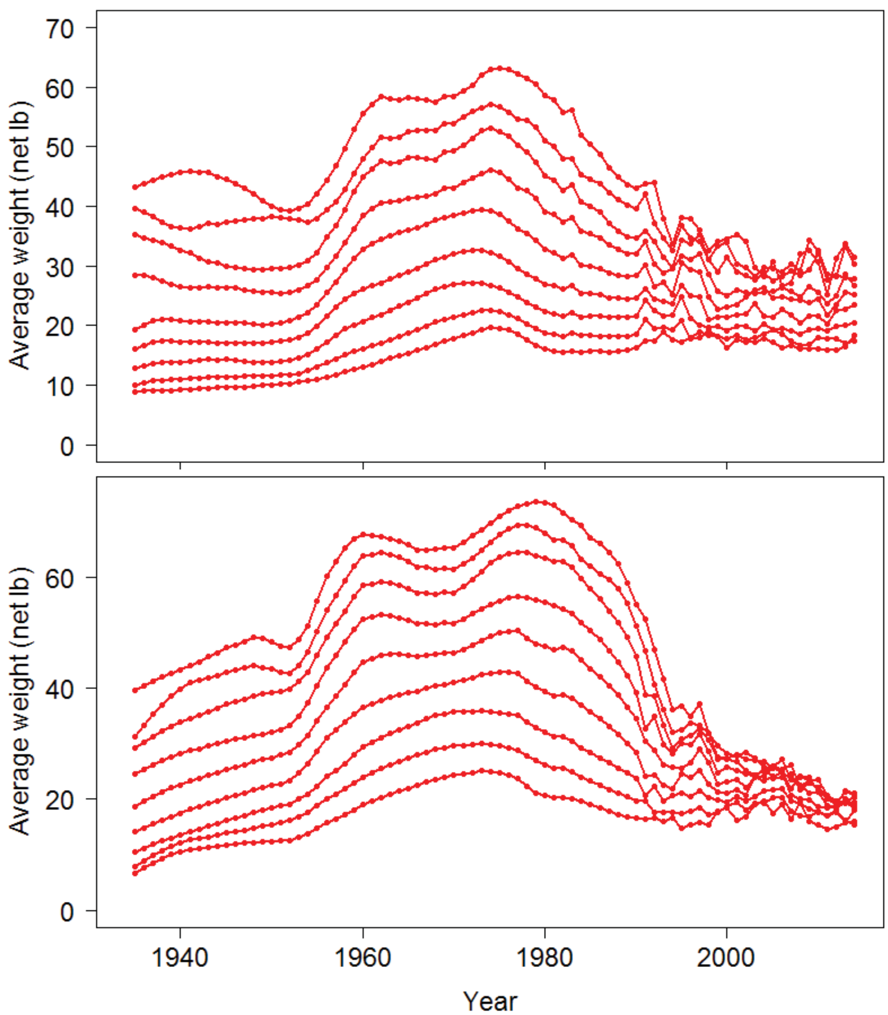


Figure 5. Estimated trends in weight at age for ages 8-16 for Area 2 (top) and Area 3 (bottom) from 1935-2014.

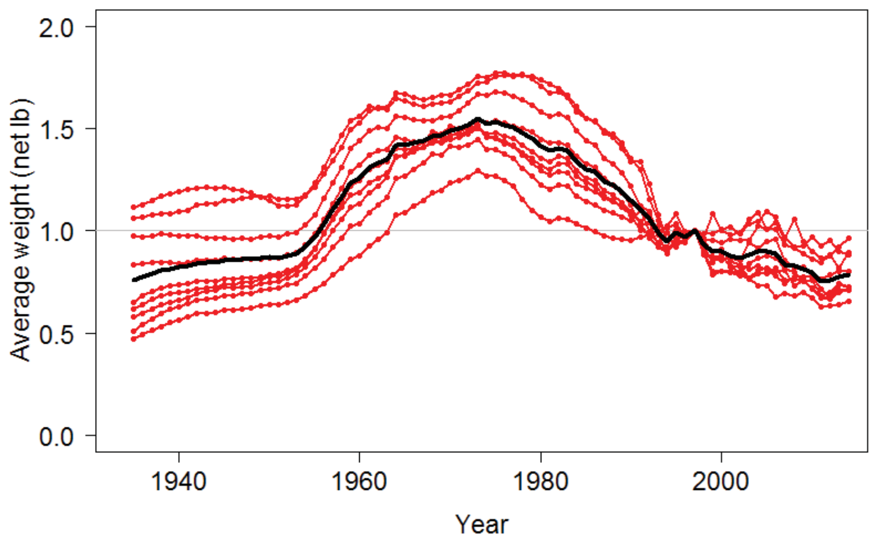


Figure 6. Estimated coastwide relative trends in weight at age for ages 8-16 (relative to 1997) from 1935-2014.

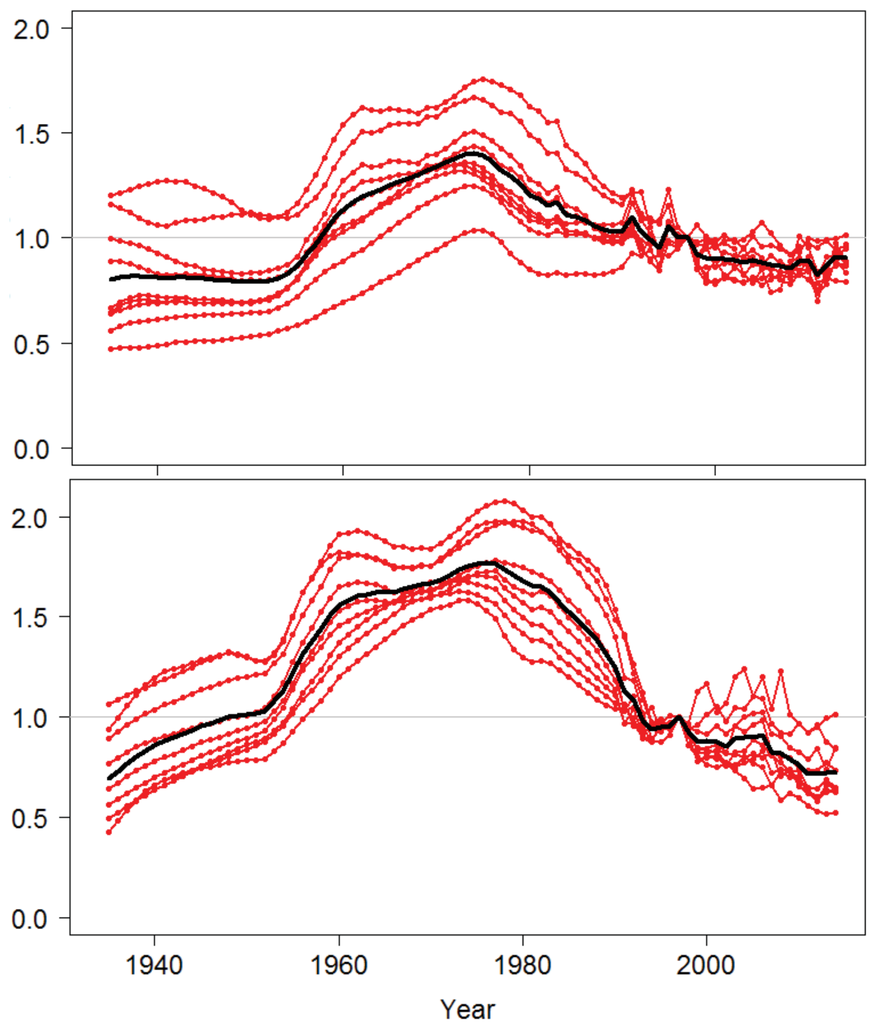


Figure 7. Estimated relative trends in weight at age for ages 8-16 (relative to 1997) for Area 2 (top) and Area 3 (bottom) from 1935-2014.

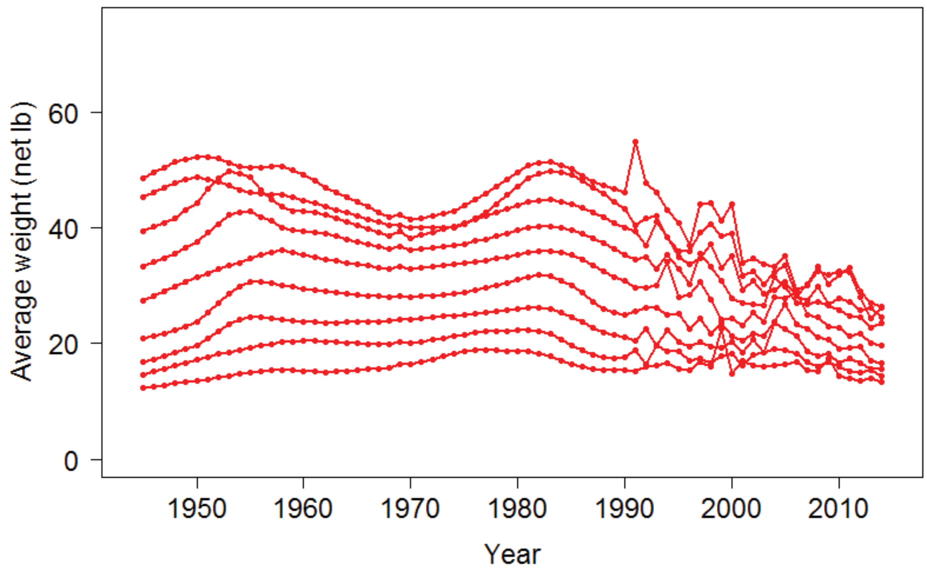


Figure 8. Estimated trends in weight at age for ages 8-16 for Area 4 from 1945-2014.

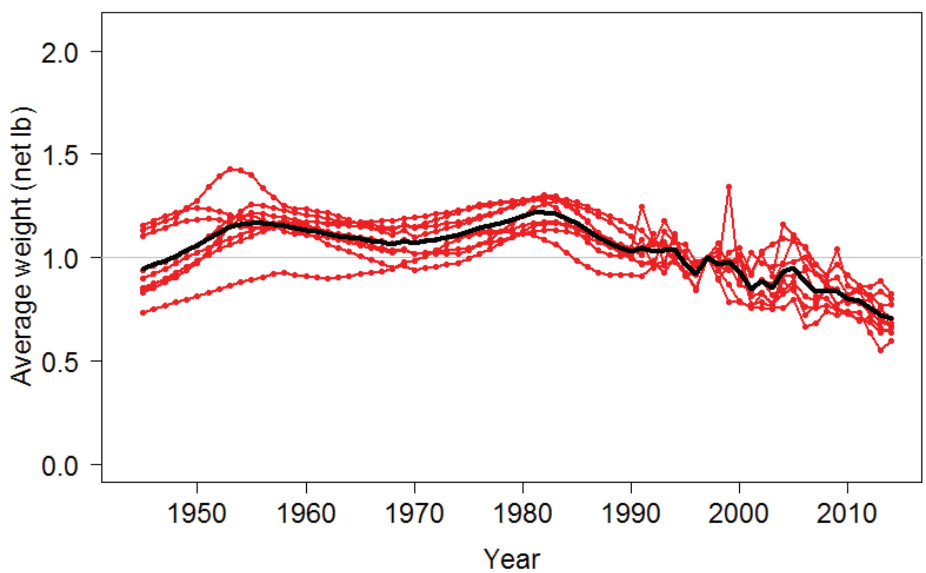


Figure 9. Estimated relative trends in weight at age for ages 8-16 (relative to 1997) for Area 4 from 1945-2014.

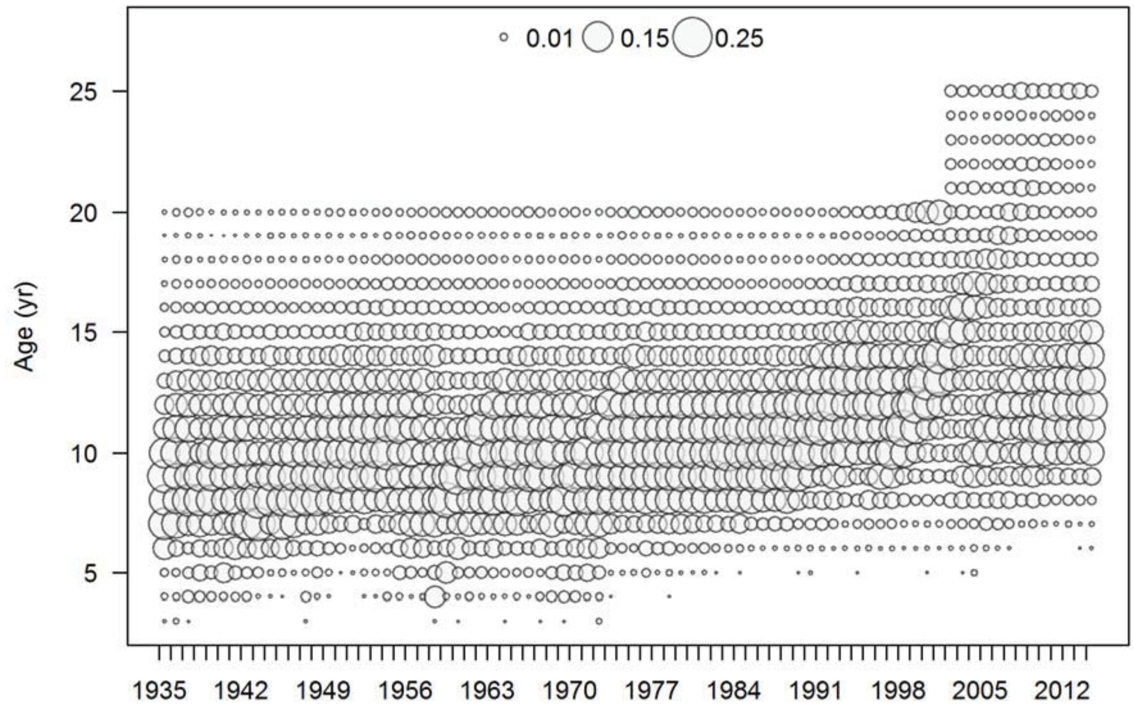


Figure 10. Coastwide age composition data for halibut captured by the commercial fishery.

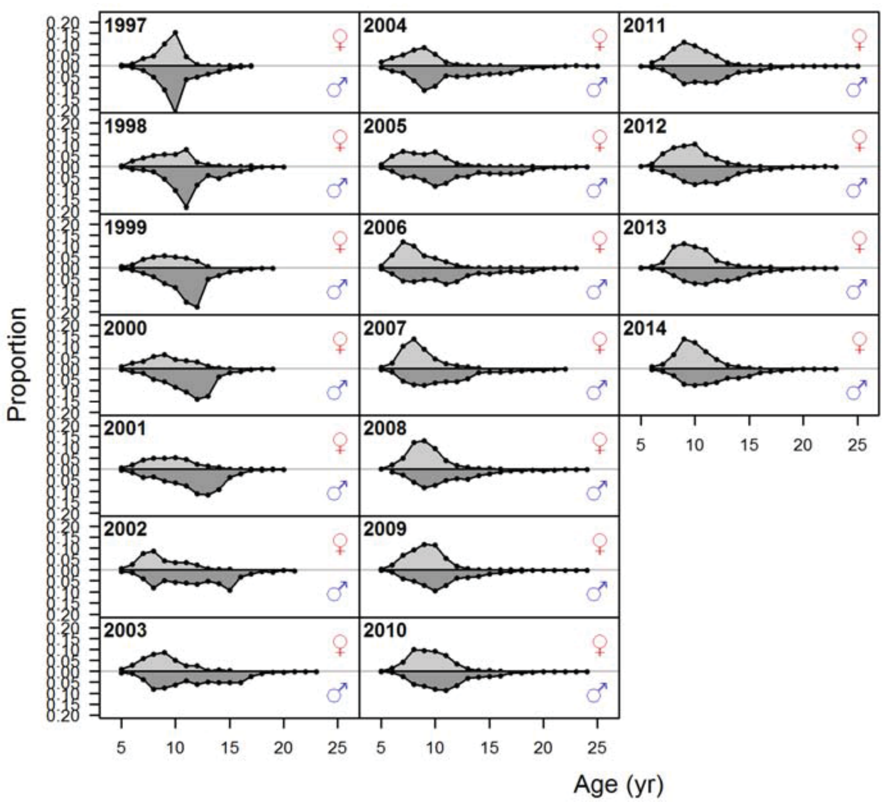


Figure 11. Coastwide age composition data for sublegal halibut captured by the setline survey. Female proportions are displayed as positive values on the y-axis, males as negative values.

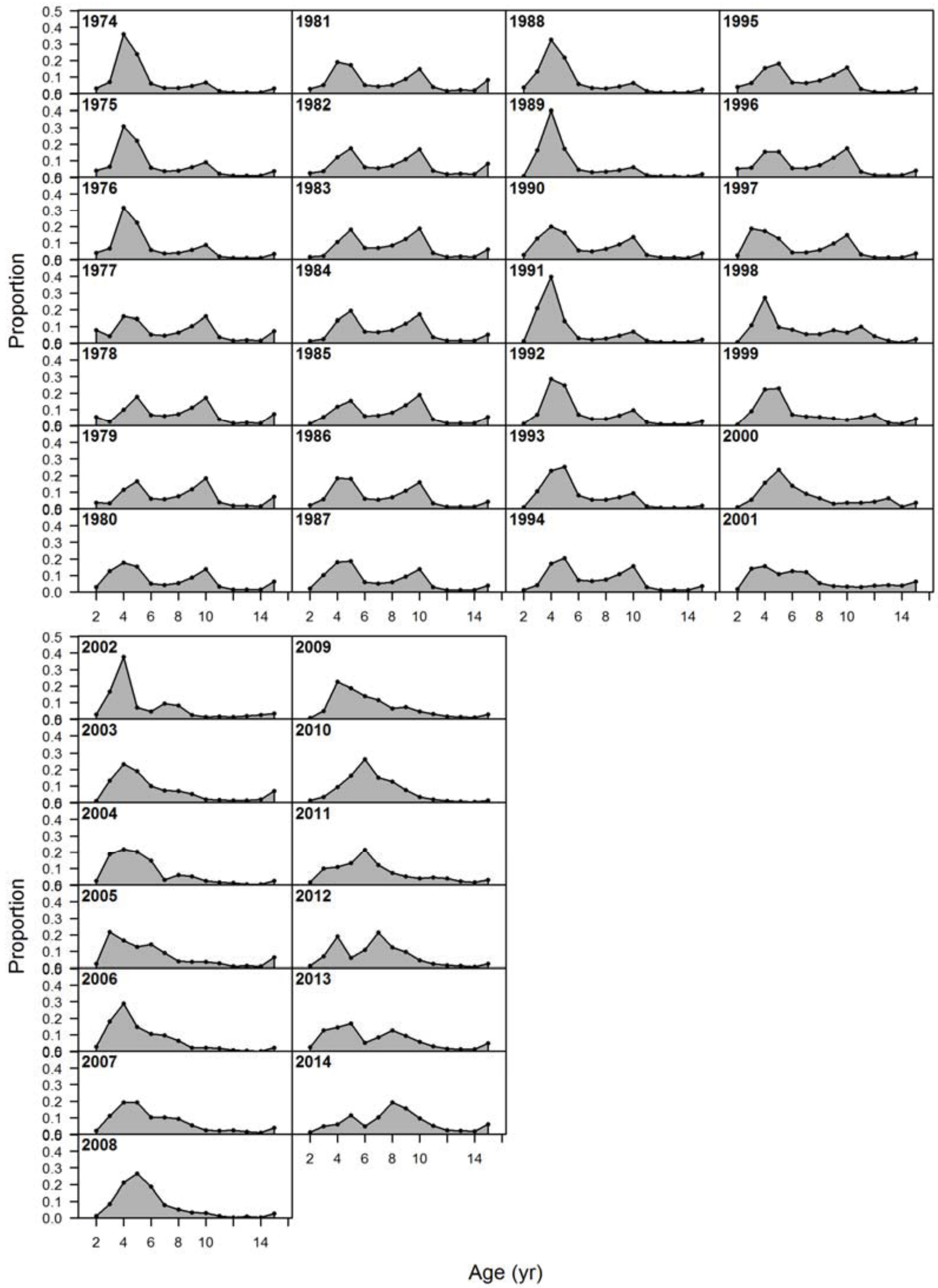


Figure 12. Coastwide age composition data created from bycatch lengths (1974-2014) and the age-length key based on NMFS trawl surveys. Some years (e.g., the early 1980s) appear to contain replicated distributions.

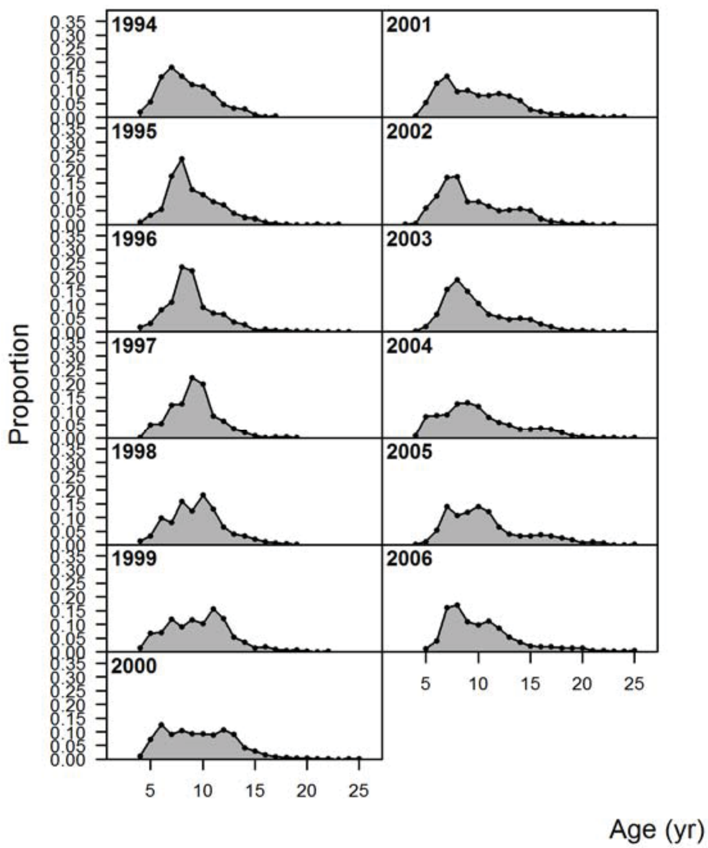


Figure 13. Age composition data from the recreational fishery in Area 3.

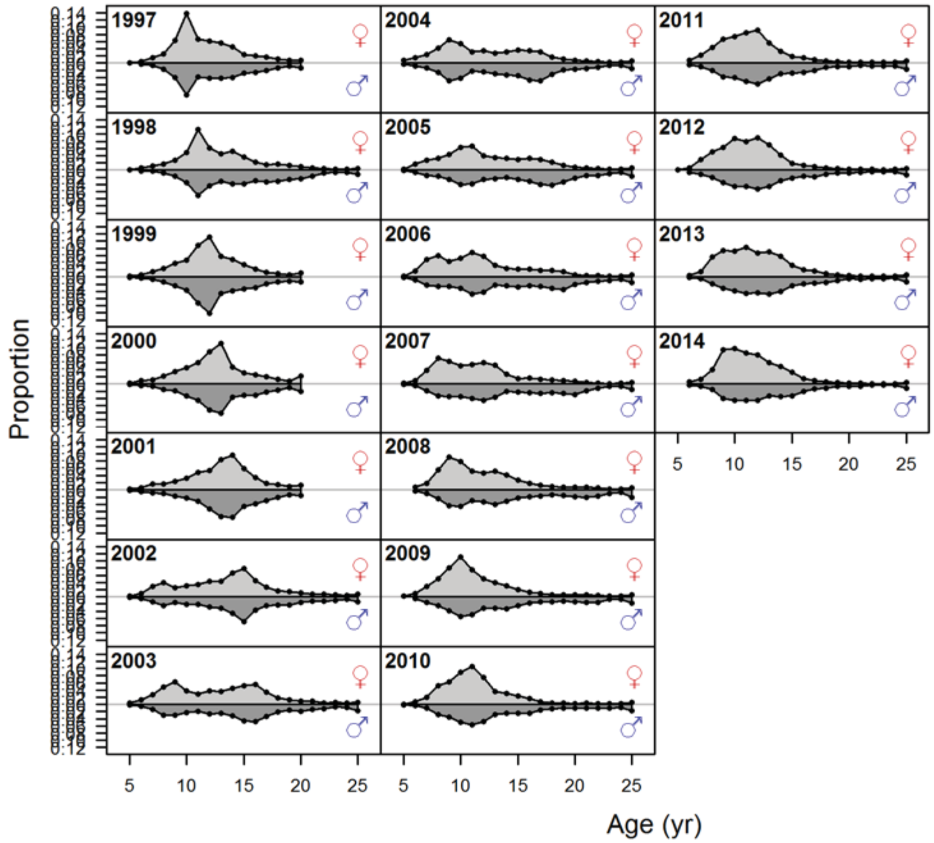


Figure 14. Coastwide age composition data from the setline survey.

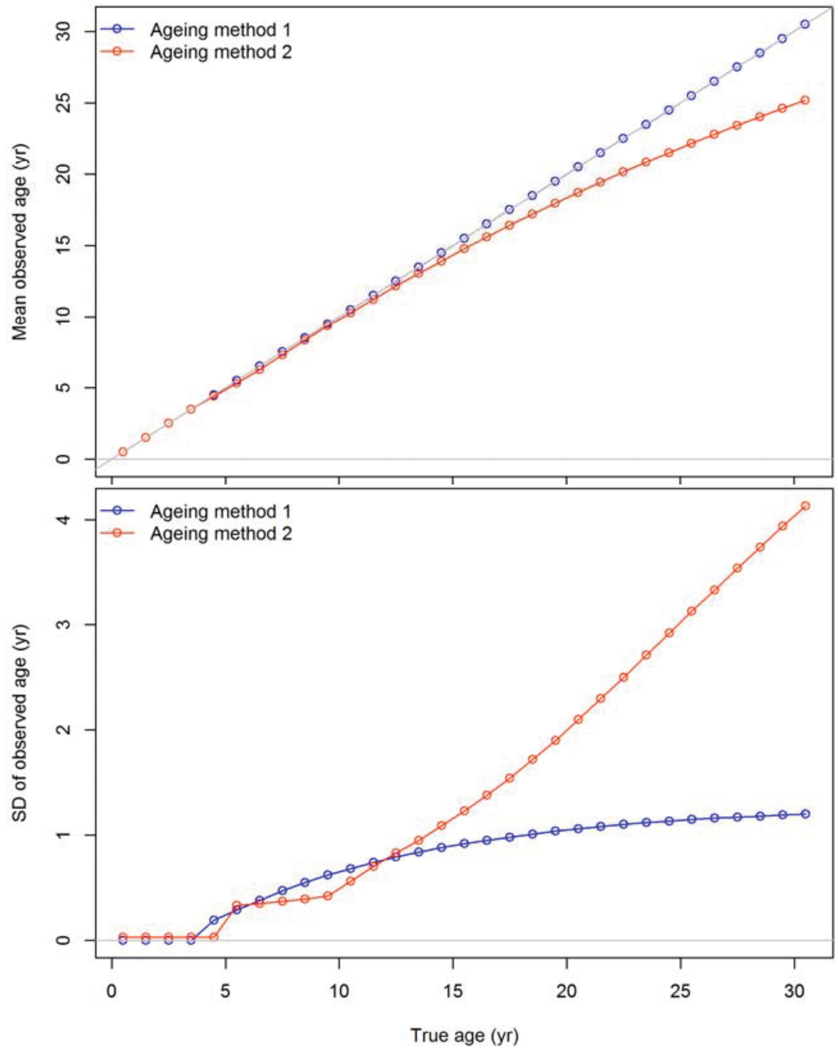


Figure 15. Degree of bias (upper panel) and imprecision (lower panel) estimated externally and assigned to break-and-bake (method 1) and surface ageing (method 2) in all assessment models.

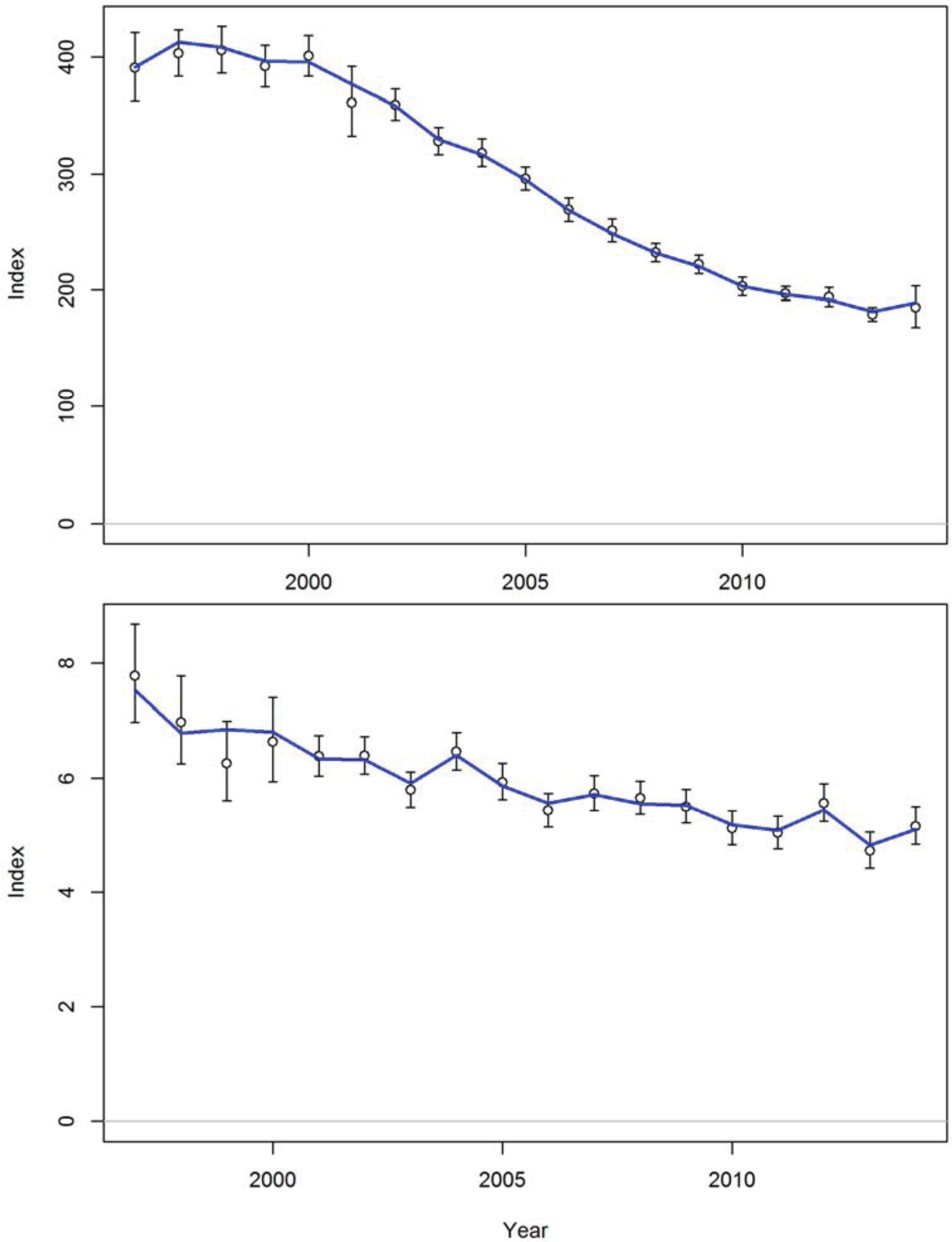


Figure 16. Fit to the index of abundance from the commercial fishery (upper panel, weight-per-unit-effort) and the setline survey (lower panel, numbers-per-unit-effort) in the coastwide short model.

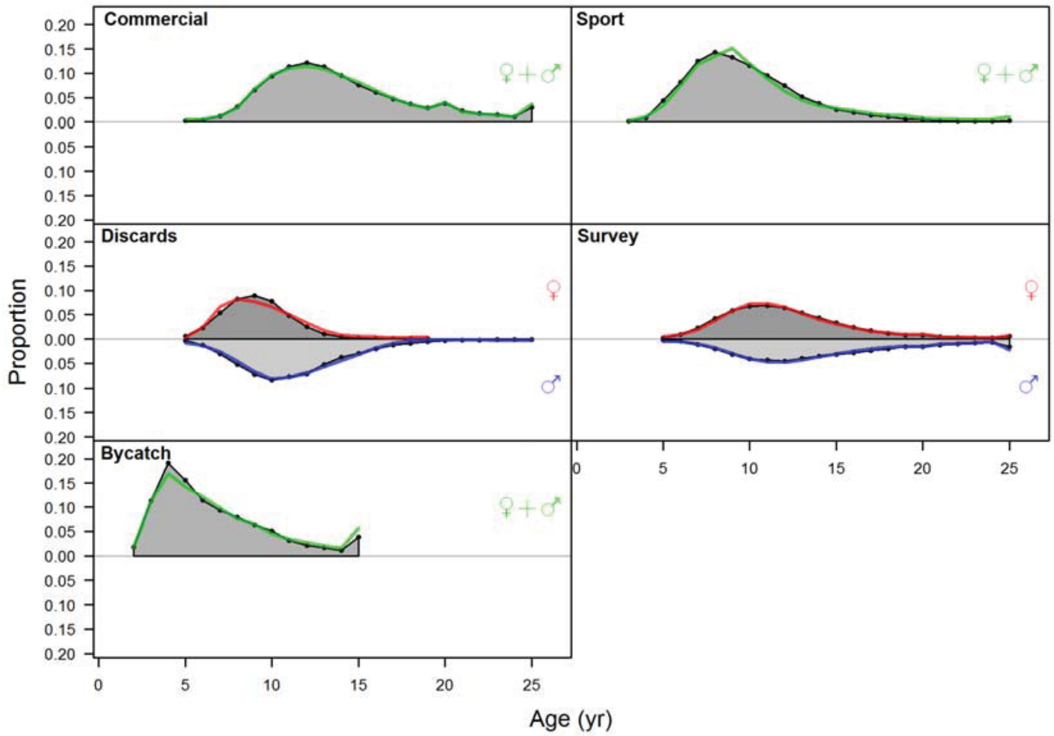


Figure 17. Aggregate fit (observed and expected values summed across all years) to the age data for each fleet in the coastwide short model.

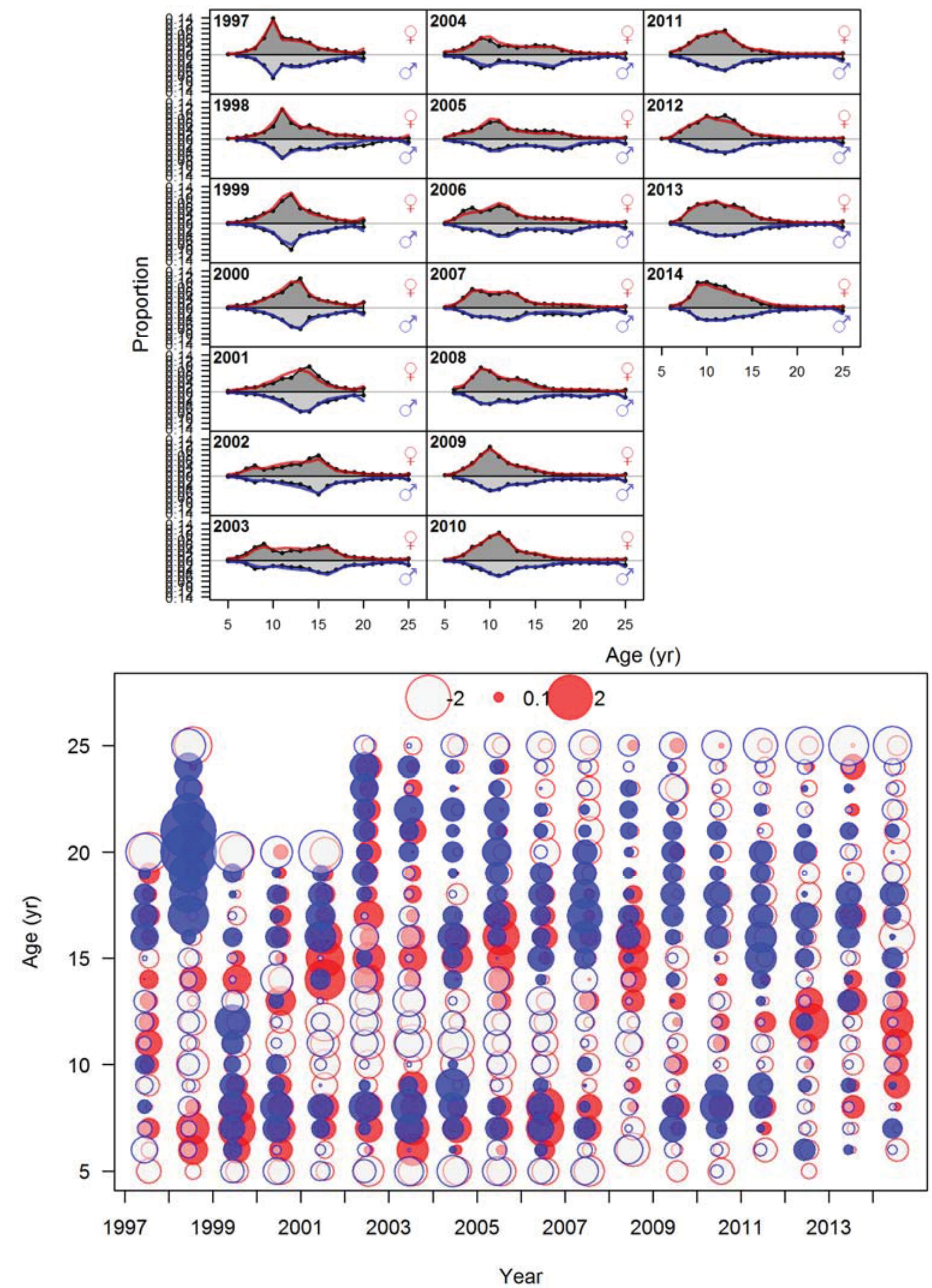


Figure 18. Fit and standardized residuals to the age data for the setline survey in the coastwide short model. Red and blue denote female and male residuals respectively.

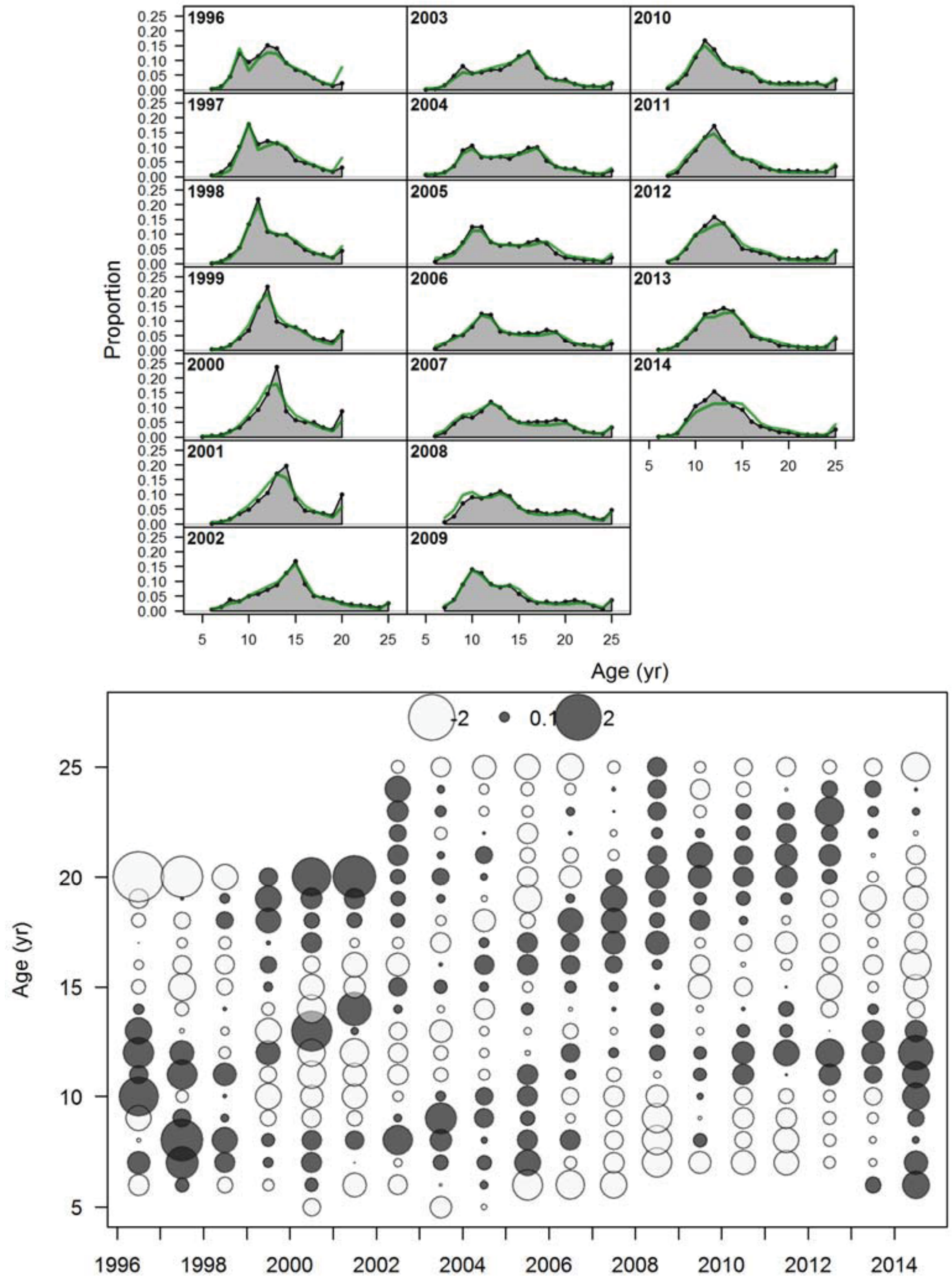


Figure 19. Fit and standardized residuals to the age data for the commercial fishery in the coastwide short model.

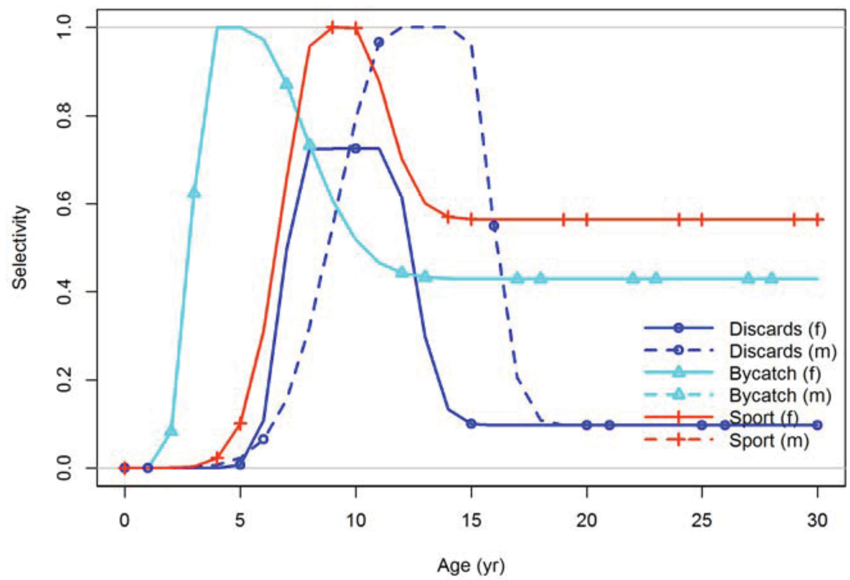


Figure 20. Selectivity patterns estimated for the discards (male and female curves), sport and bycatch fleets in the coastwide short model.

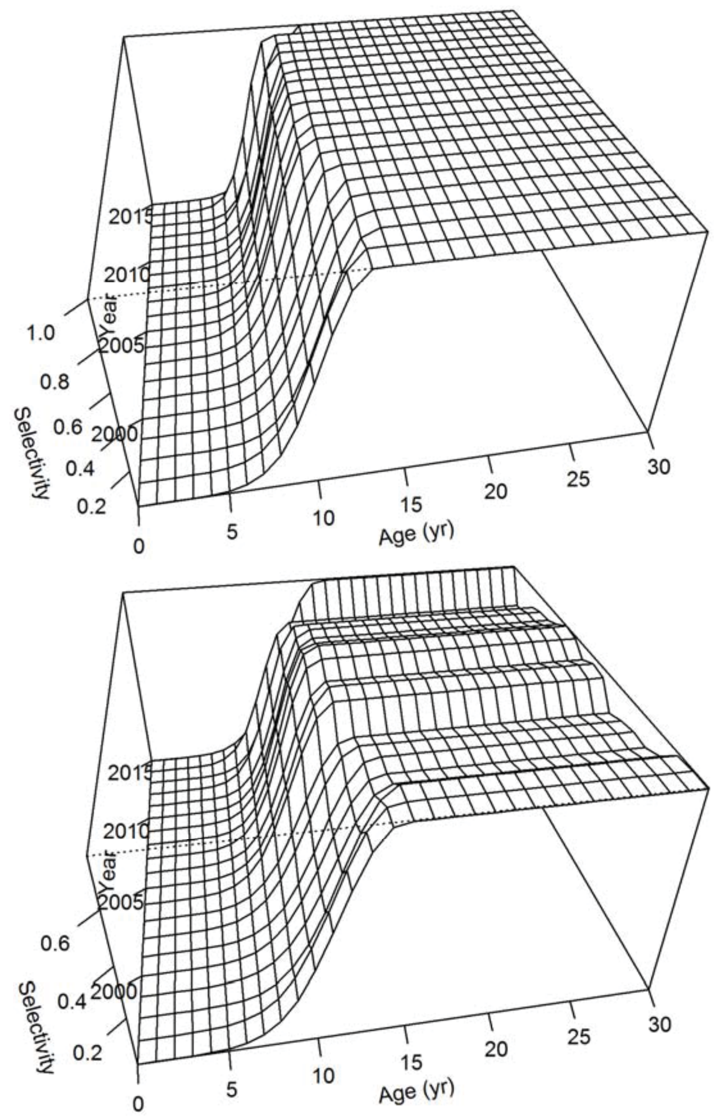


Figure 21. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the setline survey in the coastwide short model.

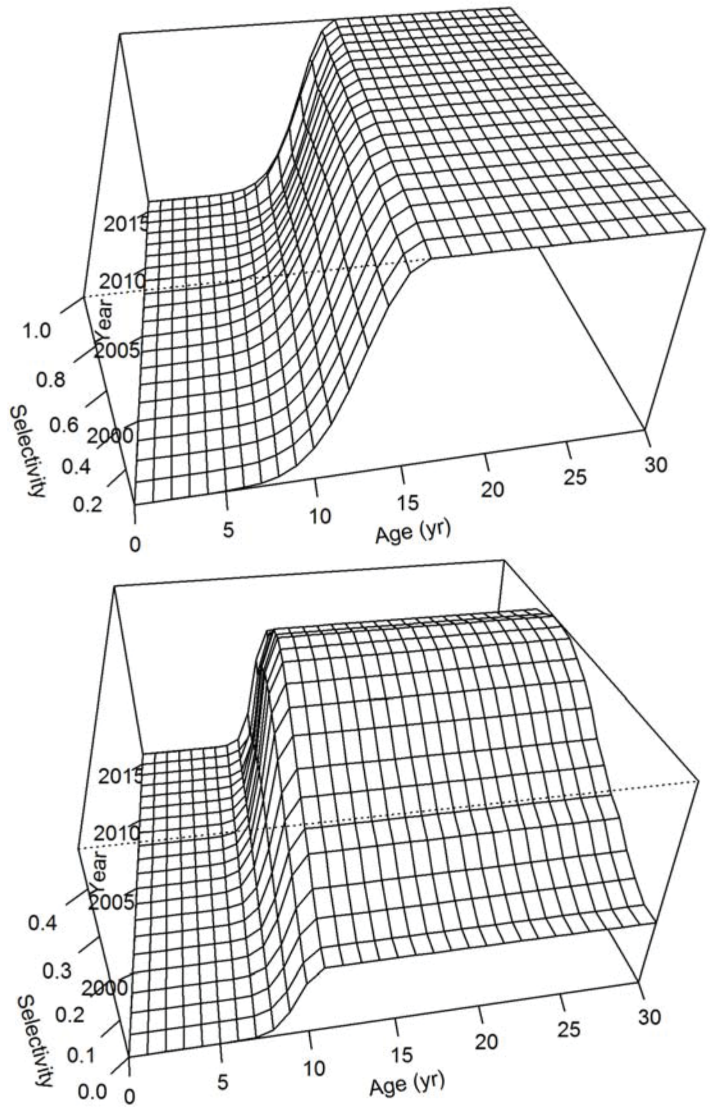


Figure 22. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the directed commercial fishery in the coastwide short model.

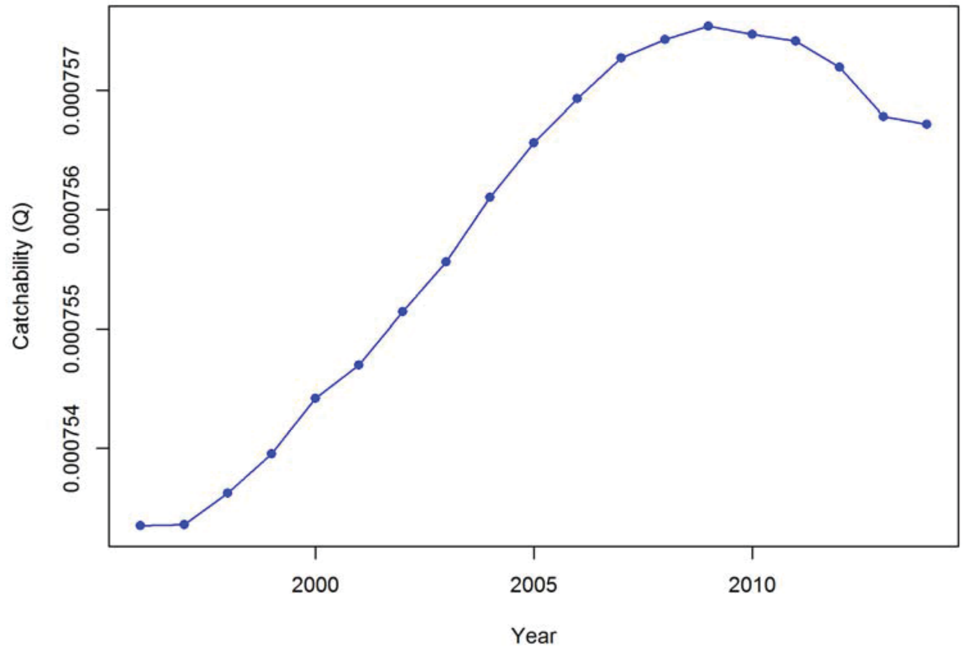


Figure 23. Estimated trend in fishery catchability in the coastwide short model.

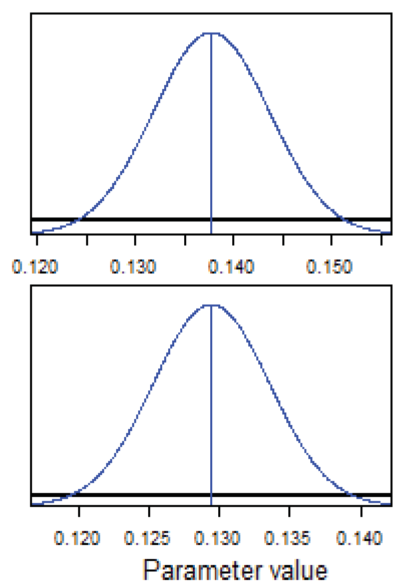


Figure 24. Prior (thick line) and MLE-based distributions for male natural mortality from the coastwide short model (top panel), and the AAF short model (bottom panel).

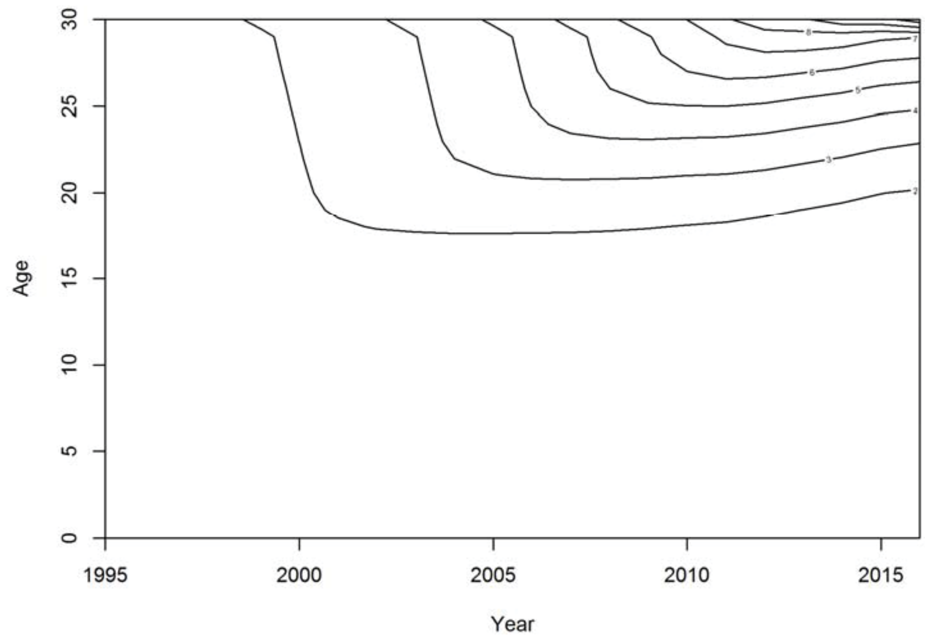


Figure 25. Population sex ratio (numbers of males/females) contours estimated by the coastwide short model.

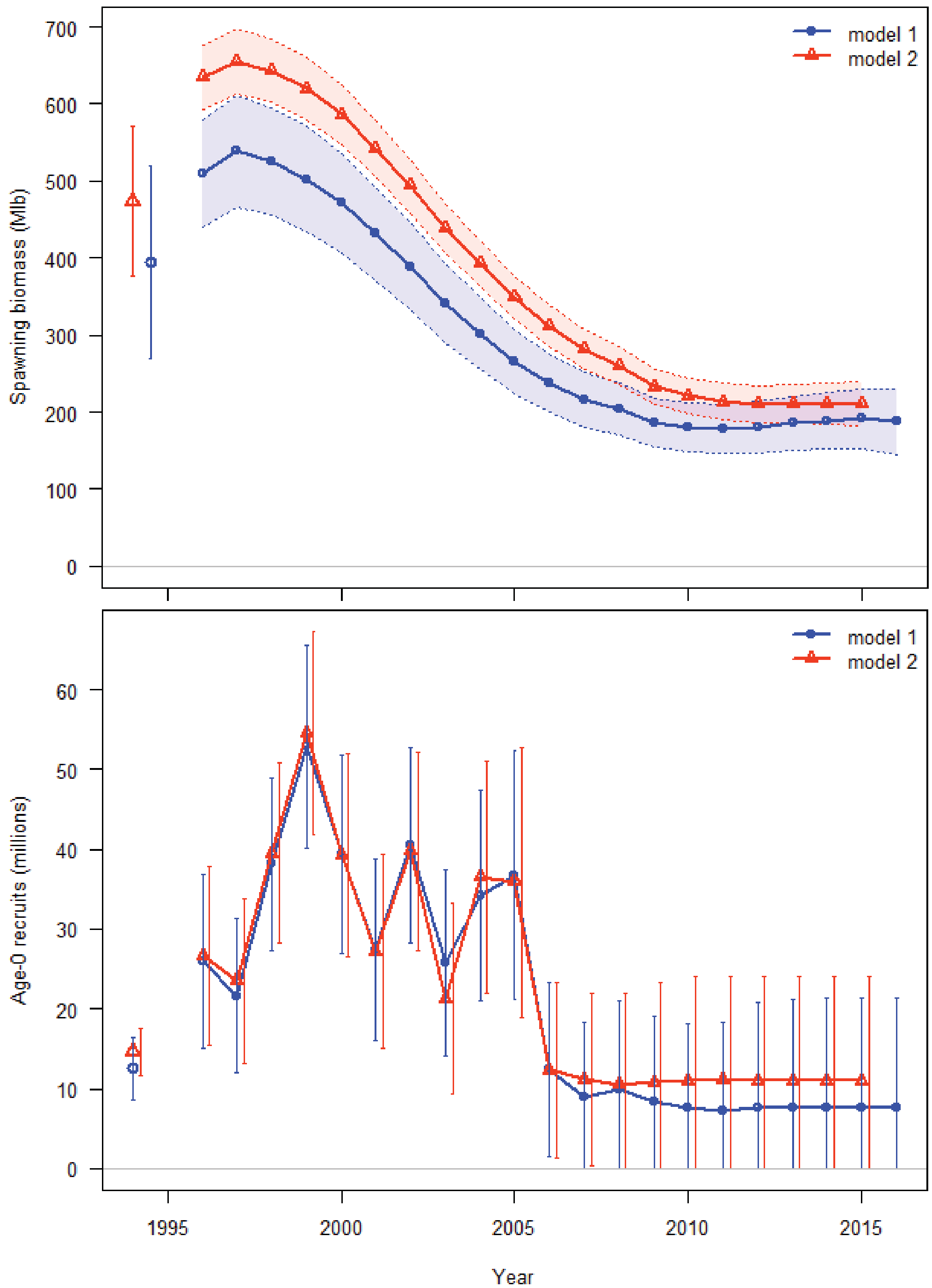


Figure 26. Comparison of the 2014 result, and the preliminary 2015 result including all updates to data and model structure for the CW short model.

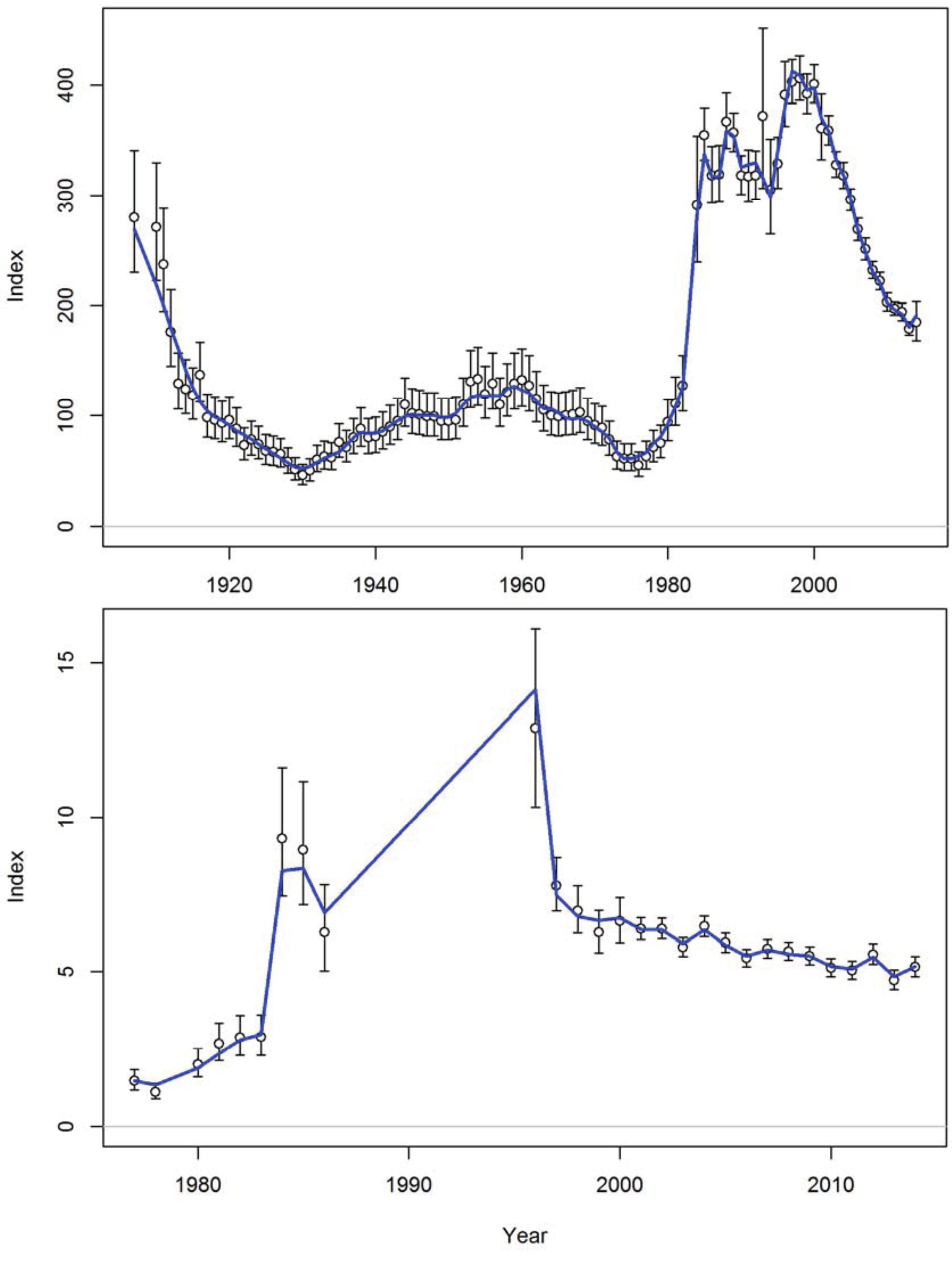


Figure 27. Fit to the index of abundance from the commercial fishery (upper panel, weight-per-unit-effort) and the setline survey (lower panel, numbers-per-unit-effort) in the coastwide long model. Note that there are unconstrained catchability breaks for the fishery in 1984, and the survey in 1982, 1984, and 1997.

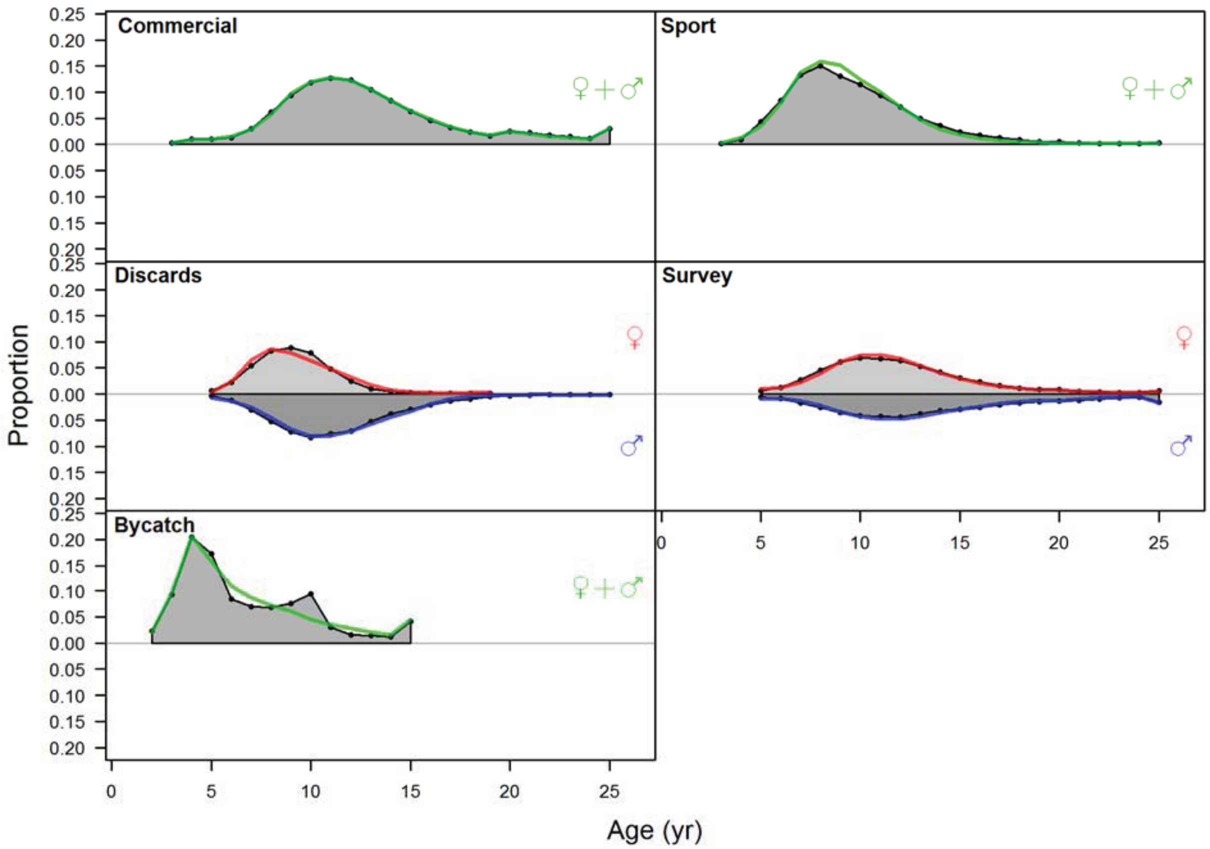


Figure 28. Aggregate fit (observed and expected values summed across all years) to the age data for each fleet in the coastwide long model.

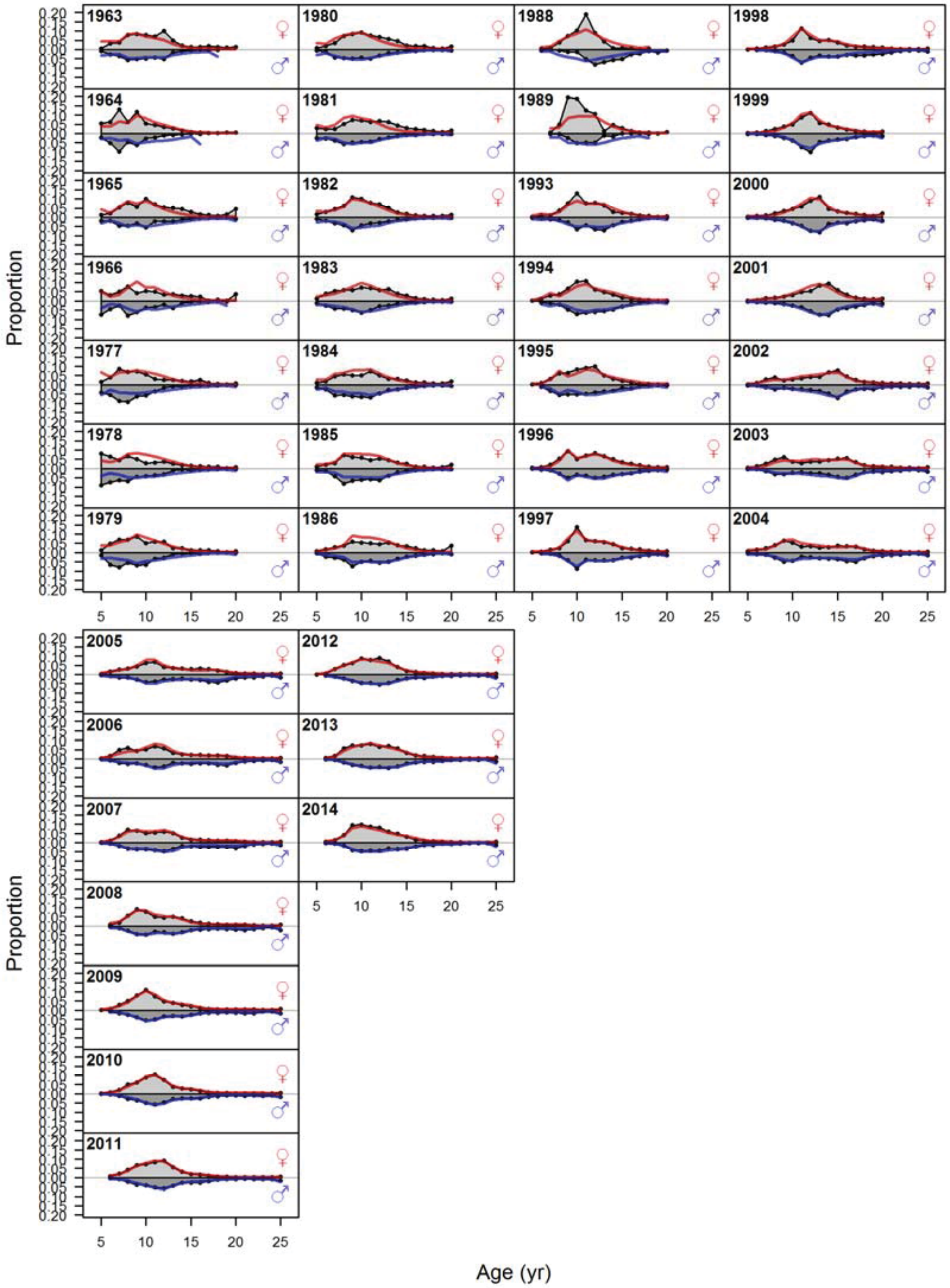


Figure 29. Fit to the age data for the survey in the coastwide long model.

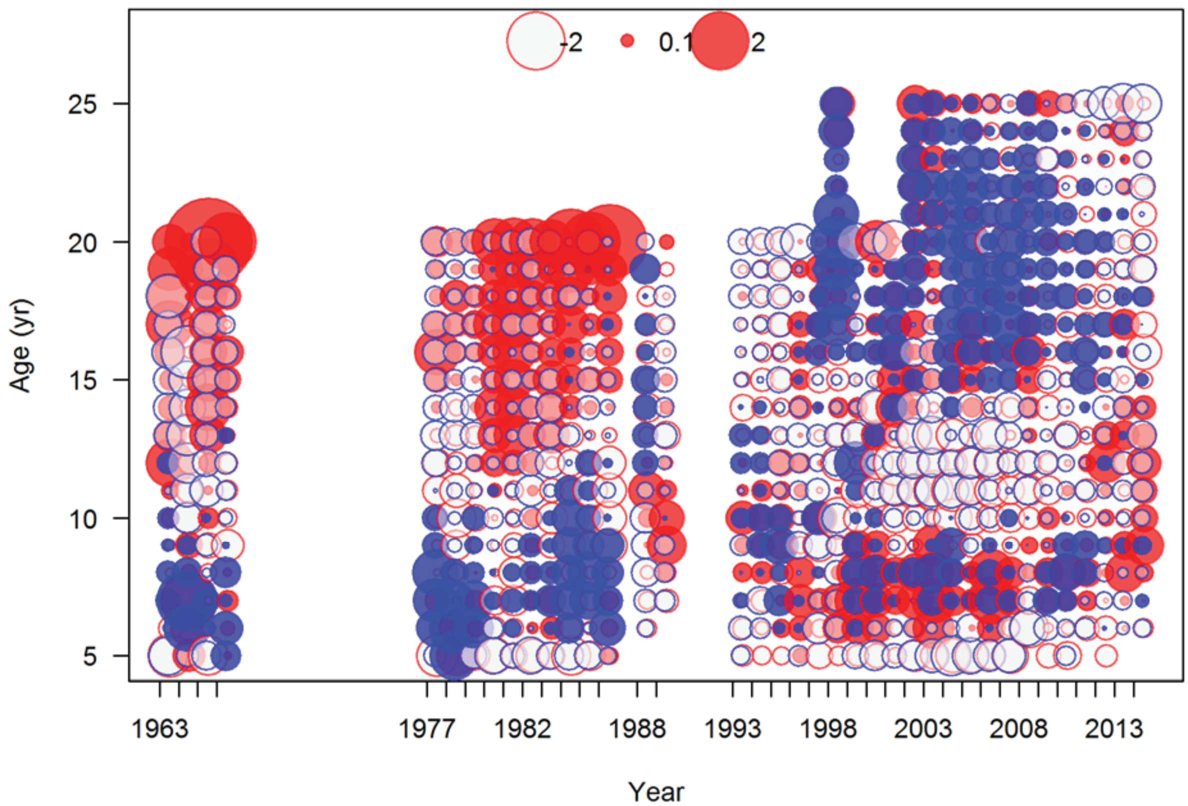


Figure 30. Standardized residuals to the age data for the survey in the coastwide long model. Red and blue denote female and male residuals respectively.

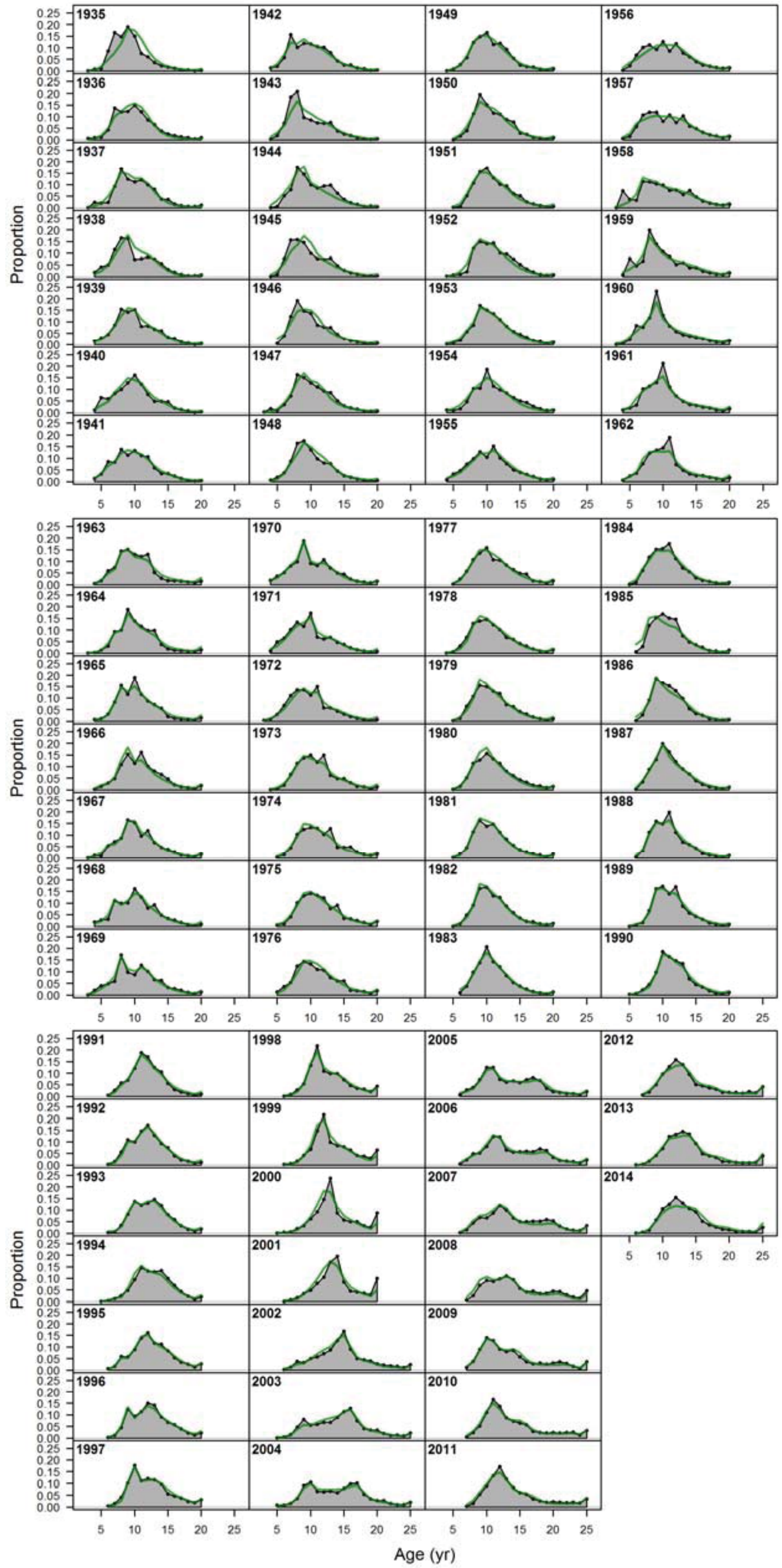


Figure 31. Fit to the age data for the commercial fishery in the coastwide long model.

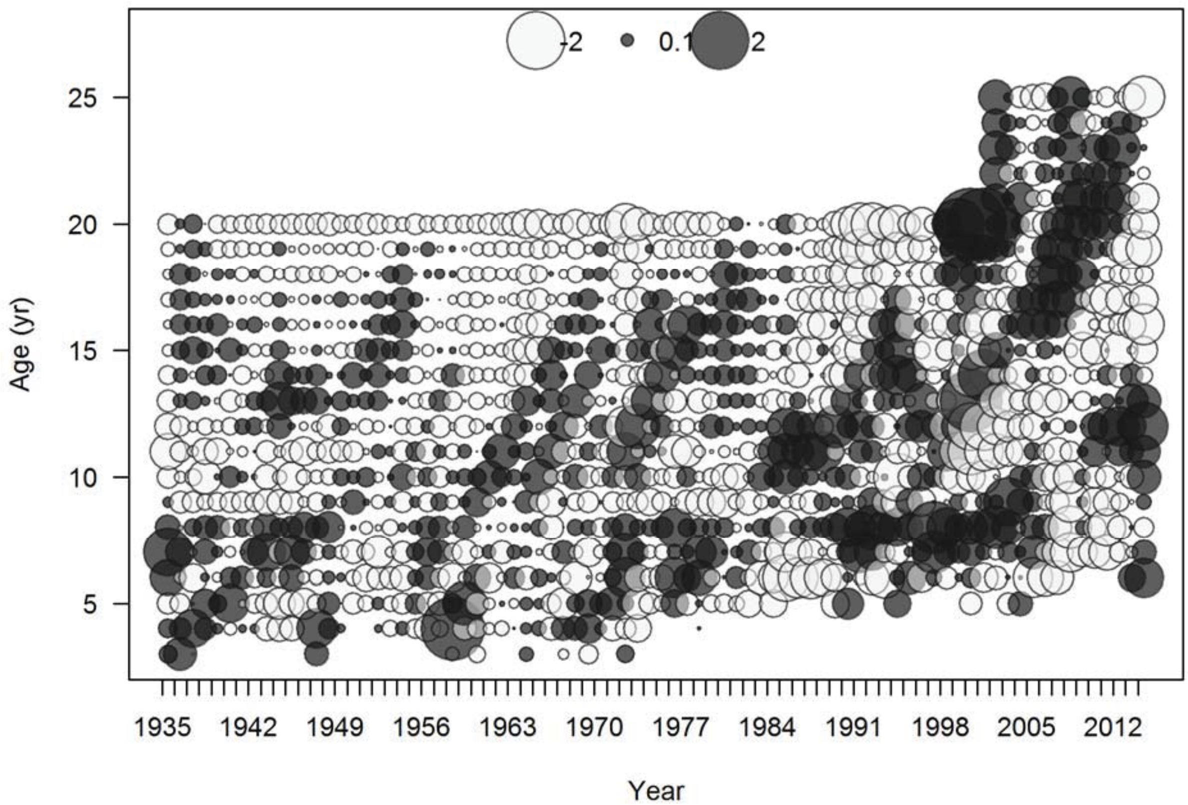


Figure 32. Standardized residuals to the age data for the commercial fishery in the coastwide long model.

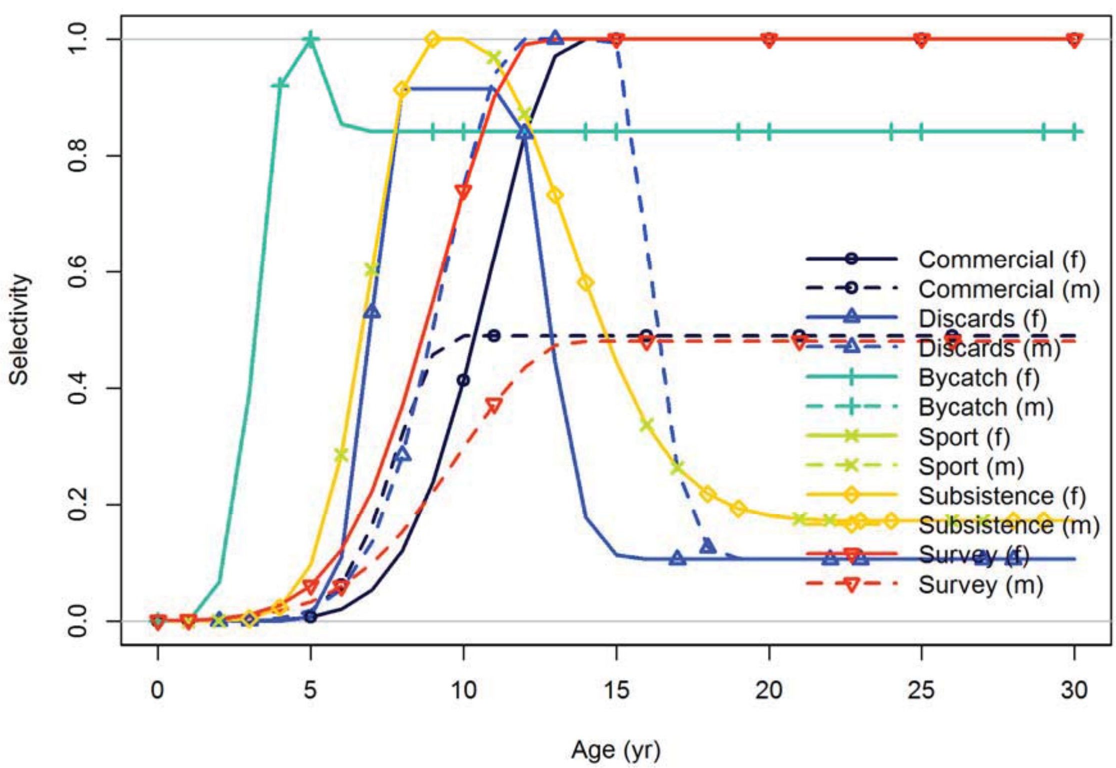


Figure 33. Terminal year selectivity patterns from the coastwide long model.

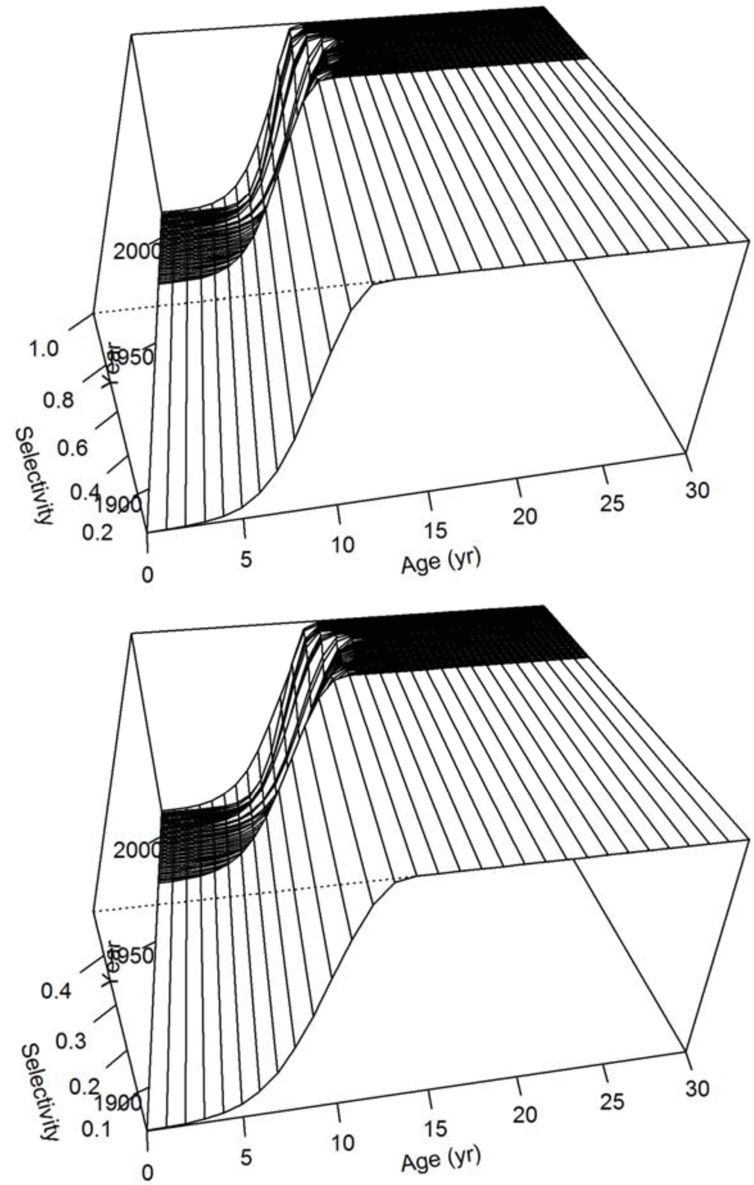


Figure 34. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the survey in the coastwide long model.

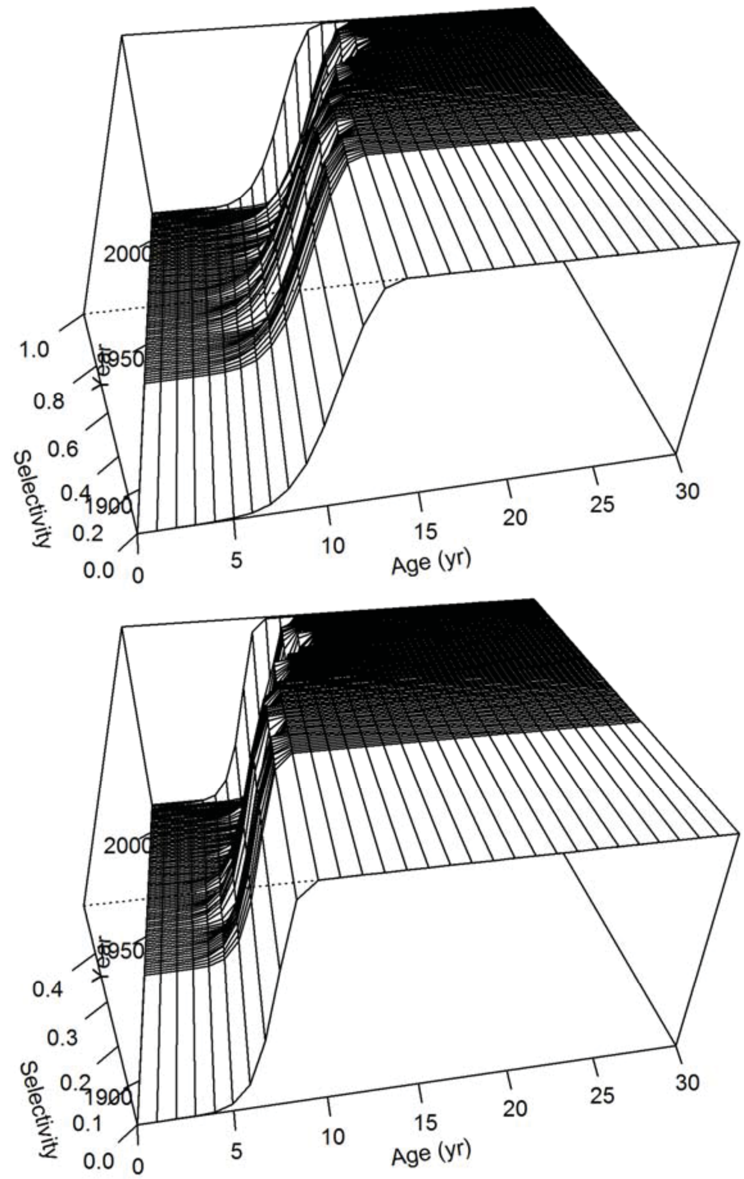


Figure 35. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the directed commercial fishery in the coastwide long model.

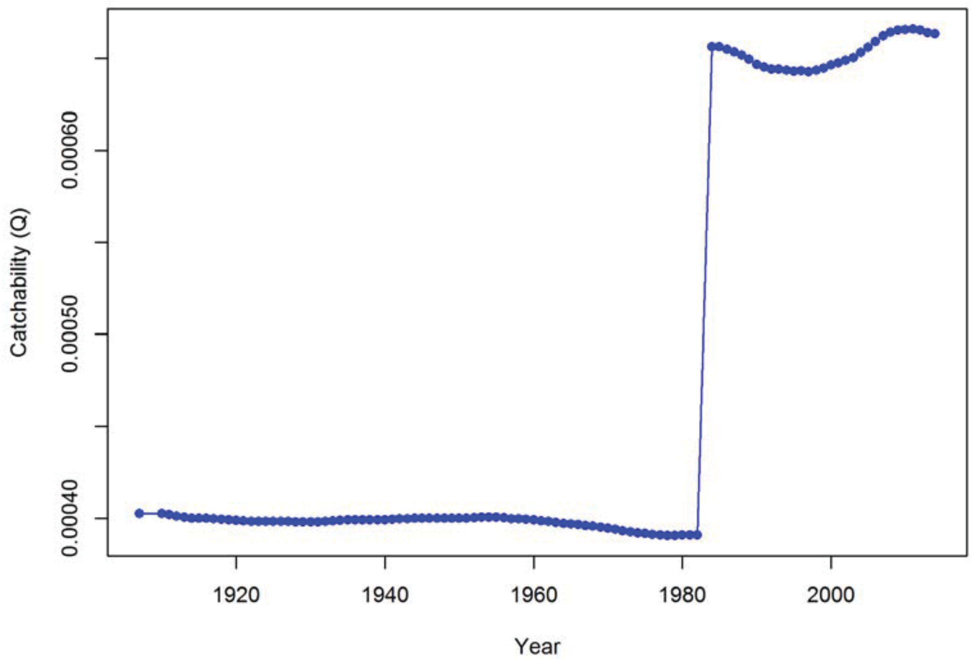


Figure 36. Estimated trend in fishery catchability in the coastwide long model.

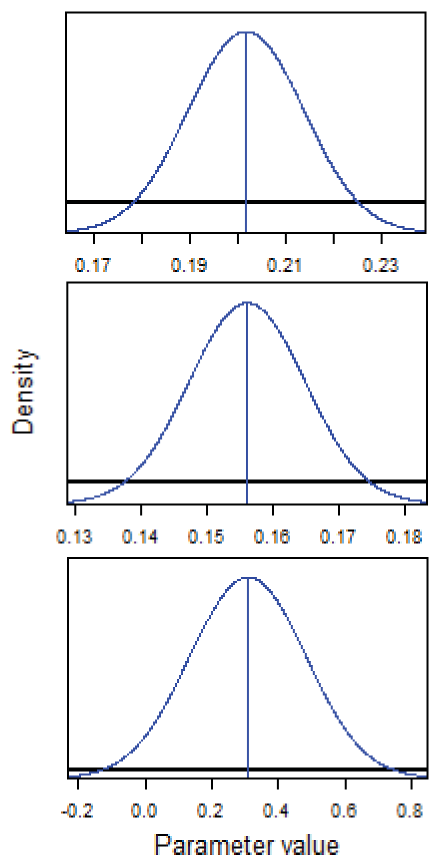


Figure 37. Prior (thick line) and MLE-based distributions for female natural mortality (top panel), male natural mortality (middle panel) and the environmental link coefficient (bottom panel) from the coastwide long model.

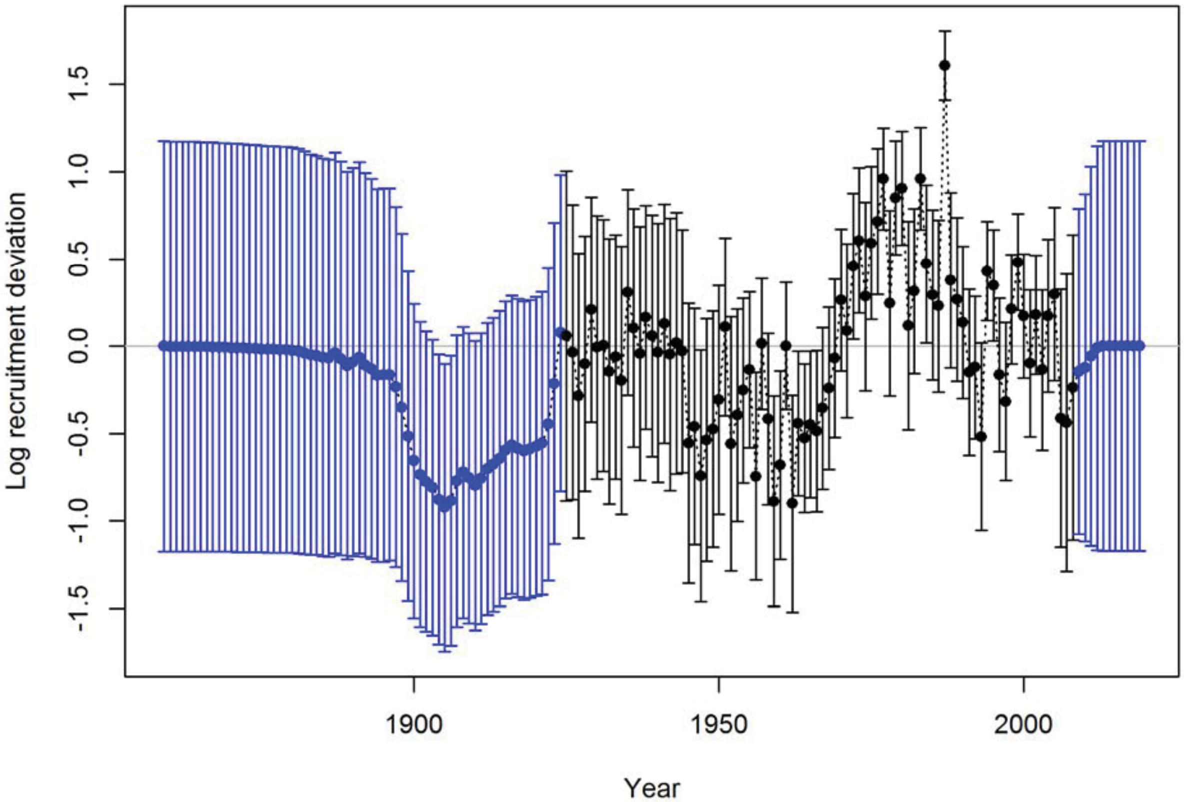


Figure 38. Recruitment deviations from the coastwide long model.

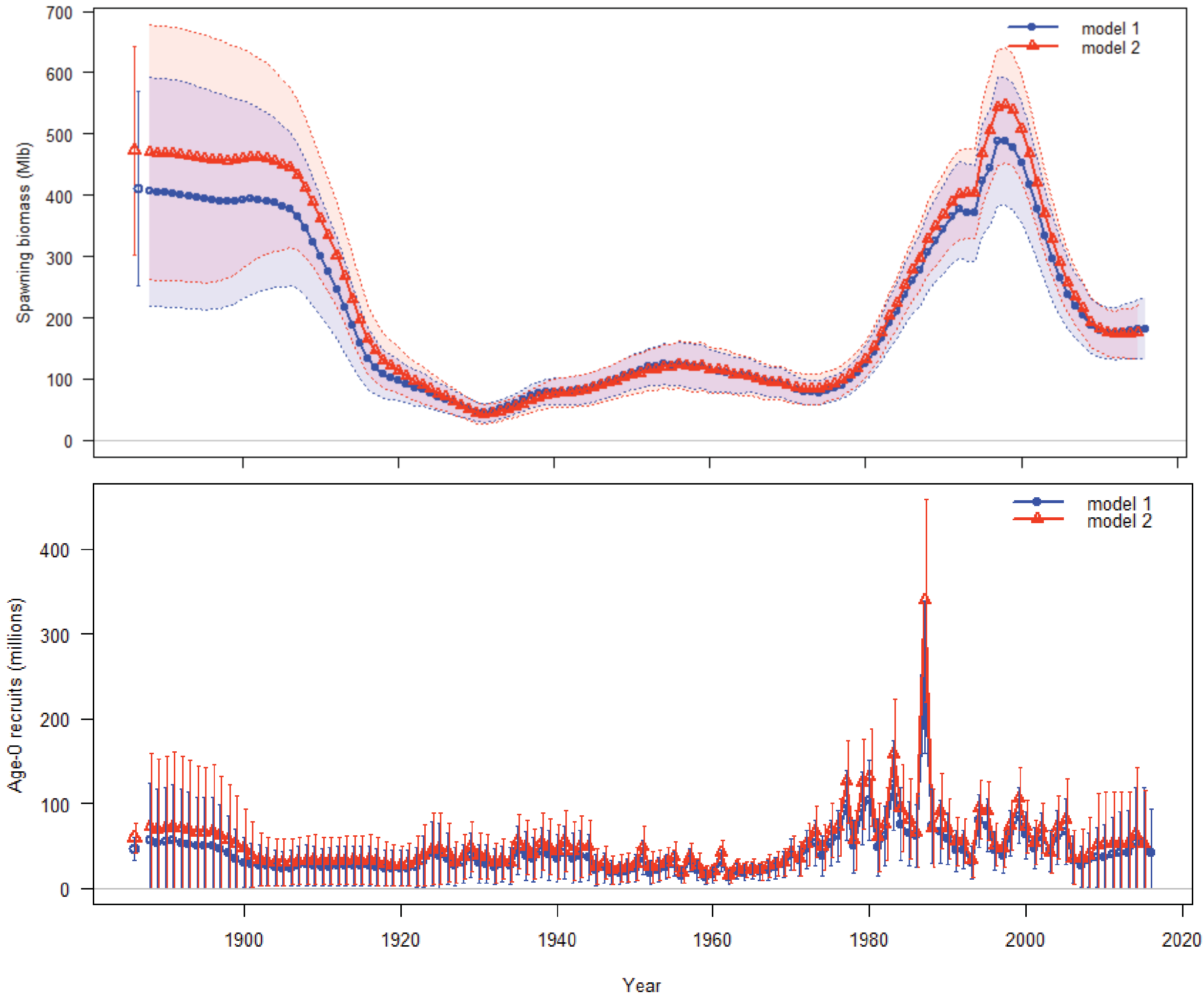


Figure 39. Comparison of spawning biomass (upper panel) and recruitment (lower panel) from the 2014 and preliminary 2015 coastwide long models including all updates to data and model structure.

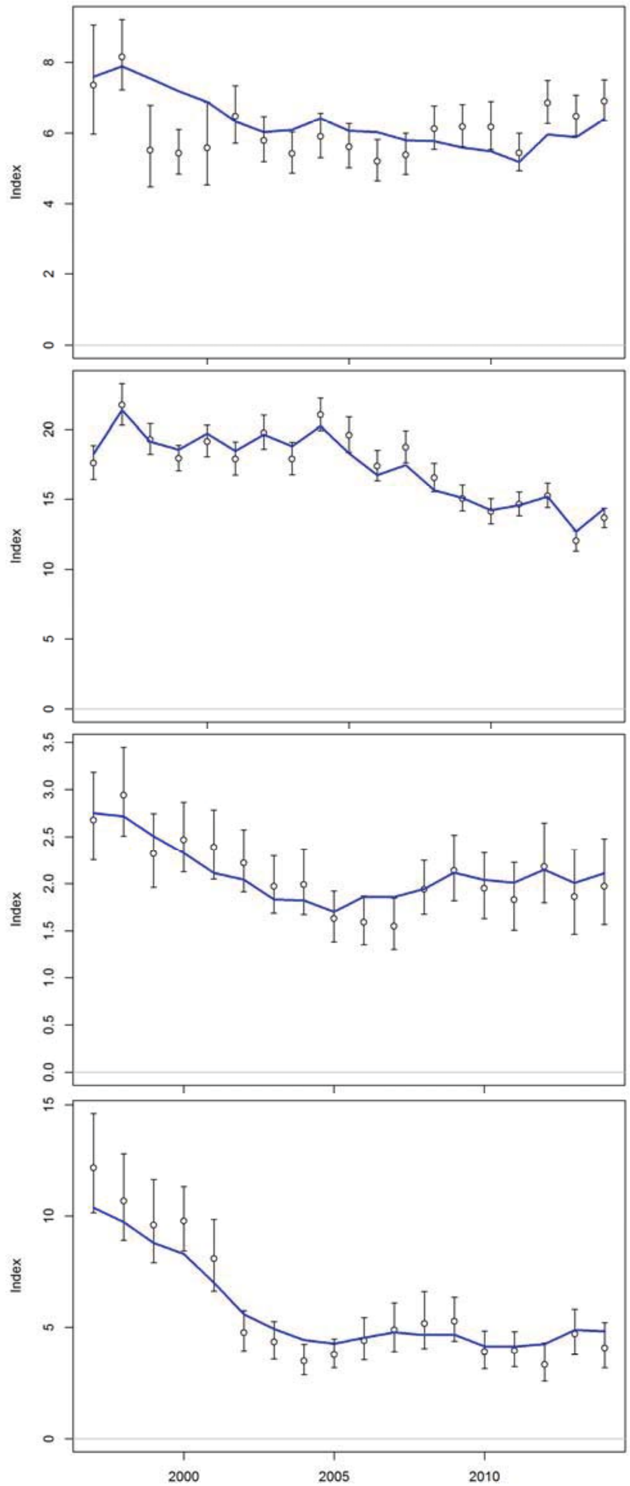


Figure 40. Fit to the index of abundance from the survey (numbers-per-unit-effort) for Area 2 (upper panel), Area 3(second panel), Area 4 (third panel) and Area 4B (bottom panel) in the AAF short model.

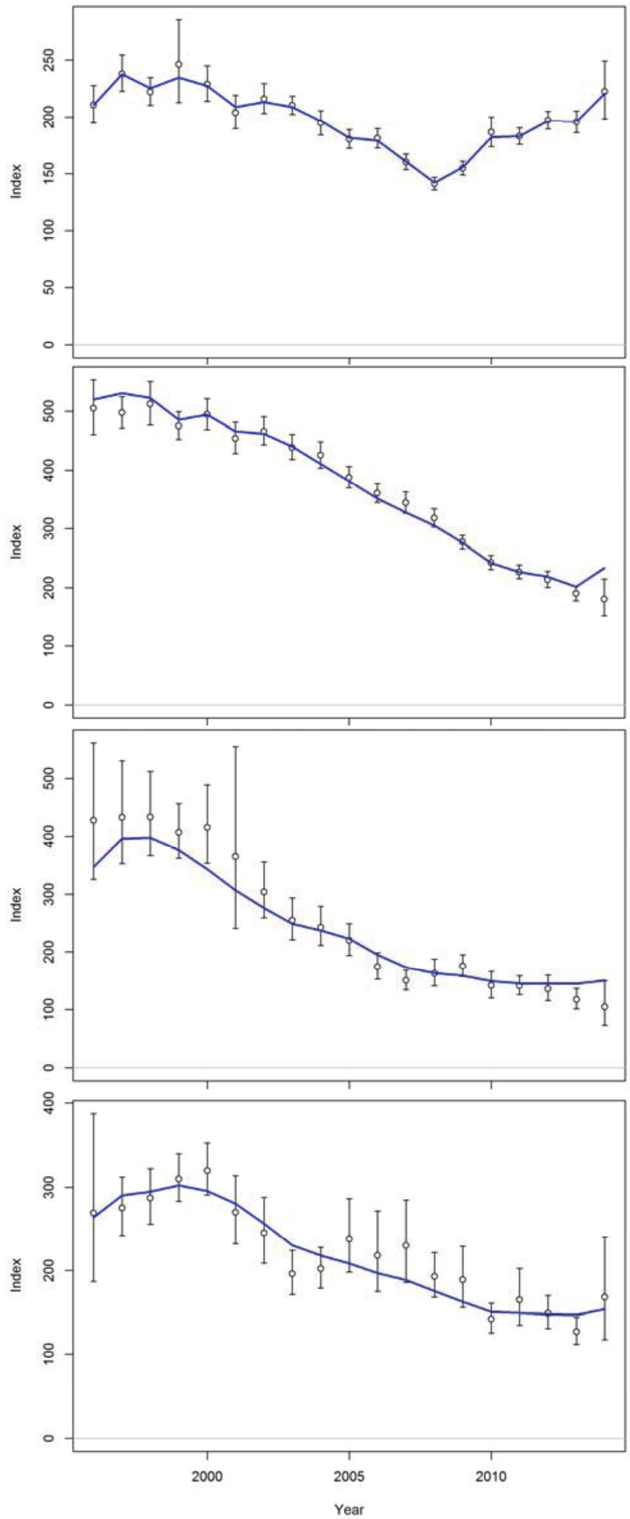


Figure 41. Fit to the index of abundance from the commercial fishery (weight-per-unit-effort) for Area 2 (upper panel), Area 3(second panel), Area 4 (third panel) and Area 4B (bottom panel) in the AAF short model.

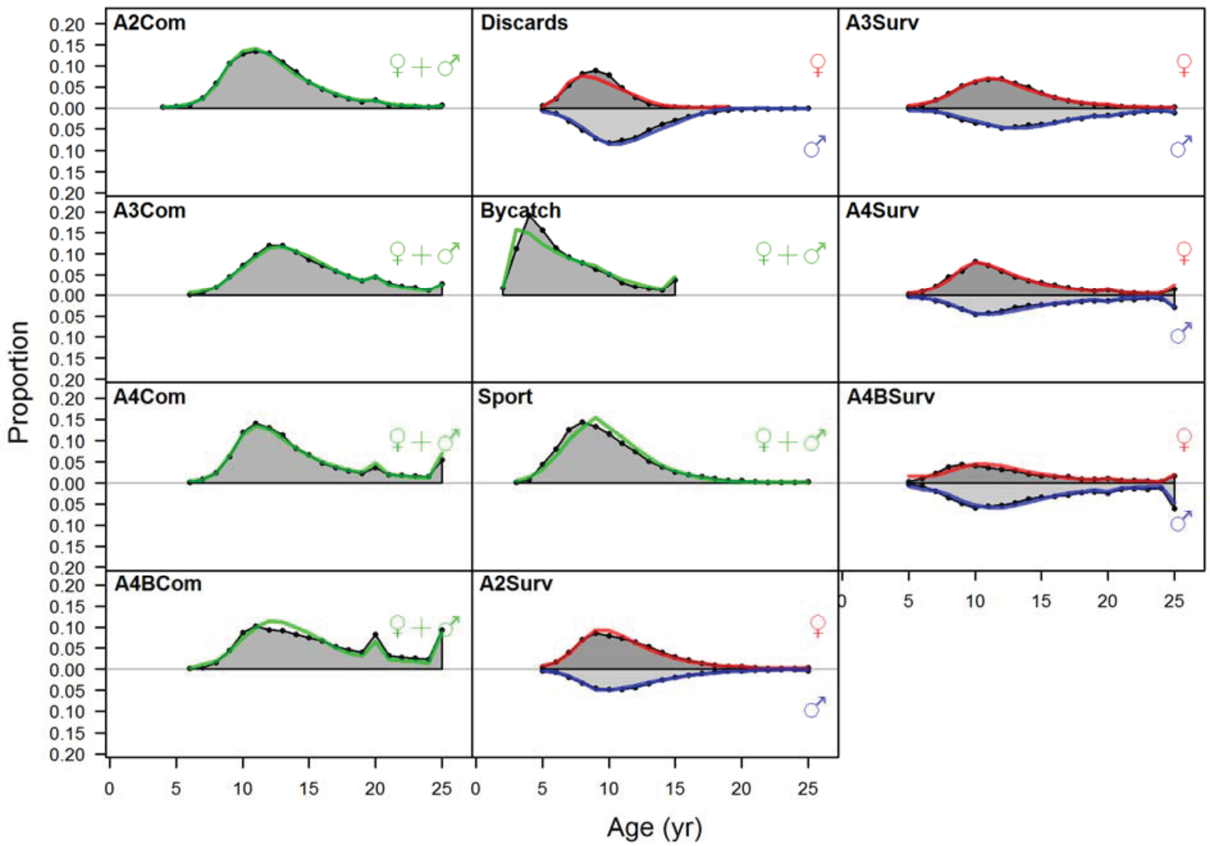


Figure 42. Aggregate fit (observed and expected values summed across all years) to the age data for each fleet in the AAF short model.

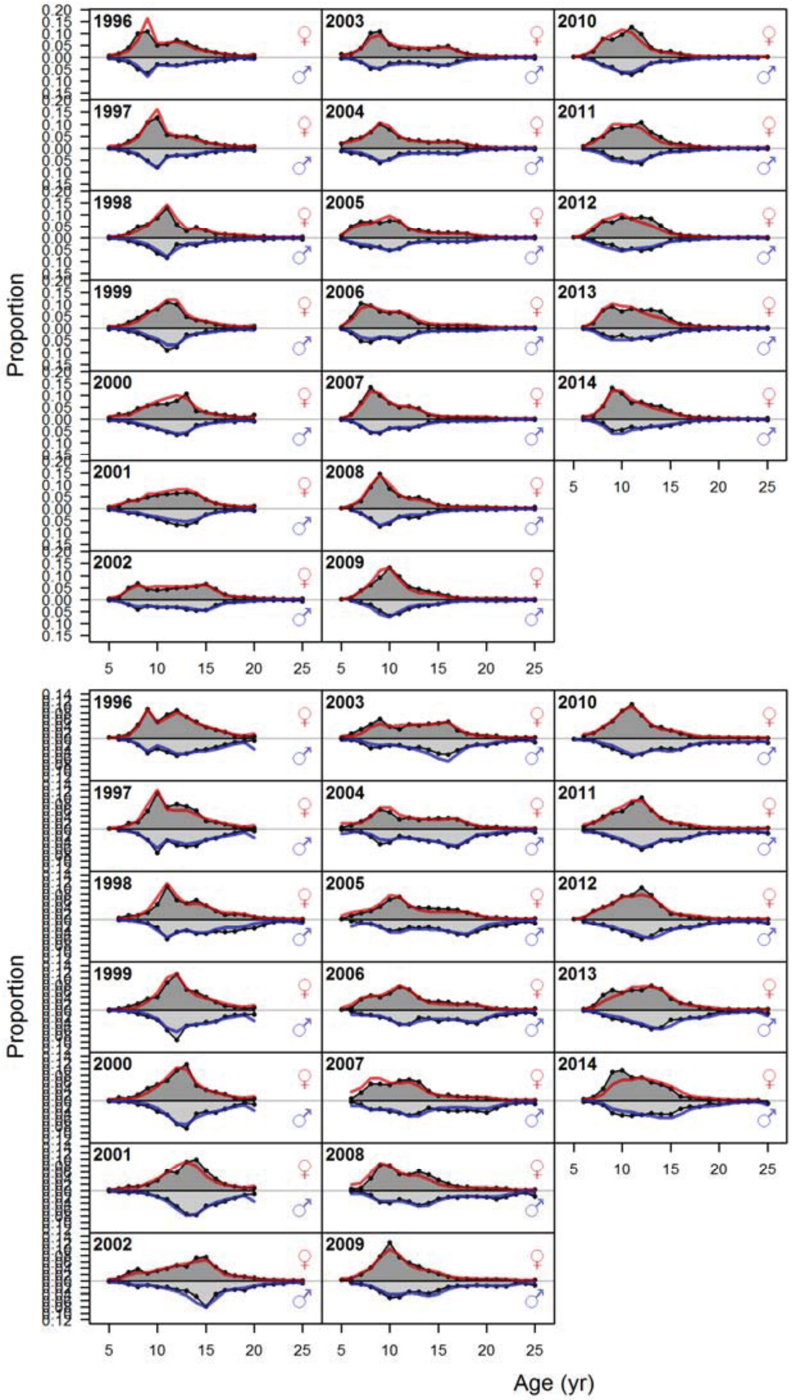


Figure 43. Fit to the age data for the survey in Area 2 (upper panel) and Area 3 (lower panel) in the AAF short model.

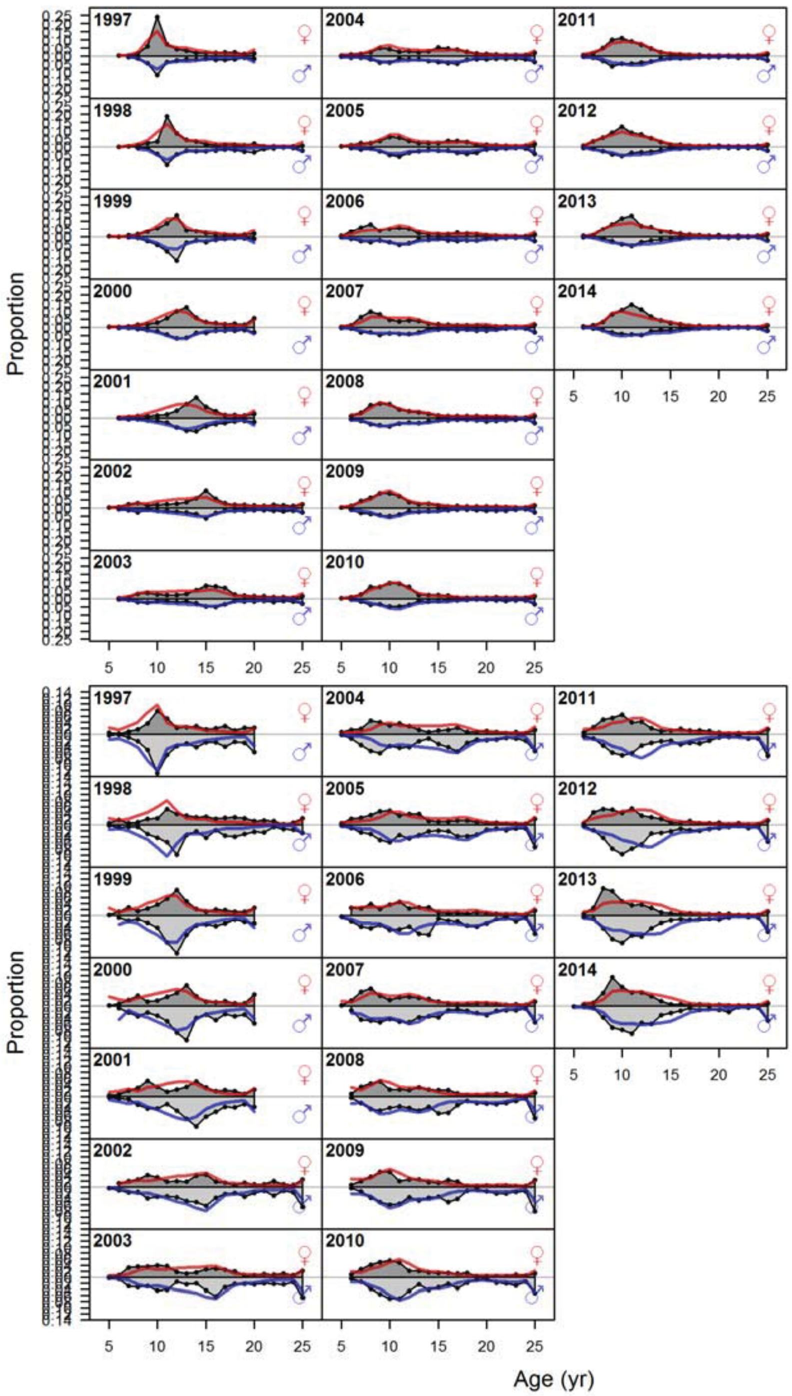


Figure 44. Fit to the age data for the survey in Area 4 (upper panel) and Area 4B (lower panel) in the AAF short model.

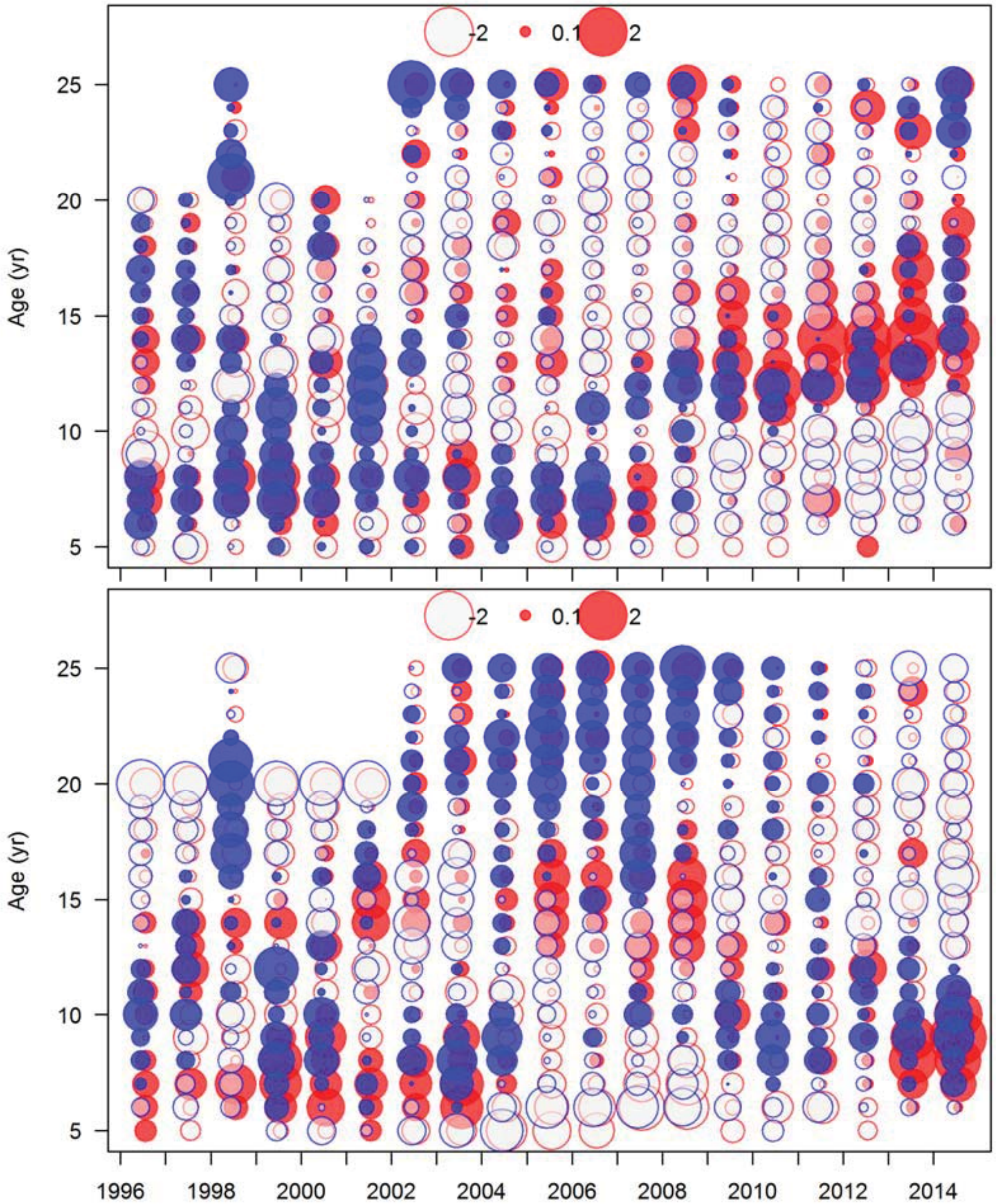


Figure 45. Standardized residuals to the age data for the survey in Area 2 (upper panel) and Area 3 (lower panel) in the AAF short model. Red and blue denote female and male residuals respectively.

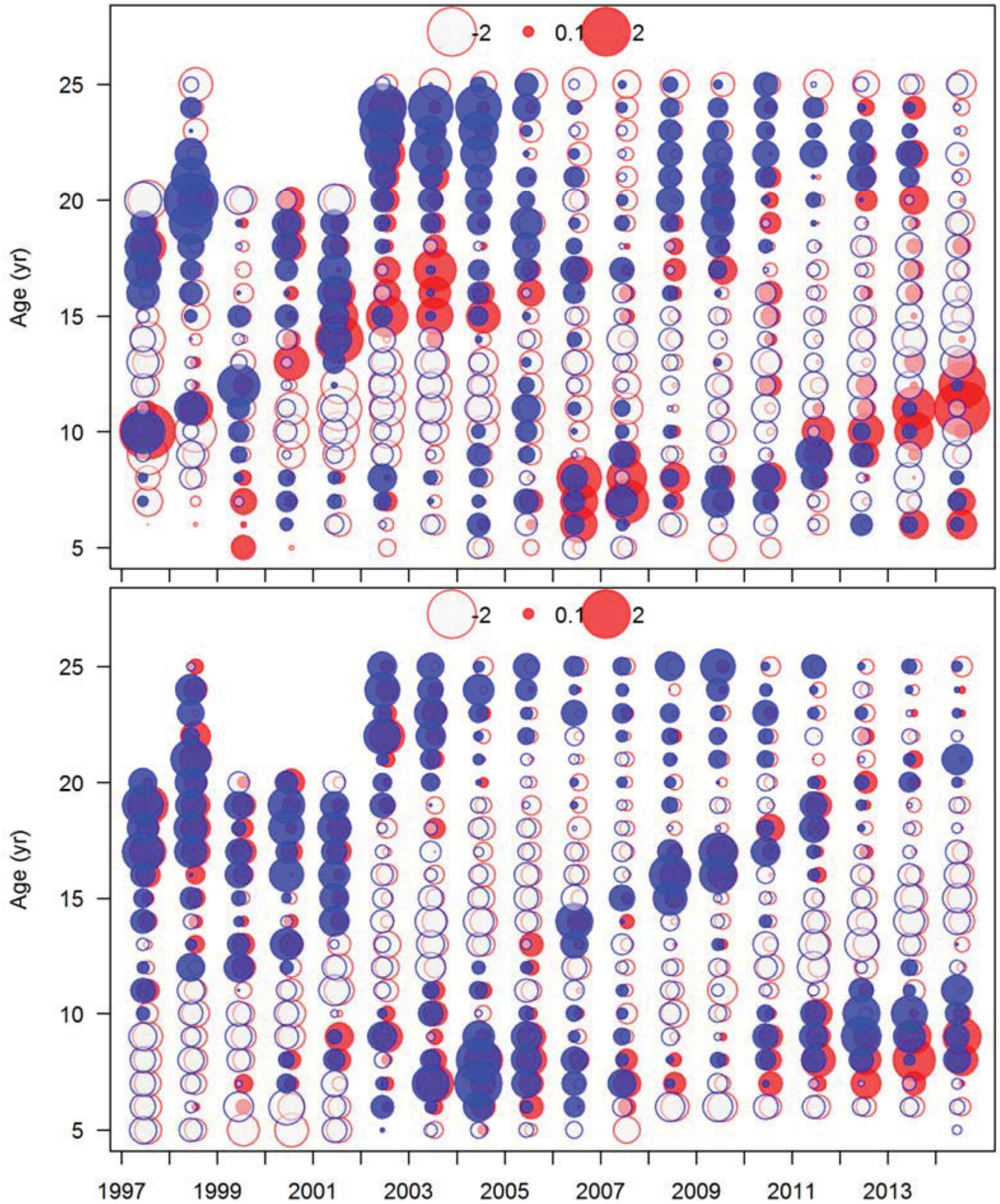
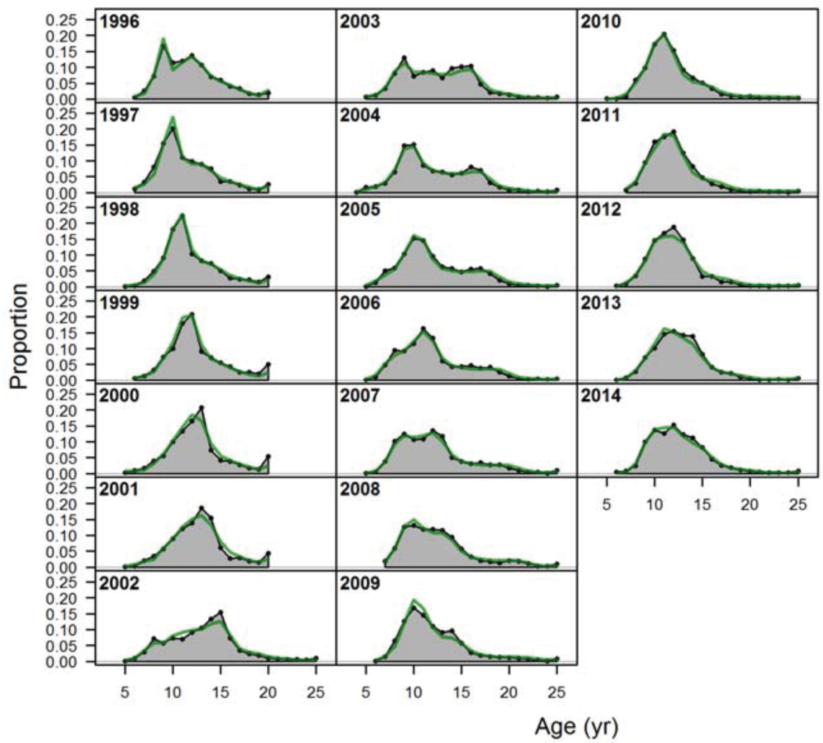


Figure 46. Standardized residuals to the age data for the survey in Area 4 (upper panel) and Area 4B (lower panel) in the AAF short model. Red and blue denote female and male residuals respectively.



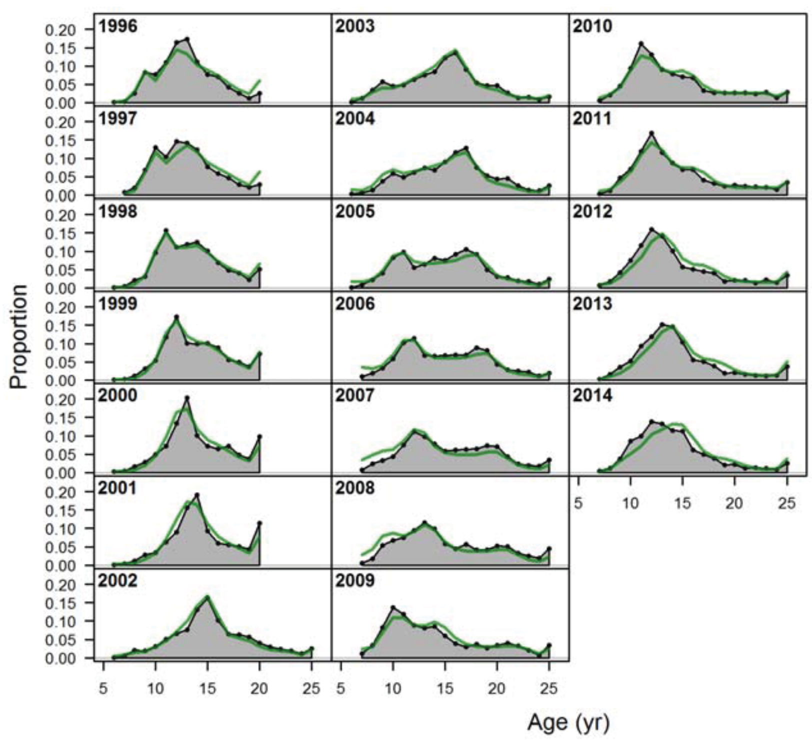
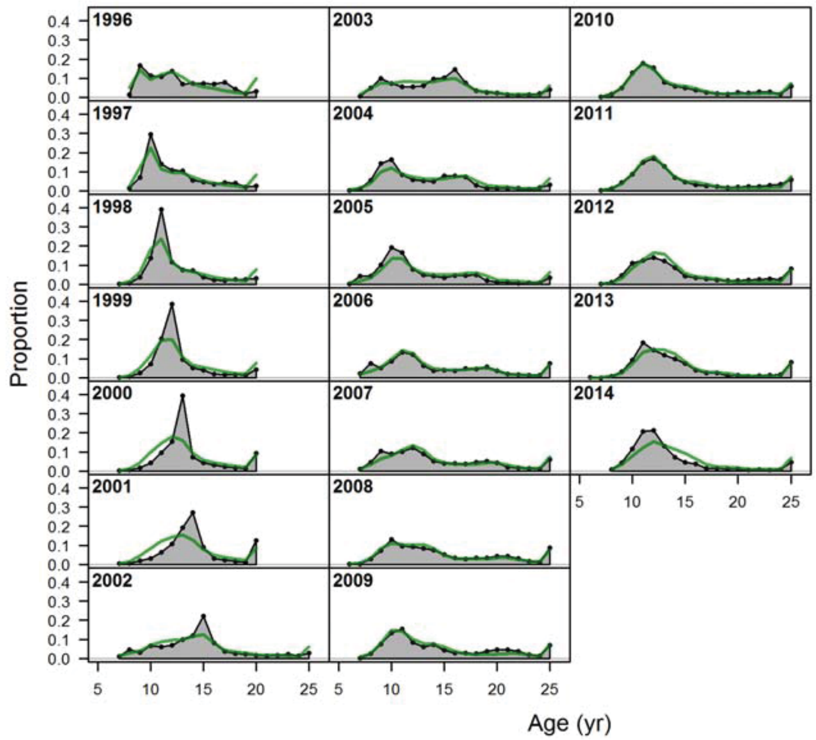


Figure 47. Fit to the age data for the commercial fishery in Area 2 (upper panel) and Area 3 (lower panel) in the AAF short model.



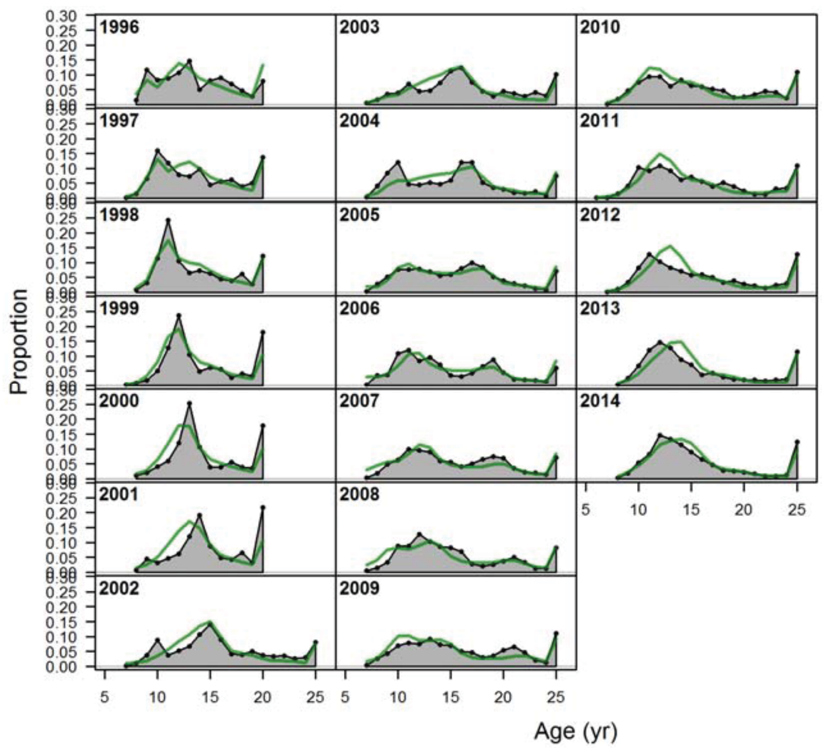
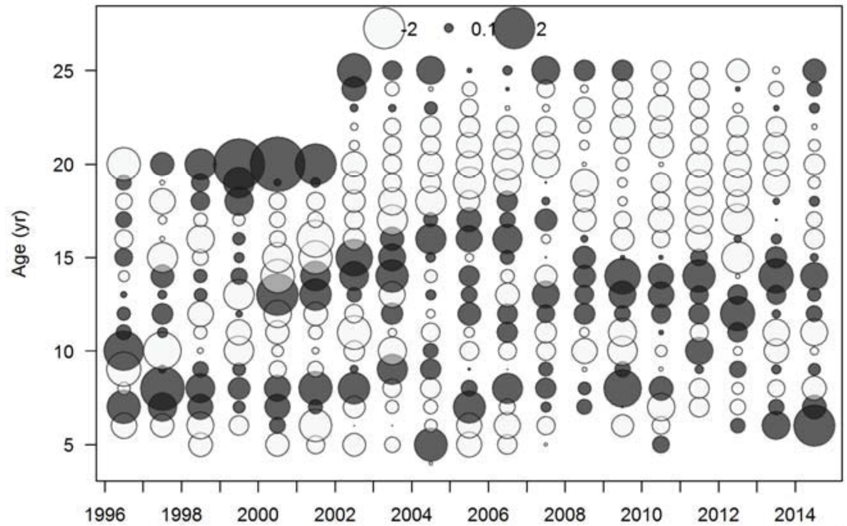


Figure 48. Fit to the age data for the commercial fishery in Area 4 (upper panel) and Area 4B (lower panel) in the AAF short model.



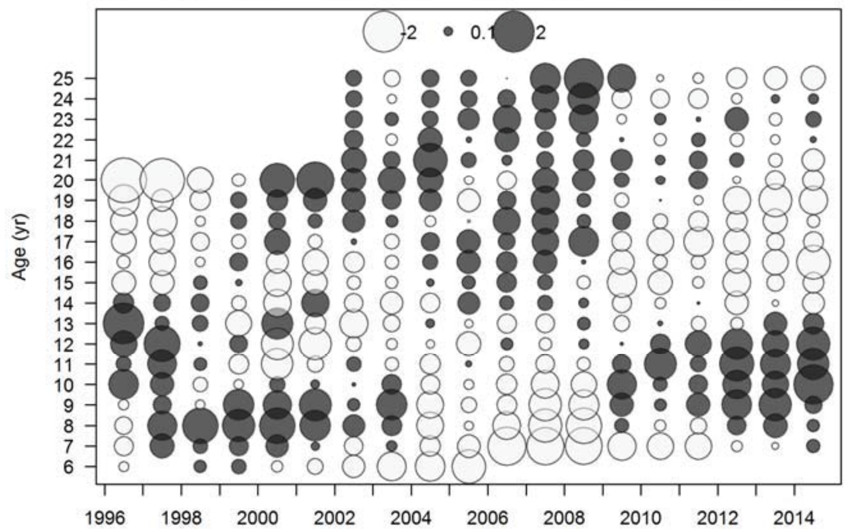


Figure 49. Standardized residuals to the age data for the commercial fishery in Area 2 (upper panel) and Area 3 (lower panel) in the AAF short model.

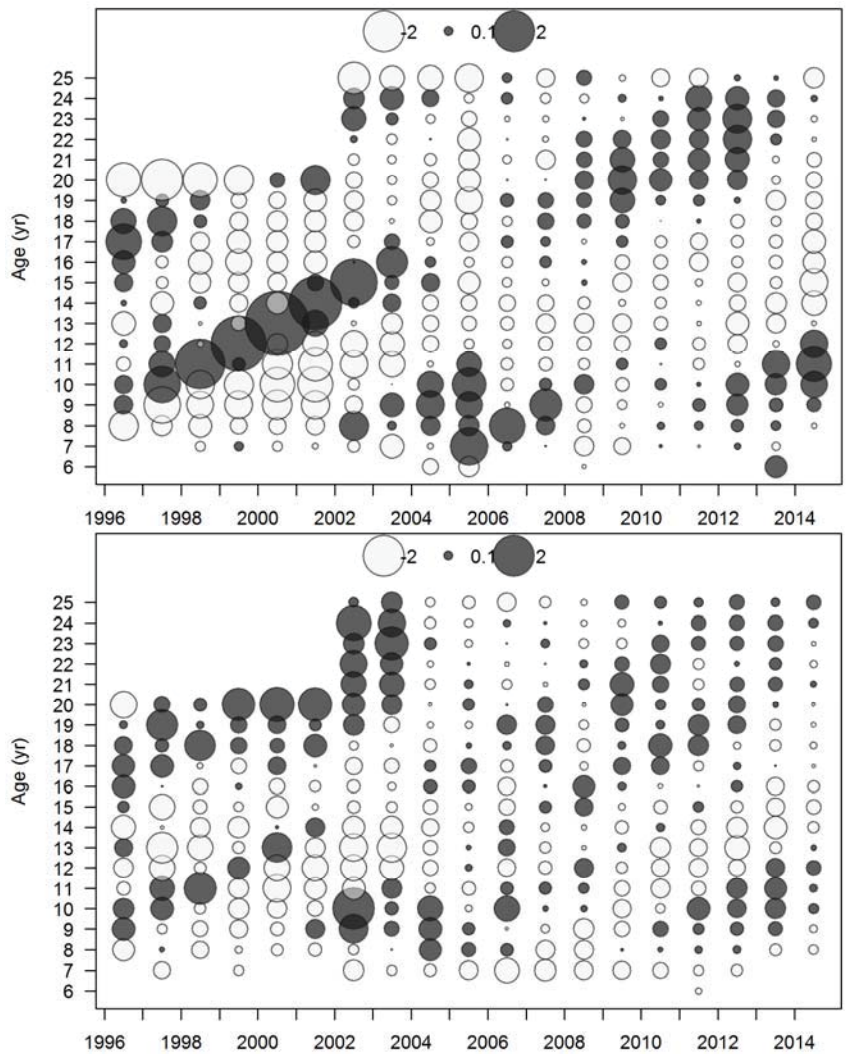


Figure 50. Standardized residuals to the age data for the commercial fishery in Area 4 (upper panel) and Area 4B (lower panel) in the AAF short model.

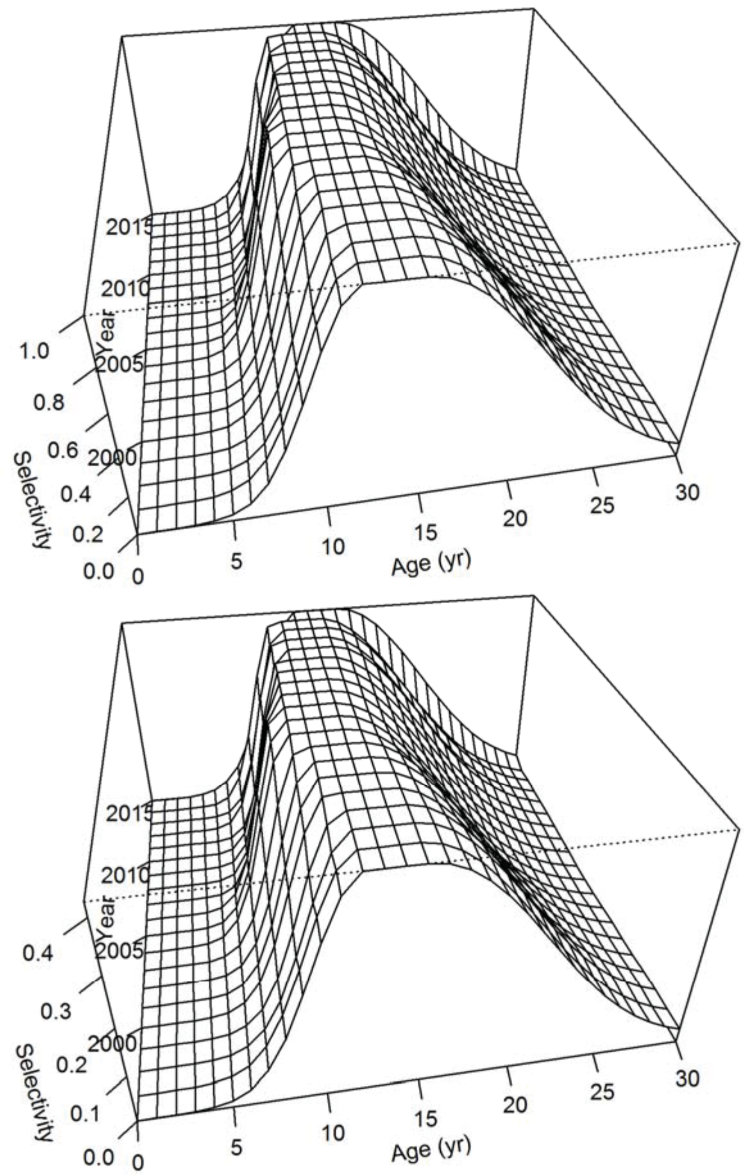


Figure 51. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 2 survey in the AAF short model.

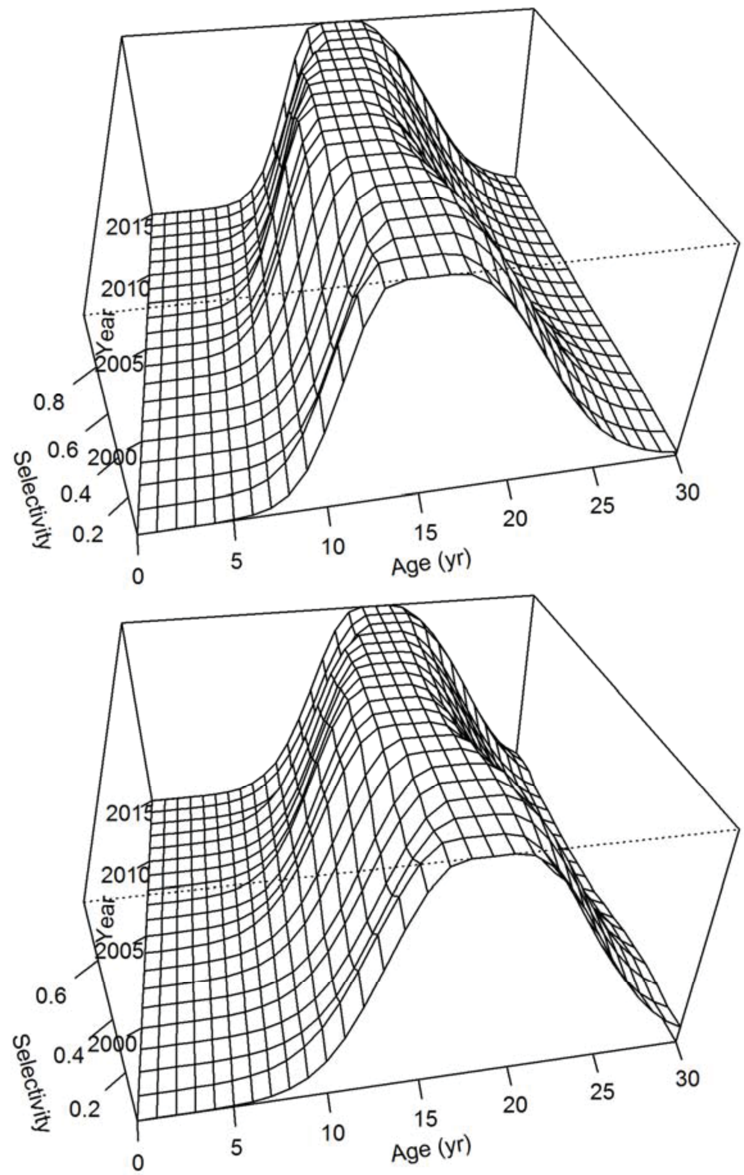


Figure 52. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 3 survey in the AAF short model.

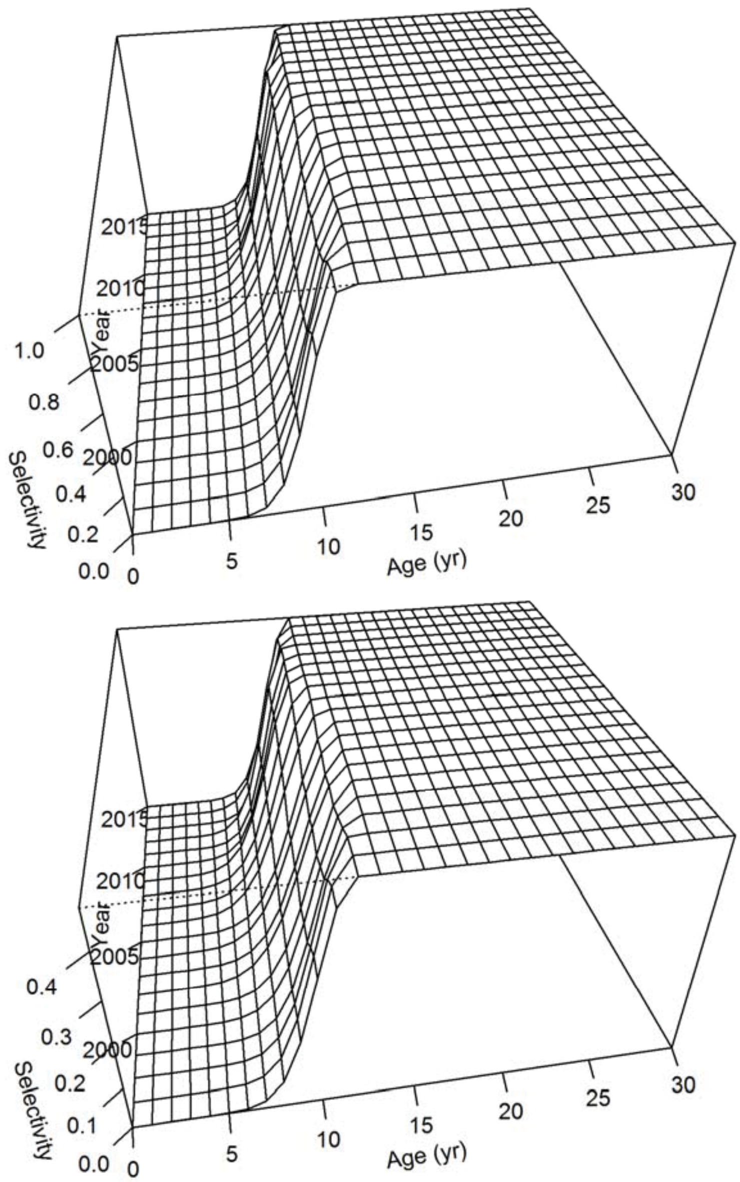


Figure 53. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4 survey in the AAF short model.

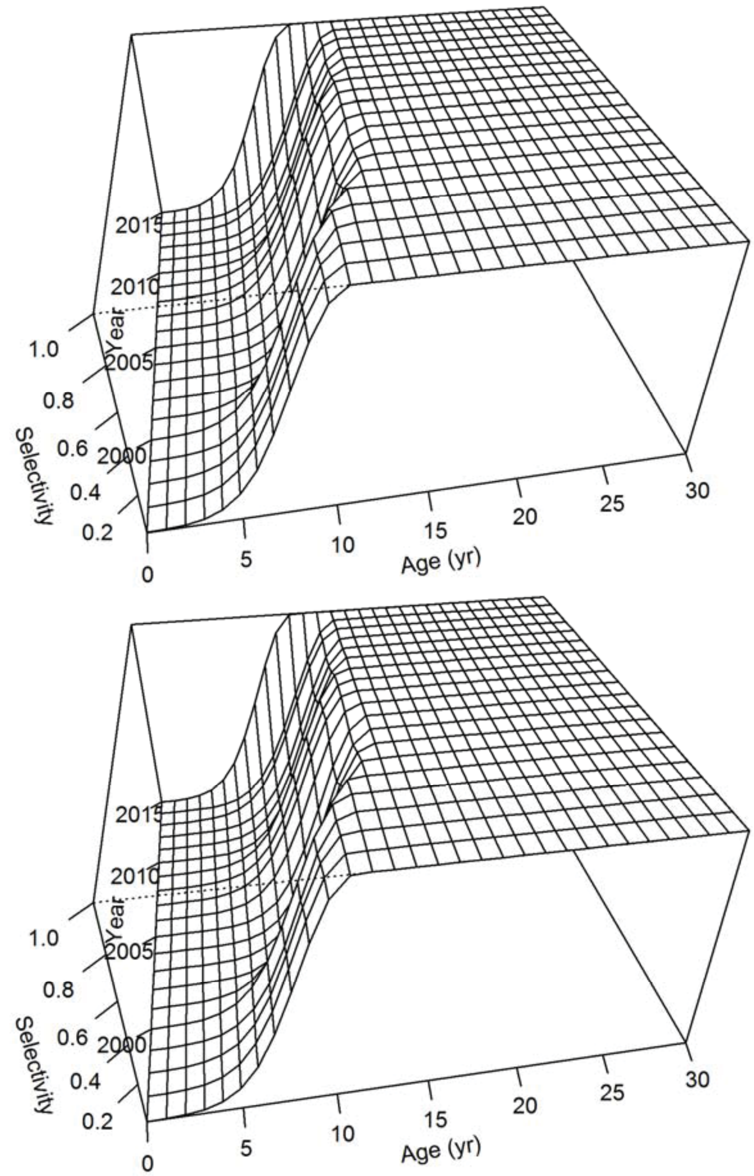


Figure 54. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4B survey in the AAF short model.

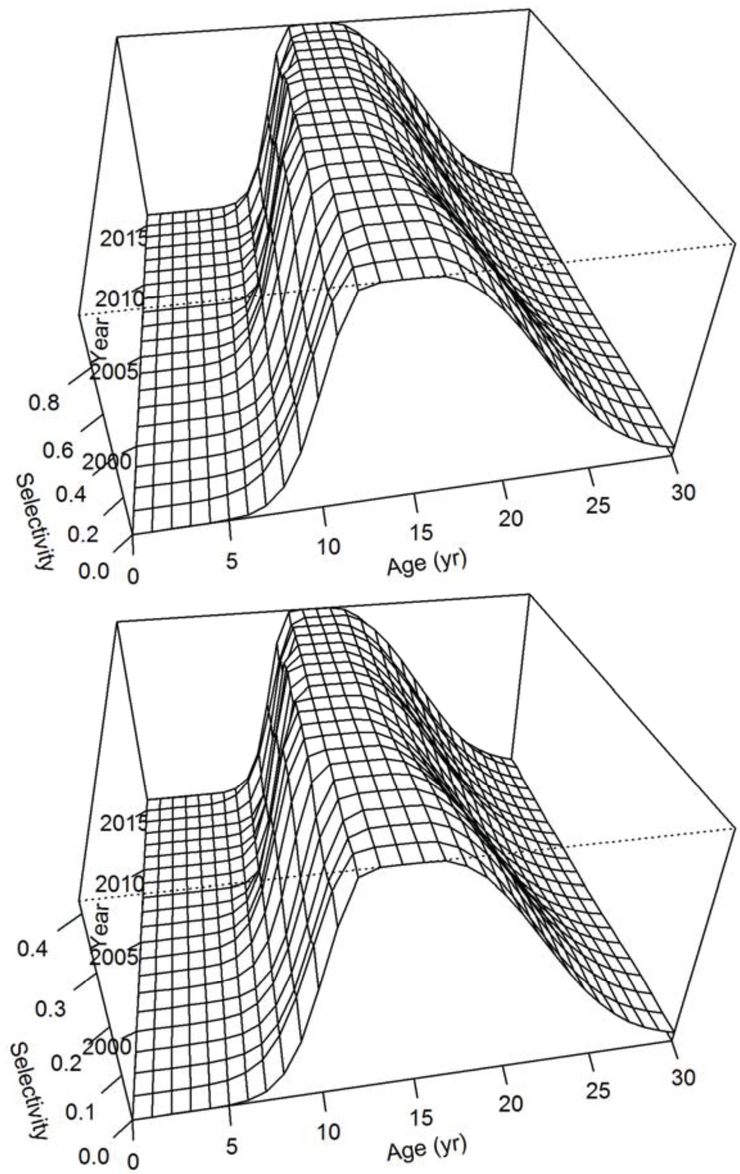


Figure 55. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 2 fishery in the AAF short model.

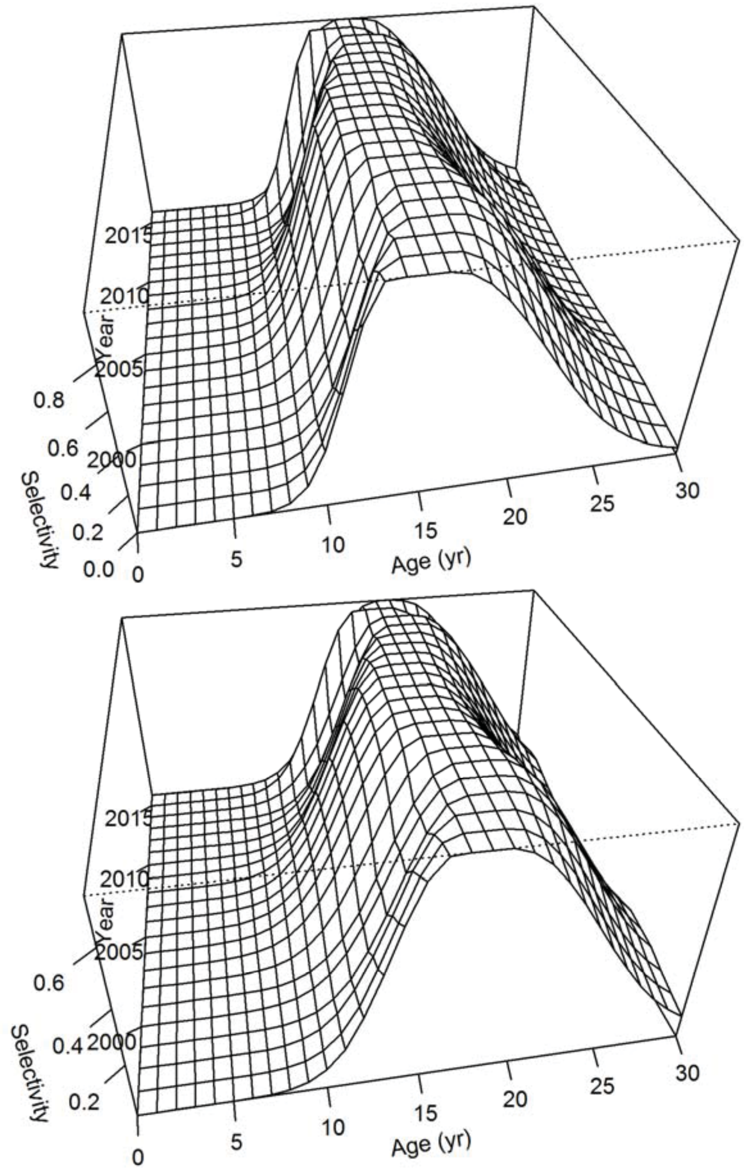


Figure 56. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 3 fishery in the AAF short model.

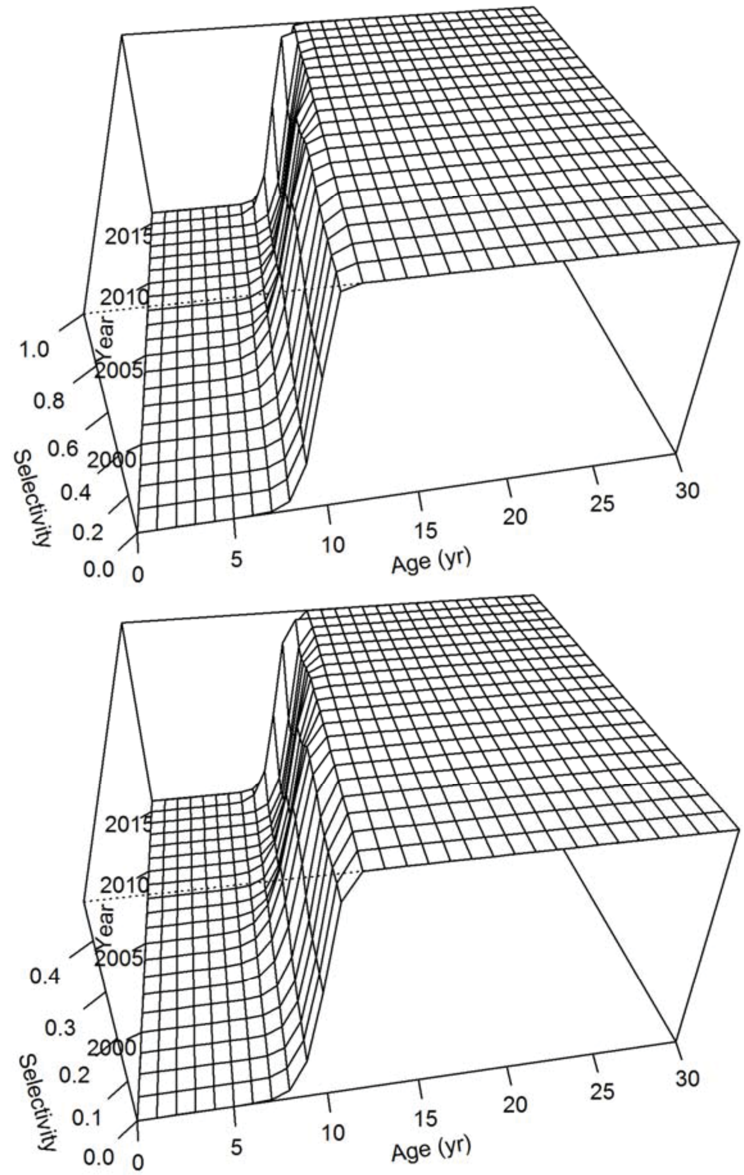


Figure 57. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4 fishery in the AAF short model.

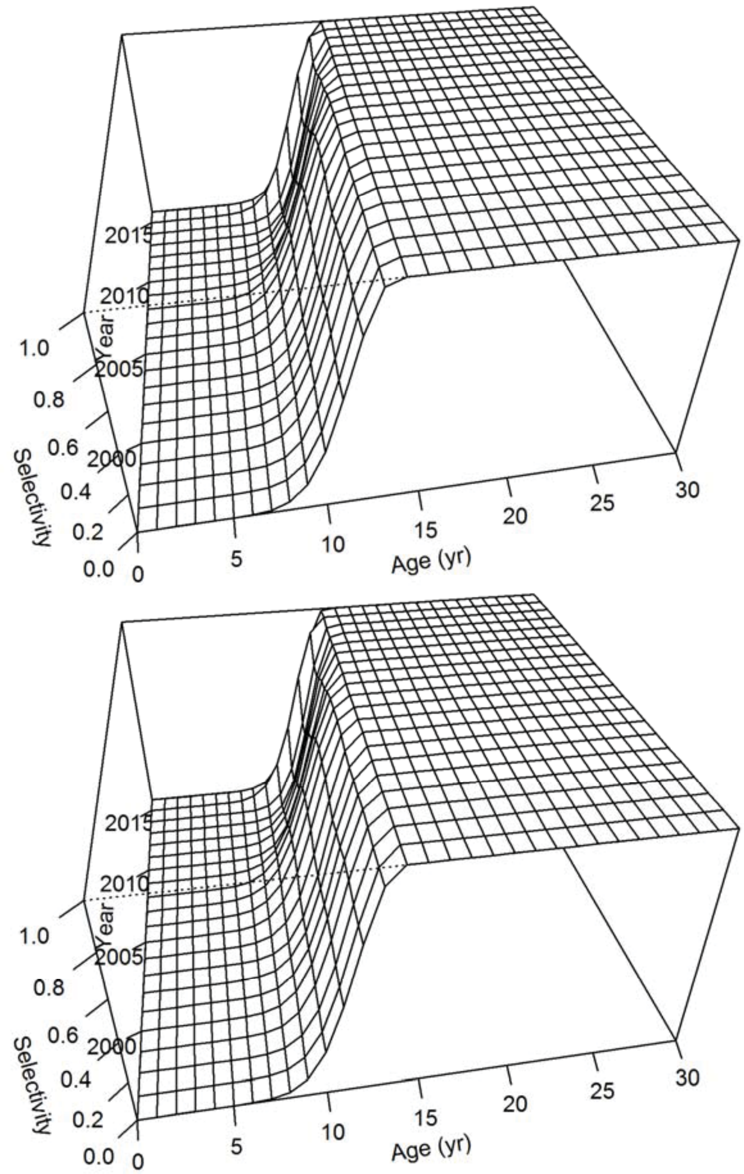


Figure 58. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4B fishery in the AAF short model.

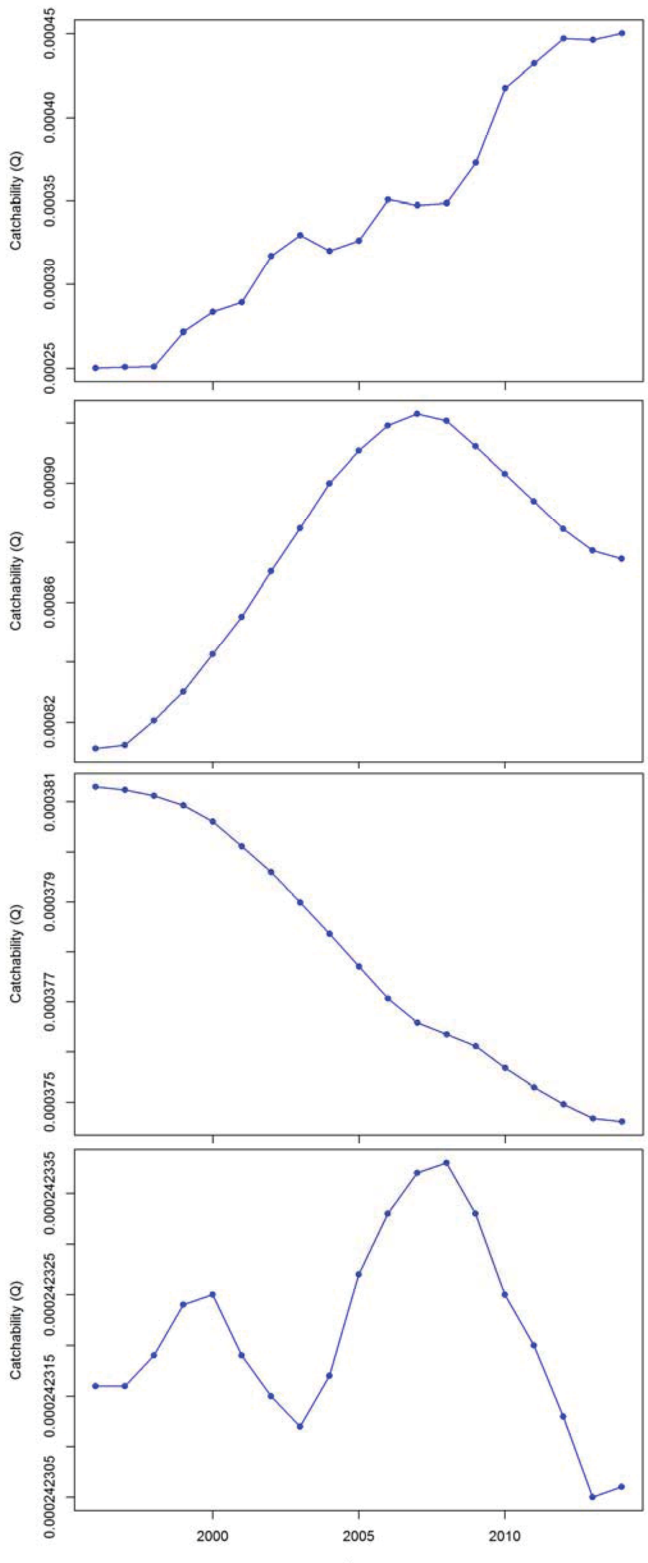


Figure 59. Estimated trends in fishery catchability for Area 2 (upper panel), Area 3 (second panel), Area 4 (third panel) and Area 4B (lower panel) in the AAF short model.

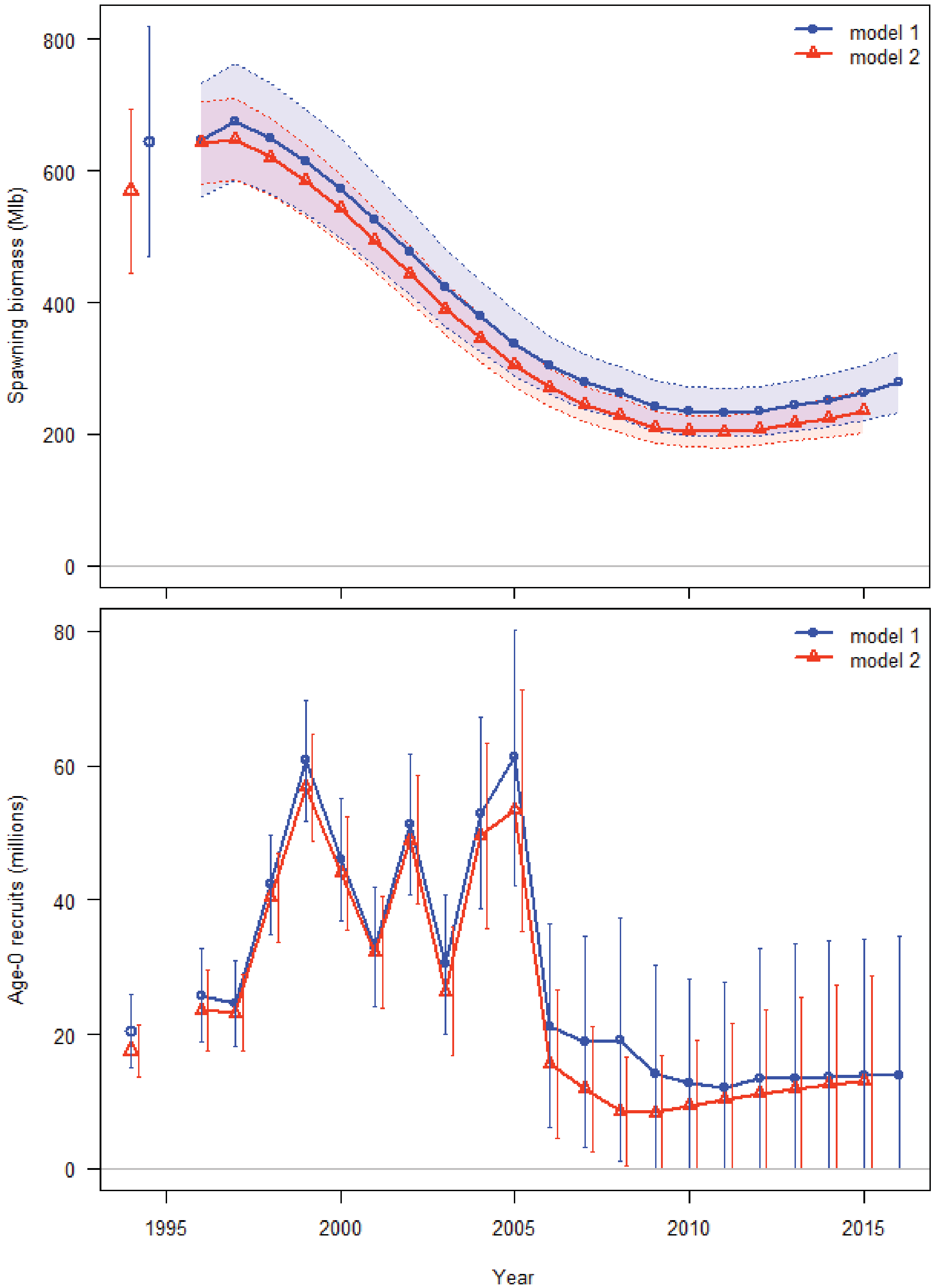


Figure 60. Comparison of the spawning biomass (upper panel) and recruitment (lower panel) from the 2014, and preliminary 2015 AAF short models including all updates to data and model structure.

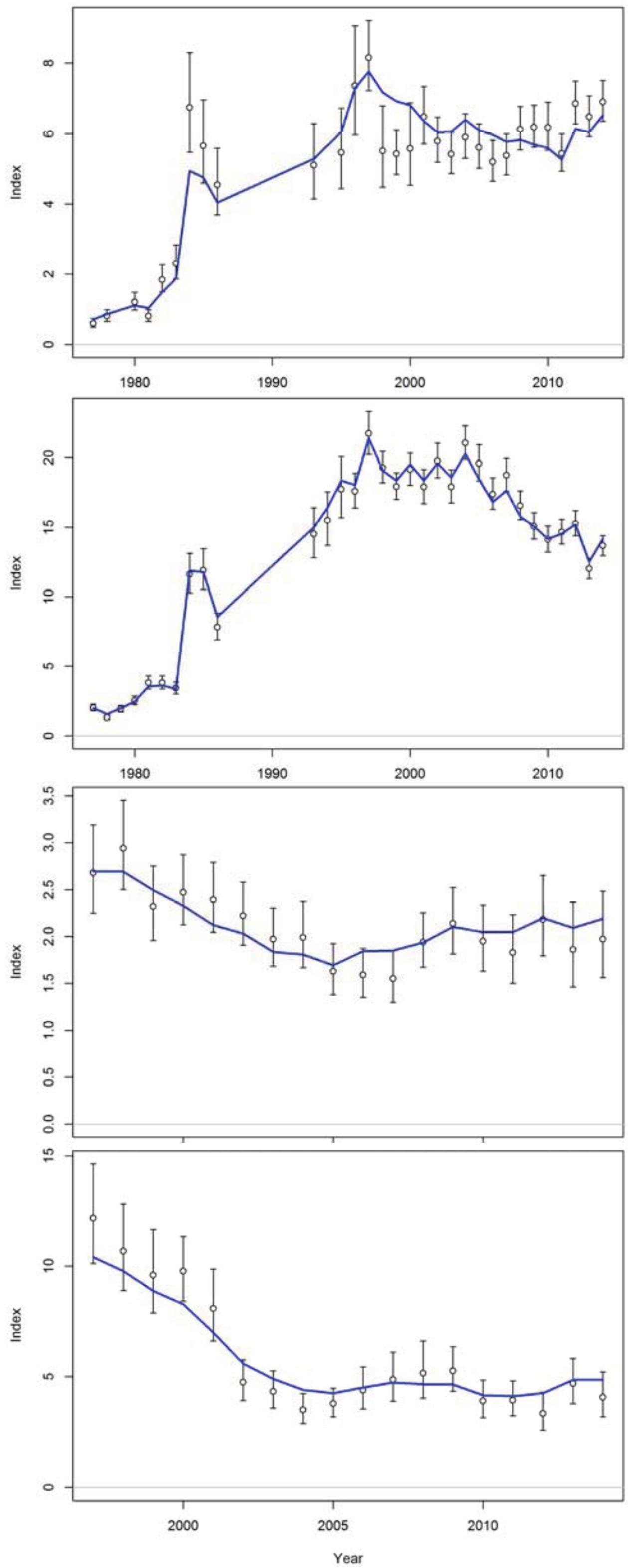


Figure 61. Fit to the index of abundance from the survey (numbers-per-unit-effort) for Area 2 (upper panel), Area 3(second panel), Area 4 (third panel) and Area 4B (bottom panel) in the AAF long model.

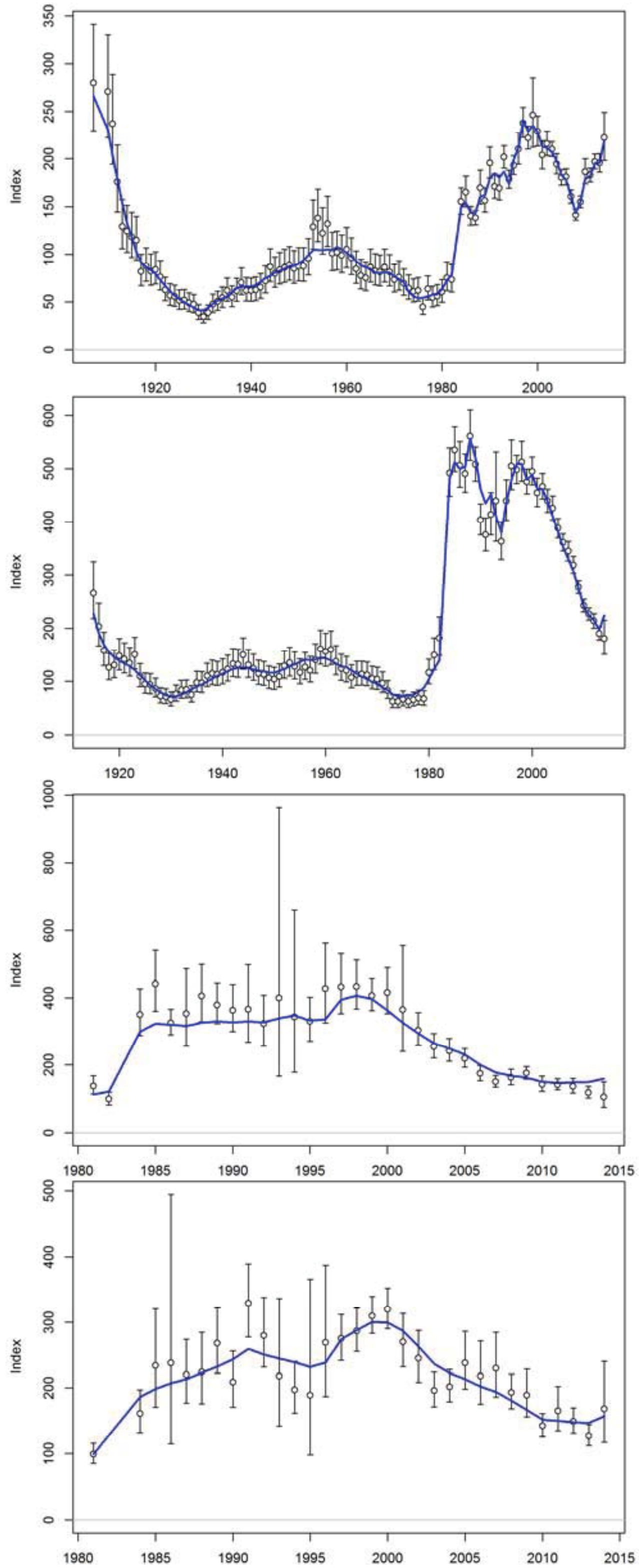


Figure 62. Fit to the index of abundance from the commercial fishery (weight-per-unit-effort) for Area 2 (upper panel), Area 3(second panel), Area 4 (third panel) and Area 4B (bottom panel) in the AAF long model.

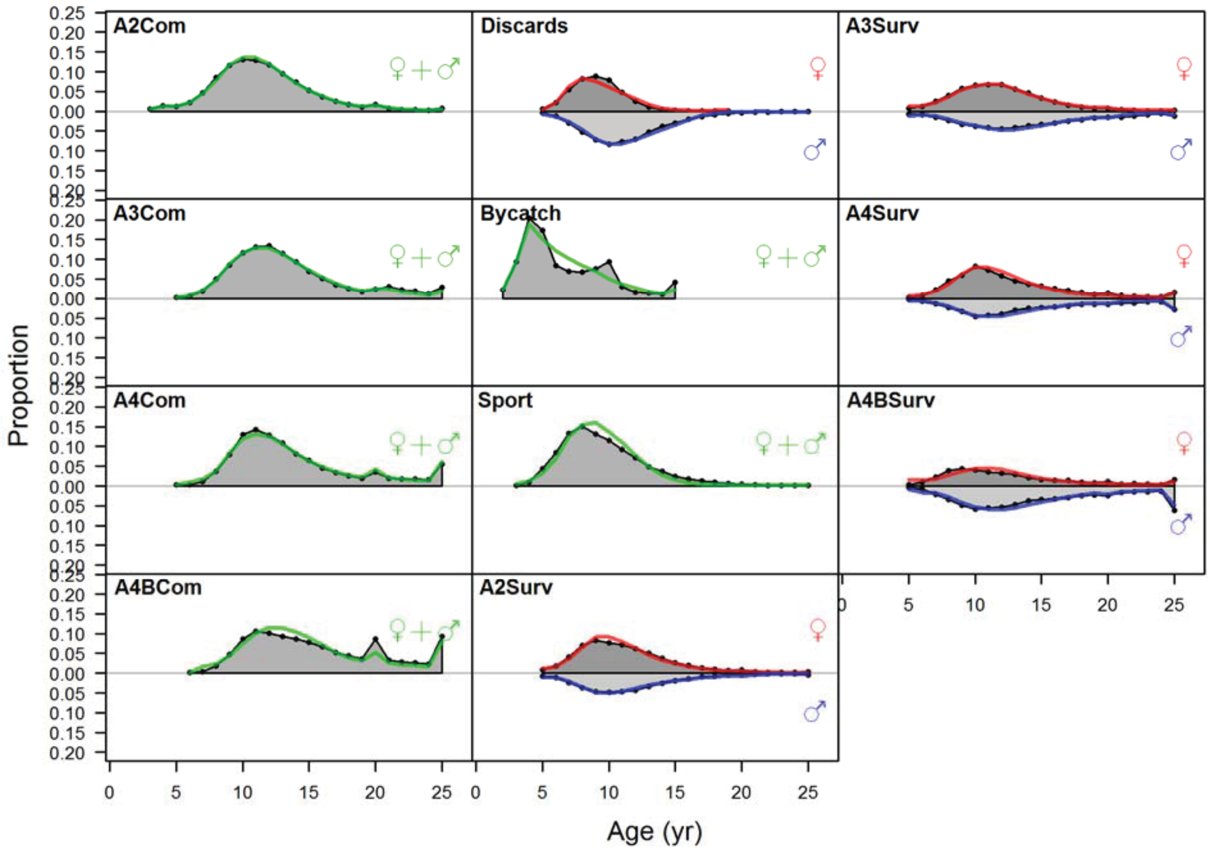


Figure 63. Aggregate fit (observed and expected values summed across all years) to the age data for each fleet in the AAF long model.

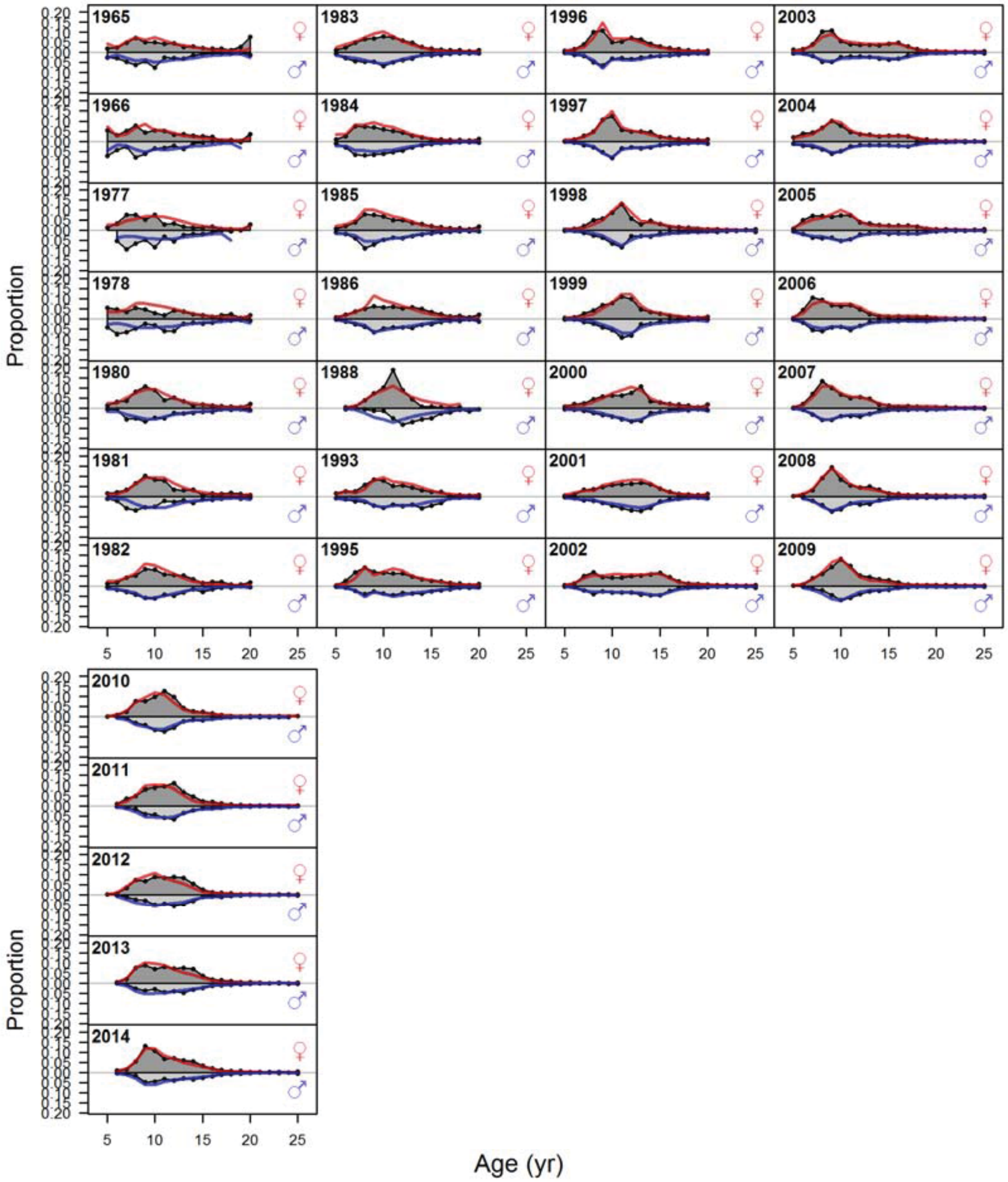


Figure 64. Fit to the age data for the survey in Area 2 in the AAF long model.

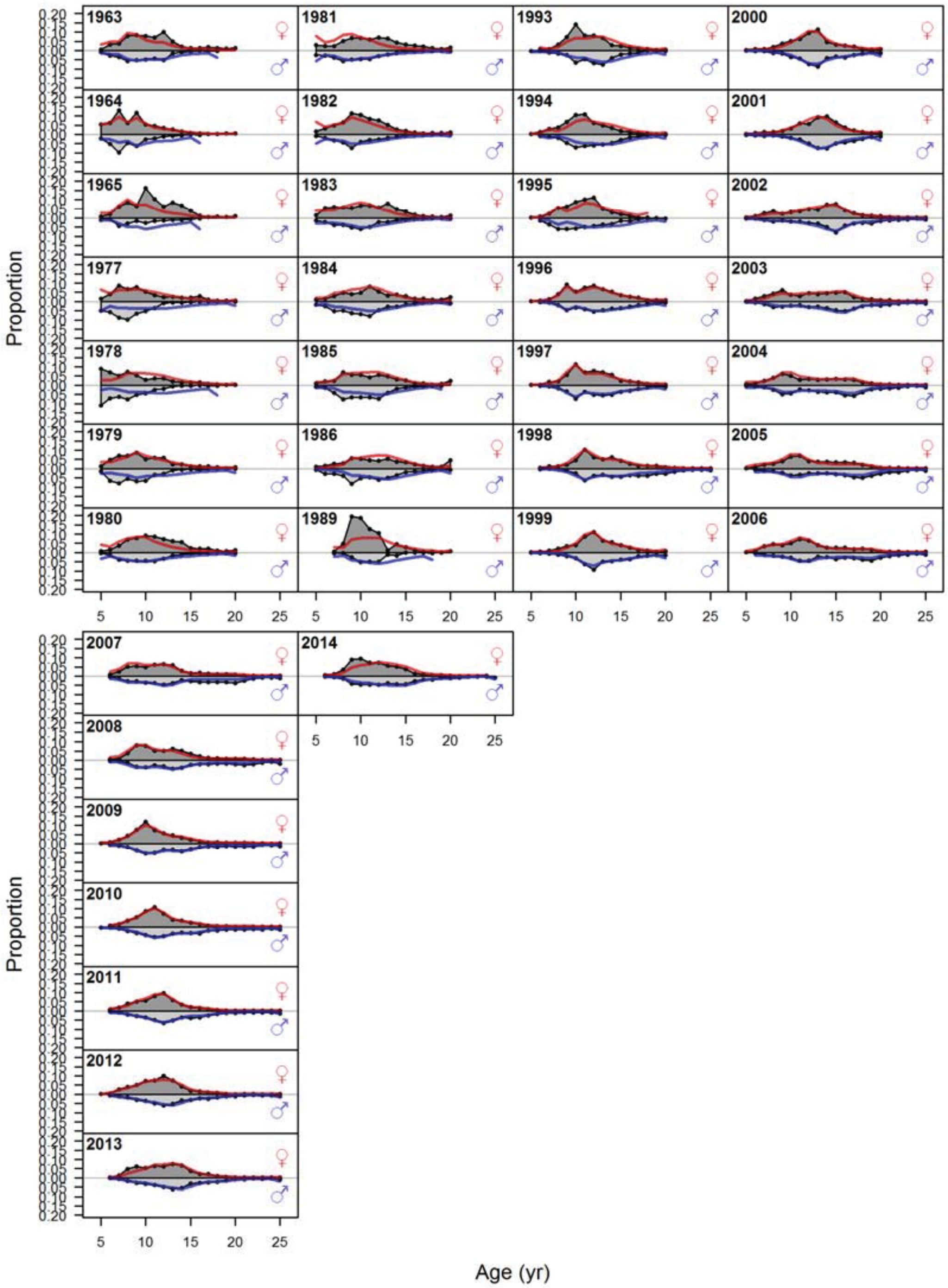


Figure 65. Fit to the age data for the survey in Area 3 in the AAF long model.

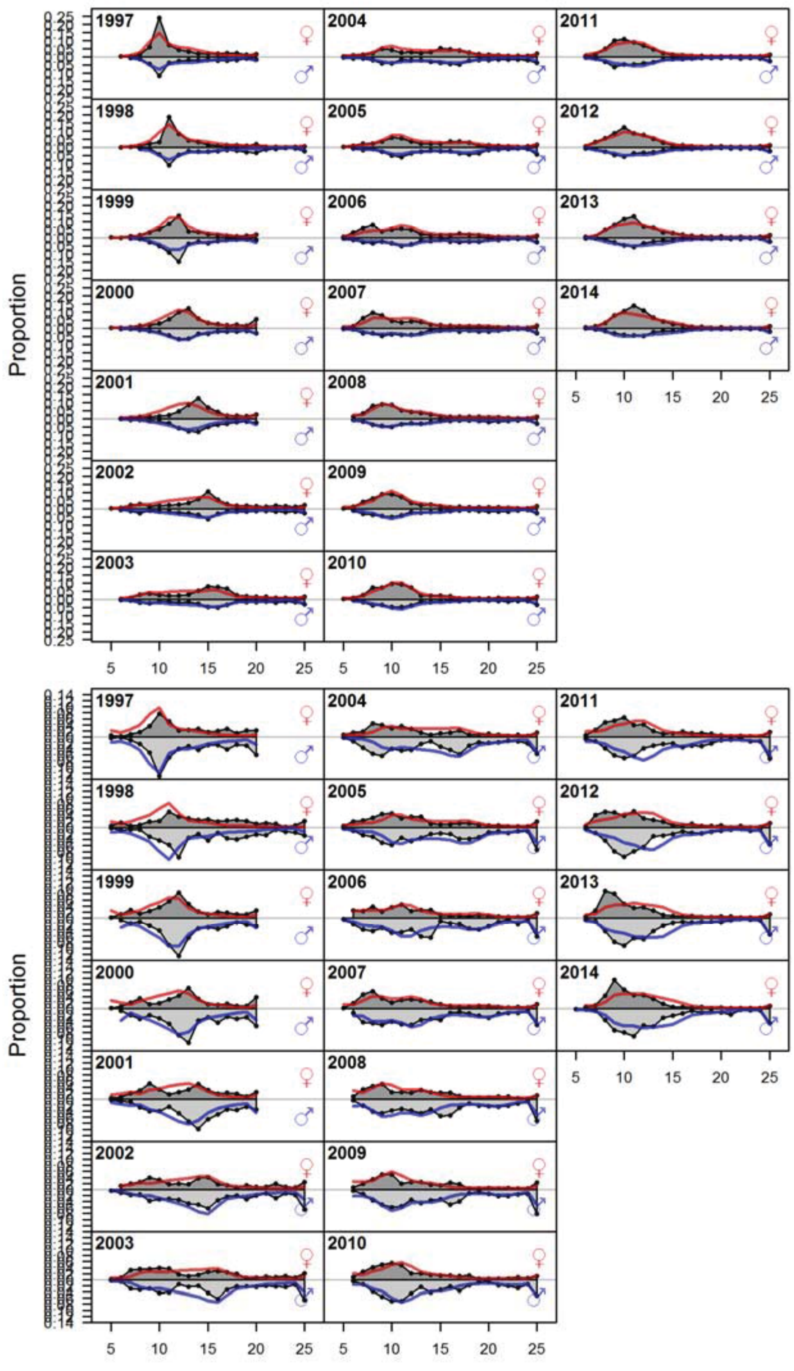


Figure 66. Fit to the age data for the survey in Area 4 (upper panel) and Area 4B (lower panel) in the AAF long model.

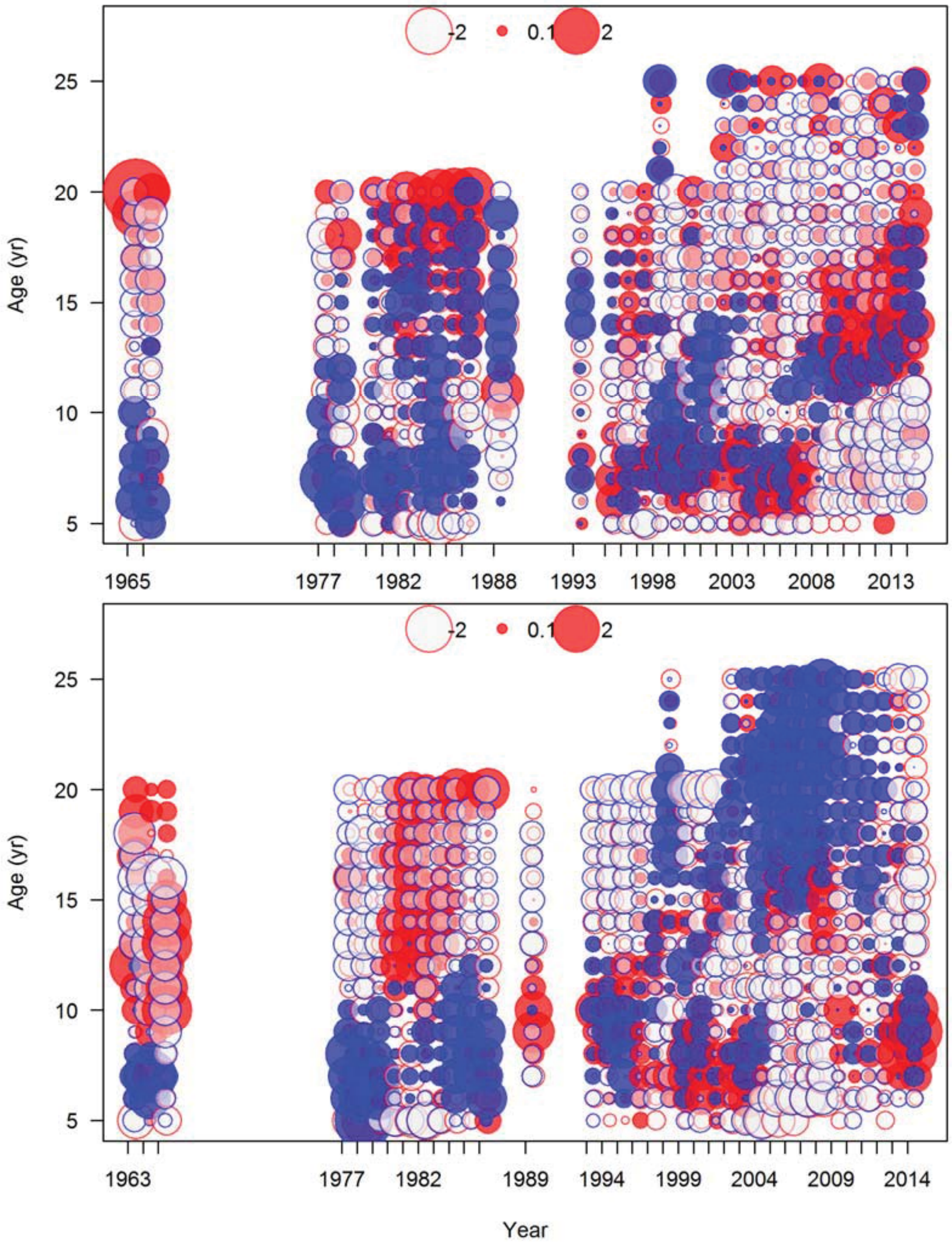


Figure 67. Standardized residuals to the age data for the survey in Area 2 (upper panel) and Area 3 (lower panel) in the AAF long model. Red and blue denote female and male residuals respectively.

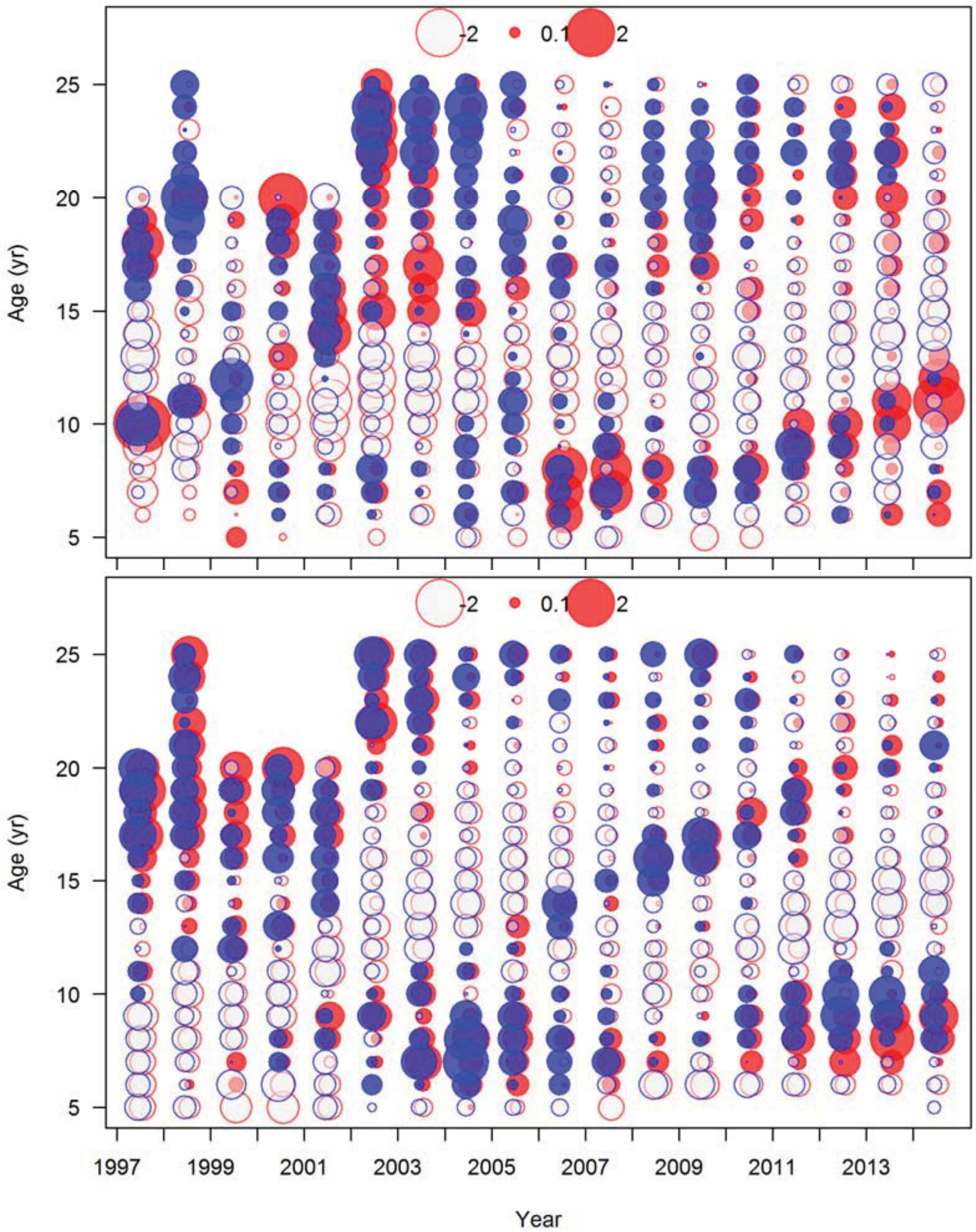


Figure 68. Standardized residuals to the age data for the survey in Area 4 (upper panel) and Area 4B (lower panel) in the AAF long model. Red and blue denote female and male residuals respectively.

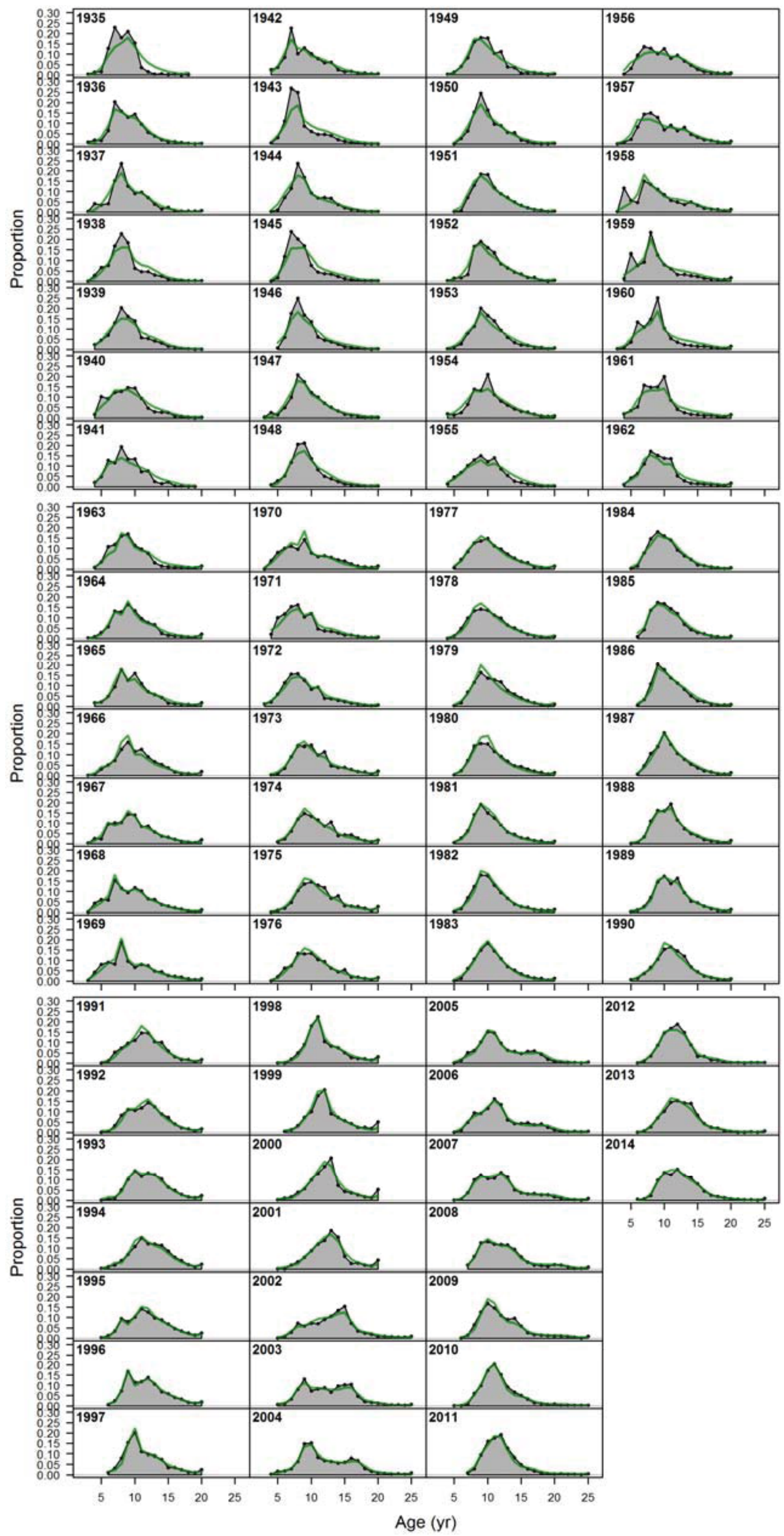


Figure 69. Fit to the age data for the commercial fishery in Area 2 in the AAF long model.

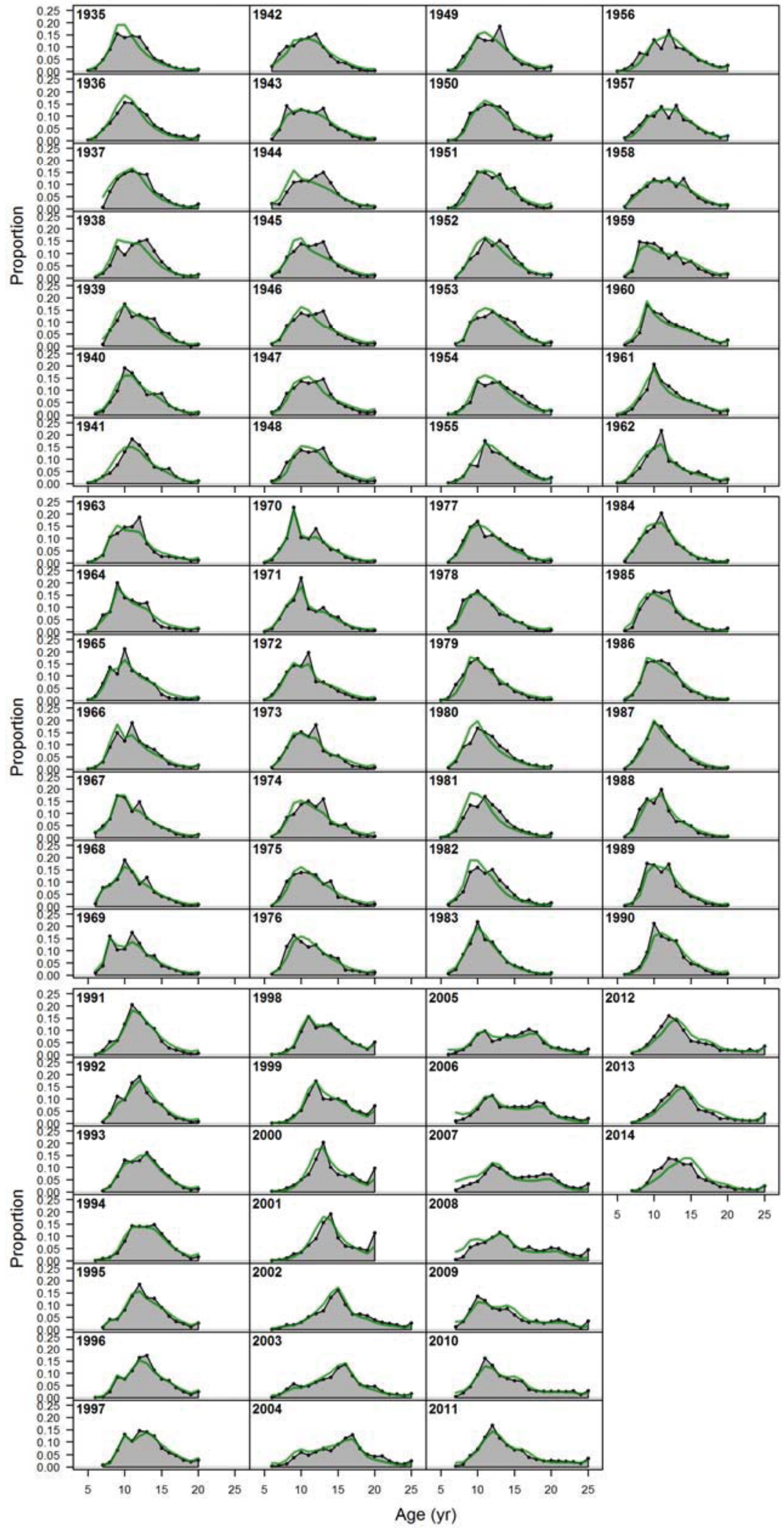


Figure 70. Fit to the age data for the commercial fishery in Area 3 in the AAF long model.

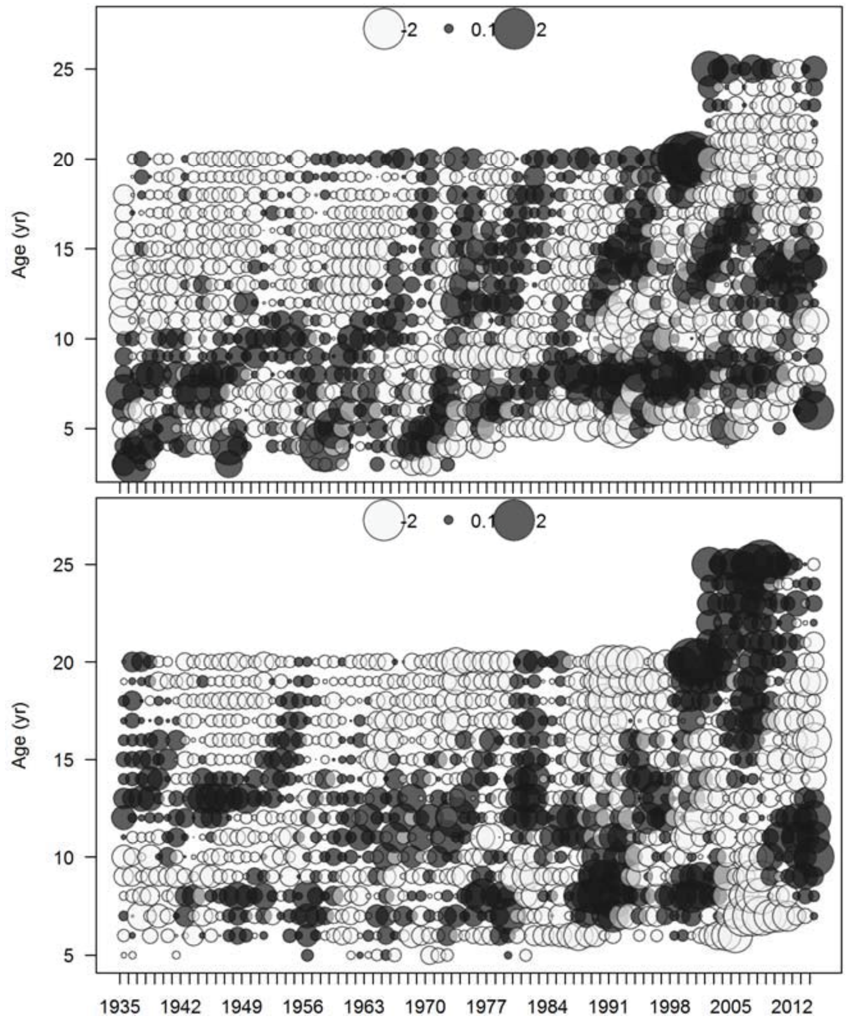


Figure 71. Standardized residuals to the age data for the commercial fishery in Area 2 (upper panel) and Area 3 (lower panel) in the AAF long model.

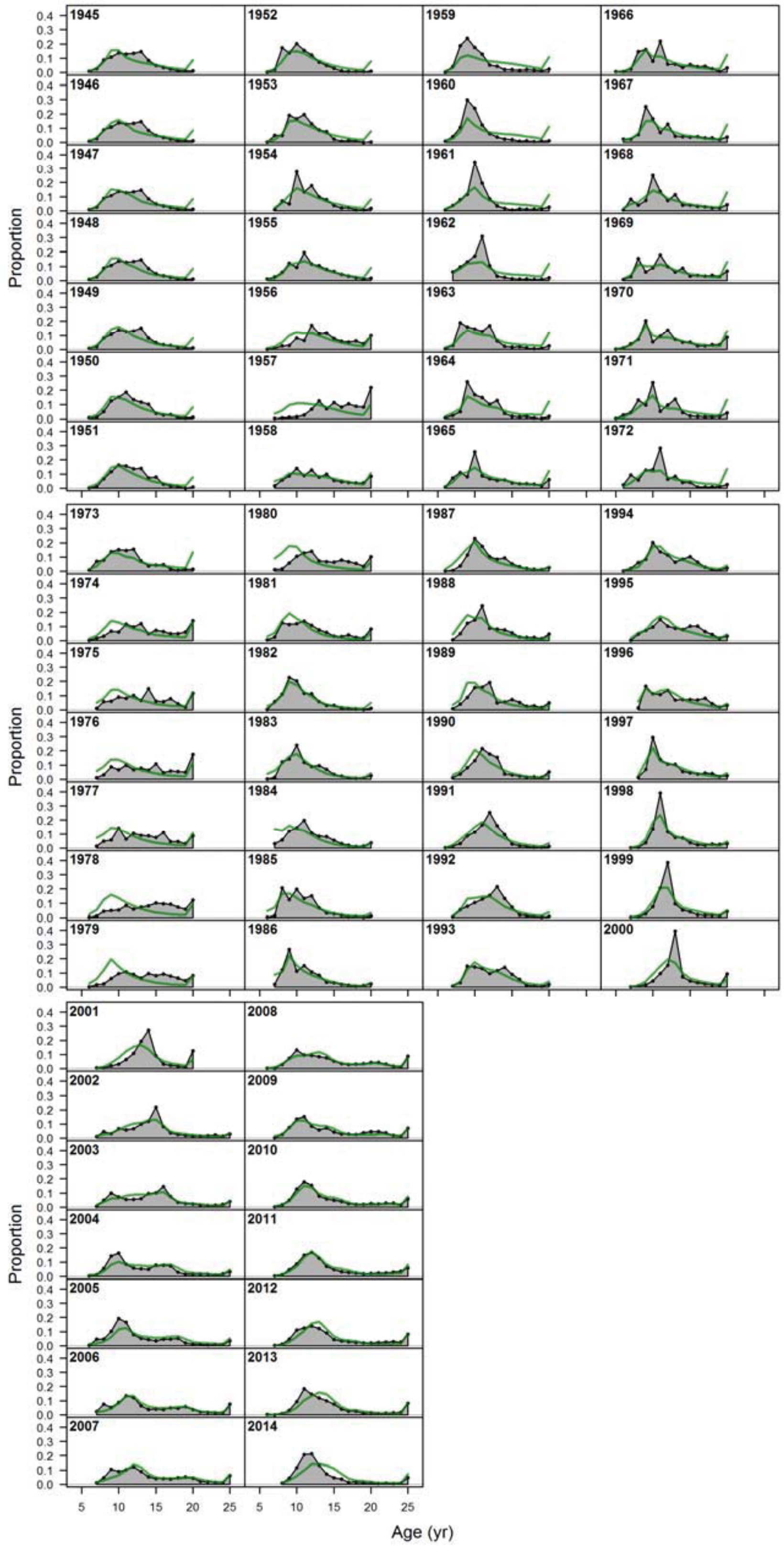


Figure 72a. Fit to the age data for the commercial fishery in Area 4 in the AAF long model.

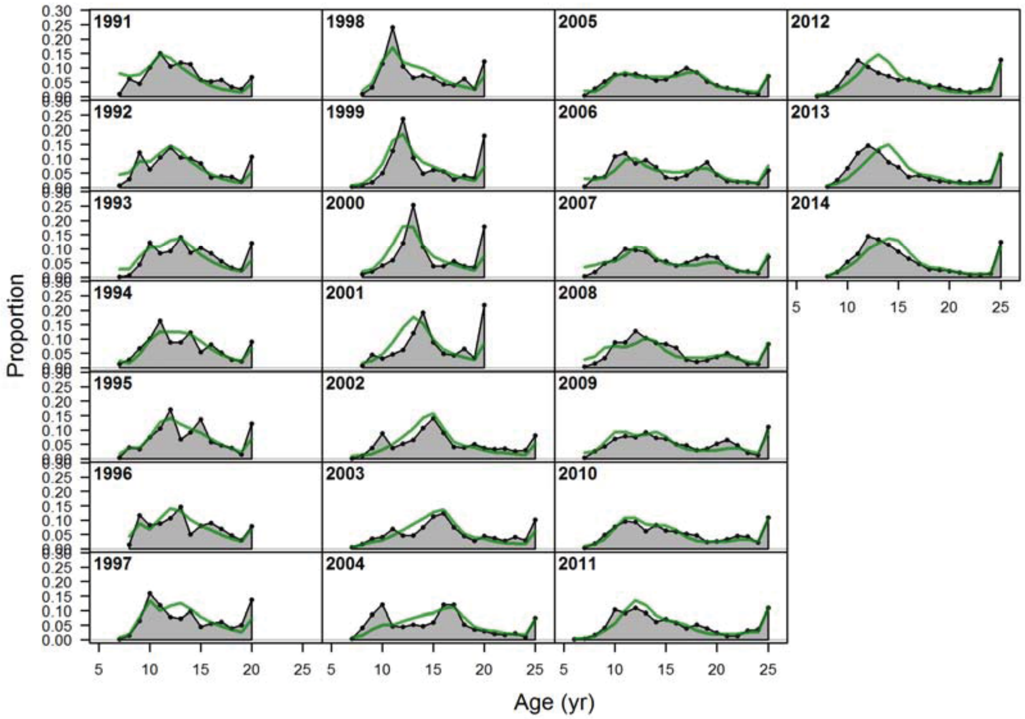


Figure 72b. Fit to the age data for the commercial fishery in Area 4B in the AAF long model.

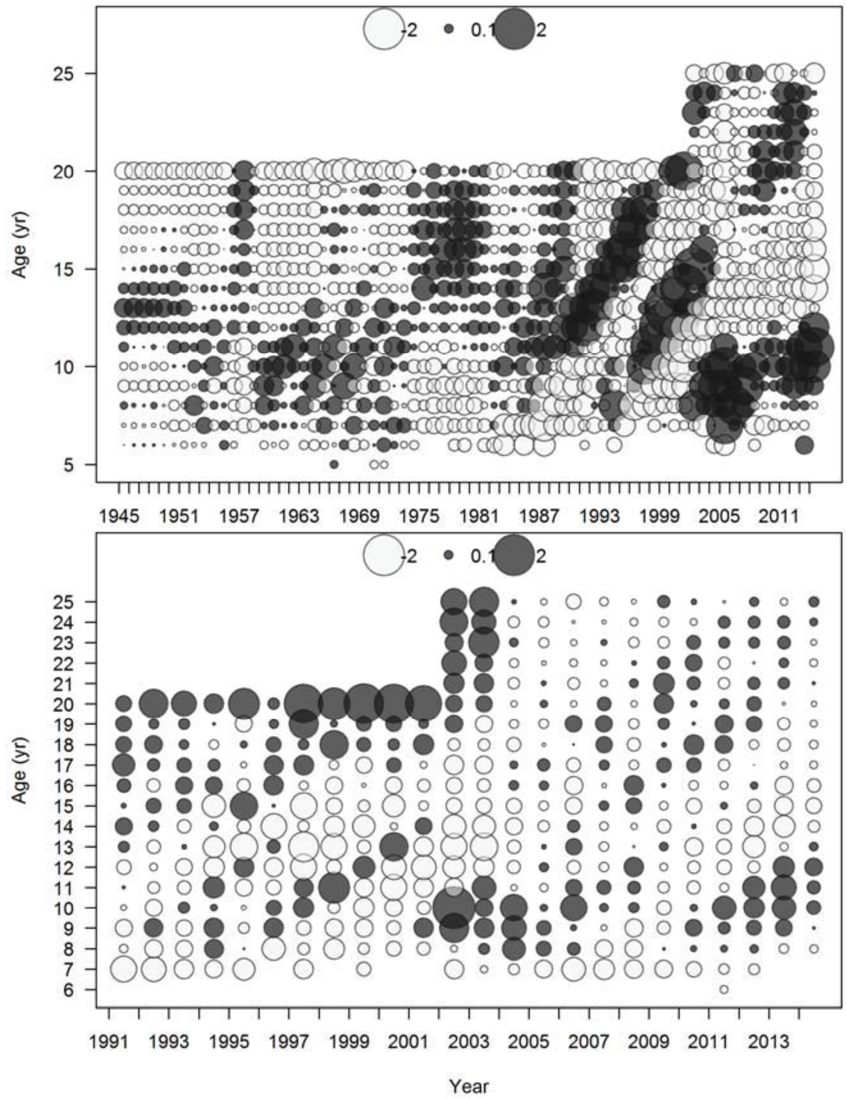


Figure 73. Standardized residuals to the age data for the commercial fishery in Area 4 (upper panel) and Area 4B (lower panel) in the AAF long model.

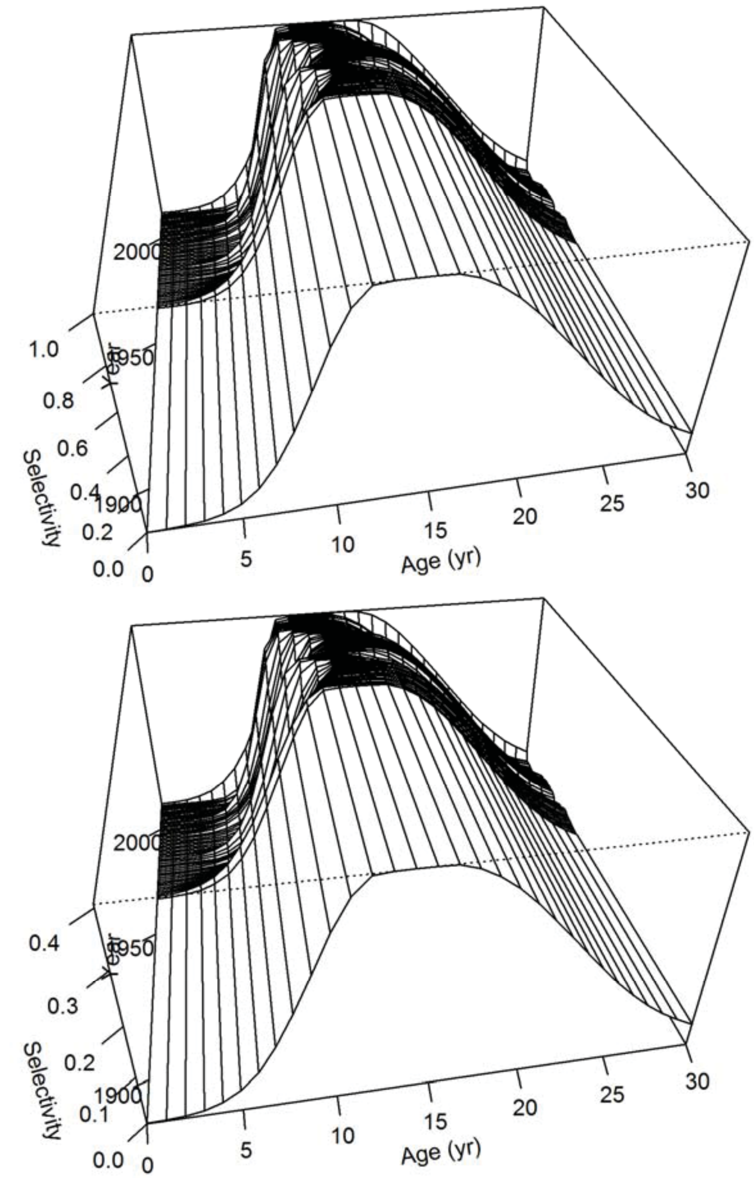


Figure 74. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 2 survey in the AAF long model.

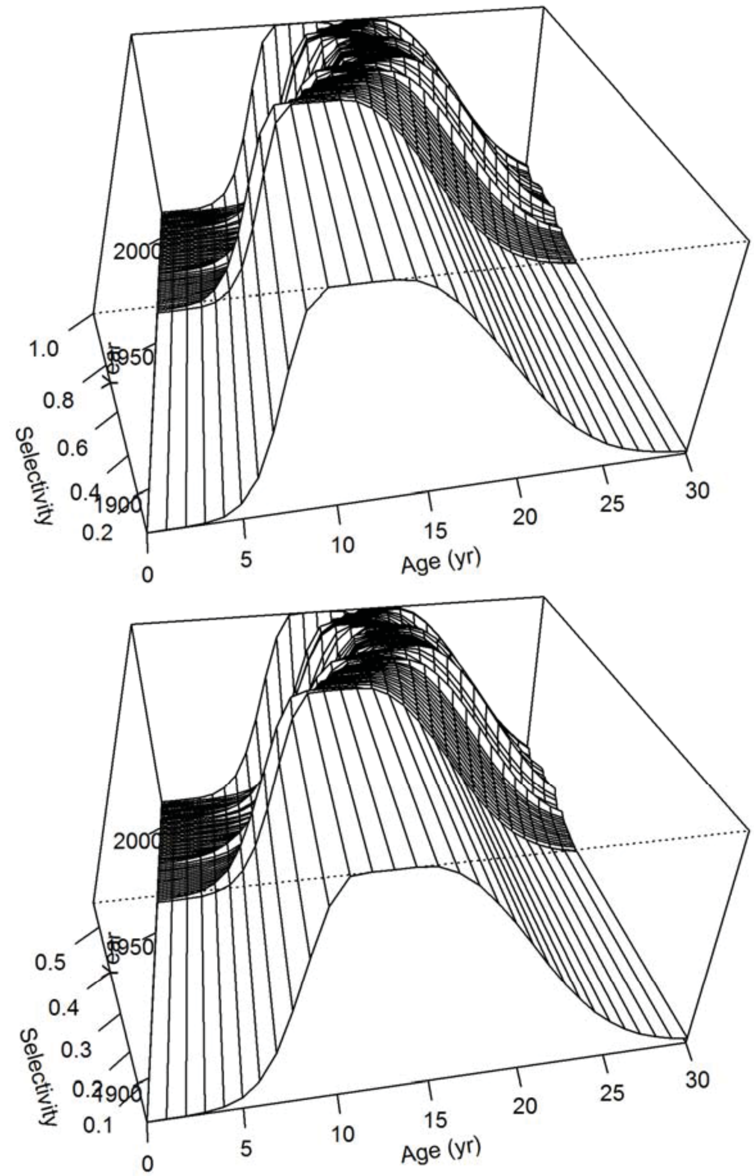


Figure 75. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 3 survey in the AAF long model.

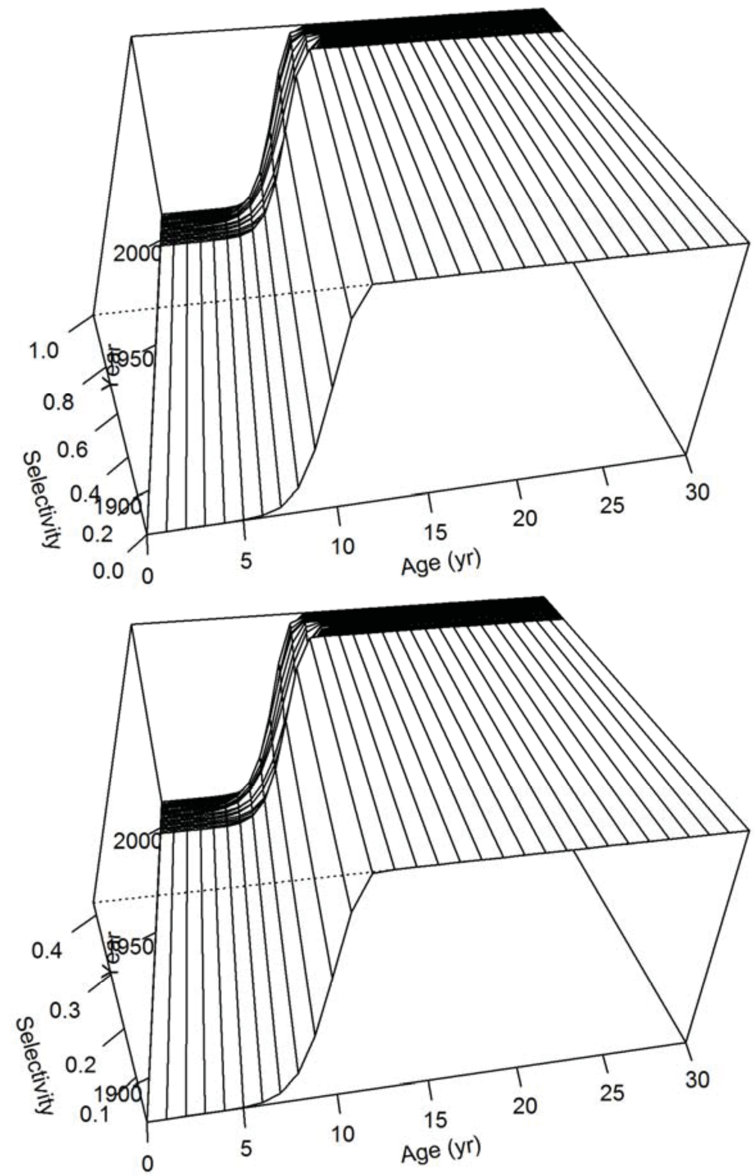


Figure 76. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4 survey in the AAF long model.

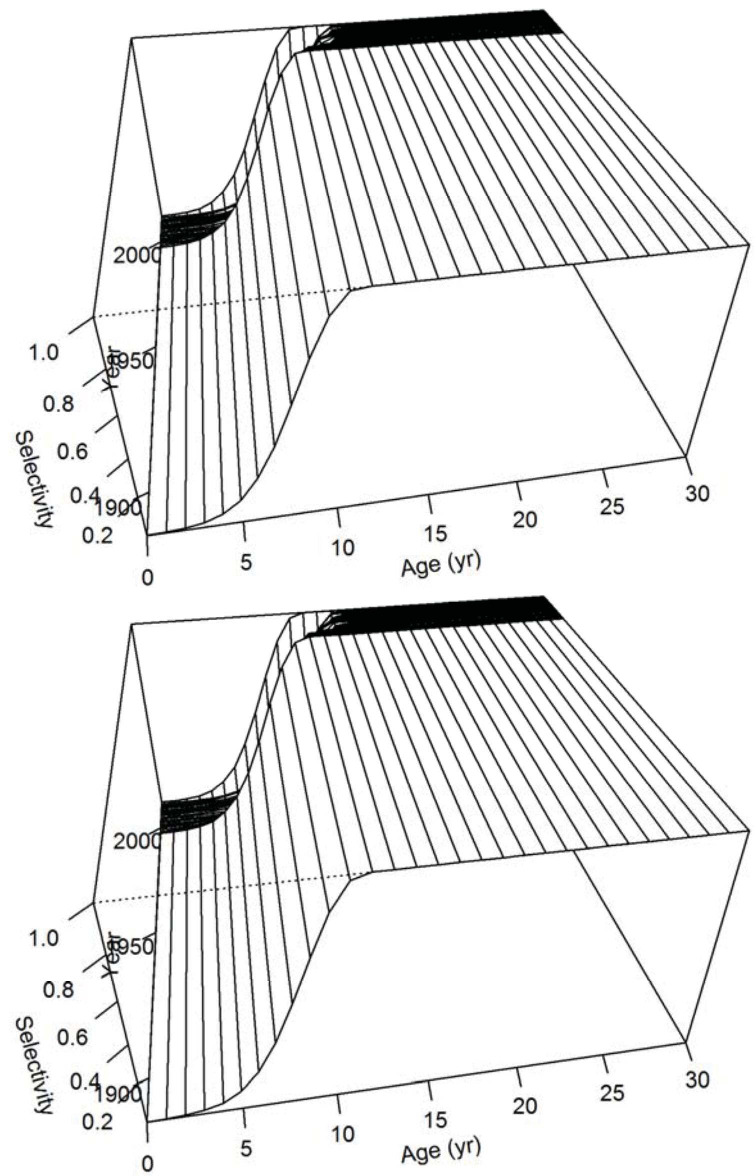


Figure 77. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4B survey in the AAF long model.

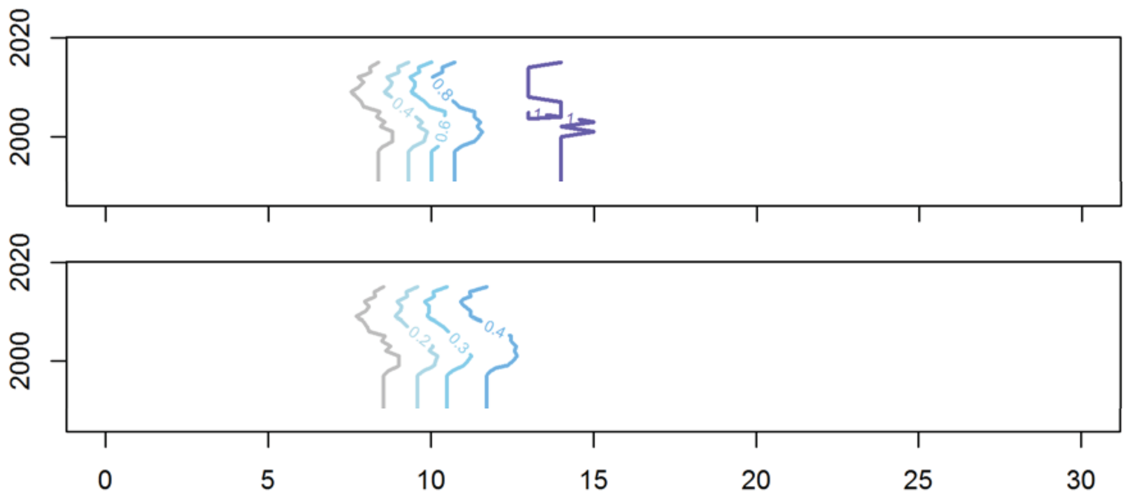


Figure 78. Recent selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4 survey in the AAF long model.

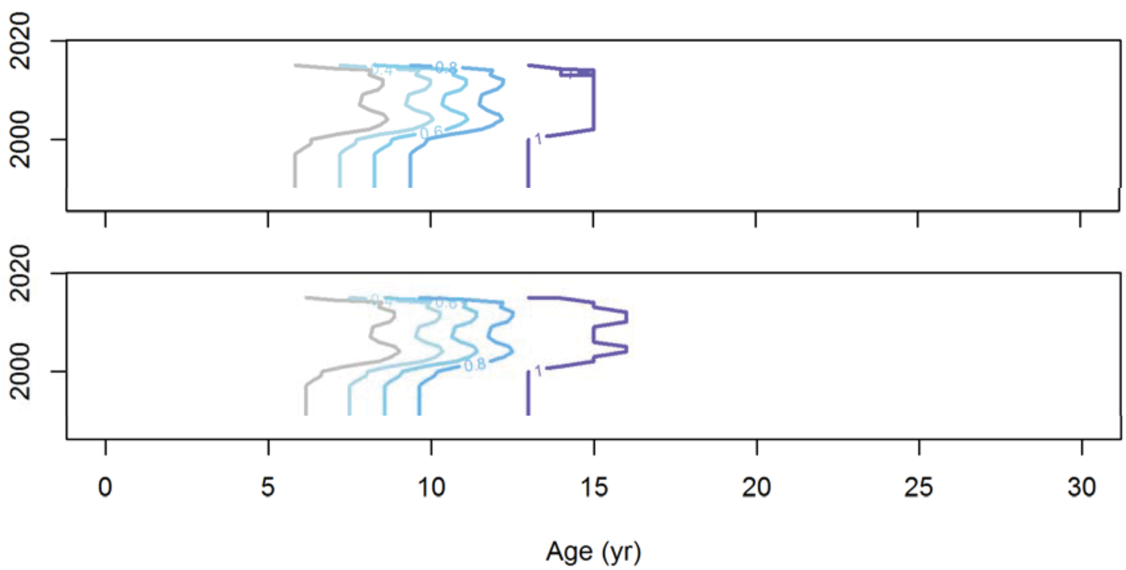


Figure 79. Recent selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4B survey in the AAF long model.

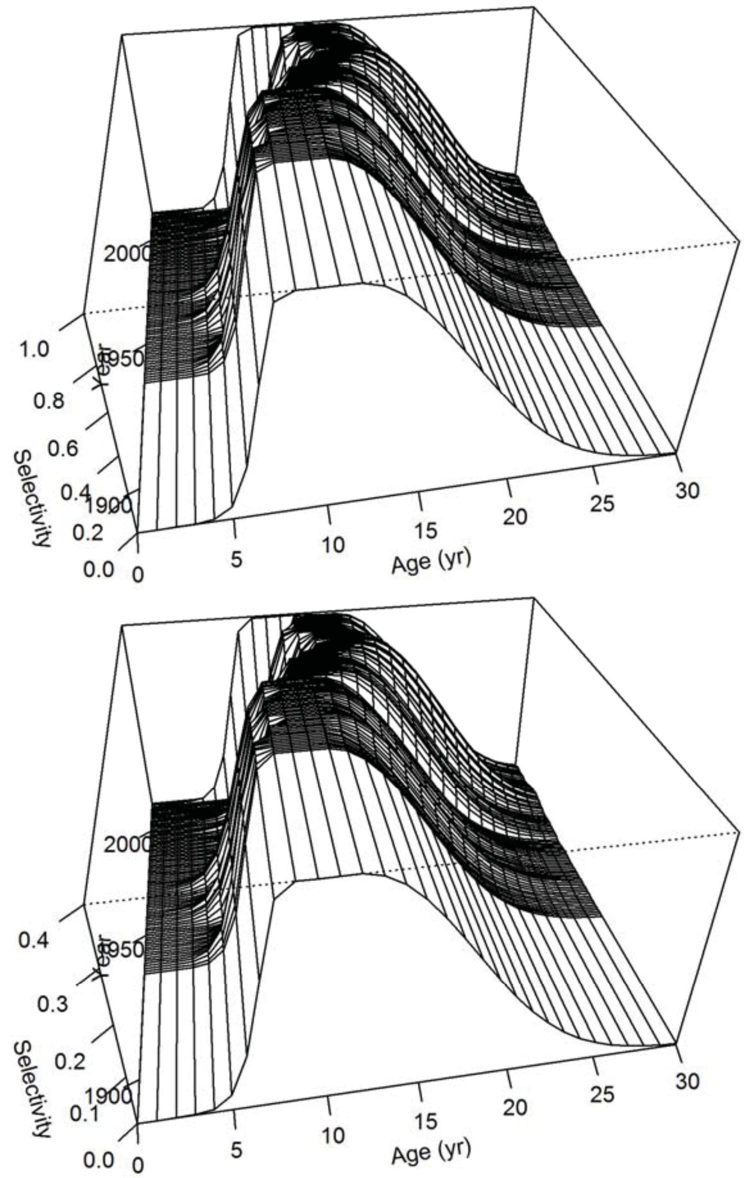


Figure 80. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 2 fishery in the AAF long model.

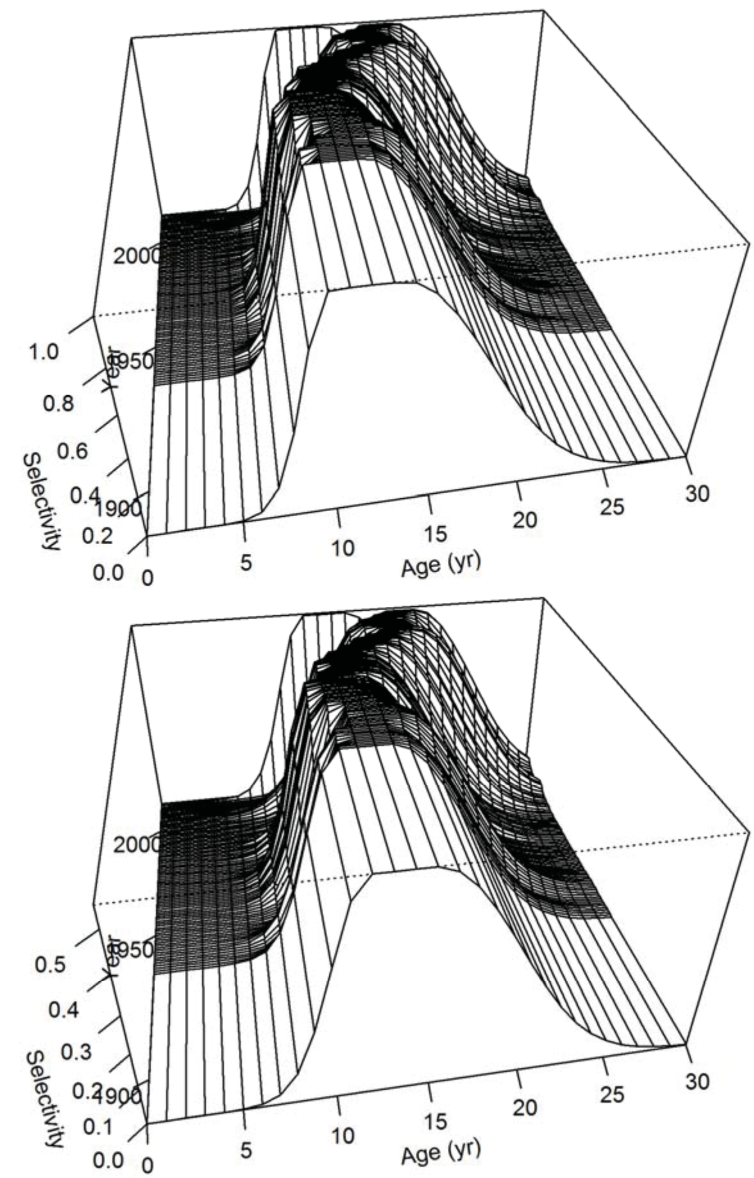


Figure 81. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 3 fishery in the AAF long model.

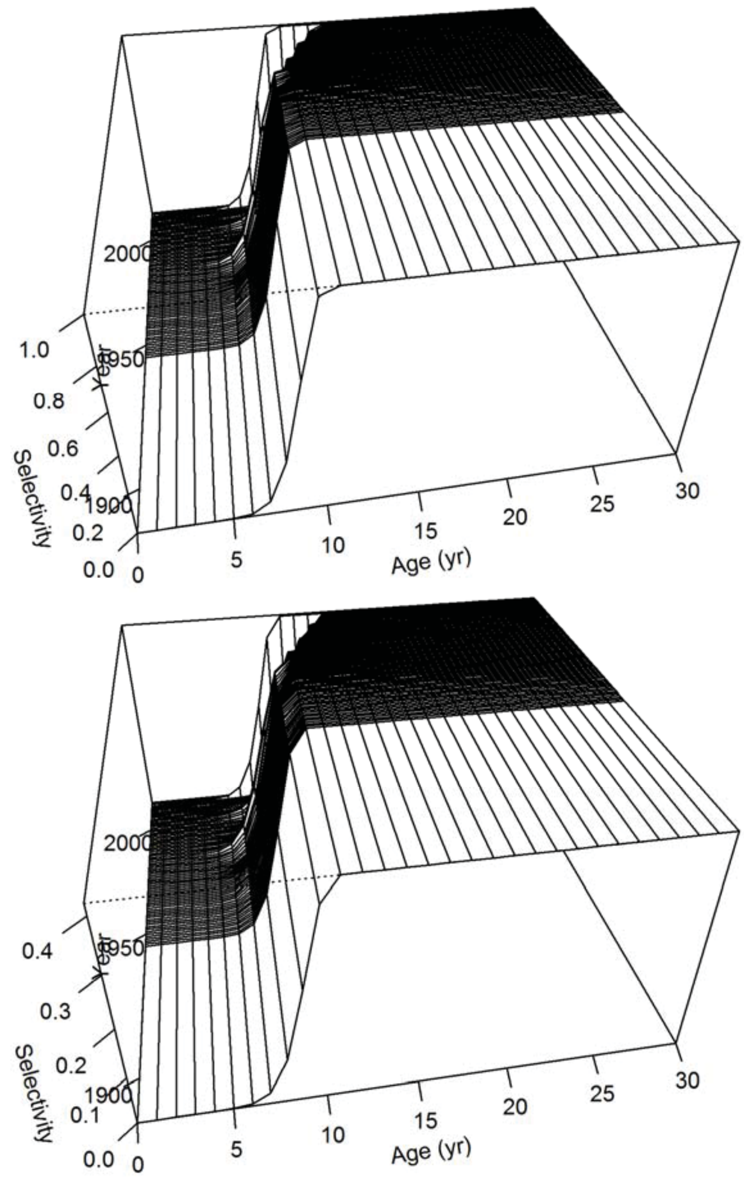


Figure 82. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4 fishery in the AAF long model.

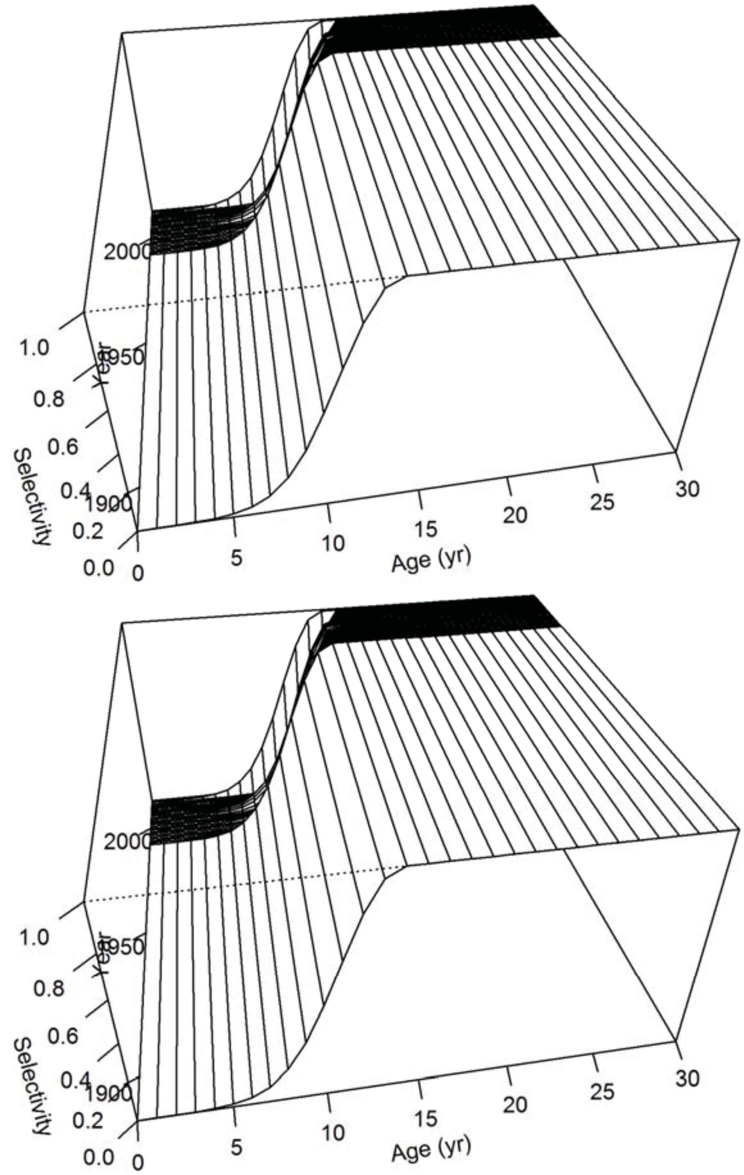


Figure 83. Selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4B fishery in the AAF long model.

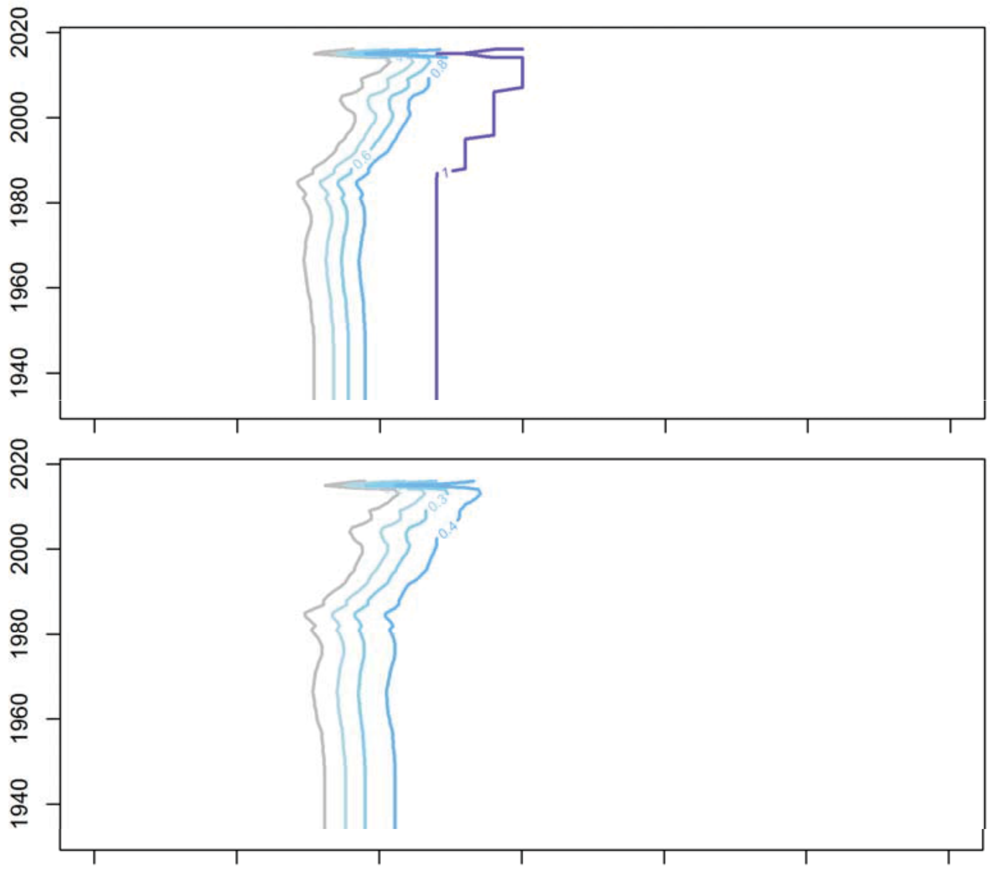


Figure 84. Recent selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4 fishery in the AAF long model.

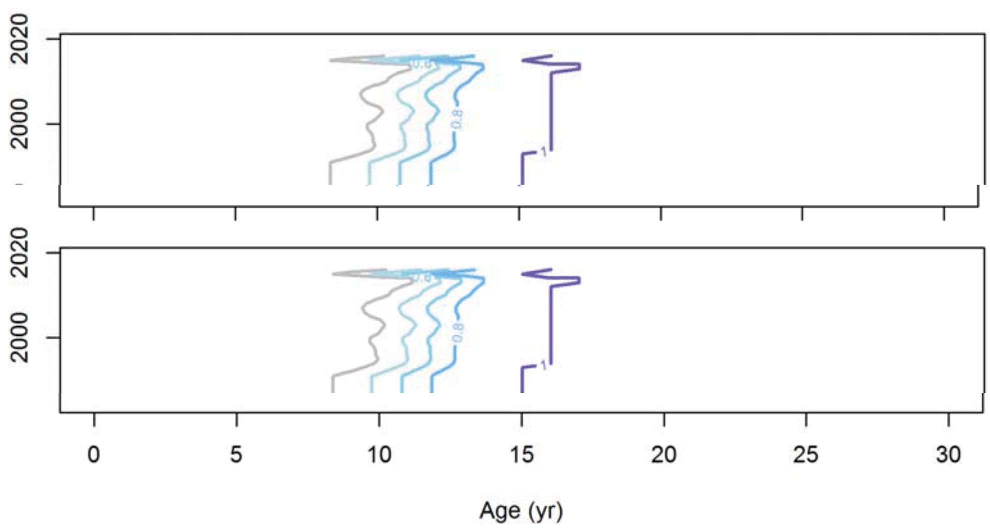


Figure 85. Recent selectivity patterns estimated for female (upper panel) and male (lower panel) halibut captured by the Area 4B fishery in the AAF long model.

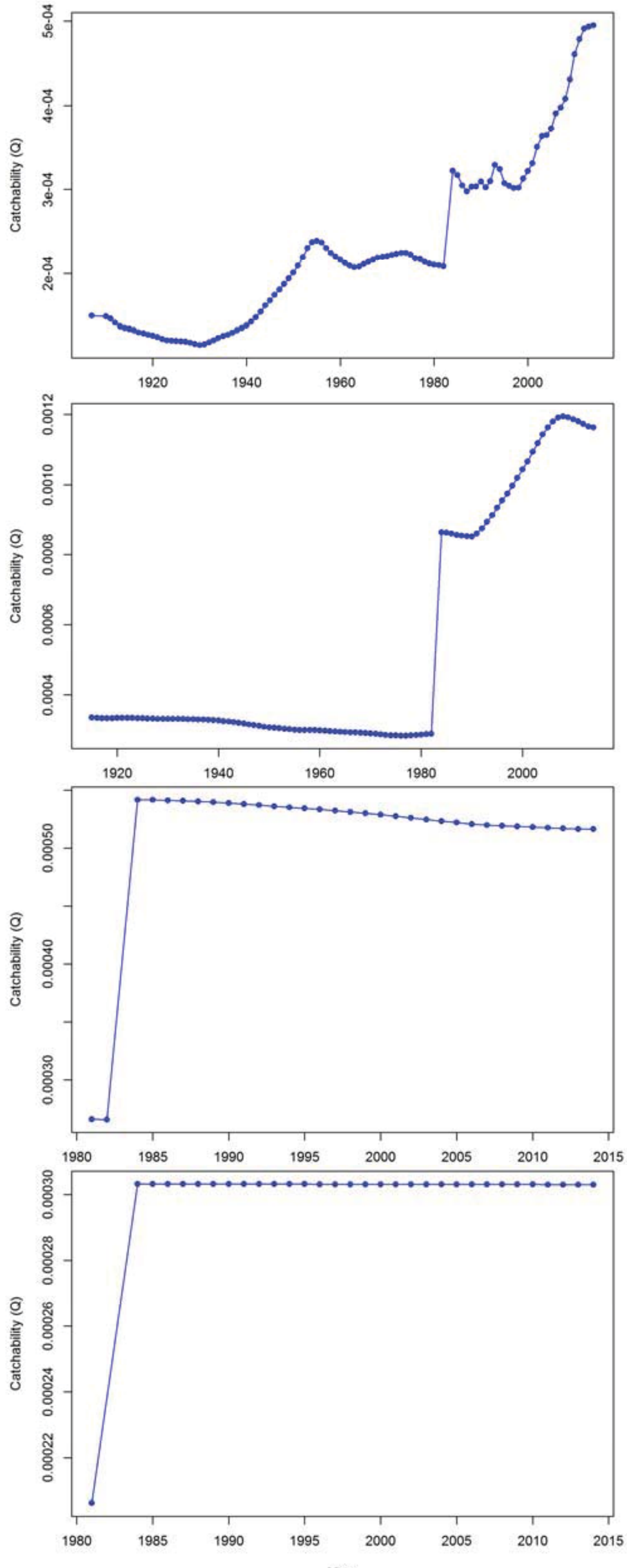


Figure 86. Estimated trends in fishery catchability for Area 2 (upper panel), Area 3 (second panel), Area 4 (third panel) and Area 4B (lower panel) in the AAF long model.

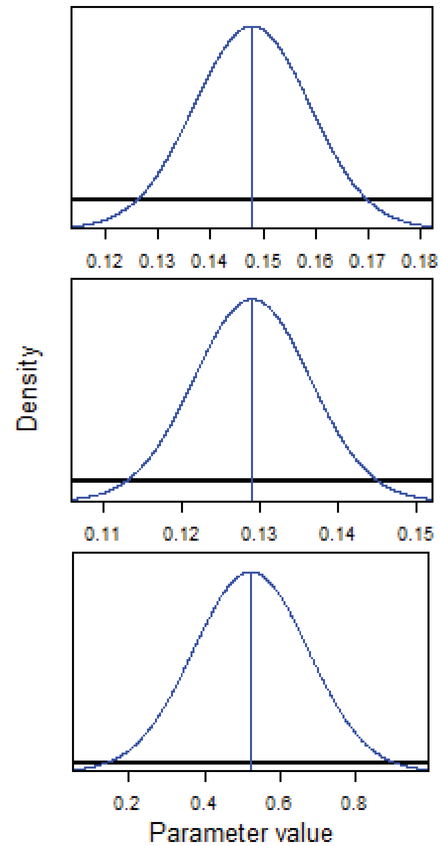


Figure 87. Prior (thick line) and MLE-based distributions for female natural mortality (top panel), male natural mortality (middle panel) and the environmental link coefficient (bottom panel) from the AAF long model.

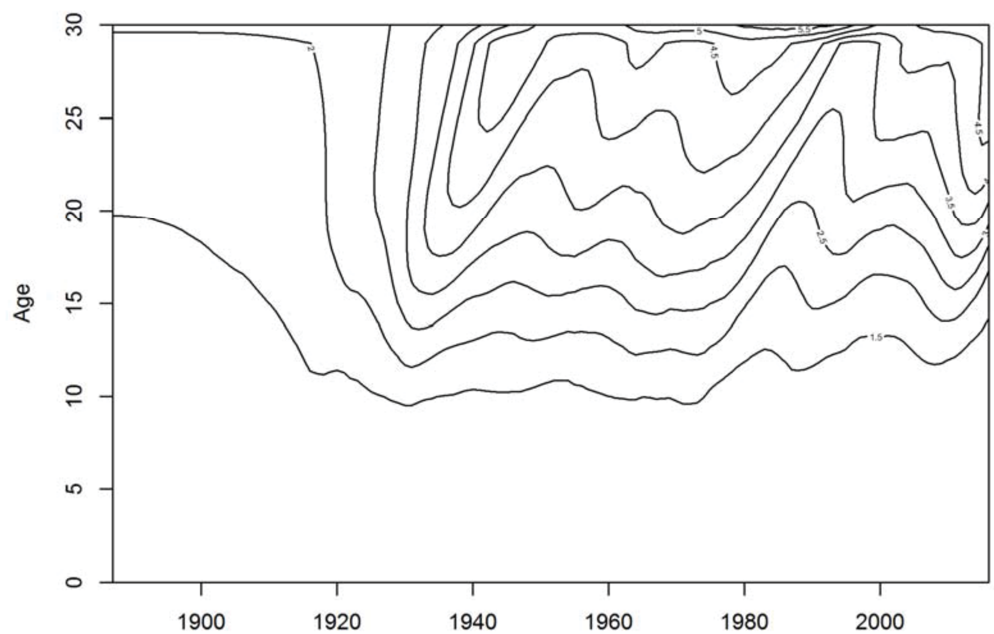


Figure 88. Population sex ratio (numbers of males/females) contours estimated by the AAF long model.

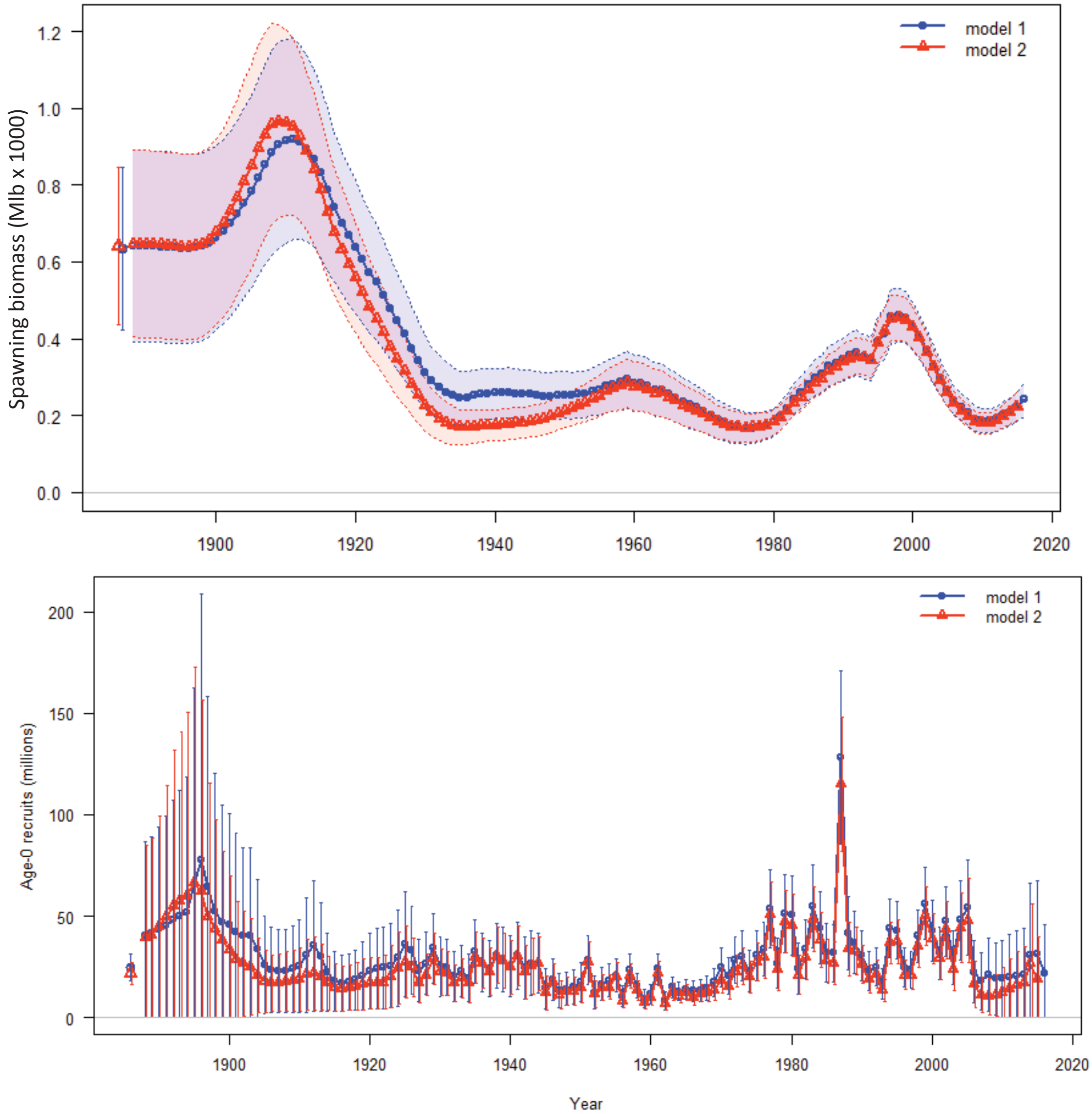


Figure 89. Comparison of the spawning biomass (upper panel) and recruitment (lower panel) estimated from the 2014, and preliminary 2015 AAF long model including all updates to data and model structure.

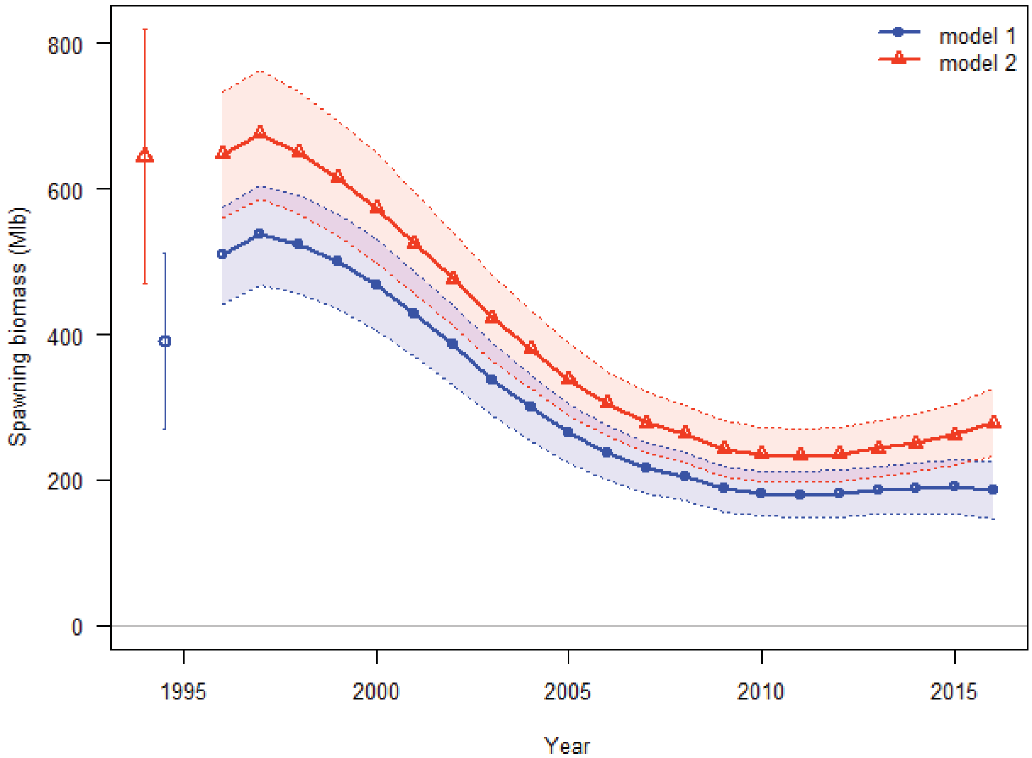


Figure 90. Comparison of the AAF short model (upper series) and the CW short model (lower series).

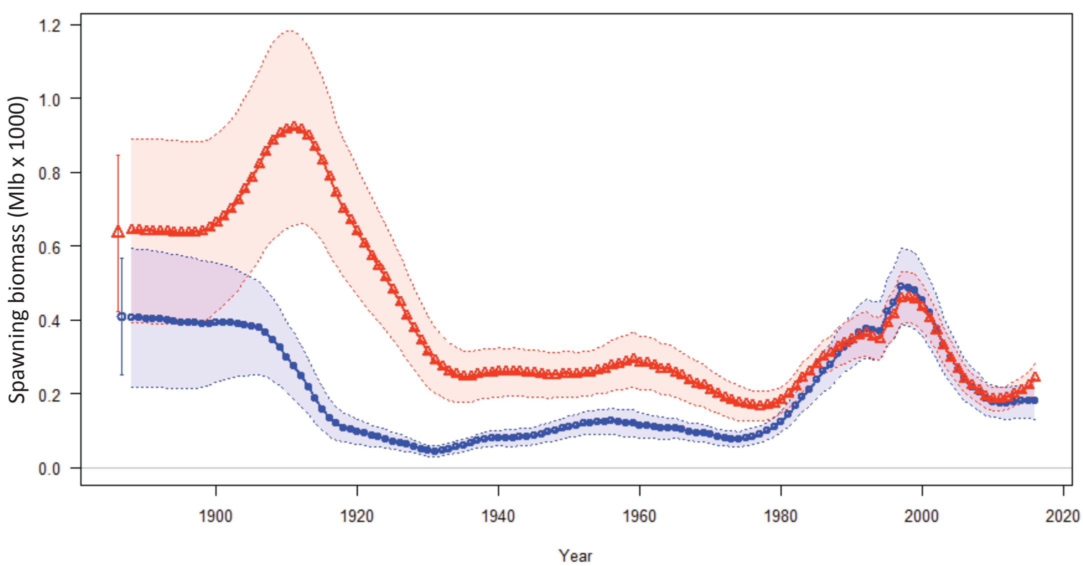


Figure 91. Comparison of the long AAF model (upper series in the early years), and the CW long model.

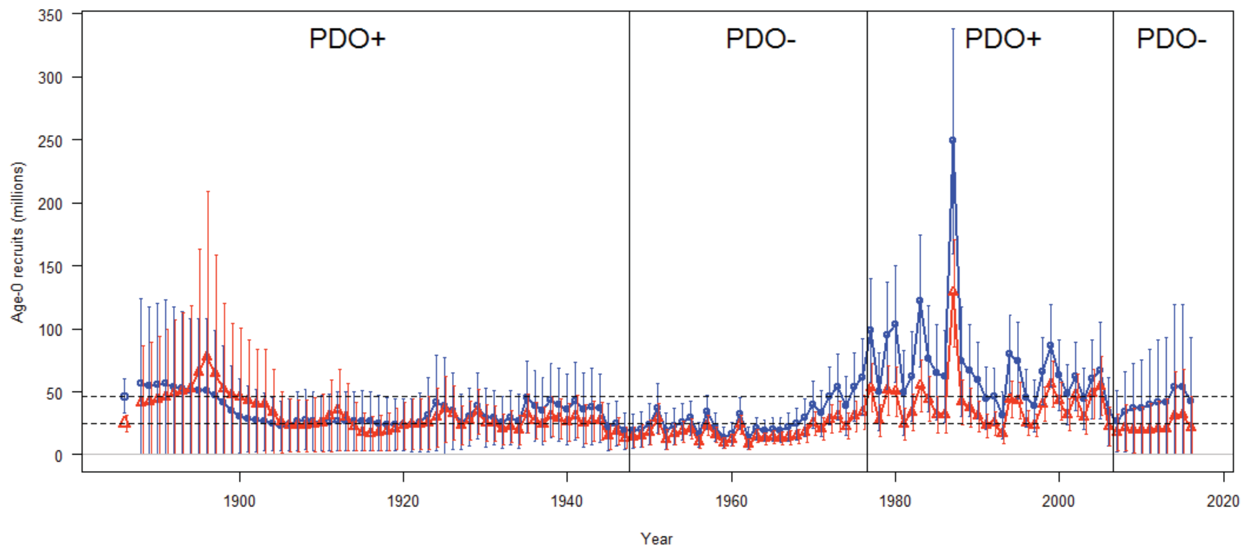


Figure 92. Comparison of recent recruitment estimates from the coastwide (blue series) and AAF long (red series) time-series models. Periods of the PDO are indicated by the vertical lines; mean recruitment for each model is indicated by the dashed lines.

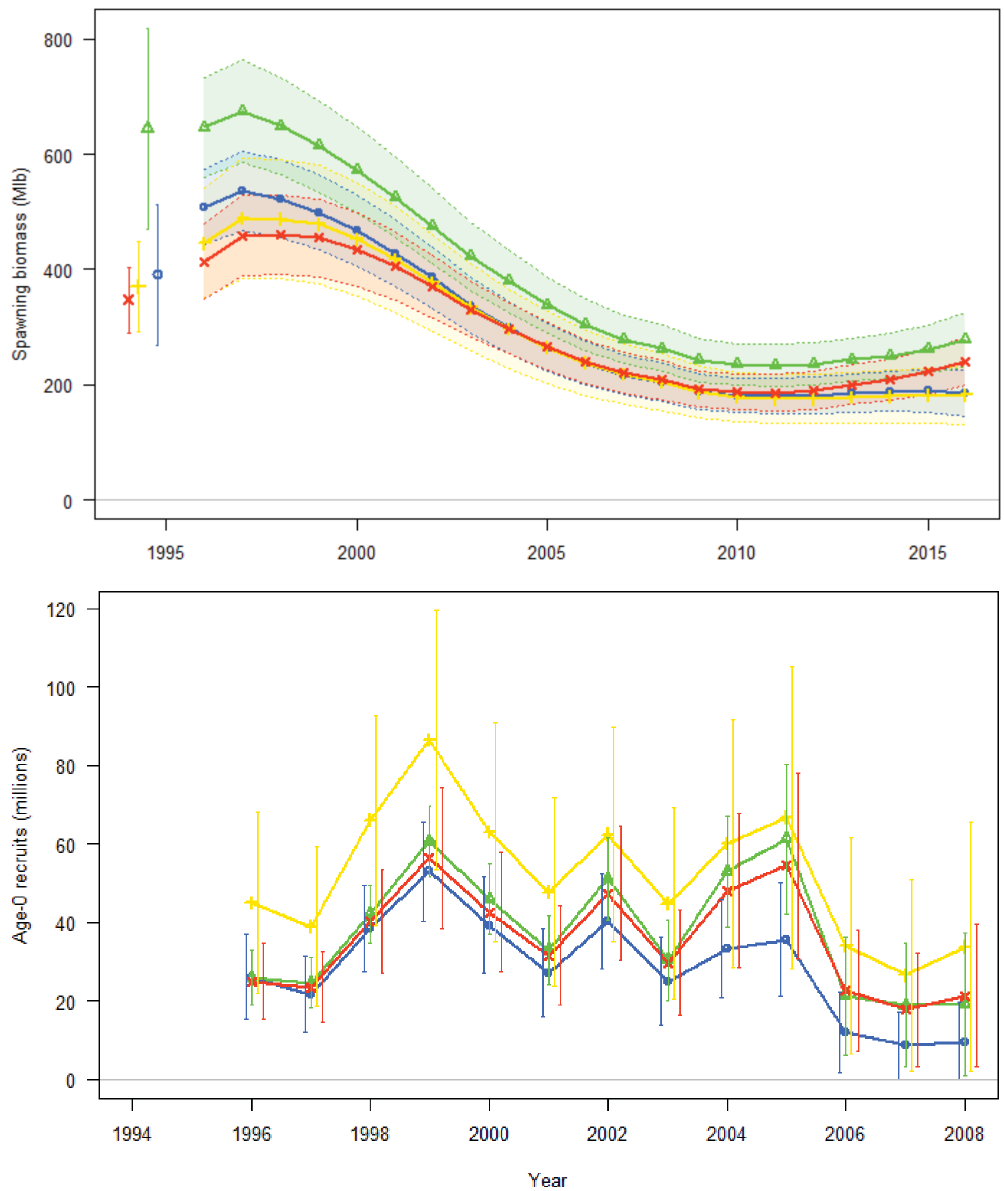


Figure 93. Comparison of recent spawning biomass (upper panel) and recruitment (lower panel) estimates from all four updated models (blue series = coastwide short, red = AAF short, yellow = coastwide long, green = AAF long).

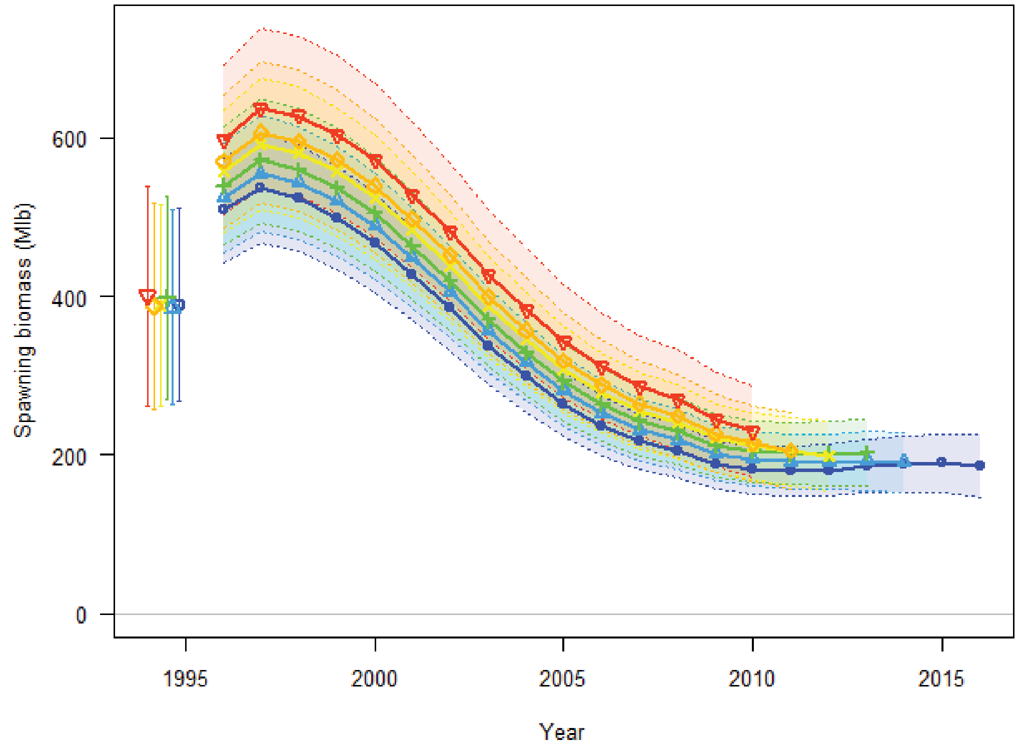


Figure 94. Five-year retrospective analysis (skipping 2015, which currently has no data) for the CW short model.

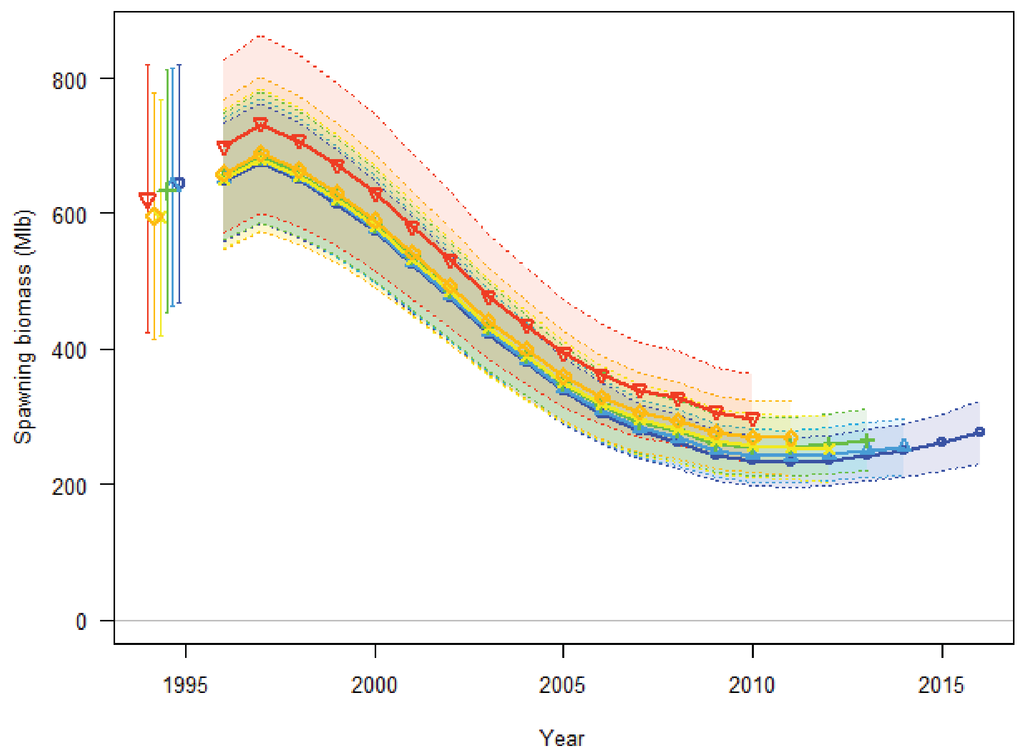


Figure 95. Five-year retrospective analysis (skipping 2015, which currently has no data) for the AAF short model.

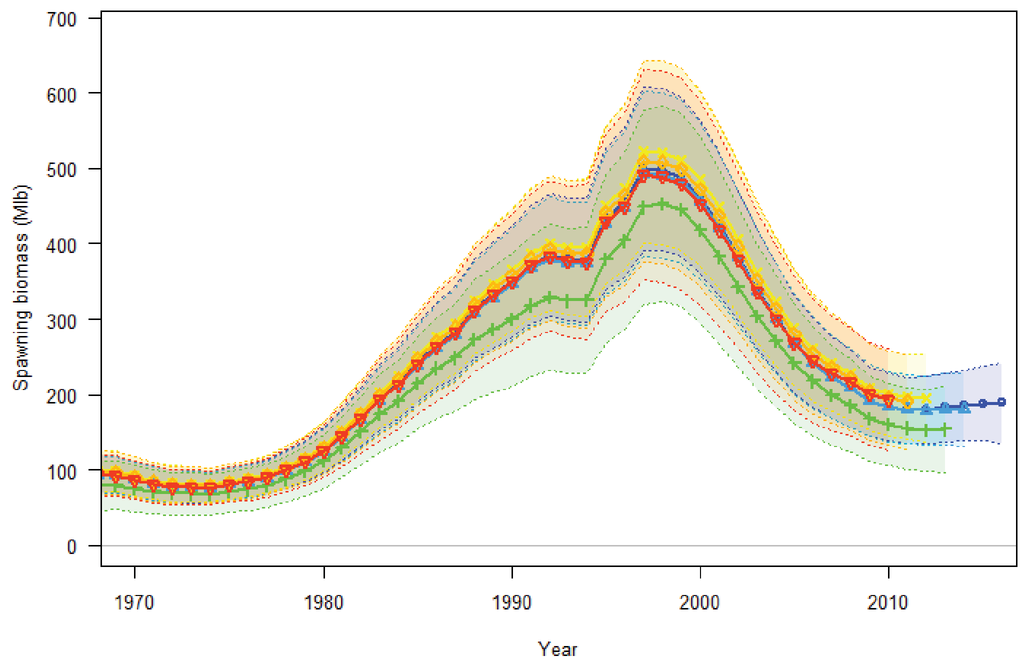


Figure 96. Five-year retrospective analysis (skipping 2015, which currently has no data) for the CW long model.

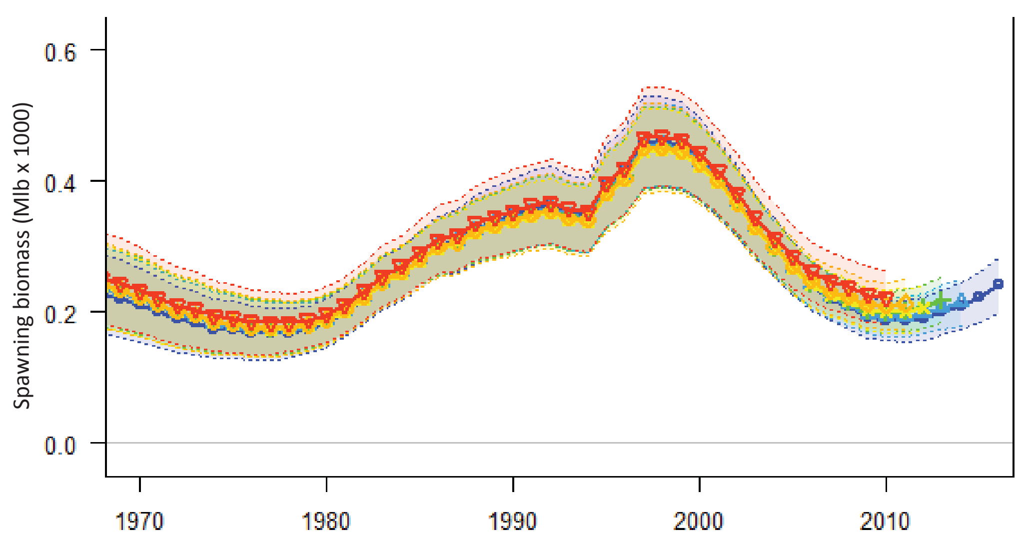


Figure 97. Five-year retrospective analysis (skipping 2015, which currently has no data) for the AAF long model.

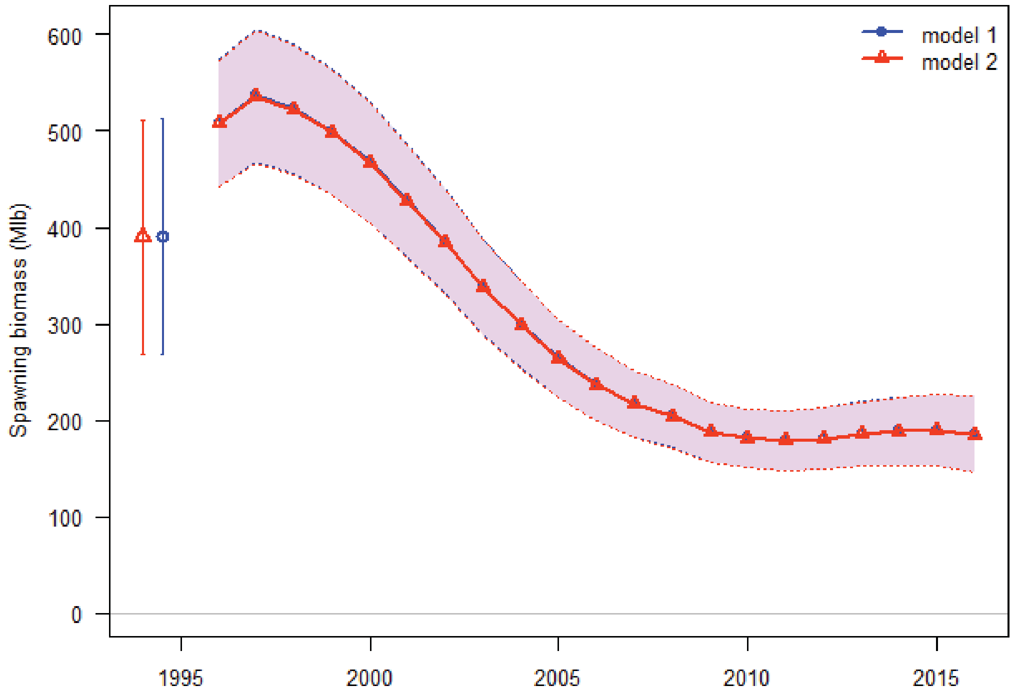


Figure 98. Comparison of the CW short model (model 1) and an alternative model that did not allow any temporal variation in fishery catchability (model 2).

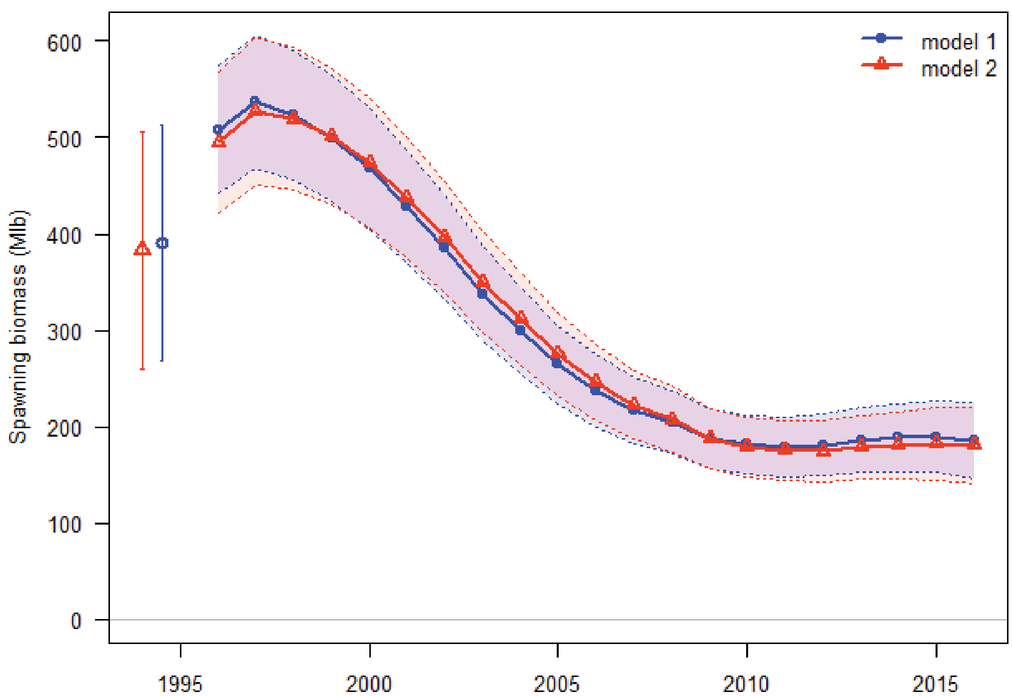


Figure 99. Comparison of the CW short model (model 1) and an alternative model that did not allow the ratio of male to female selectivity to vary over time (model 2).

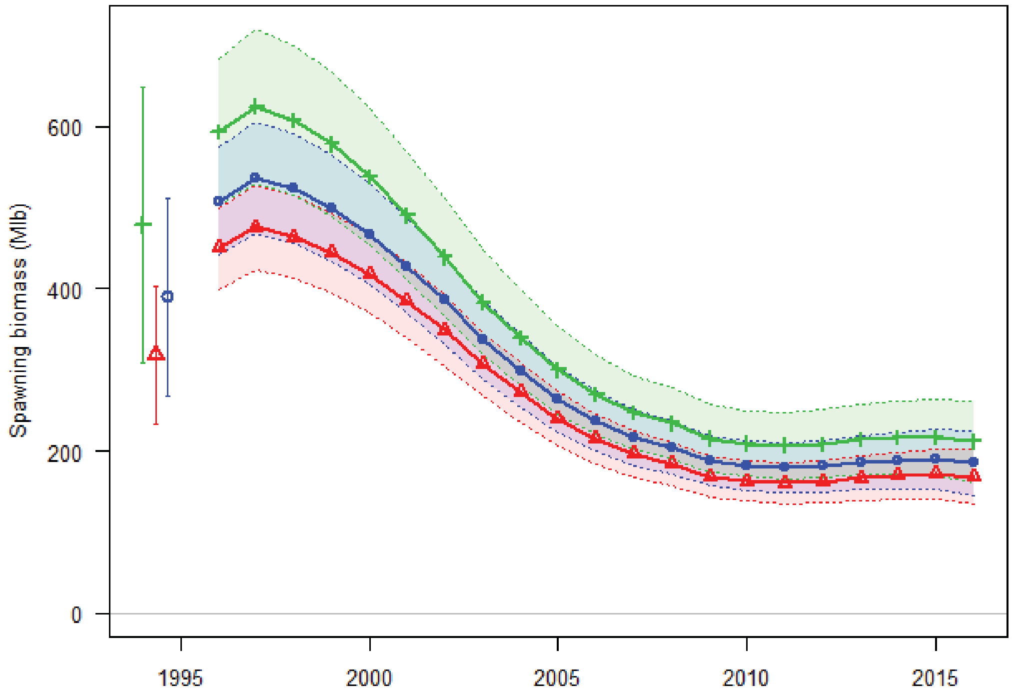


Figure 100. Comparison of the CW short model (middle series) with two alternative models forcing the natural mortality female halibut to be 0.18 (upper series) and 0.12 (lower series).

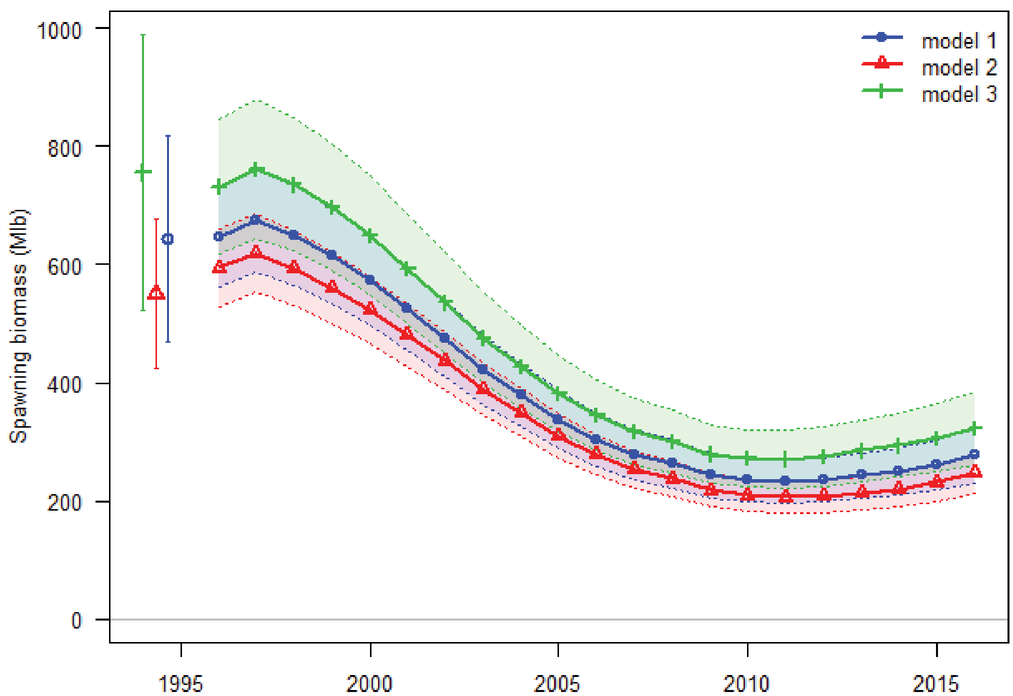


Figure 101. Comparison of the AAF short model (middle series) with two alternative models forcing the natural mortality female halibut to be 0.18 (upper series) and 0.12 (lower series).

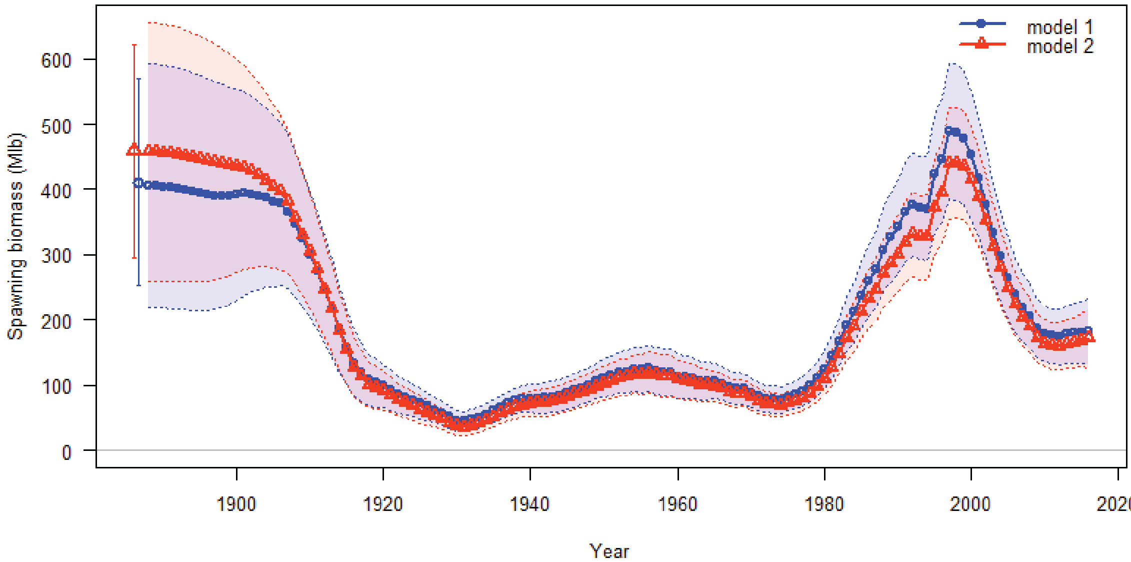


Figure 102. Comparison of the CW long model (model 1) with an alternative model allowing steepness to be estimated at 1.0 (model 2).

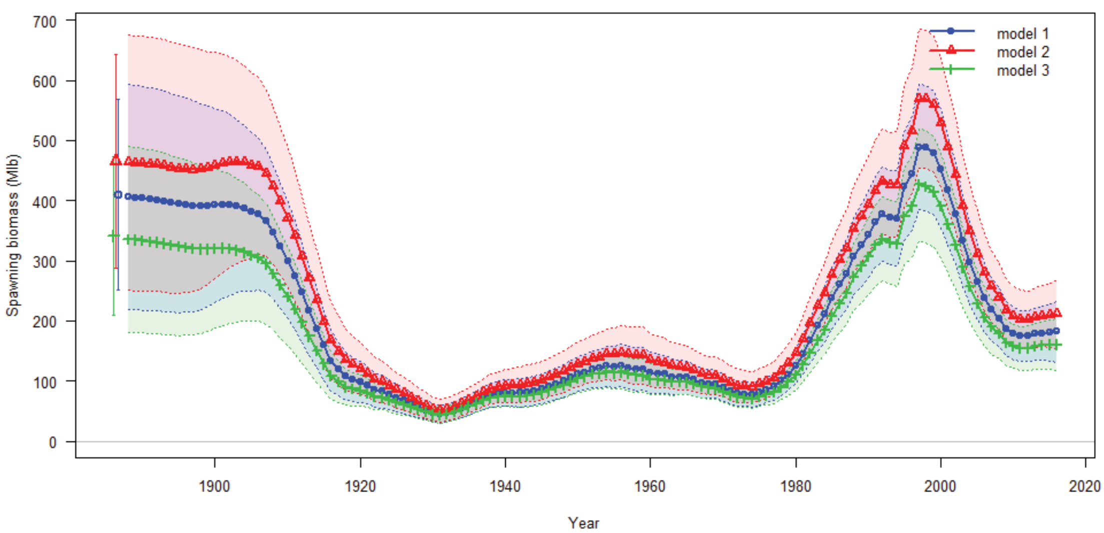


Figure 103. Comparison of the CW long model (middle series) with two alternative models making the relative selectivity of male halibut 10% lower (upper series) and 10% higher (lower series).

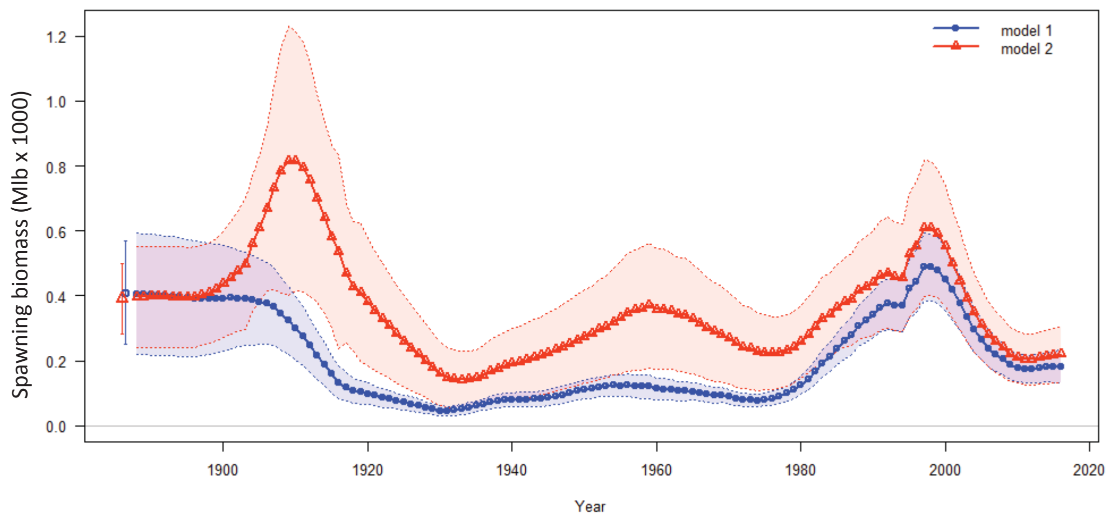


Figure 104. Comparison of the CW long model (lower series) with the CW long model allowing dome-shaped selectivity during the time-periods <1958, 1959-1980, 1981-1996.

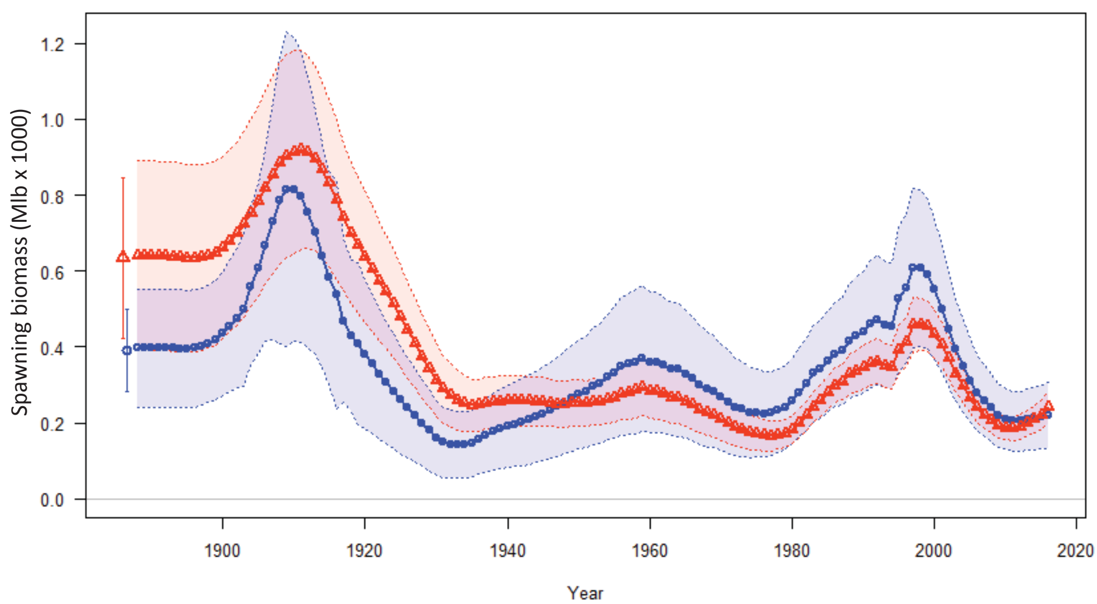


Figure 105. Comparison of spawning biomass estimates from the long AAF model (red series) and a long CW model (blue series) allowing dome-shaped selectivity during the time-periods <1958, 1959-1980, 1981-1996 (blue series; lower at the start of the time-period).

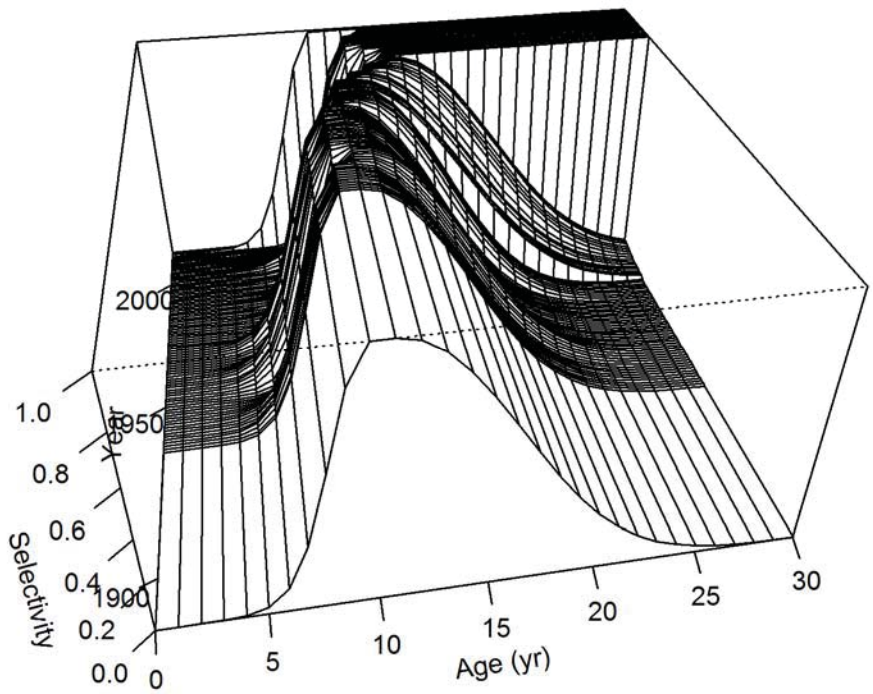


Figure 106. Estimated female selectivity pattern for the long CW model allowing dome-shaped selectivity during the time-periods <1958, 1959-1980, 1981-1996.

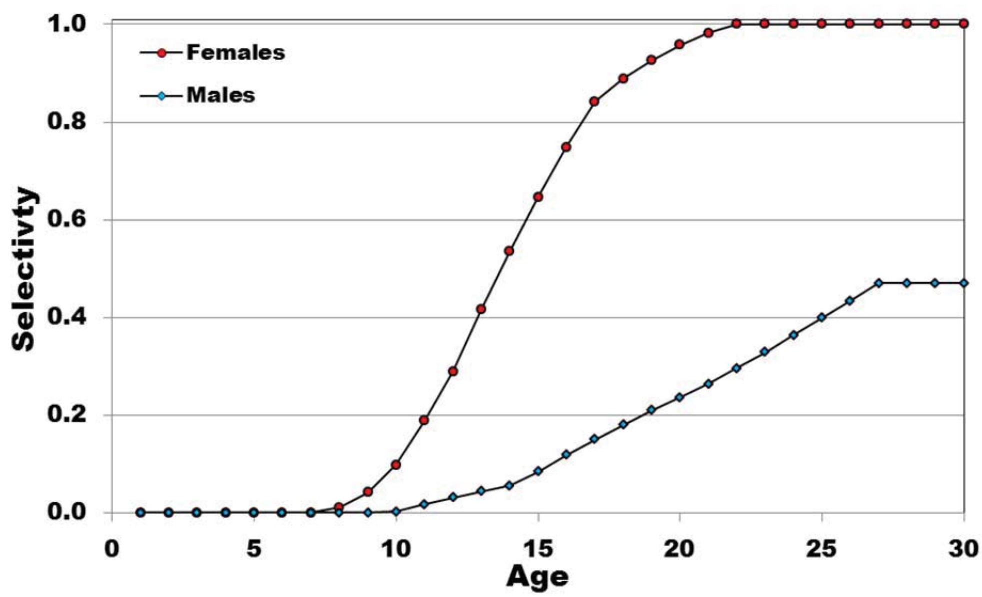


Figure 107. Terminal year selectivity pattern assigned to the exploitable biomass calculation, consistent with the existing IPHC harvest policy.

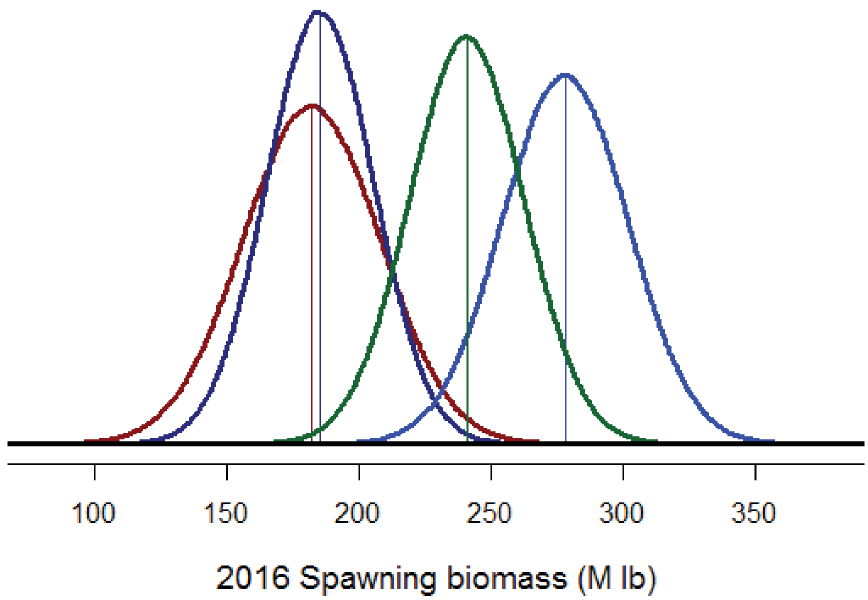


Figure 108. Estimated distributions from each of the four preliminary models for 2016 spawning biomass.

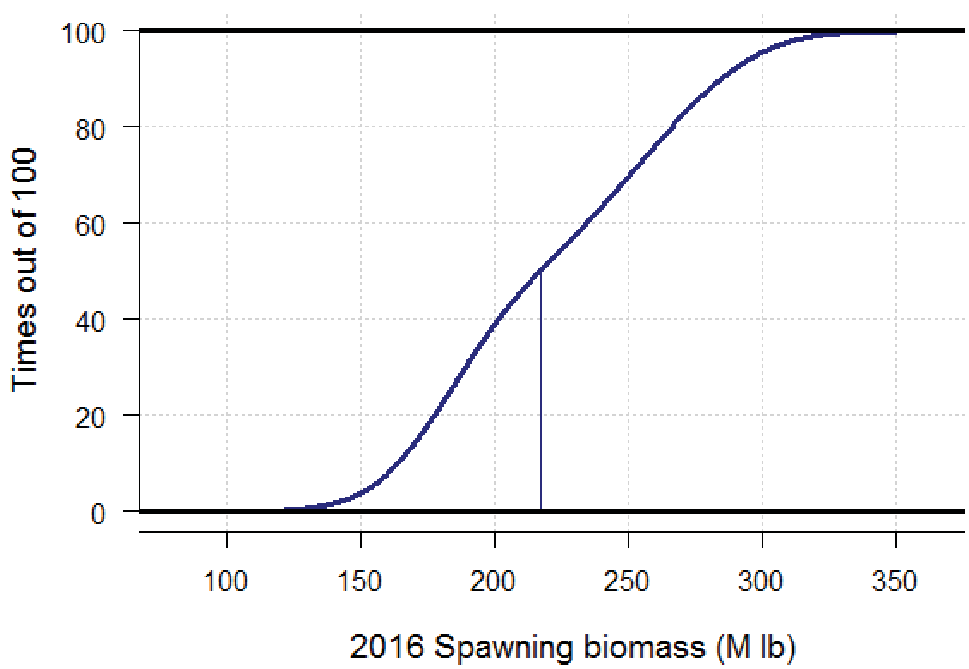


Figure 109. Cumulative distribution function for the integrated estimate of 2016 spawning biomass from the four preliminary models.

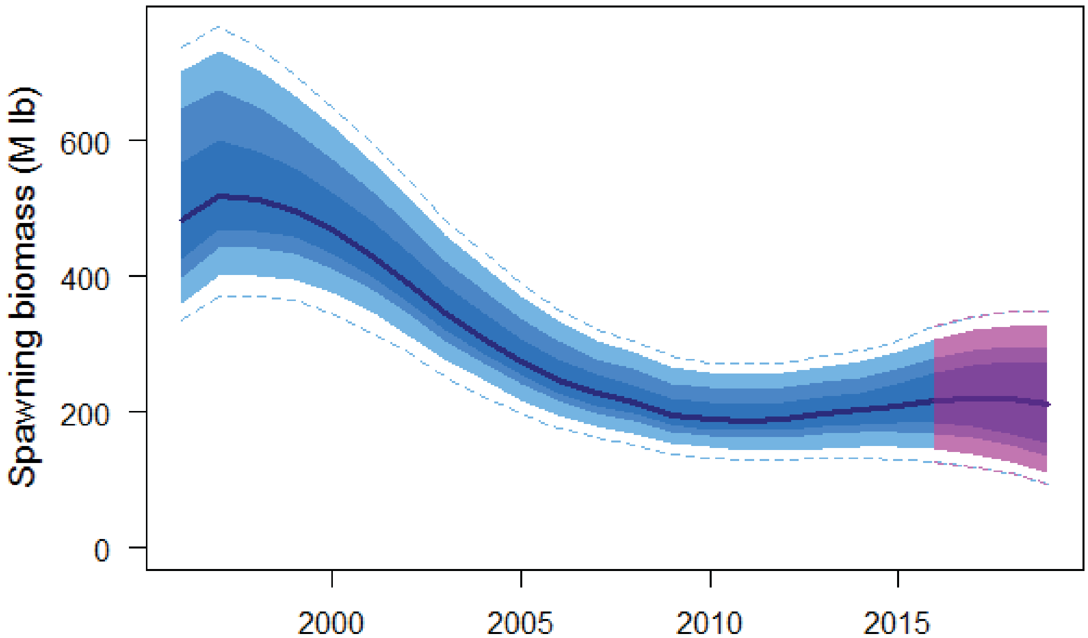


Figure 110. Integrated model results, with three year projection in lighter color. Line represents the median, color bands the interquartile (50/100), 75/100, 95/100, and the dashed lines represent the 99/100 range.

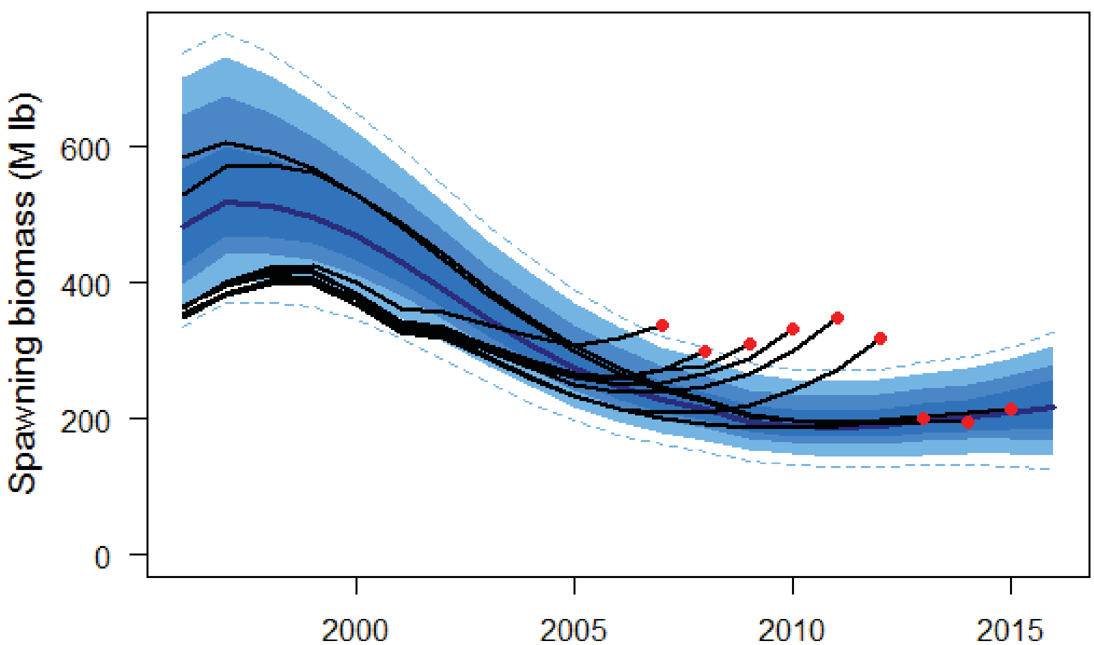


Figure 111. Retrospective comparison of stock assessment results since 2006. Red circles represent the terminal point estimate (MLEs from 2006-11, ensemble medians from 2012) from each historical assessment.

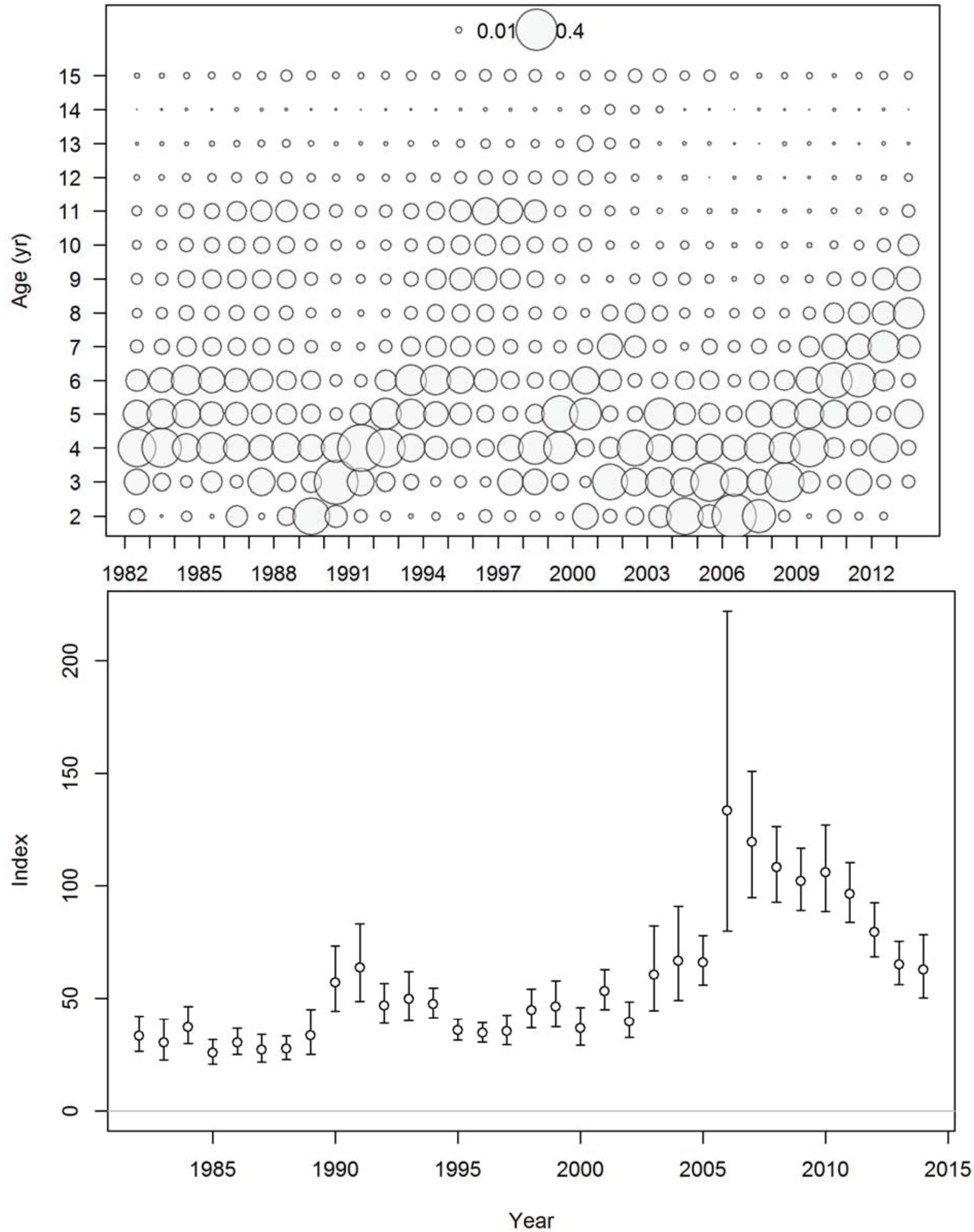


Figure 112. Estimated proportions-at-age (upper panel, years prior to 1998 from age-length key in 1997, 2014 not yet available) and index data (in numbers; lower panel) from recent NMFS Bering Sea trawl surveys.

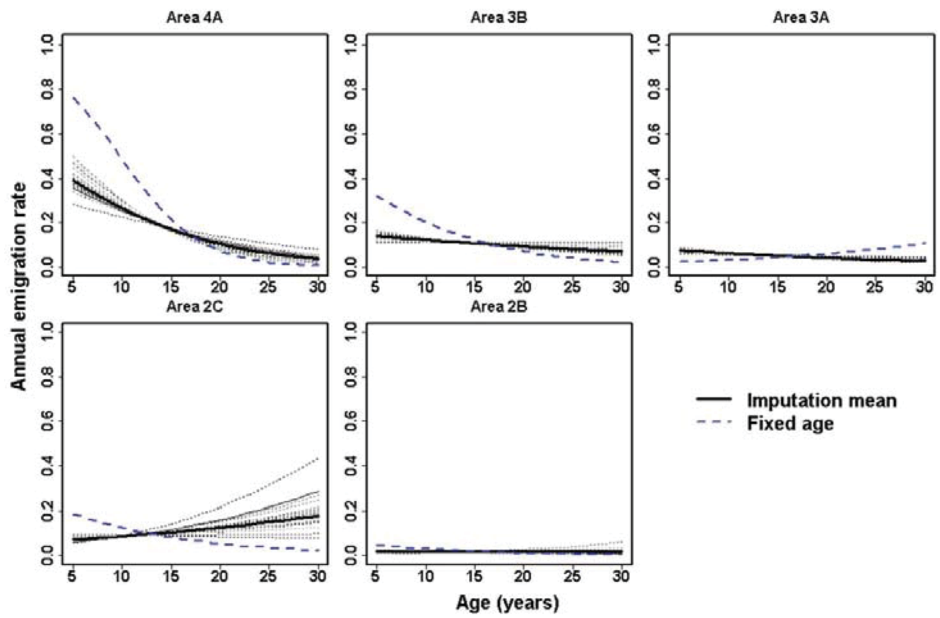


Figure 113. Emigration rates by age based on imputed age (solid line denotes the mean, dotted lines represent example estimates) and fixed age models (dashed line); reproduced from Figure 5 in Webster (2015).

Appendix A: Background material

Included with this document for SRB review is more extensive material supporting each assessment model, as well as several key references. These materials include:

1) Input files for each of the four assessment models (one directory for each of: coastwide short, coastwide long, AAF short, and AAF long): input data file, weight-at-age file, control file with model configuration, starter and forecast files with additional settings. Each of these has been annotated to aid in locating the various sections, as well as identifying which options and features were implemented or irrelevant.

2) Output from each of the stock assessment models: a sub-directory of all plotting and diagnostic output from each model created by the r4ss package (the entire set can be loaded at once via the HTML files), and the full report file from each model. The report file has not been annotated beyond the standard output from Stock Synthesis.

3) A summary of the modelling approach implemented in Stock Synthesis and the detailed model equations. This overview is supplemented with detail regarding specific features in the user manual. This is provided to allow for a cross-check of specific options used in each stock assessment model with the descriptions and technical details. *References*: Methot Jr, R.D., and Wetzel, C.R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Res. 142: 86-99. Methot Jr, R.D., and Wetzel, C.R. 2013b. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Appendix A: Technical description of the Stock Synthesis assessment program. Fish. Res. 142: 26 p. Methot Jr, R.D. 2015. User manual for Stock Synthesis. Model version 3.24s. NOAA Fisheries. Seattle, WA. 152 p.

4) The summary of data sources and the stock assessment results from 2014. *References*: Stewart, I.J. 2015. Overview of data sources for the Pacific halibut stock assessment and related analyses, IPHC Report of Assessment and Research Activities 2014. p. 87-160. Stewart, I.J., and Martell, S. 2015. Assessment of the Pacific halibut stock at the end of 2014. IPHC Report of Assessment and Research Activities 2014. p. 161-180.

5) Two recent manuscripts describing the history of the halibut stock assessment and the general rationale for the ensemble approach. *References*: Stewart, I.J., and Martell, S.J.D. 2014. A historical review of selectivity approaches and retrospective patterns in the Pacific halibut stock assessment. Fish. Res. 158: 40-49. Stewart, I.J., and Martell, S.J.D. 2015b. Reconciling stock assessment paradigms to better inform fisheries management. ICES J. Mar. Sci. *Advance online publication*.

Assessment of the Pacific halibut stock at the end of 2014

Ian J. Stewart and Steven Martell

Abstract

This stock assessment reports the status of the Pacific halibut resource in the northeastern Pacific Ocean. Halibut removals from all sources have ranged annually from 34 to 100 million pounds over the last 100 years, averaging 64 million pounds. After a peak in 2004, annual removals have decreased each year in response to management measures. Total removals in 2014 were estimated to be 43 million pounds, down from 48 million pounds in 2013. The 2014 setline survey total WPUE increased by 6% relative to 2013 (2% for legal-sized halibut only). Observed age distributions continue to indicate a relatively stable stock, but with no clear evidence of particularly strong recruitments in recent years. Individual size-at-age remains low relative to levels observed in the past several decades, although comparable to those estimated for the early portion of the 20th century. The 2014 scientific review process produced a number of important recommendations that have been incorporated into this assessment, including the development and evaluation of several alternative models. Two of these, using the Areas-As-Fleets (AAF) approach were included along with two coastwide models in the 2014 ensemble. The 2014 results therefore represent the integration of four separate stock assessment models, accounting for the uncertainty within each model and among models to generate the final decision table.

The 2014 stock assessment results indicate that the Pacific halibut stock declined rapidly from the late 1990s through 2011, as a result of the decline in the exceptionally strong 1987 year-class, recruitment strengths that are generally smaller than those observed through the 1980s and 1990s, as well as decreasing size-at-age. In the last few years, female spawning biomass is estimated to have stabilized near 200 million pounds, with trends varying among the four assessment models. The median 2015 estimate of exploitable biomass, consistent with the IPHC's current harvest policy, is 181 million pounds. The two long time-series models provided a differing perception of current vs. historical stock sizes. The AAF model suggests that the stock is currently increasing gradually and at 35% of the equilibrium unfished stock size; however the model estimates that current spawning biomass is at only 133% of the minimum values estimated for the 1970s. The coastwide model suggests that the stock is currently stable at 37% of the equilibrium unfished stock size; however the model estimates that current spawning biomass is at 211% of the minimum values estimated for the 1970s. These differences represent considerable uncertainty in both the current stock size and trend. Three-year projections were conducted for a range of alternative management actions; and probabilities of various risk metrics are reported in a decision-making table framework. The application of the current harvest policy results in the Blue Line of the decision table with a coastwide TCEY of 33.49 million pounds. The stock is projected to be stable at or near Blue Line levels of future harvest, increase under reduced removals and decrease as removals exceed around 40 Mlb.

Introduction

This stock assessment reports the status of the Pacific halibut resource in the northeastern Pacific Ocean, including the territorial waters of the United States and Canada. As in recent assessments, the resource is modeled as a single stock extending from northern California to the Aleutian Islands and Bering Sea, including all inside waters of the Strait of Georgia and Puget Sound. Potential connectivity with the western Pacific Ocean resource is considered slight and is unaccounted for.

The halibut fishery has been closely managed for nearly 100 years, and much is known about the history of fishery removals, population trends, and biological characteristics. The 2014 assessment continues to make use of the extensive historical time-series, as well as integrating both structural and estimation uncertainty via an ensemble of individual models. These models now include implicit treatment of spatial structuring in the data sources and properties of the fishery and setline survey.

Data sources

A thorough exploration of data sources for the entire historical record, as well as updated 2013 information was completed and reviewed by the Scientific Review Board (SRB) during 2013 (Stewart 2014; Cox et al. 2014). This effort has been extended during 2014 to provide summary datasets by geographic region: Area 2 (2A, 2B, and 2C), Area 3 (3A and 3B), Area 4 (Area 4A and 4CDE), and Area 4B. Briefly, halibut removals (including all sources of mortality: target fishery landings and discards, bycatch in non-target fisheries, research, sport, and personal use) have totaled 7 billion pounds, ranging annually from 34 to 100 million pounds over the last 100 years (Table 3 and Fig. 35 in Stewart (2015); all weights in this document are reported as 'net' weights, head and guts removed; this is approximately 75% of the round weight). The average removal over this period has been 64 million pounds. Annual removals were above the 100-year average from 1985 through 2010. After a peak in 2004, annual removals have decreased each year due to management actions in response to declining survey and commercial catch rates and stock assessment estimates. Total removals in 2014 were estimated to be 43 million pounds, down from 48 million pounds in 2013. The 2014 setline survey total WPUE increased by 6% relative to 2013, and the legal-size (O32) WPUE by 2%. Commercial catch-rates increased in 2014 by 7% at the coastwide level; however, these records were unverified and incomplete at the time of this assessment. Survey and fishery age distributions continue to indicate a relatively stable stock, with no clear evidence of particularly strong recruitments in recent years. Individual size-at-age remains low relative to levels observed in the past several decades, although comparable to those estimated for the early portion of the 20th century.

Assessment

The stock assessment for Pacific halibut has evolved through many different modeling approaches over the last 30 years (Clark 2003). These changes have reflected improvements in fisheries analysis methods, changes in model assumptions, and responses to recurrent retrospective biases and other lack-of-fit (Stewart and Martell 2014). The 2012 stock assessment resolved the most recent retrospective bias (Stewart et al. 2013), and produced estimates of stock size that were considerably lower than previous analyses. This type of abrupt change between annual cycles, although necessary, is undesirable from a management perspective. The 2013 stock assessment (Stewart and Martell 2014) introduced the ensemble approach which draws from the field of weather and hurricane forecasting (e.g., Hamill et al. 2012). This approach recognizes that there is no "perfect" assessment model, and that robust risk assessment can only be achieved via the inclusion of multiple models in the estimation of management quantities and the uncertainty about these quantities. This approach was also used for the 2012 assessment, albeit in a crude manner, by including alternate models using differing values of natural mortality. For 2014, several alternative models were evaluated for inclusion into the stock assessment ensemble.

The 2014 Ensemble

The IPHC's Scientific Review Board (SRB) met to evaluate modelling progress on 23 June, 2014, and again to review the final set of models for the 2014 ensemble on 22-23 October, 2014 (Cox et al. 2015). These meetings guided the development of a simple stock production model, a Virtual Population Analysis (VPA), and two alternative statistical catch-at-age models, as well as a number of supplementary analyses that provided insight into the dynamics of the halibut population and fishery.

Two models were evaluated but not included directly into the ensemble. The VPA model requires a number of very strong simplifying assumptions in processing the input data and results. These include aggregating all male and female observations, and treating directly the numbers-at-age regardless of sex. Due to the use of surface ageing prior to 2002, the data also had to be aggregated into a plus group at age-15, and fishery and survey catch-at-age must be assumed to be known without error. To produce results comparable to the other models, female spawning biomass had to be estimated via sex-ratio at age from the setline survey. Despite these strong assumptions, VPA models are in use for many fisheries, and therefore provide another check on the scale and trend information from the statistical catch-at-age models. The VPA model estimated a slightly smaller stock size, but very similar trends over the recent and longer time-series (Stewart and Martell, *in review*). Also evaluated in 2014 was a simple surplus production model. This model assumes that change in the setline survey abundance is directly proportional to stock surplus production (the annual yield which can be removed and the stock biomass will remain unchanged). Removals of U26 halibut must be ignored, since these fish are not captured by the survey, thus the surplus yield does not account for all sources of removals. However, this model estimated only four parameters (the initial stock size, the average surplus production or maximum sustainable yield, the stock size producing that yield and the catchability coefficient linking the survey abundance to the population size). This analysis cannot produce estimates of female spawning biomass, or other harvest policy reference points, but did suggest that the surplus production in recent years had been between 40 and 45 Mlb. These values are consistent with both the decision table and harvest policy calculations, and therefore generally corroborate the ensemble results.

Building from the 2013 re-analysis of historical data sources, the summary of data into geographic regions in 2014 (Stewart 2015) provided the basis for creating two AAF models, one using only the most recent and comprehensive data (the short time-series, beginning in 1996), and the second utilizing the full historical record. Briefly, AAF models are commonly applied when biological differences among areas or sampling programs make coastwide summary of data sources problematic. AAF models continue to treat the population dynamics as a single panmictic stock, but fit to each of the spatial datasets individually, allowing for differences in selectivity and catchability of the fishery and survey among regions. In addition, the AAF models accommodate temporal and spatial trends in where and how data have been collected and fishery catches have occurred because each region need not have data for each year modelled.

For 2014, the final ensemble included four individual models: each of both short and long time-series models based on coastwide and AAF data structures. The short time-series model used in 2012 was not retained in the 2014 ensemble, due to its non-orthogonal and highly processed treatment of input data, as well as the redundancy with the alternative short time-series coastwide model developed in 2013. All of these four models were implemented using the Stock Synthesis software, a widely used modeling platform developed at the National Marine Fisheries Service (Methot and Wetzel 2013). This combination of models included a broad suite of structural and parameter uncertainty, including natural mortality rates (estimated in the long time-series models, fixed in the short time-series models), environmental effects on recruitment (estimated in the long time-series models), fishery and survey selectivity (by region in the AAF models) and other model parameters. These sources of uncertainty have historically been very important to the understanding of the stock, as well as the annual assessment results (Clark and Parma 1999, Clark and Hare 2006, Stewart and Martell 2015). The benefits of the long time-series models include historical perspective on recent trends and biomass levels; however these benefits come at a computational and complexity cost. The short time-series models make fewer assumptions about the properties of less comprehensive historical data, but they suffer from much less information in the short data series as well as little context for current dynamics. In aggregate, these models provide for a risk analysis that is more robust to changes to a single model, or the addition of new models in the future than a single assessment model.

As was the case in 2013, each of the models in the ensemble was equally weighted, and differences in uncertainty within models propagated in the integration of results. In the future it should be possible to refine this weighting based on the lack-of-fit to key data sources, retrospective patterns within models, as well as consistency of the results with biological understanding. It is also anticipated that spatially explicit models will be evaluated for potential inclusion into the ensemble in future years. In this manner, the ensemble approach can be transparently improved in the future as additional models and refinements to existing models become available.

The risk analysis and decision table include the full probability distribution from the assessment. Therefore, key quantities such as reference points and stock size are reported as cumulative distributions, such that the entire plausible range can be evaluated. Where necessary, point estimates reported in this assessment correspond to median values from the ensemble.

Comparison with previous assessments

Comparison with previous stock assessments indicates that the 2014 spawning biomass results are very similar to those from 2012 and 2013, which lie inside the 50% interval of the ensemble in recent years (Fig. 1). Models prior to 2012, which had shown a problematic retrospective pattern, suggested terminal stock sizes in the mid-2000s that are no longer considered plausible. The estimates from these models for the late 1990s now occur at the lower edge of the plausible range: all four of the current models suggest a larger spawning biomass during that period. Point estimates from the 2013 ensemble for 2014 were extremely similar to the current results given the degree of uncertainty (Table 1).

Biomass, recruitment, and reference point results

Ensemble

The results of the 2013 stock assessment indicate that the Pacific halibut stock has been declining continuously over much of the last decade (Fig. 2). The differences among the individual models contributing to the ensemble are most pronounced prior to the early 2000s (Fig. 3). However, current stock size estimates also differ substantially among the four models (Fig. 4). The differences in both scale and recent trend reflect the structural assumptions, e.g., higher natural mortality estimated in the long coastwide model and dome-shaped selectivity for Areas 2 and 3 in the AAF models. Differences are also apparent in the recent recruitment estimates, which suggest larger recruitments in 1999, 2002 and 2004-2005 than in other recent years (Fig. 5). These recent recruitments are much lower than the 1987 year class, and (in the coastwide model) substantially below those in the late 1970s and early 1980s (Fig. 6). Recruitments after 2008 do not yet have information available in the fishery or survey data, and therefore remain highly uncertain. In addition to recruitment trends, observed decreases in size-at-age have also been an important contributor to recent stock declines. In the last few years, the estimated female spawning biomass appears to have stabilized near 200 million pounds (Table 2, Fig. 2, and Fig. 7), with plausible values ranging from 150 Mlb to 250 Mlb. The estimate of exploitable biomass consistent with the IPHC's current harvest policy is 181 Mlb at the beginning of 2015. The current level of spawning biomass is estimated to be 42% of the equilibrium condition in the absence of fishing, with a 10 out of 100 chance that the stock is below the 30% relative spawning biomass harvest policy threshold. All sources of estimated removals for 2014 correspond to a fishing intensity point estimate of $F_{43\%}$ (Fig. 9). Harvest levels of this magnitude are generally consistent with target rates for many similar stocks.

Long time-series models

The two long time-series models provide historical biomass estimates that are integrated with the current stock assessment results. The two long time-series models provided a differing perception of current vs. historical stock sizes (Fig. 10). The AAF model suggests that the stock is currently increasing gradually and at 35% of the equilibrium unfished stock size; however the model estimates that current spawning biomass is at only 133% of the minimum values estimated for the 1970s. The coastwide model suggests that the stock is currently stable at 37% of the equilibrium unfished stock size; however the model estimates that current spawning biomass is at 211% of the minimum values estimated for the 1970s. These differences represent considerable uncertainty in both the current stock size and trend. They are likely attributable to the separation of signals from each region (particularly Area 2, with the longest time-series of data), and allowance for different properties in each region's fishery and survey.

Both of the long time-series models indicate that average halibut recruitment is estimate to be higher (32 and 72% for the coastwide and AAF models respectively) during favorable Pacific Decadal Oscillation (PDO) regimes, a standard indicator of productivity in the north Pacific. This result is consistent with that of Clark and Hare (2002, 2006). Historically, these regimes included positive conditions prior to 1947, poor conditions from 1947-1977, positive conditions from 1978-2006, and poor conditions from 2007 to 2013.

Major sources of uncertainty

This stock assessment includes significant uncertainty associated with estimation of model parameters, treatment of the data sources (e.g., short and long time-series), natural mortality (fixed vs. estimated), approach to spatial structure in the data, and other differences among the models included in the ensemble. Although this is a substantial improvement over previous assessments, there are important sources of uncertainty that are not included.

A key source of uncertainty is the spatial structure of the assessment model, and the spatial processes in the underlying stock, particularly the distribution of recruitment (juvenile halibut), and their subsequent movement rates among regulatory areas as sub-legal and legal-sized fish. The SRB endorsed the staff's plans to continue development of additional alternative models using explicit spatial structure for future stock assessments, as well as refinement of available models to better accommodate spatial processes influencing population age- and sex-ratios. These efforts may provide alternate models for future inclusion into the ensemble approach.

As was identified in 2013, another source of uncertainty is the sex-ratio of the commercial catch. There is no direct information available (due to dressing of fish at sea prior to observation by IPHC port samplers), and so the assessment relies on sex-ratios observed in the setline survey to inform the relative selectivity for male and female halibut in the commercial fishery catch. All the models are sensitive to this assumption, particularly the coastwide models. Efforts begun in 2014 to test methods for direct marking of fish at sea will continue to be developed in 2015.

The link between halibut recruitment strengths and environmental conditions remains poorly understood, and there is no guarantee that observed correlations will continue in the future. Therefore recruitment variability remains a significant source of uncertainty in current stock estimates due to the substantial lag between birth year and direct observation in the fishery and survey data (6-10 years). Reduced size-at-age in the current stock relative to levels observed in the 1970s is a major contributor to stock trends which is poorly understood. The historical record suggests that size-at-age changes relatively slowly; therefore, although projection of future values is highly uncertain, near-term values are unlikely to be dramatically different than those currently observed.

Since 2012, natural mortality has been an important source of uncertainty included in the stock assessment. In 2012, three fixed levels were used to bracket the plausible range of values. In 2013, the three models contributing to the ensemble included both fixed and estimated values of natural mortality. In the current ensemble, the models again span both fixed (0.15/year for female halibut) and estimated values. The female value estimated in the AAF model (0.14) differs substantially from the value estimated in the coastwide model (0.21). This discrepancy contributes to the difference in scale and productivity for the two models, but is not easily reconciled at present. Although this uncertainty is directly incorporated into the ensemble results, it remains an avenue for future investigation.

Like most stock assessments, estimated removals from the stock are assumed to be accurate. Therefore uncertainty due to bycatch estimation (direct sampling variance where there is low coverage and representativeness for unobserved fishing activity), discard mortality rates, and any other unreported sources of removals in either directed or non-directed fisheries could create significant bias in this assessment.

Future expansion of the ensemble approach will continue to improve uncertainty estimates, and create assessment results that are robust to changes in individual models, data sets and other sources of historical changes in stock assessment results from year to year.

Sensitivity and retrospective analyses

The wide range of sensitivity analyses conducted during the 2013 process remain relevant to the 2014 results, as these were all conducted with the coastwide long time-series model. The most influential source of uncertainty uncovered among sensitivity analyses conducted for 2013 was the sex-ratio of the commercial catch. There is no direct information available (due to dressing of fish at sea prior to observation by IPHC port samplers), and so the 2014 assessment continues to rely on indirect estimates from the sex-ratios observed in the setline survey. Specifically, separate selectivity is estimated for the fishery and setline survey, but the relative difference in selectivity for male and female halibut estimated for the setline survey (using sex-specific data) is assumed to apply to the fishery data. Results in 2013 were found to be very sensitive to this choice: a +/- 10% change in the relative selectivity for males vs. females (and therefore the sex-ratio of the catch) resulted in a 50 million pound range in the estimate of spawning biomass (Fig. 11 in Stewart and Martell 2014).

Three sensitivity analyses were conducted in 2013 to investigate the relative importance of uncertainty in several sources of halibut removals. The results indicated that significantly higher (doubled) and lower (halved) levels of bycatch did not change the relative stock trends, but that adding additional removals suggested a larger stock. This result is expected, as the stock must have been productive enough to support these additional removals and still generate the observed trends. This general result suggests that sources of removals missing from current accounting may positively increase our estimates how much harvest the stock can support. Within the stock assessment models, this can be realized via changes in estimated natural mortality and/or the magnitude of recruitment strengths without appreciably altering the stock trend. Future analyses will be aimed at including uncertainty in discard mortality rates and the magnitude of both wastage and bycatch directly within the stock assessment models.

A retrospective analysis was performed for each of the individual models contributing to this assessment. Both coastwide models showed little pattern in the most recent years, but slightly higher estimates as additional data were removed from each (Fig. 11). The AAF models showed even less retrospective pattern (Fig. 12). All models estimates for the terminal three years of the retrospective analysis were included in the currently estimated confidence intervals.

Forecasts and decision table

Stock projections were conducted using the ensemble assessment (all four models), summaries of the 2014 estimated removals, as well as the results of apportionment calculations and harvest policy application (Webster and Stewart 2015, Stewart 2015). The steps included: 1) apportioning the coastwide estimate of exploitable biomass according to the survey catch rates in each regulatory area (Webster and Stewart 2015), 2) applying the area-specific harvest rates to estimate the total CEY, and all other removals associated with a given level of harvest, and 3) calculating the total mortality and projecting the stock trends one and three years into the future assuming constant values for all sources of removals.

The decision table provides a comparison of the relative risk, using stock and fishery metrics (columns), for a range of alternative harvest levels for 2015 (rows). The block of columns entitled “Stock Trend” (columns a-d) provides for evaluation of the risks to short term trend in spawning biomass, without reference to a particular harvest policy. The remaining columns portray these risks relative to the spawning biomass reference points (“Stock Status”; columns e-h) and fishery performance identified in the current harvest policy (columns i-m). The alternatives provided include: no mortality (useful to evaluate the stock trend due solely to population processes), no directed mortality (but accounting for bycatch and non-scaling sport and personal use removals), the Blue Line (consistent with the current harvest policy and, historically, IPHC staff advice), the *status quo* removals (repeating the FCEYs adopted for 2014), as well as arbitrary values (at 10 Mlb increments) intended to foster the evaluation of the relative change in risk probability across a range of total mortality levels. For each row, the total mortality of all sizes and from all sources, the total coastwide fishery CEY and the associated median level of fishing intensity (measured via the Spawning Potential Ratio) are reported. Fishing intensity reflects the relative reduction in equilibrium spawning biomass per recruit from all sources and sizes of removals, reported as $F_{xx\%}$, for comparison to other processes in both nations where harvest rate targets and limits are commonly reported in these units. An alternative *status quo* reports the harvest levels that maintain the same fishing intensity estimated in 2014. As in previous years, it is expected that additional alternatives will be produced during the IPHCs annual process such that all management alternatives considered for 2015 can be directly evaluated in terms projected total mortality and risk.

The stock is projected to increase gradually over 2016-2018 in the absence of any removals, and for removals of up to 20 Mlb. For removals around 40 Mlb, projections are relatively flat. The risk of stock declines beings to increase relatively rapidly for levels of harvest above 40 million pounds of total mortality resulted in projected declines in 2016, and becoming more pronounced by 2018 (Table 3; Fig. 13). The Blue Line (38.7 Mlb total removals) corresponds to a 19/100 chance of stock decline in 2016 and a 23/100 chance in 2018, somewhat more optimistic than recent assessment results.

For metrics directly based on current harvest policy (stock status, fishery trend, and fishery status), there is a relatively small chance (<24/100) that the stock will decline below the 30% or 20% reference points in projections for all the levels of removals evaluated. For removals in excess of the Blue Line, there is a greater than 50/100 probability that the fishery CEY would be smaller in 2016-2018 if the current harvest policy were applied in those years. As the stock stabilizes to biomass levels consistent with recent recruitment and size-at-age, it is reasonable to expect a greater response in stock trend to annual management decisions.

Future research

Based on data and model exploration completed during 2014, and recommendations from the SRB, future research will focus on the following topics:

1) Continued expansion of the ensemble of models used in the stock assessment. Specifically, explicit spatial models will be developed that may allow for improved incorporation of the uncertainty due to spatial processes such as migration and recruitment distribution among regulatory areas.
2) As development of additional models for the ensemble is reduced, there will be more emphasis on evaluation and diagnosis of each individual model. A document describing in detail the technical specifications, fits to the data sources and results will be developed for review during 2015.

3) Continued development of methods for sampling the sex-ratio of the commercial catch. The results of the stock assessment are sensitive to the sex-ratio, and therefore this source of uncertainty is a high priority for future data collection.
4) Further investigation of the factors contributing to recruitment strength, recruitment distribution, and the information available from trawl surveys, particularly in the Bering Sea.
5) Explore methods for including uncertainty in wastage and bycatch estimates in the assessment in order to better capture these sources uncertainty.
6) Bayesian methods for fully integrating parameter uncertainty may provide improved uncertainty estimates within the models contributing to the assessment.
7) Integration of the assessment analyses with ongoing development of the harvest policy and Management Strategy Evaluation process.

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Table 1. Comparison of 2014 biomass point estimates (median ensemble value; Mlb) from the 2013 and current assessments.

Quantity	2013 Assessment	2014 Assessment
2014 Exploitable biomass	170	170
2014 Spawning biomass	197	209

Table 2. Median population (Mlb) and fishing intensity estimates (based on median Spawning Potential Ratio) from the 2014 assessment.

Year	Spawning biomass	Fishing intensity ($F_{XX\%}$)	Exploitable biomass
1996	584.6	49%	779.2
1997	605.7	43%	809.6
1998	591.8	42%	762.7
1999	567.1	40%	746.8
2000	529.5	40%	688.3
2001	483.9	38%	603.0
2002	434.5	34%	532.2
2003	382.6	30%	460.5
2004	339.5	28%	403.6
2005	299.5	26%	352.6
2006	266.7	26%	307.9
2007	241.5	25%	266.9
2008	224.4	25%	236.3
2009	204.6	26%	203.9
2010	197.8	27%	186.4
2011	195.3	31%	175.6
2012	197.2	35%	169.2
2013	203.9	38%	168.8
2014	208.5	43%	169.7
2015	215.1	NA	180.6

Table 3. Decision table of yield alternatives (rows) and risk metrics (columns). Values in the table represent the probability, in "times out of 100" of a particular risk.

				Stock Trend				Stock Status				Fishery Trend				Fishery Status
				Spawning biomass				Spawning biomass				Fishery CEY from the harvest policy				Harvest rate
				in 2016		in 2018		in 2016		in 2018		in 2016		in 2018		in 2015
2015 Alternative	Total removals (M lb)	Fishery CEY (M lb)	Fishing intensity	is less than 2015	is 5% less than 2015	is less than 2015	is 5% less than 2015	is less than 30%	is less than 20%	is less than 30%	is less than 20%	is less than 2015	is 10% less than 2015	is less than 2015	is 10% less than 2015	is above target
No removals	0.0	0.0	$F_{100\%}$	<1/100	<1/100	<1/100	<1/100	5/100	<1/100	1/100	<1/100	<1/100	<1/100	<1/100	<1/100	0/100
FCEY = 0	13.1	0.0	$F_{73\%}$	<1/100	<1/100	<1/100	<1/100	5/100	<1/100	2/100	<1/100	<1/100	<1/100	<1/100	<1/100	<1/100
	20.0	7.7	$F_{64\%}$	<1/100	<1/100	1/100	<1/100	6/100	<1/100	3/100	<1/100	<1/100	<1/100	<1/100	<1/100	<1/100
	30.0	16.5	$F_{54\%}$	3/100	<1/100	17/100	4/100	7/100	<1/100	5/100	<1/100	3/100	2/100	3/100	2/100	4/100
Blue Line	38.7	25.0	$F_{46\%}$	19/100	<1/100	40/100	23/100	8/100	<1/100	8/100	<1/100	37/100	22/100	36/100	23/100	50/100
status quo	41.4	27.5	$F_{45\%}$	26/100	1/100	47/100	30/100	8/100	<1/100	9/100	1/100	57/100	37/100	51/100	38/100	50/100
Maintain 2014 SPR	43.3	29.5	$F_{43\%}$	31/100	1/100	56/100	36/100	8/100	<1/100	10/100	1/100	73/100	51/100	63/100	49/100	88/100
	50.0	36.0	$F_{39\%}$	44/100	5/100	75/100	51/100	9/100	1/100	13/100	1/100	99/100	91/100	95/100	84/100	>99/100
	60.0	45.8	$F_{34\%}$	65/100	22/100	96/100	82/100	11/100	1/100	23/100	2/100	>99/100	>99/100	>99/100	>99/100	>99/100
				a	b	c	d	e	f	g	h	i	j	k	l	m

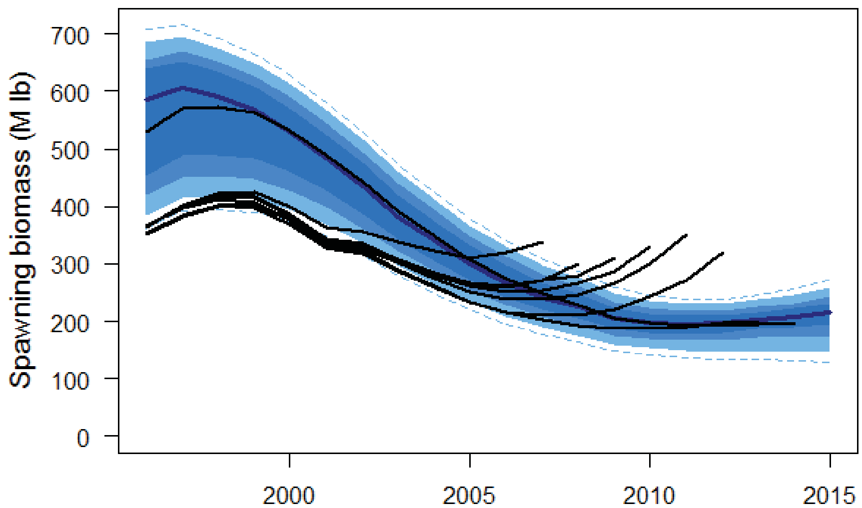

Figure 1. Retrospective comparison among recent stock assessments. The black lines denote point estimates from previous assessments conducted in 2006-2013. The dark blue line indicates the median (or "50:50 line"; with equal probability of the estimate falling above or below that level) from the 2014 assessment; colored bands moving away from the median indicate the intervals containing 50/100, 75/100, and 95/100 estimates; outer dashed lines indicating the 99/100 interval.

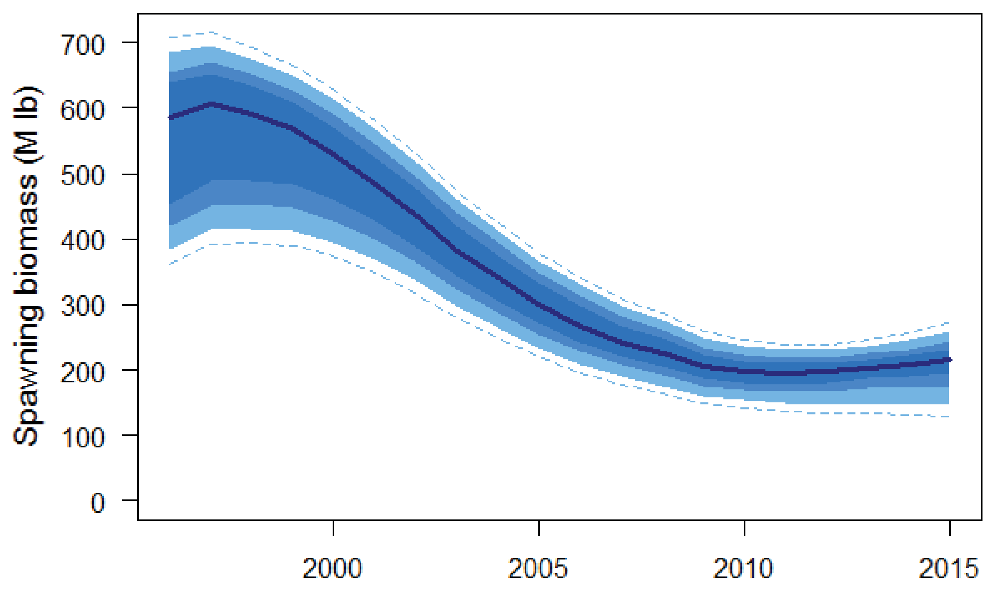

Figure 2. Trend in spawning biomass estimated in the 2014 stock assessment. The dark line indicates the median (or "50:50 line") with an equal probability of the estimate falling above or below that level; colored bands moving away from the median indicate the intervals containing 50/100, 75/100, and 95/100 estimates; outer dashed lines indicating the 99/100 interval.

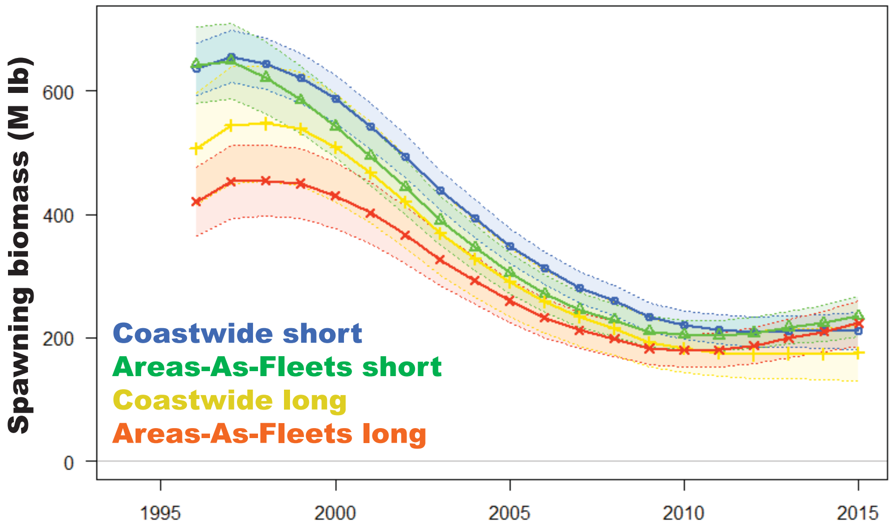

Figure 3. Comparison of models included in the 2014 stock assessment. Solid lines with points indicate point estimates, dashed lines and shading approximate 95% confidence intervals reflecting within-model uncertainty.

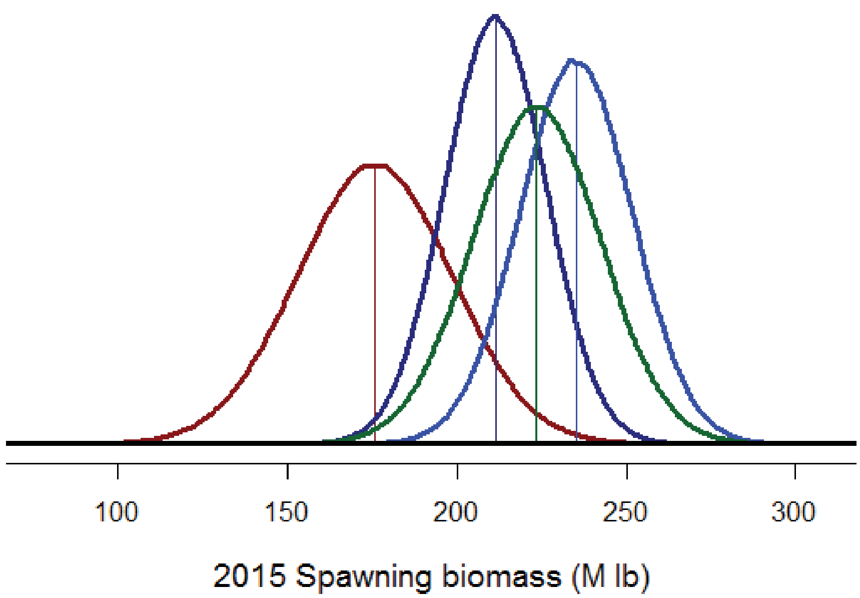

Figure 4. Distribution of individual model estimates for the 2015 spawning biomass. Vertical lines indicate the median values.

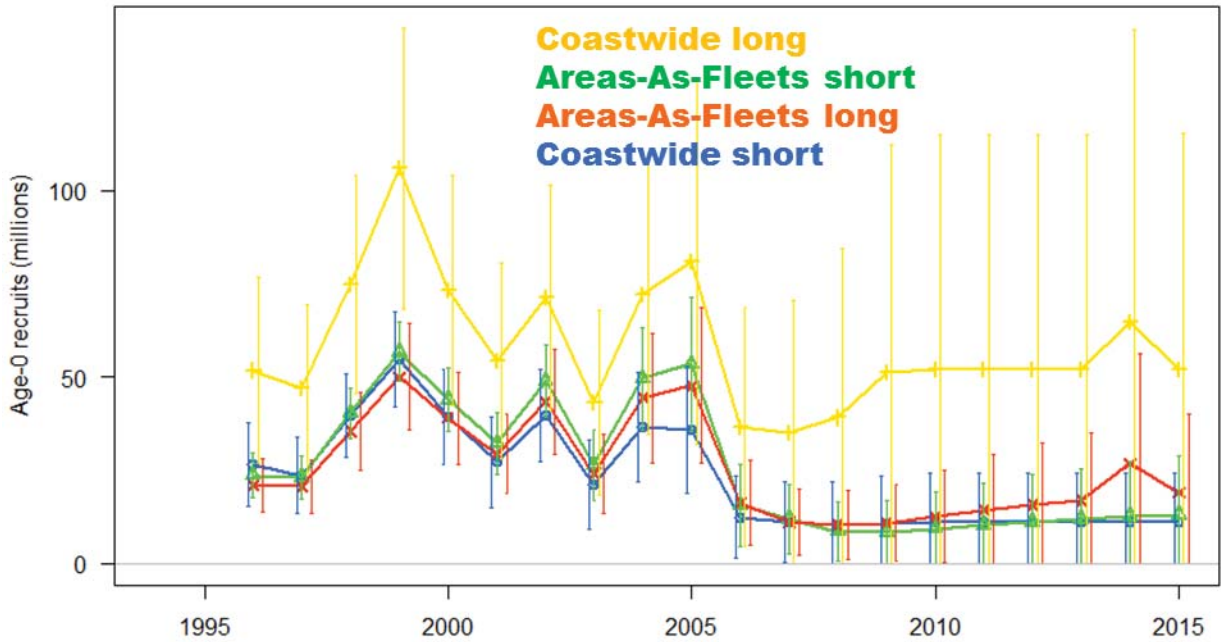

Figure 5. Trend recent recruitment strengths (by birth year) estimated by all four ensemble models. Note that estimates after 2008 are highly uncertain, as they are not yet informed by any direct observations.

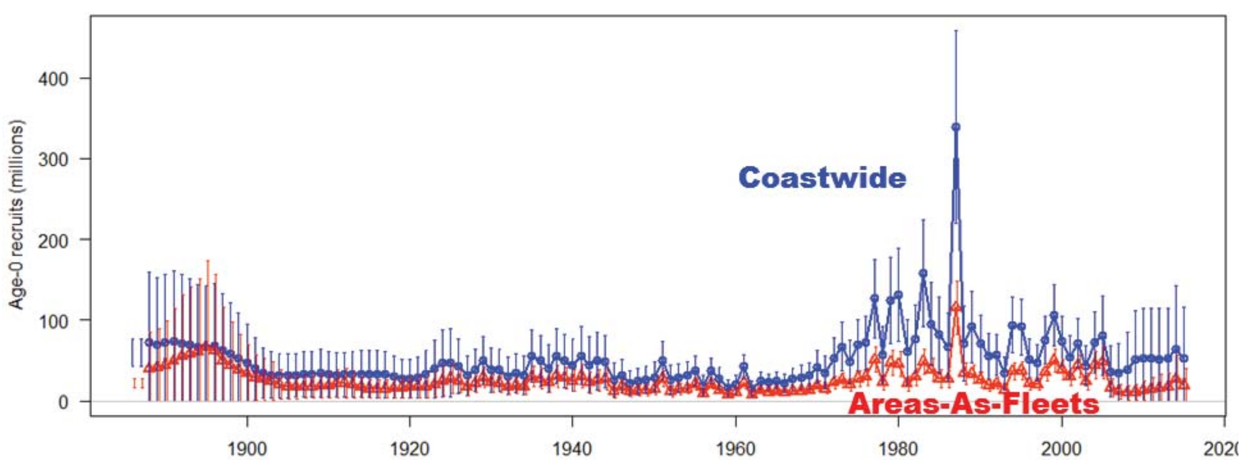

Figure 6. Trend in historical recruitment strengths (by birth year) estimated by the two long time-series models, including the effects of the Pacific Decadal Oscillation (PDO) regimes. Note that estimates after 2008 are highly uncertain, as they are not yet informed by any direct observations.

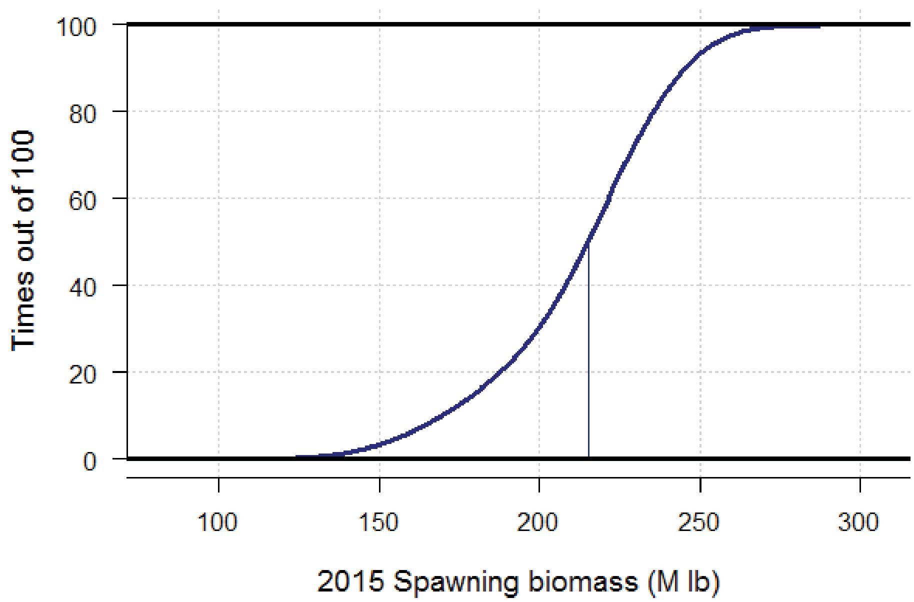

Figure 7. Cumulative distribution of 2015 spawning biomass estimates. Vertical line indicates the median value (215 Mlb).

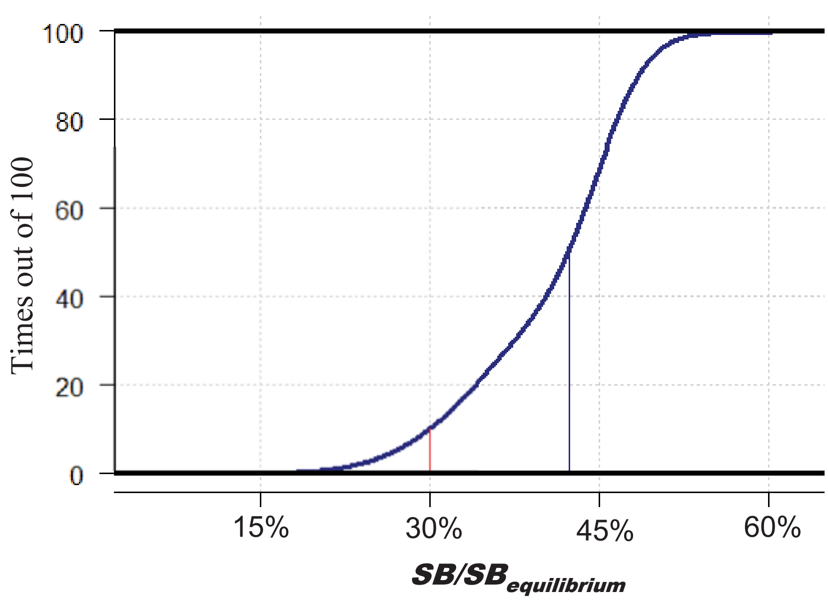

Figure 8. Cumulative distribution of 2015 spawning biomass estimates relative to the equilibrium spawning biomass in the absence of fishing. Vertical lines indicate the median value (42%), and the value corresponding to the IPHC's harvest policy threshold (30%).

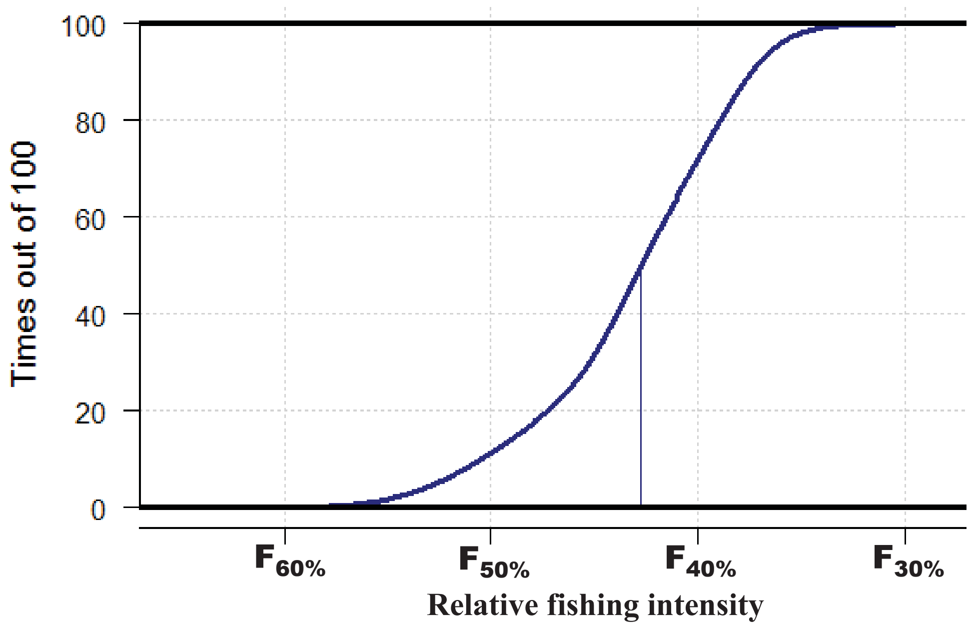

Figure 9. Cumulative distribution of the estimated relative fishing intensity (based on the Spawning Potential Ratio) in 2014. Vertical line indicates the median value (43%).

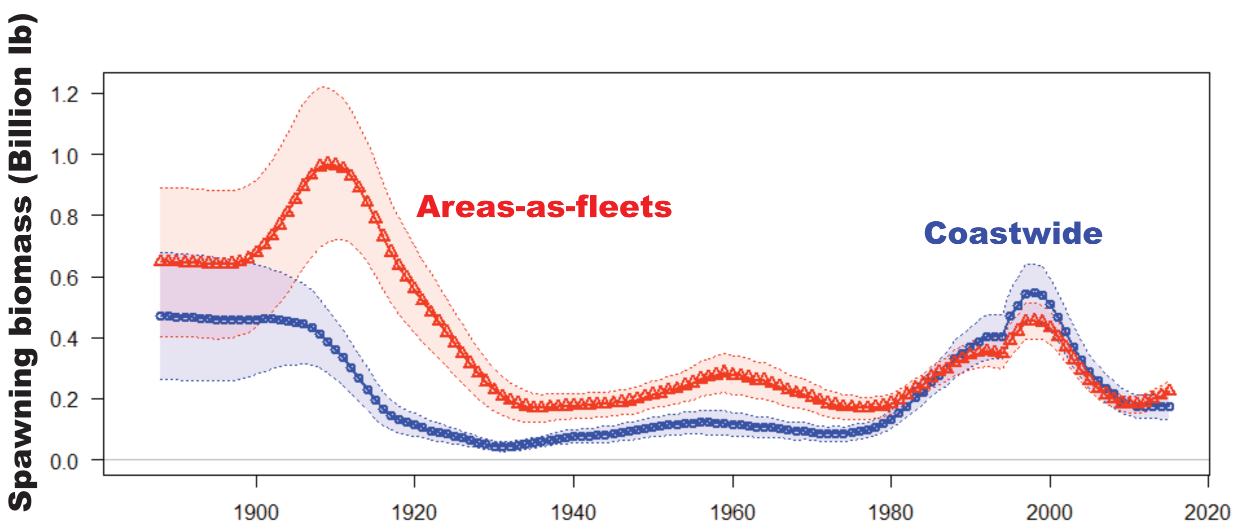

Figure 10. Spawning biomass estimates from the two long time-series models. Shaded region indicates the approximate 95% within-model confidence interval.

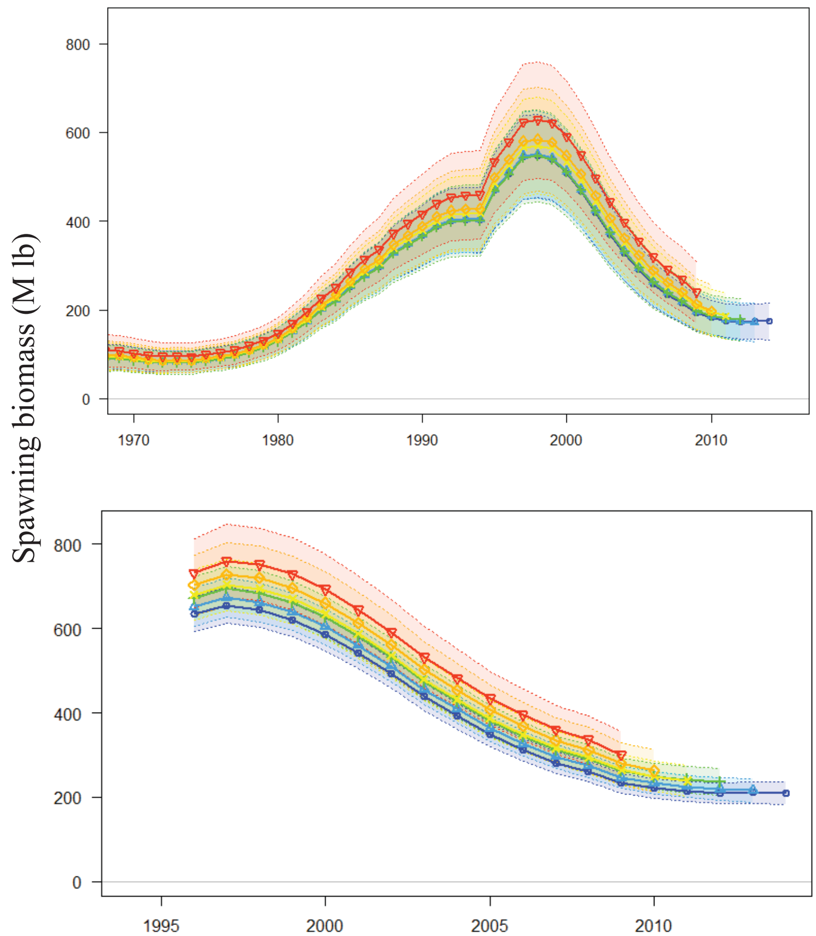

Figure 11. Results of the retrospective analysis on spawning biomass estimates using the coastwide long (upper panel) and coastwide short (lower panel) time-series models and sequentially removing one year of data for five years. Dashed lines and shaded regions indicate within-model 95% uncertainty intervals.

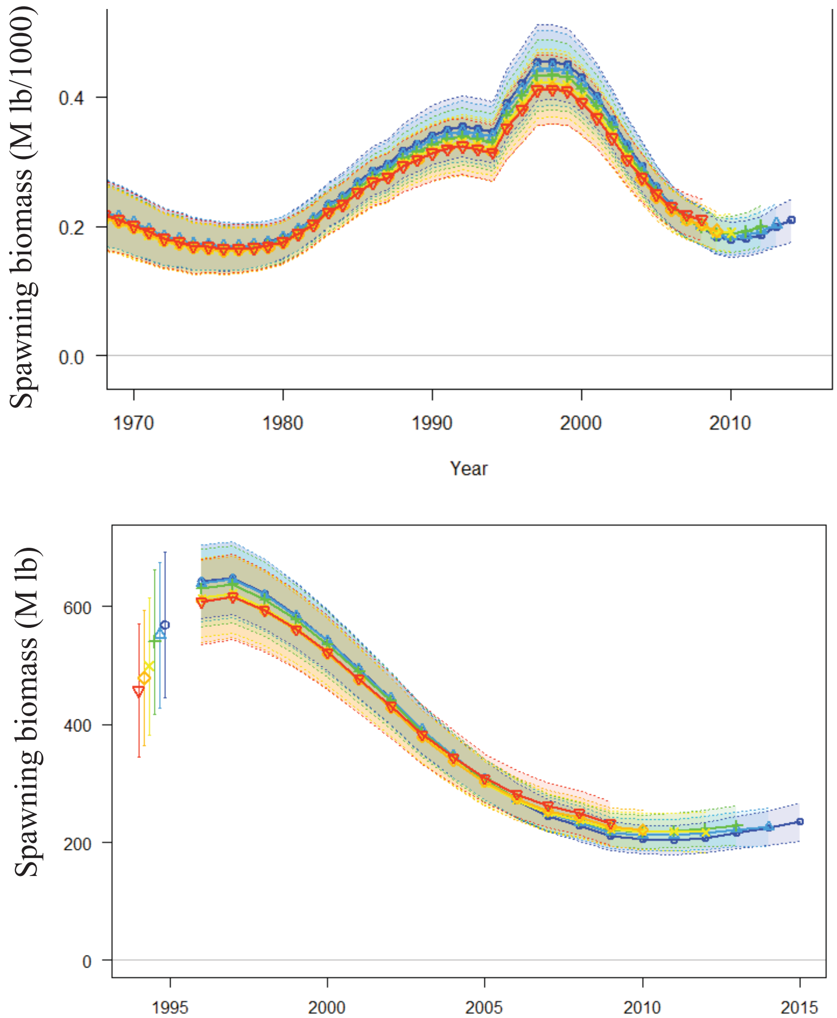

Figure 12. Results of the retrospective analysis on spawning biomass estimates using the Areas-As-Fleets long (upper panel) and Areas-As-Fleets short (lower panel) time-series models and sequentially removing one year of data for five years. Dashed lines and shaded regions indicate within-model 95% uncertainty intervals.

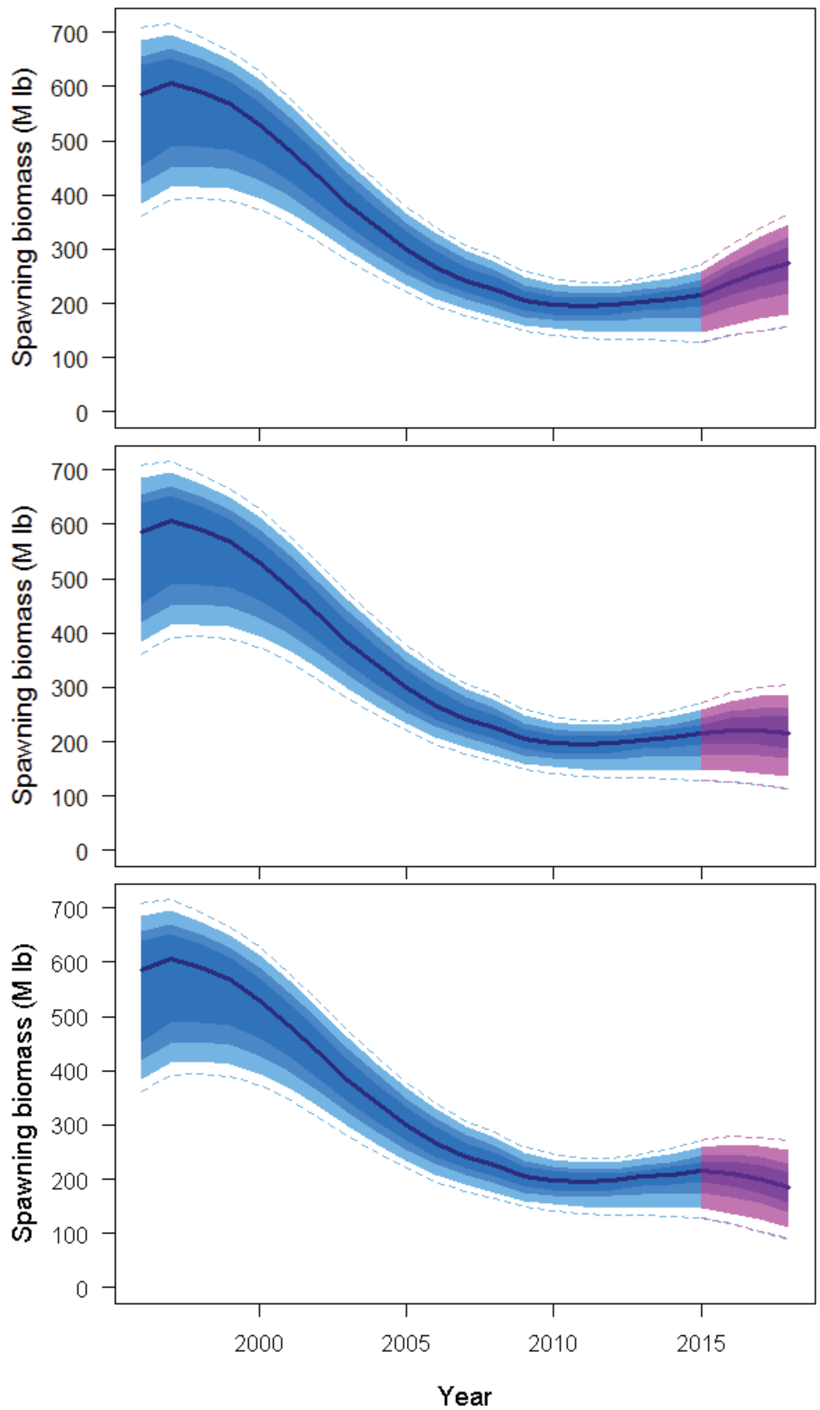

Figure 13. Three-year projections of stock trend under alternative levels of mortality: no removals (upper panel), Blue Line removals (middle panel) and 60 Mlb of total removals (lower panel).

Overview of data sources for the Pacific halibut stock assessment and related analyses

Ian J. Stewart

Introduction

This document provides a summary of the data sources available for the Pacific halibut stock assessment, apportionment, harvest policy, Management Strategy Evaluation (MSE), and related analyses. It began as background for the 2013 stock assessment, and serves as an ongoing effort to provide transparent documentation and direct evaluation of the data and processing methods employed. For each data source, a narrative is provided which includes the source, steps taken to filter and analyze the data, and the key quantities available for subsequent analysis. Data sources are described within the categories of: fishery-independent, fishery-dependent, and auxiliary sources of information. Some of the detail presented in 2014 (Stewart 2014) has not been repeated here, where there has been no change to the methods or results.

Also provided in this document is a brief synopsis of important changes to various data sources and processing, as well as a list of data sources or analyses that are currently not directly used, but are potentially available for future analysis. The latter includes some comment on avenues for additional data collection and/or analysis.

Fishery-independent data

Fishery independent data are generated each year by the IPHC's setline survey, covering most of the range of Pacific halibut habitat from the northern Bering Sea and Aleutian Islands to California, and depths of 20-275 fathoms (Soderlund et al. 2012, Henry et al. 2015). The setline survey generates catch rate information, as well as biological samples from individual fish sampled randomly from the catch including: sex, length, age, maturity, and presence of prior hooking injury. These data are reprocessed each year for use in the stock assessment as new observations become available (Fig. 1). In 2014 a substantial re-analysis of the survey data, including expanded survey coverage from 10-400 fathoms (in Area 2A and Area 4A), northern California, as well as calibration of the survey catch rates with those observed in the National Marine Fisheries Service (NMFS) sablefish longline survey in Alaska. These changes are described in Webster et al. (2015) and are reflected in all of the data presented here.

Survey WPUE (Weight-Per-Unit-Effort)

The catch-rate information from the setline survey serves as the primary source of trend information (along with commercial catch-rates) for the stock assessment. The area-specific setline survey indices of abundance (weight-per-unit-effort, WPUE) are calculated based on the catch in weight relative to the amount of gear deployed at each station. Survey effort for a particular station is standardized to an effective skate (*ES*) that is 1,800 feet long, with 100 hooks (and therefore an 18-foot average spacing), based on the number of skates fished (*S*), the average number of hooks fished per skate (N_h), and the hook-spacing (H_s; Fig. 2) based on the relationship given by Hamley and Skud (1978):

$$ES = S \cdot \left(\frac{N_h}{100}\right) \cdot 1.52 \cdot (1 - e^{-0.06 \cdot H_s})$$

Because the hook spacing is standardized for all recent survey operations, the only variability in this relationship occurs due to changes in the number of hooks (N_h) as a result of missing or extra hooks on a particular skate or skates. The weight of each halibut caught is estimated from the individual length observations via the weight-length relationship (see Auxiliary inputs section below). The sum of the catch weight is divided by the number of effective skates to obtain a station-level WPUE. These observations are then combined within a regulatory area (Fig. 3).

The area-specific WPUE is summarized via a simple arithmetic mean observed value (and SE) of WPUE for all stations (s) sampled within a regulatory area (a) during each year's (y) survey (Fig. 4):

$$\bar{I}_{a,y} = \sum_{s=1}^{Nstation} \frac{WPUE_{s,a,y}}{N_{a,y}}$$

These annual area-specific means are then weighted by the geographic extent of suitable depths occupied by Pacific halibut within each regulatory area (g_a, 0-400 fathoms) relative to the entire coast (Fig. 4). The weighted values are then summed to generate a coast-wide index of abundance:

$$I_y = \sum_{a=1}^{Areas} \bar{I}_{a,y} * \frac{g_a}{\sum_{a=1}^{Areas} g_a}$$

Due to the expansion of survey efforts into deeper and shallower waters, anomalies in historical survey coverage, a number of calibrated expansions, adjustments are made to the WPUE for specific areas and years in order to make the coast-wide time-series as consistently representative as possible. These have been outlined in previous or concurrent documents (Webster and Hare 2012, Webster et al. 2014a, Webster et al. 2014b, Webster et al. 2015).

After these adjustments have been applied, the coastwide survey legal-size (above the 32 inch minimum size limit, or O32) WPUE index is estimated to have increased by 2% from 2013 to 2014 (Table 1, Fig. 5). Although the O32 WPUE is most directly comparable to the catch rates observed in the commercial fishery, there is potentially important trend information in the catch of sublegal halibut (U32) as well. The total WPUE (including all sizes of halibut captured by the survey) increased by 6% from 2013 to 2014 (Figs. 5-6). Both series reflect a one-year increase across most regulatory areas, and are consistent with a generally flat coastwide trajectory since about 2010. The overall coastwide trend masks important differences in the historical declines, most pronounced in Areas 3A-4B, as well as the relative stability observed in Area 2 (Fig. 7).

In 2014, on the recommendation of the IPHC's Scientific Review Board (SRB), the stock assessment began fitting directly to the Numbers-Per-Unit-Effort (NPUE) from the setline survey. This avoids converting observed lengths to weights based on the length-weight relationship, and provides a delineation between changes in the number of fish and changes in the size of those fish. Broadly, very similar trends have been observed for NPUE when compared to the WPUE;

however both the O32 and total NPUE show more modest historical declines (Fig. 8). When aggregated into geographic regions, the NPUE data also show a flat trajectory for Area 2, and historical declines for Areas 3, 4, and 4B (Fig. 9-10).

Prior to 1997, survey coverage was sparse enough to preclude a more complex approach to estimate coastwide catch rates. However, data are available for at least several regulatory areas in a number of earlier years. These data represent only Areas 2B, 2C, and 3A (the geographic 'core' of the stock) for the years 1982-1996, and only Areas 2B and 3A for the years 1977-1981. In 1984, among other changes to the station design and coverage, the setline survey (following the commercial fishery the year before) converted their standard gear to include circle hooks; this greatly increased catch rates from previous years.

Survey age distributions

Otoliths are collected randomly from halibut captured by the setline survey, with sampling rates adjusted annually by regulatory area to achieve a similar number of samples from each area in each year. All otoliths collected during survey activities are read each year by IPHC age-readers. Because the survey catch is sampled randomly at the same rate for all stations within a given regulatory area and year, the raw frequency of ages is an appropriate estimate of the aggregate for the area. Age distributions differ between male and female halibut and among regulatory areas, with older fish comprised of primarily males, and occurring in much greater numbers in the western and northern regulatory areas (Fig. 11). Area 2 showed a somewhat greater number of age 9-10 halibut in 2014; however these ages were not as pronounced in other regulatory areas, particularly for male halibut.

In order to weight these area-specific distributions, an estimate of the number of halibut in each area is required. This is obtained via weighting the NPUE values by the same geographic proportions used for WPUE. The relative numbers in each regulatory area then provide a weighting for combining the age-frequency distributions into a coastwide aggregate (Fig. 12). In recent years, the strength of the 1987 year class has been particularly evident in these data. The age frequencies over the last five years do not show any signs of strong incoming cohorts (as 6-8 year-old fish).

Ages have been aggregated at age 20 (all ages 20 and older combined) for all data (survey and fishery) collected prior to 2002 when the break-and-bake ageing method was adopted for all halibut age-reading by the IPHC (see section on ageing bias and imprecision below). Most ages read prior to 2002 used surface ageing methods, except for 1998, where a randomly selected subsample of otoliths were re-aged (during 2013) and ages can be more reliably interpreted out to age-25 (see Stewart 2014, and Forsberg and Stewart 2015 for more information on these samples).

As for the catch-rate data, there are some sparse age data available prior to 1997. These age data represent only Areas 2B, 2C, and 3A for the years 1982-1996, and only Areas 2B and 3A for the years 1980-1981. These earlier data do not reveal any particularly strong cohorts, nor do the cohort strengths appear appreciably different for male and female halibut. The age data was also aggregated into geographic regions, revealing important differences in age structure (Fig. 13-14). Specifically, there have been very few halibut greater than age 20 of either sex observed in Area 2, but fish of those ages, and particularly males, become more common in the western and northern portions of the stock. Area 4B shows the highest proportion of age 25+ halibut for both males and females.

Survey weight-at-age

The survey collects individual length observations on all halibut captured, which are then converted to estimated weights via the length-weight relationship (see section below). Age estimates are also available for a random subsample of these lengths.

Ages consist of primarily surface ages prior to 2002, and exclusively break-and-bake ages from 2002 to the present. Prior analyses of weight-at-age attempted to correct for the potential bias of surface ages by converting the weights corresponding to surface ages to the 'true' weight at age given an estimated level of bias (and some assumption of the underlying age structure). Investigation of the data prior to 2002 revealed that many of the surface ages also had corresponding break-and-bake ages that were not being included in the analysis (see summary of ageing bias and precision below). Replacing all surface ages with break-and-bake ages (where available) in the weight-at-age calculations appears to adequately address the differences in the ageing methods for the recent data.

Because the sampling of ages is random within the survey catches for an area each year, the average weight-at-age by area, sex, and year is calculated. Where there are very few individuals in the population of a particular age, the number of survey age samples is also small (the age samples are not length-stratified). This pattern, in combination with incomplete survey sampling for some areas and years, results in a small number of missing weights-at-age within area and year combinations. These are simply interpolated from adjacent years. Because the survey captures few fish younger than age 7 or older than age 25, all fish outside this range are aggregated to these 'minus' and 'plus' groups. Although there has been a very strong trend of declining weight-at-age in recent years, there are marked differences in the magnitude of this decline among regulatory areas (Figs. 15-22, plotted only from ages 7-18 here for clarity). There also appear to be some patterns associated with specific cohorts; e.g., females in Area 2C born in the late-1990s (Fig. 16, upper panel). There do not appear to be consistent or strong trends from 2010-2014 in the area-specific data.

These different trends among areas require appropriate weighting of the areas to create a coastwide time-series that represents the entire stock. The estimates of numbers of fish generated from survey NPUE and geographic extent are used to weight the individual regulatory areas. At the coastwide level the stronger declines observed in the areas for which the greatest number of halibut are estimated to be present are evident, especially for the years prior to 2010 (Fig. 23). A broader comparison of historical observations predicted from a mix of fishery and survey data (See Fishery weight at age section below) indicates that the declines in size-at-age were even more pronounced from the mid-1970s to the mid-1990s than in the recent period covered by the setline survey (Fig. 24).

For input to the stock assessment, a full matrix of weight-at-age by year and sex is required, despite the small number of fish present in the youngest and oldest ages. To complete the matrix, a linear ramp in weight-at-age is applied below age 7. For the plus group (25+), the average age is calculated; this average age is then used to extrapolate the weight-at-age for ages 25-30. This is necessary because the average weight-at-age for all 25+ halibut combined should not be attributed to exactly age 25: the average age must be >25 unless all fish are exactly 25.

Spawning output-at-age

Survey data are also used to define the population-level weight-at-age and spawning biomass. Unlike the survey index calculation, where interannual sampling variability is logically included, the true population level quantities should be smoother than the raw observations. In analyses previous to 2013, these quantities had been smoothed across ages within each year without regard for sample size, which induced significant correlation among ages, and spurious 'dog-legs' that extended over several adjacent ages. Reanalysis of these quantities in 2013 (Stewart 2014) indicated that applying a smoother across years within each age produced results more consistent with those expected for population level values. These summaries most clearly show the population-level decline in weight-at-age observed for both male and female halibut over the recent time-series available from the survey (Fig. 24). Survey observations of weight-at-age might include some bias relative to the population if size-based selectivity is operating on the distribution of lengths within each age. However, the matrix of population-level weight-at-age is most important in the assessment for those ages that are mature, for halibut mainly ages 11 and higher (see Maturity section below) which are less likely to experience significant bias.

Fishery-dependent data

Commercial fishery landings

An annual estimate of total mortality of halibut from all sources is required for all stock assessment and related analyses. Removals can be categorized into five major components: fishery landings, fishery wastage (a combination of sub-legal and legal-sized fish), sport (recreational), personal use or subsistence removals, and bycatch of halibut in fisheries targeting other species (Fig. 26).

Landings of halibut from the directed fishery are documented through the use of commercial fish tickets, reported to the IPHC (Gilroy et al. 2015). From 1981 to the present, these landings are fully delineated by regulatory area (including all of the portions of Area 4; Fig. 27). Prior to 1981, landings are available only in aggregated form for all of Regulatory Area 4. Landings from 1935 to 1980 are not currently included in the IPHC's database; however previous analysts have left a number of 'flat files' which appear to correspond well with tables published in technical reports, and other IPHC documents. Because the raw data are not able to be reprocessed directly, the landings estimates prior to 1981 are more uncertain than those after 1981. Historical landings prior to 1935 were reconstructed within current regulatory areas from summaries by historical statistical areas (Bell et al. 1952). Reported landings of halibut begin in 1888; however, already over one million pounds were being landed per year at that time. The reconstruction by regulatory area of total landings included some use of ratios between Areas 2A and 2B among adjacent years for ambiguous records, therefore the area-specific distributions are therefore more uncertain than the total landings. Several patterns emerge from the longer time series of landings including: the period of substantially reduced fishing in the 1970s in all areas, and the sequential exploitation of Areas 2, 3, and 4 over the entire time series (Table 2, Fig. 28).

Sport (recreational) removals

Sport or recreational removals are reported to the IPHC by the various agencies in charge of managing these fisheries, including Alaska Department of Fish and Game, the Department of Fisheries and Oceans Canada, and the states of Washington, Oregon, and California (Kaimmer 2015). The scientific basis for data collection programs, analyses, and the quality of the subsequent estimates vary considerably by year and source. The 2014 estimates (and several previous years, where available) include mortality estimates for released fish. This is the first year that recreational discard mortality has been included in IPHC analyses. It is generally assumed that there was little sport fishing for Pacific halibut prior to the mid-1970s. Sport removals have grown rapidly since that time, with peak harvests estimated at over 10 million pounds annually during the mid-2000s. They have been reduced in recent years as the IPHC has lowered stock-wide mortality (Fig. 29). Among regulatory areas, Area 3A represents over half of the total removals, with Areas 2C, 2B, and 2A each contributing somewhat less (in declining order).

Personal use or subsistence removals

Subsistence harvest estimates are provided to the IPHC by the DFO and NMFS (Gilroy 2015). Estimates are not generated annually in all cases, and therefore some values are applied through intervening years until the next estimate is made available. This has been the case for the most recent several years. There are currently no estimates available prior to 1991. The time-series created from these estimates is relatively noisy, but occurs on a scale much smaller (< 2 million pounds) than other critical inputs to the analyses (Fig. 30).

Commercial fishery wastage

'Wastage' describes all mortality of halibut that occurs during the directed fishery, but that does not become part of the landed catch. There are three main sources of wastage: 1) fish that are estimated to have been captured by fishing gear that was subsequently lost during fishing operations, 2) fish that are discarded for regulatory reasons (e.g., the vessel's trip limit or harvester's IFQ limit have been exceeded), and 3) fish that are captured and discarded because they are below the legal size limit of 32 inches. The methods applied to produce each of these estimates differ due to the amount and quality of information available (see Gilroy and Stewart 2015).

Based on these methods, wastage in the commercial fishery is estimated to have been highest in the late 1980s, subsequently declining (particularly in Area 3A in 1995 when the derby fishery was converted to a quota system), and then increasing from 1995 to 2010 as the size-at-age of halibut declined and more fish at older ages remained below the minimum size limit (Fig. 31, upper panel). The estimates of wastage cannot be delineated within Regulatory Area 4 prior to 1981, but there is very little wastage estimated prior to that time (Fig. 31, lower panel).

Bycatch in non-target fisheries

The estimated bycatch from non-target fisheries by regulatory area is reported to the IPHC by the NMFS and DFO on an annual basis (Williams 2015). These estimates vary greatly in quality and precision depending upon year, fishery, type of estimation method, and many other factors. Bycatch has been delineated among Areas 4A, 4B, and 4CDE only from 1990 to the present, during which time it has declined from a peak of over 20 million pounds to a projected value of approximately 9.3 million pounds in 2014 (Fig. 32, upper panel). Over the last several years bycatch has decreased in most regulatory areas, and stayed relatively flat for all of Area 4 (Fig. 32, lower panel), but has increased in Area 4CDE. Prior to 1991, available bycatch estimates are aggregated for all of Area 4. From the 1960s to 1990s, annual values were variable with a peak in the early 1960s corresponding to the peak of foreign fishing in (currently) Alaska waters, primarily Areas 3A and 3B. There was likely less bycatch prior to the development of the foreign fishery in U.S. waters in the early 1960s; however, bycatch estimates are only available from 1962 to the present.

Summary of total halibut removals

Recent aggregate total removals from all sources reveal that although the directed commercial fishery represents the majority of the anthropogenic mortality, other sources, including bycatch and sport removals, tend to contribute a larger proportion when the total is lower (Fig. 33). Total removals in 2014 are approaching those from the 1970s and below the 100-year average of 64 million pounds. Recent total removals from all sources by regulatory area reveal that Area 3A has been the dominant contributor to total mortality throughout the last five decades, that Area 4 has increased in its proportion of the total, and that the other areas have been somewhat consistent (Table 3, Fig. 34).

The full time-series of estimated removals illustrates that all four of the major peaks in the commercial fishery mortality have been of similar magnitude (around 70 million pounds) but that each peak has been larger than the previous with regard to total mortality from all sources (Table 4, Fig. 35). When the removals by source are compared among regulatory areas, there are a number of differing patterns in magnitude and distribution (Figs. 36-38).

Fishery catch-rate and biological data

Directed commercial fishery data is processed similarly to the setline survey data (Fig. 39), with the important exception that there are no sex-specific biological observations available due to the dressing of halibut at sea.

Directed fishery WPUE

Commercial fishery logbook data is collected by port samplers, and reported directly to the IPHC by fishermen. This dataset represents a valuable source of information about many aspects of the commercial fishery, including seasonal and spatial patterns, gear usage, and other details. A relatively simple method is employed to calculate the annual index of fishery WPUE, and a detailed exploratory analysis of the logbook standardization data and methods was completed during 2014 (Monnahan and Stewart 2015).

The data that are included in the current fishery WPUE standardization are: the regulatory area of fishing (regardless of the port of delivery), the type of fishing gear used (only fixed-hook data are used in Areas 2C, 3A, 3B, 4A, 4B, 4C, 4D; both fixed-hook and snap gear are used in Areas 2A and 2B), the year of fishing (some logbooks are not obtained by port samplers until the following year), the number of skates fished (excluding any gear that was lost), the spacing of the hooks, the number of hooks on each skate, and the pounds of legal-sized halibut captured and landed. Only sets specifically targeting Pacific halibut are included in the analysis and all sets with hook-spacing of less than four feet are assumed to be non-halibut targeting, except in Area 2A.

For each regulatory area and year combination, the sum of the recorded landings is divided by the sum of the effective skates (the calculation of effective skates is identical to that applied to the survey data). Due to the small number of fixed-hook sets in regulatory Areas 2A and 2B, snap gear is included in the calculation for these areas. This is done by dividing the snap gear effort by a factor of 1.35 (Clark 2002). There are too few logs available on an annual basis from Area 4E to include that regulatory area in the WPUE calculations.

The WPUE by regulatory area is combined into a coastwide total by multiplying the area-specific values by the geographic extent of the 0-400 fathom bathymetry in each area (as for survey WPUE). This is consistent with the concept that the commercial WPUE is also a 'survey' of the stock and therefore the estimates are a proxy for density, but diverges from the more common approach of weighting the commercial WPUE from each area by the catch in that area relative to the total. It may be preferable in the future to explore the use of catch- instead of geographic-weighting.

As has been observed over several previous stock assessments, the final verified record of logbooks available approximately 10-12 months after the end of the annual fishing season (August to September of the following year) have tended to show a lower catch rate than the preliminary data available in November and used in the stock assessment each year. These differences reflect the inclusion of logbooks that were not collected by port samplers during the year of fishing (and subsequently mailed in to the IPHC, or collected by port samplers during the 2013 fishing season), as well as logbooks that had been collected but were not available for analysis in 2012 (the fishing season extended until early November; the stock assessment data were finalized the day the fishery closed). After the development of indices for the 2014 stock assessment an inconsistency in the treatment of unverified logs was also identified in the data processing routines. As a result, preliminary estimates of fishery catch-rates were slightly higher than the final estimates presented here at the coastwide level, with much of the difference occurring in Area 2B where there is a higher proportion of sets targeting mixed-species. Correction of this inconsistency may reduce the *post hoc* change in future years, although the change will continue to be monitored and investigated. Other potential contributing factors could be the combination of a decline in WPUE during the fishing season, and a higher probability of logs from later in the season being unavailable at the time of the assessment. The final 2013 logbook data was 4% lower than estimated for the 2014 process (Stewart 2014). Based on this pattern, since 2013 the variance of the terminal year of the WPUE series has been inflated to reflect this additional uncertainty. Therefore, the 3% increase currently estimated from the revised 2013 value (Table 5, Fig. 40) should be interpreted with caution and tempered by inspection of previous trends, particularly at the area-specific level.

Recent trends in the commercial WPUE series differ substantially among regulatory areas, with Areas 2A, 2B and 2C showing increases, and Areas 3A through 4A showing clear continued declines. In Areas 3A through 4 fishery catch rates were substantially higher in the late 1980s through the late 1990s than at present (Table 5, Fig. 40).

Effort data for years prior to 1981 do not currently exist in the IPHC's database. For historical data, as is the case for other sources of information, there exist flat files from previous analysts that include effort and landed catch by regulatory area. These data have been used for other analyses, and date back to 1907. Prior to 1935, records of effort are reported in various technical and other IPHC reports, and there are a number of differing time-series available. For this summary, total catch and total effort were tabulated from Chapman (1962) for the years 1921-1934, and from Thompson and Bell (1931), although there are differing series in at least Skud (1975) and several others. The oldest historical records do include even earlier years, but have not been included here pending more detailed investigation. It would be preferable to access and process the historical log data directly from data stored in a database with meta-data, but this is not currently possible.

The most dramatic change in the commercial WPUE time series corresponds to the transition from "J" to circle hooks in 1984 (Fig. 41), although there have been many other changes in the definition of effort over the time series (see synopsis in Leaman et al. 2012). Changes in catch rates prior to the 1980s also reflect the historical progression of the fishery from south to north over much of the time-series (Fig. 28). Despite these caveats, it is clear that catch rates were quite low around the time of the formation of the Halibut Commission (in fact, this was the motivation for the original convention), and again in the late 1970s (Table 5, Fig. 41). Additional uncertainty throughout the historical series is reflected by increased CVs (fixed at 0.1) for all years prior to 1996.

Fishery age distributions

Recent fishery ages are created from otoliths collected by port samplers in proportion to the landings in the ports that are annually staffed by the IPHC (Erikson and MacTavish 2015). Because of this method, the raw ages can be directly aggregated within each area and year to estimate the age composition of the catch. Because port samplers also collect individual lengths, the average weight within each area can also be directly estimated via the length-weight relationship. Dividing the total commercial catch for each regulatory area and year by the average fish weight gives an estimate of the number of fish captured. To aggregate the proportions-at-age from each area into a coastwide or regional total, each regulatory area is weighted by the numbers of fish in the catch relative to the total number of fish captured over all areas. For the period included in recent stock assessments, the coastwide age distribution displays a very similar pattern to that of the setline survey ages: a very strong 1987 cohort moving through the stock (Fig. 42), followed by catches comprised primarily of 9 to 15 year-old halibut.

Commercial fishery ages prior to 1991 have been summarized by several previous analysts, in some cases processed originally by one analyst and then subsequently by another (Clark et al. 2000). For this summary, a file produced for the analysis by Clark et al. (2000) was obtained, which included proportions at age by regulatory area from 1935 to 1990. Additional work could be done to verify which of these proportions can and can't be recreated from the current IPHC database. Weighting of the area-specific proportions followed the method applied to the more recent data, first obtaining an average individual weight (in this case by multiplying the proportions at age by the estimated average weight at age from the historical records), and then dividing the total landings by that weight to get an estimate of the number of fish in the landings by year and area. Again following the survey analysis methodology, the numbers in the landings by area were used to weight the proportions-at-age for a coastwide total.

The resultant fishery age-frequency distributions reveal that halibut in the commercial landings from the 1930s to 1973 (when the current minimum size limit was implemented) have been predominantly age 6 to 14 (Fig. 43). Several strong cohorts can be observed in the data, but none more conspicuous than the 1987 cohort. When the fishery age data are aggregated by geographic region, a similar pattern emerges to that seen in the setline survey data: a greater proportion of older halibut in Areas 4 and 4B than in Areas 2 and 3, but a similar overall age over which much of the catch has been taken and clear evidence that the 1987 cohort was very strong across the entire range of the population (Fig. 44).

Fishery weight-at-age

Both lengths and otoliths are collected by port samplers, and the lengths can be converted into individual weight estimates. No sex information is available from port samples. The average weight of a landed halibut has shown relatively flat trends over Areas 2A, 2B, and 2C, steep declines in Areas 3A and 3B and somewhat less pronounced declines in Area 4 (Fig. 45). Several areas showed an increase in average weight in 2013, but the coastwide trend has been relatively flat over the last five years. These observations accurately reflect the fishery landings, but combine the relative influences of weight-at-age, age- and sex-structure, as well as selectivity relative to the underlying population.

Historical observations of average weight are more problematic. Specifically, from 1963-1990 the IPHC did not collect individual lengths from the commercial landings. It was thought at the time that otoliths measurements could be used to adequately estimate the body size of the fish (Southward 1962), and therefore the weight. Subsequent investigation of the relationship between otolith measurements and individual length (Clark 1992) resulted in the resumption of length sampling in 1991. For this reason, the weights-at-age for most of the historical period should be considered much more uncertain than recent observations. Despite these considerations, there is a clear pattern of increasing fish size in the landings from the 1930s through the 1970s, followed by a subsequent decline to the present (Fig. 46). Also clearly visible is the effect of the implementation of the 32 inch minimum size limit in 1973.

Following the same method applied to the age-composition data (weighting the historical weight-at-age for each regulatory area by the number of fish in the landings for that area), a coastwide weight-at-age can be constructed for the entire time-series. Unfortunately, this series is not sex-specific due to the dressing of fish at sea prior to sampling by port samplers. However, there are similar trends for the best represented ages (8-16) over the historical period. One way to investigate these patterns is to divide the time series of weight-at-age for each age relative to the first year in which we have a coastwide estimate from survey data (1997). Only legal-sized fish from the survey catch are included in these weights-at-age in order to make them comparable to fishery landings. These deviations show very similar temporal patterns, despite expected differences on an absolute scale (see figure in Stewart 2014). As a proxy for sex-specific weights-at-age for the entire time-series, the survey weights-at-age from 1997 were scaled by the time series of annual deviations calculated from the fishery data. This implicitly assumes that male and female halibut have experienced similar trends in size-at-age and recent data that are available by sex support this assumption.

Auxiliary inputs

Several additional sources of information are included in the stock assessment or related analyses and treated as data, even though they represent the products of analyses themselves. These are briefly summarized here but considerable additional background material exists.

Weight-length relationship

The weight-length relationship for Pacific halibut was developed in 1926, re-evaluated in 1991 (Clark), and has been applied as standard practice for al years of IPHC management. The relationship between fork length (L_f), and individual net (headed and gutted) weights (W_n) is given by:

$$W_n = 0.00000692 \cdot {L_f}^{3.24}$$

This relationship reflects the slightly greater than cubic increase in weight with increasing length (Fig. 47). In 2013, the IPHC staff initiated a program to begin sampling individual weights during port sampling. In 2015, this program will include continued data collection during port sampling, as well as sampling on survey vessels. Over the next several years these data should allow for a reanalysis of the length-weight relationship, as well as an improved understanding of the differences in measurements collected on freshly dead fish, fish that have been stored on ice, as well as the relative contributions of head-weights, ice and slime on standardization to net weight.

Maturity schedule

The maturity schedule for Pacific halibut has been investigated several times historically, and maturity-at-age found to be very stable despite long-term changes in length- and weight-at-age (Clark and Hare 2006). Estimates of the age at which 50% of female halibut are sexually mature average 11.6 years among regulatory areas, with very few fish mature at ages less than five and nearly all fish mature by about age-17. The maturity schedule used for stock assessment has not been updated in recent years, and it is represented by a logistic fit that is truncated below age 8 (Fig. 46).

Ageing bias and imprecision

Ages are often treated and referred to as 'data', however they represent estimates of age based (most commonly) on the counting the rings formed annually on otoliths. These estimates are therefore subject to both bias and imprecision depending on the method employed to obtain them. Halibut tend to be relatively easy to age (compared to longer-lived groundfish), and historical estimates of the imprecision of the standard method of 'break-and-bake' ageing showed that the method was very precise (Clark 2004a, b, Clark and Hare 2006). Validation of the method relative to actual age has been performed via analysis of radiocarbon levels observed in known-age otoliths, and the relationship has since been used as the standard for North Pacific groundfish species (Piner and Wischniowski 2004).

Prior to 2002, surface ageing was employed as the primary tool for ageing Pacific halibut, and this method is known to be biased for older individuals and less precise than other methods when applied to many marine species. Estimates of bias and imprecision for break-and-bake and surface ages were updated in 2013 based on re-aging of setline survey samples from 1998 (See Stewart 2014, and Forsberg and Stewart 2015). Analysis of surface ages from each decade back to the 1920s also corroborated those results (Forsberg and Stewart 2015).

Pacific Decadal Oscillation

Previous research identified a strong correlation between the environmental conditions in the northeast Pacific Ocean, specifically the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) and recruitment of halibut to the commercial fishery during the 1900s. A description of ongoing PDO research as well as access to the time-series of estimates can be found at: http://jisao.washington.edu/pdo/. For Pacific halibut, the positive 'phase' of the PDO (years up to and including 1947 and 1977-2006) and subsequent recruitment of juveniles into the commercial fishery appears to be correlated (Clark et al. 1999, Clark and Hare 2002). Recent reinvestigation of this analysis revealed that the correlation still appears strong using all available data (Stewart and Martell 2014). It is therefore worthwhile to monitor the recent trends in the PDO time series for qualitative purposes, as this represents some of the only information available related to juvenile halibut abundance prior to their entry into the survey and fishery around age 8-10. Inspection of the most recent PDO values indicates that deviations after 2006 have been negative with the exception of 2014 (Fig. 49). This represents the longest period of negative annual values observed since the late 1970s. The positive value in 2014 should be interpreted cautiously however, as many other environmental indicators were highly anomalous, and it is very unclear whether 2014 represents comparable conditions to previous PDO observations.

Conclusions

Despite the heterogeneous nature of the various datasets, there is a considerable quantity of historical data available for Pacific halibut, perhaps more than for any other single groundfish species in the region. The IPHC has the benefit of an extremely long time-series of data collection, a high degree of cooperation from the commercial fleet, and therefore a unique resource for historical fishery and biological patterns in the northeast Pacific Ocean. The data themselves, after accounting for important known changes in fishery and survey activities, are remarkably coherent and potentially highly informative for stock assessment, harvest policy, and MSE analyses.

Summary data processing in 2014

This document does not attempt to describe all previous data sources and processing methods used for stock assessment. It is intended to provide an overview of what might be considered current 'best practices'. Some of the more important changes to previously employed methods are outlined here along with the rationale for the changes made.

- As in 2013, fishery age data are no longer disaggregated into male and female observations based on survey sex-ratios, but modelled as aggregate age-frequency data for both sexes combined.
- Setline survey total NPUE is now used as the primary index of relative abundance, rather than only the O32 survey WPUE.
- As summarized above, commercial fishery and setline survey data were summarized both at the coastwide level and also by geographic region (Area 2, Area 3, Area 4, and Area 4B) during 2014 for use in assessment modelling (see Stewart and Martell 2015).
- Mortality associated with catch-and-release in the recreational fishery has been included in estimates for 2014 (see Kaimmer 2015).
- Length-frequency data collected by the North Pacific Observer Program have been updated to include the most recent complete year of sampling (2013). These data are important for use in delineating the proportion of the bycatch estimated to be above and below 26 inches for the harvest policy calculations.

Data sources for future analysis and potential research projects

This section represents a 'laundry-list' of potential extensions to current efforts, as well as new analyses that could benefit the halibut stock assessment or related analyses in the future. It is not a prioritized list, nor is it to be comprehensive: there are certainly other datasets not listed here but potentially available for analysis. A number of the projects are already underway.

- New approaches are needed for sampling the sex of commercial fish that have been dressed at sea. The IPHC is continuing this research with both genetic and direct marking projects. At-sea marking will be based on the field work done in 2014 (McCarthy 2015).
- Reevaluation of the historical length-weight relationship to determine whether recent changes in length-at-age are also accompanied by changes in weight-at-length. A pilot study on this topic was begun by IPHC port samplers in 2013.

- A historical investigation on the factors influencing observed size-at-age, and ageing of additional samples from key periods and areas to support this analysis is ongoing at the IPHC as part of a large collaborative North Pacific Research Board project.
- There is the potential that trawl surveys, accessing juvenile halibut habitat and capturing much younger fish than those observed from longline sampling (fishery or survey), could provide information on recruitment strengths for halibut several years prior to currently available sources of data. The NMFS conducts annual trawl surveys in the Bering Sea (Sadorus and Lauth 2015), and biannual surveys in the Aleutian Islands and Gulf of Alaska (Sadorus et al. 2014). The NMFS also conducts annual trawl surveys off the U.S. west coast (Keller et al. 2012) which also enumerate halibut catches. The DFO conducts both trawl and longline surveys off the B.C. coast which could be included in an analysis of juvenile or adult habitat. Analyses of these data are ongoing (See Sadorus et al. 2015, and Cox et al. 2015).
- The NMFS conducts ichthyoplankton surveys in the southwest Bering Sea that could be investigated with regard to potential correlation of planktonic halibut with the distribution and/or abundance of Pacific halibut spawning biomass.
- Mapping of survey catch rates and biological observations is an ongoing project at the IPHC. This should provide greater ability to evaluate and interpret trends in the survey data in the future.
- Recreational catch-rate and length/age-distribution data are available from Alaska Department of Fish and Game. Although these data do not include samples from all potential recreational removals, they could be investigated as inputs to the stock assessment or for comparison with predicted age distributions.
- There is a vast quantity of archived historical data that is currently inaccessible until organized, keypunched and formatted into the IPHC's database with appropriate meta-data. Information on historical fishery landings, effort, and age samples would provide a much clearer (and more reproducible) perception of the historical period.
- Estimates of migration rates by size, and regulatory area are available from the extensive tagging programs that the IPHC has conducted. These data require careful interpretation, as there are many unknown factors (e.g., reporting rates) that could potentially confound the results. However, they may be useful in both a quantitative and qualitative context for establishing migration rates could be further explored in the context of the stock assessment, harvest policy and MSE analyses.
- Additional efforts could be made to reconstruct estimates of personal use or subsistence harvest prior to 1991.
- Standardizing the setline survey catch rates for use in the stock assessment currently includes only gear-related aspects of the data. Model-based estimators, potentially explicitly spatial, might be explored in order to determine the degree to which the time series may be influenced by spatial and other factors relating to exogenous variables.
- There are length-frequency data available for some portions of the bycatch of Pacific halibut captured in fisheries targeting other species. These data have not been included in the fitting of recent stock assessments, although this could be explored. These data have been used to partition the bycatch into U26, and O26 components for apportionment. Such data could be transformed into predicted ages via an annual age-length key and treated as age data for the stock assessment. However, the values themselves are poorly estimated (high

variance and not all contributing sources have length-frequency observations available for appropriate weighting), therefore the accuracy of these values would be suspect. Specifically, the representativeness of the samples relative to the total estimated bycatch would need to be evaluated.

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Table 1. Time-series of adjusted setline survey WPUE by regulatory Area (O32; net lb/skate). Years prior to 1984 are based on surveys conducted with "J" hooks. Values from 1995 to 2013 were recalculated in 2014 (see Webster et al. 2015).

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1977	NA	13.7	NA	58.4	NA	NA	NA	NA	NA
1978	NA	19.1	NA	26.9	NA	NA	NA	NA	NA
1979	NA	NA	NA	41.0	NA	NA	NA	NA	NA
1980	NA	25.5	NA	76.2	NA	NA	NA	NA	NA
1981	NA	16.5	NA	131.4	NA	NA	NA	NA	NA
1982	NA	20.6	113.7	130.3	NA	NA	NA	NA	NA
1983	NA	18.0	142.2	119.0	NA	NA	NA	NA	NA
1984	NA	57.4	259.6	361.2	NA	NA	NA	NA	NA
1985	NA	41.7	260.5	377.5	NA	NA	NA	NA	NA
1986	NA	37.8	282.6	305.1	NA	NA	NA	NA	NA
1987	NA	NA	NA	NA	NA	NA	NA	NA	NA
1988	NA	NA	NA	NA	NA	NA	NA	NA	NA
1989	NA	NA	NA	NA	NA	NA	NA	NA	NA
1990	NA	NA	NA	NA	NA	NA	NA	NA	NA
1991	NA	NA	NA	NA	NA	NA	NA	NA	NA
1992	NA	NA	NA	NA	NA	NA	NA	NA	NA
1993	NA	95.7	NA	261.1	NA	NA	NA	NA	NA
1994	NA	NA	NA	255.1	NA	NA	NA	NA	NA
1995	24.1	143.9	NA	316.4	NA	NA	NA	NA	NA
1996	26.1	141.2	309.1	313.3	347.0	NA	NA	NA	NA
1997	28.1	129.2	400.2	326.4	408.5	275.3	281.9	20.5	135.5
1998	28.8	81.0	229.2	277.6	428.6	343.6	216.6	26.7	124.9
1999	29.4	86.0	204.3	239.7	433.1	332.3	203.3	24.4	117.6
2000	31.2	89.2	233.7	270.1	368.7	314.6	216.5	23.5	117.1
2001	33.0	99.2	238.5	253.6	352.8	228.0	171.4	23.5	108.3
2002	26.4	90.2	261.1	295.2	292.7	193.0	119.3	24.1	104.7
2003	17.5	71.2	222.4	226.4	257.3	176.4	104.1	21.4	87.2
2004	21.5	84.1	171.2	266.0	232.9	157.7	73.4	20.4	86.5
2005	22.3	70.4	170.8	272.5	207.6	122.6	86.3	13.0	79.3
2006	12.9	57.4	142.8	229.2	178.5	97.6	95.5	14.1	69.1
2007	14.9	56.1	139.3	209.0	188.4	76.5	87.4	12.0	64.6
2008	14.7	87.8	104.3	186.7	124.1	95.5	103.5	10.7	59.2
2009	6.4	84.4	113.3	146.8	111.6	96.3	106.8	12.9	54.4
2010	13.4	86.9	108.1	115.4	89.9	83.6	68.4	11.0	45.6
2011	20.7	78.1	133.6	118.9	78.5	66.3	68.1	9.3	43.9
2012	23.0	101.2	157.1	135.6	85.7	73.2	48.5	10.5	49.3
2013	18.8	91.2	183.0	115.1	62.9	48.1	57.3	9.1	43.4
2014	17.8	90.0	186.5	113.3	64.0	62.2	49.9	10.2	44.2

Table 2. Time-series of fishery landings by regulatory Area (million lb, net wt.).

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1888	0.07	0.89	0.50	0.00	0.00	NA	NA	NA	NA	1.47
1889	0.07	0.79	0.44	0.00	0.00	NA	NA	NA	NA	1.29
1890	0.07	0.84	0.47	0.00	0.00	NA	NA	NA	NA	1.37
1891	0.11	1.30	0.73	0.00	0.00	NA	NA	NA	NA	2.13
1892	0.14	1.69	0.94	0.00	0.00	NA	NA	NA	NA	2.77
1893	0.16	1.96	1.09	0.00	0.00	NA	NA	NA	NA	3.22
1894	0.19	2.29	1.28	0.00	0.00	NA	NA	NA	NA	3.76
1895	0.21	2.59	1.45	0.00	0.00	NA	NA	NA	NA	4.25
1896	0.27	3.31	1.84	0.00	0.00	NA	NA	NA	NA	5.42
1897	0.33	4.02	2.24	0.00	0.00	NA	NA	NA	NA	6.59
1898	0.39	4.73	2.64	0.00	0.00	NA	NA	NA	NA	7.77
1899	0.45	5.45	3.04	0.00	0.00	NA	NA	NA	NA	8.94
1900	0.68	8.17	4.56	0.00	0.00	NA	NA	NA	NA	13.41
1901	0.90	10.90	6.08	0.00	0.00	NA	NA	NA	NA	17.87
1902	1.13	13.62	7.60	0.00	0.00	NA	NA	NA	NA	22.34
1903	1.27	15.37	8.57	0.00	0.00	NA	NA	NA	NA	25.21
1904	1.41	17.12	9.55	0.00	0.00	NA	NA	NA	NA	28.08
1905	1.11	13.41	7.48	0.00	0.00	NA	NA	NA	NA	22.00
1906	1.81	21.95	12.24	0.00	0.00	NA	NA	NA	NA	36.00
1907	2.52	30.48	17.00	0.00	0.00	NA	NA	NA	NA	50.00
1908	2.55	30.86	17.21	0.00	0.00	NA	NA	NA	NA	50.62
1909	2.58	31.23	17.42	0.00	0.00	NA	NA	NA	NA	51.23
1910	2.61	31.61	17.63	0.00	0.00	NA	NA	NA	NA	51.85
1911	2.87	34.71	19.36	0.00	0.00	NA	NA	NA	NA	56.93
1912	3.00	36.29	20.24	0.86	0.04	NA	NA	NA	NA	60.43
1913	2.79	33.80	18.85	10.58	0.52	NA	NA	NA	NA	66.54
1914	2.24	27.11	15.12	21.87	1.08	NA	NA	NA	NA	67.43
1915	2.22	26.84	14.97	23.31	1.15	NA	NA	NA	NA	68.48
1916	1.53	18.46	10.30	18.56	0.92	NA	NA	NA	NA	49.76
1917	1.55	18.78	10.47	16.96	0.84	NA	NA	NA	NA	48.60
1918	1.32	16.02	8.93	10.88	0.54	NA	NA	NA	NA	37.69
1919	1.34	16.22	9.05	12.90	0.64	NA	NA	NA	NA	40.14
1920	1.62	19.73	11.01	13.59	0.67	NA	NA	NA	NA	46.62
1921	3.39	23.37	10.22	14.75	0.73	NA	NA	NA	NA	52.46
1922	2.61	19.02	9.22	11.63	0.02	NA	NA	NA	NA	42.49
1923	2.62	16.71	9.72	21.60	0.67	NA	NA	NA	NA	51.32
1924	1.82	15.14	9.86	24.82	1.50	NA	NA	NA	NA	53.14
1925	2.20	13.65	7.99	22.16	4.66	NA	NA	NA	NA	50.66
1926	2.32	16.12	7.17	21.01	5.85	NA	NA	NA	NA	52.47
1927	2.62	14.09	7.42	22.62	8.20	NA	NA	NA	NA	54.95
1928	2.27	16.63	7.58	22.54	5.25	NA	NA	NA	NA	54.26
1929	2.18	13.77	9.85	22.27	8.86	NA	NA	NA	NA	56.92
1930	1.58	12.12	8.53	18.19	9.09	NA	NA	NA	NA	49.51
1931	1.63	13.53	7.39	14.61	7.06	NA	NA	NA	NA	44.22
1932	1.90	13.25	7.74	16.71	4.89	NA	NA	NA	NA	44.49
1933	1.75	13.37	8.15	19.67	3.97	NA	NA	NA	NA	46.91
1934	2.45	14.12	7.68	15.88	4.58	NA	NA	NA	NA	44.72
1935	1.77	14.21	7.58	19.96	3.82	0.00	NA	NA	NA	47.34
1936	0.90	13.67	8.75	20.09	5.52	0.00	NA	NA	NA	48.92
1937	0.92	15.29	7.87	20.47	5.00	0.00	NA	NA	NA	49.54
1938	0.95	16.00	7.15	20.66	4.79	0.00	NA	NA	NA	49.55
1939	1.36	17.67	6.56	21.16	4.15	0.00	NA	NA	NA	50.90
1940	0.98	17.81	7.62	22.50	4.48	0.00	NA	NA	NA	53.38

Table 2. Continued.

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1941	0.51	16.53	7.25	21.84	6.10	0.00	NA	NA	NA	52.23
1942	0.72	14.37	8.35	21.50	5.46	0.00	NA	NA	NA	50.39
1943	1.24	15.97	8.15	20.51	7.83	0.00	NA	NA	NA	53.70
1944	0.90	15.07	10.38	20.36	6.73	0.00	NA	NA	NA	53.44
1945	0.73	14.58	8.49	20.07	9.52	0.01	NA	NA	NA	53.40
1946	0.90	18.37	9.90	22.40	8.50	0.20	NA	NA	NA	60.27
1947	0.57	17.67	9.50	20.44	7.33	0.19	NA	NA	NA	55.70
1948	0.41	17.67	9.75	19.93	7.50	0.30	NA	NA	NA	55.56
1949	0.62	16.34	9.45	21.12	7.38	0.12	NA	NA	NA	55.03
1950	0.70	17.46	8.84	23.86	6.30	0.08	NA	NA	NA	57.23
1951	0.59	20.04	9.97	20.86	4.54	0.05	NA	NA	NA	56.05
1952	0.62	20.63	9.56	27.27	3.62	0.56	NA	NA	NA	62.26
1953	0.50	23.80	8.41	22.84	3.81	0.48	NA	NA	NA	59.84
1954	0.85	24.90	11.04	29.46	4.21	0.13	NA	NA	NA	70.58
1955	0.61	18.65	8.54	23.06	6.57	0.09	NA	NA	NA	57.52
1956	0.53	20.06	14.51	22.11	9.12	0.26	NA	NA	NA	66.59
1957	0.60	17.69	12.25	22.85	7.43	0.04	NA	NA	NA	60.85
1958	0.52	18.49	11.20	24.52	7.60	2.18	NA	NA	NA	64.51
1959	0.67	16.83	13.03	25.36	11.00	4.31	NA	NA	NA	71.20
1960	0.89	18.16	12.72	21.05	12.90	5.90	NA	NA	NA	71.61
1961	0.50	16.08	12.29	23.07	13.28	4.07	NA	NA	NA	69.27
1962	0.45	15.03	13.24	24.04	13.48	8.62	NA	NA	NA	74.86
1963	0.41	15.52	10.24	22.31	13.98	8.77	NA	NA	NA	71.24
1964	0.28	11.86	7.43	22.56	15.04	2.62	NA	NA	NA	59.78
1965	0.21	11.97	12.07	22.98	14.07	1.88	NA	NA	NA	63.18
1966	0.18	11.04	12.04	25.77	11.05	1.94	NA	NA	NA	62.02
1967	0.20	10.11	9.41	19.66	13.26	2.58	NA	NA	NA	55.22
1968	0.14	10.15	6.11	14.77	15.83	1.60	NA	NA	NA	48.59
1969	0.23	12.82	9.33	20.08	13.92	1.90	NA	NA	NA	58.27
1970	0.16	10.26	9.37	19.91	13.37	1.78	NA	NA	NA	54.84
1971	0.32	9.85	6.61	17.76	11.04	1.08	NA	NA	NA	46.65
1972	0.37	10.13	5.78	16.30	9.28	1.02	NA	NA	NA	42.88
1973	0.23	6.73	5.98	13.50	4.79	0.52	NA	NA	NA	31.74
1974	0.52	4.62	5.60	8.19	1.67	0.71	NA	NA	NA	21.31
1975	0.46	7.13	6.24	10.60	2.56	0.63	NA	NA	NA	27.62
1976	0.24	7.28	5.53	11.04	2.73	0.72	NA	NA	NA	27.54
1977	0.21	5.43	3.19	8.64	3.19	1.22	NA	NA	NA	21.88
1978	0.10	4.61	4.32	10.30	1.32	1.35	NA	NA	NA	22.00
1979	0.05	4.86	4.53	11.34	0.39	1.37	NA	NA	NA	22.54
1980	0.02	5.65	3.24	11.97	0.28	0.71	NA	NA	NA	21.87
1981	0.20	5.66	4.01	14.23	0.45	NA	0.49	0.39	0.31	25.74
1982	0.21	5.54	3.50	13.52	4.80	NA	1.17	0.01	0.25	29.01
1983	0.27	5.44	6.38	14.13	7.76	NA	2.50	1.34	0.58	38.39
1984	0.43	9.05	5.87	19.77	6.69	NA	1.05	1.10	1.01	44.97
1985	0.49	10.39	9.21	20.84	10.89	NA	1.72	1.24	1.33	56.10
1986	0.58	11.23	10.61	32.80	8.82	NA	3.38	0.26	1.95	69.63
1987	0.59	12.25	10.69	31.31	7.76	NA	3.69	1.50	1.69	69.47
1988	0.49	12.86	11.36	37.91	7.08	NA	1.93	1.59	1.17	74.39
1989	0.47	10.43	9.53	33.74	7.84	NA	1.03	2.65	1.26	66.95
1990	0.33	8.57	9.73	28.85	8.69	NA	2.50	1.33	1.59	61.60
1991	0.36	7.19	8.69	22.93	11.93	NA	2.26	1.51	2.22	57.08
1992	0.44	7.63	9.82	26.78	8.62	NA	2.70	2.32	1.59	59.89
1993	0.50	10.63	11.29	22.74	7.86	NA	2.56	1.96	1.73	59.27

Table 2. Continued.

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1994	0.37	9.91	10.38	24.84	3.86	NA	1.80	2.02	1.55	54.73
1995	0.30	9.62	7.77	18.34	3.13	NA	1.62	1.68	1.44	43.88
1996	0.30	9.55	8.87	19.69	3.66	NA	1.70	2.07	1.51	47.34
1997	0.41	12.42	9.92	24.64	9.06	NA	2.91	3.32	2.52	65.20
1998	0.46	13.17	10.20	25.70	11.16	NA	3.42	2.90	2.75	69.76
1999	0.45	12.71	10.14	25.32	13.84	NA	4.37	3.57	3.92	74.31
2000	0.48	10.81	8.45	19.27	15.41	NA	5.16	4.69	4.02	68.29
2001	0.68	10.29	8.40	21.54	16.34	NA	5.02	4.47	3.97	70.70
2002	0.85	12.07	8.60	23.13	17.31	NA	5.09	4.08	3.52	74.66
2003	0.82	11.79	8.41	22.75	17.22	NA	5.02	3.86	3.26	73.14
2004	0.88	12.16	10.23	25.17	15.46	NA	3.56	2.72	2.92	73.11
2005	0.80	12.33	10.63	26.03	13.17	NA	3.40	1.98	3.48	71.82
2006	0.83	12.01	10.49	25.71	10.79	NA	3.33	1.59	3.23	67.98
2007	0.79	9.77	8.47	26.49	9.25	NA	2.83	1.42	3.85	62.87
2008	0.68	7.76	6.21	24.52	10.75	NA	3.02	1.76	3.88	58.57
2009	0.49	6.64	4.96	21.76	10.78	NA	2.53	1.59	3.31	52.05
2010	0.42	6.73	4.49	20.50	10.11	NA	2.33	1.83	3.32	49.72
2011	0.54	6.69	2.45	14.67	7.32	NA	2.35	2.05	3.43	39.51
2012	0.57	5.98	2.69	12.03	5.05	NA	1.58	1.74	2.34	31.99
2013	0.54	6.04	3.03	11.08	4.09	NA	1.23	1.25	1.77	29.04
2014	0.54	5.88	3.44	7.63	2.93	NA	0.90	1.12	1.26	23.69

Table 3. Time-series of total removals by regulatory Area (million lb, net wt.).

Year	2A	2B	2C	3A	3B	4	Total
1888	0.07	0.89	0.50	0.00	0.00	0.00	1.47
1889	0.07	0.79	0.44	0.00	0.00	0.00	1.29
1890	0.07	0.84	0.47	0.00	0.00	0.00	1.37
1891	0.11	1.30	0.73	0.00	0.00	0.00	2.13
1892	0.14	1.69	0.94	0.00	0.00	0.00	2.77
1893	0.16	1.96	1.09	0.00	0.00	0.00	3.22
1894	0.19	2.29	1.28	0.00	0.00	0.00	3.76
1895	0.21	2.59	1.45	0.00	0.00	0.00	4.25
1896	0.27	3.31	1.84	0.00	0.00	0.00	5.42
1897	0.33	4.02	2.24	0.00	0.00	0.00	6.59
1898	0.39	4.73	2.64	0.00	0.00	0.00	7.77
1899	0.45	5.45	3.04	0.00	0.00	0.00	8.94
1900	0.68	8.17	4.56	0.00	0.00	0.00	13.41
1901	0.90	10.90	6.08	0.00	0.00	0.00	17.87
1902	1.13	13.62	7.60	0.00	0.00	0.00	22.34
1903	1.27	15.37	8.57	0.00	0.00	0.00	25.21
1904	1.41	17.12	9.55	0.00	0.00	0.00	28.08
1905	1.11	13.41	7.48	0.00	0.00	0.00	22.00
1906	1.81	21.95	12.24	0.00	0.00	0.00	36.00
1907	2.52	30.48	17.00	0.00	0.00	0.00	50.00
1908	2.55	30.86	17.21	0.00	0.00	0.00	50.62
1909	2.58	31.23	17.42	0.00	0.00	0.00	51.23
1910	2.61	31.61	17.63	0.00	0.00	0.00	51.85
1911	2.87	34.71	19.36	0.00	0.00	0.00	56.93
1912	3.00	36.29	20.24	0.86	0.04	0.00	60.43
1913	2.79	33.80	18.85	10.58	0.52	0.00	66.54
1914	2.24	27.11	15.12	21.87	1.08	0.00	67.43
1915	2.22	26.84	14.97	23.31	1.15	0.00	68.48
1916	1.53	18.46	10.30	18.56	0.92	0.00	49.76
1917	1.55	18.78	10.47	16.96	0.84	0.00	48.60
1918	1.32	16.02	8.93	10.88	0.54	0.00	37.69
1919	1.34	16.22	9.05	12.90	0.64	0.00	40.14
1920	1.62	19.73	11.01	13.59	0.67	0.00	46.62
1921	3.39	23.37	10.22	14.75	0.73	0.00	52.46
1922	2.61	19.02	9.22	11.63	0.02	0.00	42.50
1923	2.62	16.71	9.72	21.60	0.67	0.00	51.32
1924	1.82	15.14	9.86	24.82	1.50	0.00	53.14
1925	2.20	13.65	7.99	22.16	4.66	0.00	50.66
1926	2.32	16.12	7.17	21.01	5.85	0.00	52.47
1927	2.62	14.09	7.42	22.62	8.20	0.00	54.95
1928	2.27	16.63	7.58	22.54	5.25	0.00	54.26
1929	2.18	13.77	9.85	22.27	8.86	0.00	56.93
1930	1.58	12.12	8.53	18.19	9.09	0.00	49.51
1931	1.63	13.53	7.39	14.61	7.06	0.00	44.22
1932	1.90	13.25	7.74	16.71	4.89	0.00	44.49
1933	1.75	13.37	8.15	19.67	3.97	0.00	46.91
1934	2.45	14.12	7.68	15.88	4.58	0.00	44.72
1935	1.77	14.21	7.58	19.96	3.82	0.00	47.34
1936	0.90	13.67	8.75	20.09	5.52	0.00	48.92
1937	0.92	15.29	7.87	20.47	5.00	0.00	49.54
1938	0.95	16.00	7.15	20.66	4.79	0.00	49.55
1939	1.36	17.67	6.56	21.16	4.15	0.00	50.90
1940	0.98	17.81	7.62	22.50	4.48	0.00	53.38

Table 3. Continued.

Year	2A	2B	2C	3A	3B	4	Total
1941	0.51	16.53	7.25	21.84	6.10	0.00	52.23
1942	0.72	14.37	8.35	21.50	5.46	0.00	50.39
1943	1.24	15.97	8.15	20.51	7.83	0.00	53.70
1944	0.90	15.07	10.38	20.36	6.73	0.00	53.44
1945	0.73	14.58	8.49	20.07	9.52	0.01	53.40
1946	0.90	18.37	9.90	22.40	8.50	0.20	60.27
1947	0.57	17.67	9.50	20.44	7.33	0.19	55.70
1948	0.41	17.67	9.75	19.93	7.50	0.30	55.56
1949	0.62	16.34	9.45	21.12	7.38	0.12	55.03
1950	0.70	17.46	8.84	23.86	6.30	0.08	57.23
1951	0.59	20.04	9.97	20.86	4.54	0.05	56.05
1952	0.62	20.63	9.56	27.27	3.62	0.56	62.26
1953	0.50	23.80	8.41	22.84	3.81	0.48	59.84
1954	0.85	24.90	11.04	29.46	4.21	0.13	70.58
1955	0.61	18.65	8.54	23.06	6.57	0.09	57.52
1956	0.53	20.06	14.51	22.11	9.12	0.26	66.59
1957	0.60	17.69	12.25	22.85	7.43	0.04	60.85
1958	0.52	18.49	11.20	24.52	7.60	2.18	64.51
1959	0.67	16.83	13.03	25.36	11.00	4.31	71.20
1960	0.89	18.16	12.72	21.05	12.90	5.90	71.61
1961	0.50	16.08	12.29	23.07	13.28	4.07	69.27
1962	0.45	16.21	13.45	25.96	14.65	12.76	83.47
1963	0.41	16.60	10.45	25.62	16.77	10.81	80.66
1964	0.28	12.96	7.64	31.93	17.30	5.59	75.70
1965	0.21	13.40	12.27	29.08	24.51	5.06	84.54
1966	0.18	12.70	12.25	30.28	19.03	5.34	79.79
1967	0.20	11.76	9.85	24.29	18.16	7.30	71.56
1968	0.14	12.11	6.63	20.25	17.41	7.28	63.81
1969	0.23	15.00	9.79	23.89	15.09	9.50	73.50
1970	0.16	11.73	9.93	23.30	16.21	9.80	71.13
1971	0.32	11.59	7.15	20.74	12.40	14.18	66.37
1972	0.37	11.88	6.54	21.71	10.98	10.69	62.16
1973	0.23	8.24	6.82	17.95	7.49	8.55	49.27
1974	1.00	6.43	6.17	13.50	5.10	8.33	40.54
1975	0.94	9.18	6.93	13.85	4.65	4.28	39.84
1976	0.72	9.51	6.28	14.64	5.20	5.29	41.63
1977	0.70	7.39	3.87	13.02	5.12	4.14	34.24
1978	0.59	6.20	4.82	13.75	3.17	6.38	34.90
1979	0.54	6.84	5.56	17.62	1.33	6.79	38.68
1980	0.52	7.16	4.12	18.44	1.53	9.95	41.72
1981	0.70	7.01	4.87	19.85	2.02	7.62	42.06
1982	0.74	6.60	4.33	18.16	7.04	6.21	43.08
1983	0.81	6.63	7.30	18.15	9.80	8.72	51.41
1984	1.03	10.55	6.86	23.10	8.30	7.89	57.73
1985	1.17	12.33	10.53	24.26	11.86	8.70	68.86
1986	1.40	13.27	12.25	37.92	9.82	11.56	86.22
1987	1.52	14.85	12.31	37.64	9.14	13.00	88.46
1988	1.22	15.28	13.13	46.69	7.40	13.70	97.42
1989	1.29	12.69	11.75	42.11	9.03	12.43	89.29
1990	0.95	11.07	12.42	38.29	11.15	14.36	88.25
1991	0.94	9.76	12.31	34.55	14.48	16.69	88.73
1992	1.15	9.98	12.83	37.11	11.12	17.78	89.97
1993	1.23	13.24	14.36	33.48	9.24	14.39	85.94

Table 3. Continued.

Year	2A	2B	2C	3A	3B	4	Total
1994	1.02	12.03	13.46	35.04	5.46	15.18	82.19
1995	1.17	12.56	10.02	26.33	5.00	13.67	68.75
1996	1.16	11.24	11.52	27.81	5.76	14.09	71.59
1997	1.41	14.12	12.67	33.74	10.82	16.97	89.72
1998	1.95	14.90	13.19	33.81	12.88	17.23	93.96
1999	1.80	14.38	12.45	33.05	15.93	20.01	97.62
2000	1.69	12.55	11.19	28.02	17.34	21.74	92.53
2001	2.00	12.03	10.78	29.75	18.53	21.04	94.14
2002	1.93	14.08	11.09	30.25	19.79	20.35	97.49
2003	1.55	13.90	11.56	32.32	19.64	19.29	98.25
2004	1.71	14.64	14.28	35.61	17.49	16.23	99.95
2005	1.90	15.15	14.41	36.08	14.93	16.93	99.40
2006	2.01	14.96	14.08	35.15	12.73	15.99	94.91
2007	1.75	12.58	12.48	36.96	10.89	15.74	90.40
2008	1.67	10.29	10.29	34.25	12.85	15.61	84.95
2009	1.57	8.71	8.15	30.74	12.93	14.08	76.17
2010	1.21	8.77	7.20	29.08	12.21	13.89	72.36
2011	1.10	8.83	4.00	23.00	9.30	13.40	59.64
2012	1.22	7.85	4.80	18.52	7.07	12.21	51.67
2013	1.17	7.71	5.75	17.47	5.50	10.43	48.04
2014	1.07	7.73	5.98	13.60	4.53	9.61	42.51

Table 4. Time-series of estimated removals by source (million lb, net wt.).

Year	Commercial landings	Commercial wastage	Bycatch	Sport	Personal use	Total
1888	1.47	0.00	0.00	0.00	0.00	1.47
1889	1.29	0.00	0.00	0.00	0.00	1.29
1890	1.37	0.00	0.00	0.00	0.00	1.37
1891	2.13	0.00	0.00	0.00	0.00	2.13
1892	2.77	0.00	0.00	0.00	0.00	2.77
1893	3.22	0.00	0.00	0.00	0.00	3.22
1894	3.76	0.00	0.00	0.00	0.00	3.76
1895	4.25	0.00	0.00	0.00	0.00	4.25
1896	5.42	0.00	0.00	0.00	0.00	5.42
1897	6.59	0.00	0.00	0.00	0.00	6.59
1898	7.77	0.00	0.00	0.00	0.00	7.77
1899	8.94	0.00	0.00	0.00	0.00	8.94
1900	13.41	0.00	0.00	0.00	0.00	13.41
1901	17.87	0.00	0.00	0.00	0.00	17.87
1902	22.34	0.00	0.00	0.00	0.00	22.34
1903	25.21	0.00	0.00	0.00	0.00	25.21
1904	28.08	0.00	0.00	0.00	0.00	28.08
1905	22.00	0.00	0.00	0.00	0.00	22.00
1906	36.00	0.00	0.00	0.00	0.00	36.00
1907	50.00	0.00	0.00	0.00	0.00	50.00
1908	50.62	0.00	0.00	0.00	0.00	50.62
1909	51.23	0.00	0.00	0.00	0.00	51.23
1910	51.85	0.00	0.00	0.00	0.00	51.85
1911	56.93	0.00	0.00	0.00	0.00	56.93
1912	60.43	0.00	0.00	0.00	0.00	60.43
1913	66.54	0.00	0.00	0.00	0.00	66.54
1914	67.43	0.00	0.00	0.00	0.00	67.43
1915	68.48	0.00	0.00	0.00	0.00	68.48
1916	49.76	0.00	0.00	0.00	0.00	49.76
1917	48.60	0.00	0.00	0.00	0.00	48.60
1918	37.69	0.00	0.00	0.00	0.00	37.69
1919	40.14	0.00	0.00	0.00	0.00	40.14
1920	46.62	0.00	0.00	0.00	0.00	46.62
1921	52.46	0.00	0.00	0.00	0.00	52.46
1922	42.49	0.00	0.00	0.00	0.00	42.49
1923	51.32	0.00	0.00	0.00	0.00	51.32
1924	53.14	0.00	0.00	0.00	0.00	53.14
1925	50.66	0.00	0.00	0.00	0.00	50.66
1926	52.47	0.00	0.00	0.00	0.00	52.47
1927	54.95	0.00	0.00	0.00	0.00	54.95
1928	54.26	0.00	0.00	0.00	0.00	54.26
1929	56.92	0.00	0.00	0.00	0.00	56.92
1930	49.51	0.00	0.00	0.00	0.00	49.51
1931	44.22	0.00	0.00	0.00	0.00	44.22
1932	44.49	0.00	0.00	0.00	0.00	44.49
1933	46.91	0.00	0.00	0.00	0.00	46.91
1934	44.72	0.00	0.00	0.00	0.00	44.72
1935	47.34	0.00	0.00	0.00	0.00	47.34
1936	48.92	0.00	0.00	0.00	0.00	48.92
1937	49.54	0.00	0.00	0.00	0.00	49.54
1938	49.55	0.00	0.00	0.00	0.00	49.55
1939	50.90	0.00	0.00	0.00	0.00	50.90

Table 4. Continued.

Year	Commercial landings	Commercial wastage	Bycatch	Sport	Personal use	Total
1940	53.38	0.00	0.00	0.00	0.00	53.38
1941	52.23	0.00	0.00	0.00	0.00	52.23
1942	50.39	0.00	0.00	0.00	0.00	50.39
1943	53.70	0.00	0.00	0.00	0.00	53.70
1944	53.44	0.00	0.00	0.00	0.00	53.44
1945	53.40	0.00	0.00	0.00	0.00	53.40
1946	60.27	0.00	0.00	0.00	0.00	60.27
1947	55.70	0.00	0.00	0.00	0.00	55.70
1948	55.56	0.00	0.00	0.00	0.00	55.56
1949	55.03	0.00	0.00	0.00	0.00	55.03
1950	57.23	0.00	0.00	0.00	0.00	57.23
1951	56.05	0.00	0.00	0.00	0.00	56.05
1952	62.26	0.00	0.00	0.00	0.00	62.26
1953	59.84	0.00	0.00	0.00	0.00	59.84
1954	70.58	0.00	0.00	0.00	0.00	70.58
1955	57.52	0.00	0.00	0.00	0.00	57.52
1956	66.59	0.00	0.00	0.00	0.00	66.59
1957	60.85	0.00	0.00	0.00	0.00	60.85
1958	64.51	0.00	0.00	0.00	0.00	64.51
1959	71.20	0.00	0.00	0.00	0.00	71.20
1960	71.61	0.00	0.00	0.00	0.00	71.61
1961	69.27	0.00	0.00	0.00	0.00	69.27
1962	74.86	0.00	8.61	0.00	0.00	83.47
1963	71.24	0.00	9.42	0.00	0.00	80.66
1964	59.78	0.00	15.91	0.00	0.00	75.70
1965	63.18	0.00	21.36	0.00	0.00	84.54
1966	62.02	0.00	17.77	0.00	0.00	79.79
1967	55.22	0.00	16.34	0.00	0.00	71.56
1968	48.59	0.00	15.22	0.00	0.00	63.81
1969	58.27	0.00	15.23	0.00	0.00	73.50
1970	54.84	0.00	16.29	0.00	0.00	71.13
1971	46.65	0.00	19.72	0.00	0.00	66.37
1972	42.88	0.00	19.28	0.00	0.00	62.16
1973	31.74	0.00	17.53	0.00	0.00	49.27
1974	21.31	0.20	19.03	0.00	0.00	40.54
1975	27.62	0.31	11.91	0.00	0.00	39.84
1976	27.54	0.34	13.75	0.00	0.00	41.63
1977	21.88	0.29	11.78	0.29	0.00	34.24
1978	22.00	0.28	12.24	0.38	0.00	34.90
1979	22.54	0.30	15.28	0.56	0.00	38.68
1980	21.87	0.30	18.70	0.85	0.00	41.72
1981	25.74	0.35	14.86	1.11	0.00	42.06
1982	29.01	0.40	12.37	1.30	0.00	43.08
1983	38.39	0.53	10.88	1.62	0.00	51.41
1984	44.97	0.72	10.19	1.84	0.00	57.73
1985	56.10	2.70	7.70	2.36	0.00	68.86
1986	69.63	4.65	8.76	3.18	0.00	86.22
1987	69.47	4.20	11.28	3.51	0.00	88.46
1988	74.39	3.49	14.66	4.88	0.00	97.42
1989	66.95	3.46	13.65	5.23	0.00	89.29
1990	61.60	3.38	17.68	5.59	0.00	88.25
1991	57.08	3.46	19.67	6.51	2.01	88.74

Table 4. Continued.

Year	Commercial landings	Commercial wastage	Bycatch	Sport	Personal use	Total
1992	59.89	2.50	20.29	6.18	1.11	89.97
1993	59.27	2.05	15.96	7.73	0.93	85.94
1994	54.73	2.51	16.95	7.07	0.93	82.19
1995	43.88	0.93	15.93	7.46	0.54	68.75
1996	47.34	1.15	14.46	8.08	0.54	71.59
1997	65.20	1.45	13.51	9.03	0.54	89.73
1998	69.76	1.72	13.16	8.59	0.74	93.96
1999	74.31	1.65	13.54	7.38	0.75	97.62
2000	68.29	1.45	13.02	9.01	0.76	92.53
2001	70.70	1.69	12.88	8.10	0.77	94.14
2002	74.66	1.72	12.33	8.01	0.77	97.49
2003	73.14	2.08	12.31	9.35	1.38	98.25
2004	73.11	2.30	12.29	10.70	1.55	99.96
2005	71.82	2.22	12.97	10.86	1.54	99.41
2006	67.98	2.46	12.79	10.19	1.48	94.91
2007	62.87	2.59	11.99	11.46	1.49	90.39
2008	58.57	2.76	11.60	10.67	1.34	84.95
2009	52.05	2.94	11.08	8.78	1.31	76.16
2010	49.72	3.21	10.35	7.85	1.24	72.36
2011	39.51	2.46	9.42	7.10	1.14	59.64
2012	31.99	1.67	10.10	6.77	1.14	51.67
2013	29.04	1.43	8.84	7.59	1.14	48.04
2014	23.69	1.29	9.32	7.08	1.14	42.51

Table 5. Time-series of commercial fishery WPUE by regulatory Area (net lb/skate). Years prior to 1984 are based on fishing conducted with "J" hooks.

Year	2A	2B	2C	3A	3B	4A	4B	4C	4D	Total
1907	NA	NA	NA	NA	NA	NA	NA	NA	NA	280
1910	NA	NA	NA	NA	NA	NA	NA	NA	NA	271
1911	NA	NA	NA	NA	NA	NA	NA	NA	NA	237
1912	NA	NA	NA	NA	NA	NA	NA	NA	NA	176
1913	NA	NA	NA	NA	NA	NA	NA	NA	NA	129
1914	NA	NA	NA	NA	NA	NA	NA	NA	NA	124
1915	NA	NA	NA	NA	NA	NA	NA	NA	NA	118
1916	NA	NA	NA	NA	NA	NA	NA	NA	NA	137
1917	NA	NA	NA	NA	NA	NA	NA	NA	NA	98
1918	NA	NA	NA	NA	NA	NA	NA	NA	NA	96
1919	NA	NA	NA	NA	NA	NA	NA	NA	NA	93
1920	NA	NA	NA	NA	NA	NA	NA	NA	NA	96
1921	NA	NA	NA	NA	NA	NA	NA	NA	NA	88
1922	NA	NA	NA	NA	NA	NA	NA	NA	NA	73
1923	NA	NA	NA	NA	NA	NA	NA	NA	NA	78
1924	NA	NA	NA	NA	NA	NA	NA	NA	NA	74
1925	NA	NA	NA	NA	NA	NA	NA	NA	NA	68
1926	NA	NA	NA	NA	NA	NA	NA	NA	NA	67
1927	NA	NA	NA	NA	NA	NA	NA	NA	NA	65
1928	NA	NA	NA	NA	NA	NA	NA	NA	NA	58
1929	NA	NA	NA	NA	NA	NA	NA	NA	NA	51
1930	NA	NA	NA	NA	NA	NA	NA	NA	NA	46
1931	NA	NA	NA	NA	NA	NA	NA	NA	NA	50
1932	NA	NA	NA	NA	NA	NA	NA	NA	NA	60
1933	NA	NA	NA	NA	NA	NA	NA	NA	NA	63
1934	NA	NA	NA	NA	NA	NA	NA	NA	NA	62
1935	NA	NA	NA	NA	NA	NA	NA	NA	NA	76
1936	NA	NA	NA	NA	NA	NA	NA	NA	NA	71
1937	NA	NA	NA	NA	NA	NA	NA	NA	NA	80
1938	NA	NA	NA	NA	NA	NA	NA	NA	NA	88
1939	NA	NA	NA	NA	NA	NA	NA	NA	NA	80
1940	NA	NA	NA	NA	NA	NA	NA	NA	NA	81
1941	NA	NA	NA	NA	NA	NA	NA	NA	NA	85
1942	NA	NA	NA	NA	NA	NA	NA	NA	NA	90
1943	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1944	NA	NA	NA	NA	NA	NA	NA	NA	NA	110
1945	NA	NA	NA	NA	NA	NA	NA	NA	NA	102
1946	NA	NA	NA	NA	NA	NA	NA	NA	NA	101
1947	NA	NA	NA	NA	NA	NA	NA	NA	NA	99
1948	NA	NA	NA	NA	NA	NA	NA	NA	NA	99
1949	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1950	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1950	NA	NA	NA	NA	NA	NA	NA	NA	NA	95

Table 5. Continued.

Year	2A	2B	2C	3A	3B	4A	4B	4C	4D	Total
1951	NA	NA	NA	NA	NA	NA	NA	NA	NA	96
1952	NA	NA	NA	NA	NA	NA	NA	NA	NA	110
1953	NA	NA	NA	NA	NA	NA	NA	NA	NA	131
1954	NA	NA	NA	NA	NA	NA	NA	NA	NA	133
1955	NA	NA	NA	NA	NA	NA	NA	NA	NA	119
1956	NA	NA	NA	NA	NA	NA	NA	NA	NA	129
1957	NA	NA	NA	NA	NA	NA	NA	NA	NA	110
1958	NA	NA	NA	NA	NA	NA	NA	NA	NA	121
1959	NA	NA	NA	NA	NA	NA	NA	NA	NA	129
1960	NA	NA	NA	NA	NA	NA	NA	NA	NA	132
1961	NA	NA	NA	NA	NA	NA	NA	NA	NA	127
1962	NA	NA	NA	NA	NA	NA	NA	NA	NA	115
1963	NA	NA	NA	NA	NA	NA	NA	NA	NA	105
1964	NA	NA	NA	NA	NA	NA	NA	NA	NA	100
1965	NA	NA	NA	NA	NA	NA	NA	NA	NA	99
1966	NA	NA	NA	NA	NA	NA	NA	NA	NA	100
1967	NA	NA	NA	NA	NA	NA	NA	NA	NA	101
1968	NA	NA	NA	NA	NA	NA	NA	NA	NA	103
1969	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1970	NA	NA	NA	NA	NA	NA	NA	NA	NA	91
1971	NA	NA	NA	NA	NA	NA	NA	NA	NA	89
1972	NA	NA	NA	NA	NA	NA	NA	NA	NA	78
1973	NA	NA	NA	NA	NA	NA	NA	NA	NA	63
1974	59	64	57	65	57	NA	NA	NA	NA	61
1975	59	68	53	66	68	NA	NA	NA	NA	61
1976	33	53	42	60	65	NA	NA	NA	NA	55
1977	83	61	45	61	73	NA	NA	NA	NA	63
1978	39	63	56	78	53	NA	NA	NA	NA	71
1979	50	48	80	86	37	NA	NA	NA	NA	75
1980	37	65	79	118	113	NA	NA	NA	NA	94
1981	33	67	144	142	160	158	99	110	NA	111
1982	22	69	146	168	203	103	NA	91	NA	127
1983	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1984	63	147	284	502	474	366	161	NA	197	291
1985	62	139	345	500	592	337	234	594	330	357
1986	55	118	290	506	506	260	238	427	218	320
1987	53	130	260	498	478	342	220	384	241	321
1988	134	137	281	503	654	453	224	371	201	368
1989	113	133	258	457	590	409	268	333	432	358
1990	168	176	270	354	484	418	209	288	381	319
1991	158	149	233	319	466	471	329	223	399	318
1992	117	171	230	397	440	372	280	249	412	319
1993	147	208	256	393	514	463	218	257	851	373
1994	93	215	207	354	377	463	197	167	480	306
1995	116	219	234	417	476	349	189	286	475	330
1996	159	227	239	473	557	515	269	297	543	392
1997	226	241	246	458	563	483	275	335	671	405
1998	194	232	236	452	611	525	287	287	627	408
1999	342	213	199	437	538	497	310	271	535	393
2000	263	229	187	443	579	548	320	223	556	403

Table 5. Continued.

Year	2A	2B	2C	3A	3B	4A	4B	4C	4D	Total
2001	171	227	196	469	431	474	270	203	511	362
2002	181	223	244	508	399	402	245	148	503	360
2003	173	221	233	485	365	355	196	105	388	329
2004	143	203	240	486	328	315	202	120	445	319
2005	137	195	203	446	293	301	238	91	379	296
2006	156	201	170	403	292	241	218	72	280	270
2007	96	198	160	398	257	206	230	65	237	252
2008	69	174	161	370	234	206	193	94	247	232
2009	98	188	155	318	211	234	189	88	249	222
2010	149	222	158	285	173	182	142	82	188	204
2011	92	240	175	280	140	189	165	75	166	198
2012	102	248	207	263	133	194	149	60	155	195
2013	110	246	195	238	112	160	127	56	157	179
2014	109	286	228	230	99	132	168	60	167	185

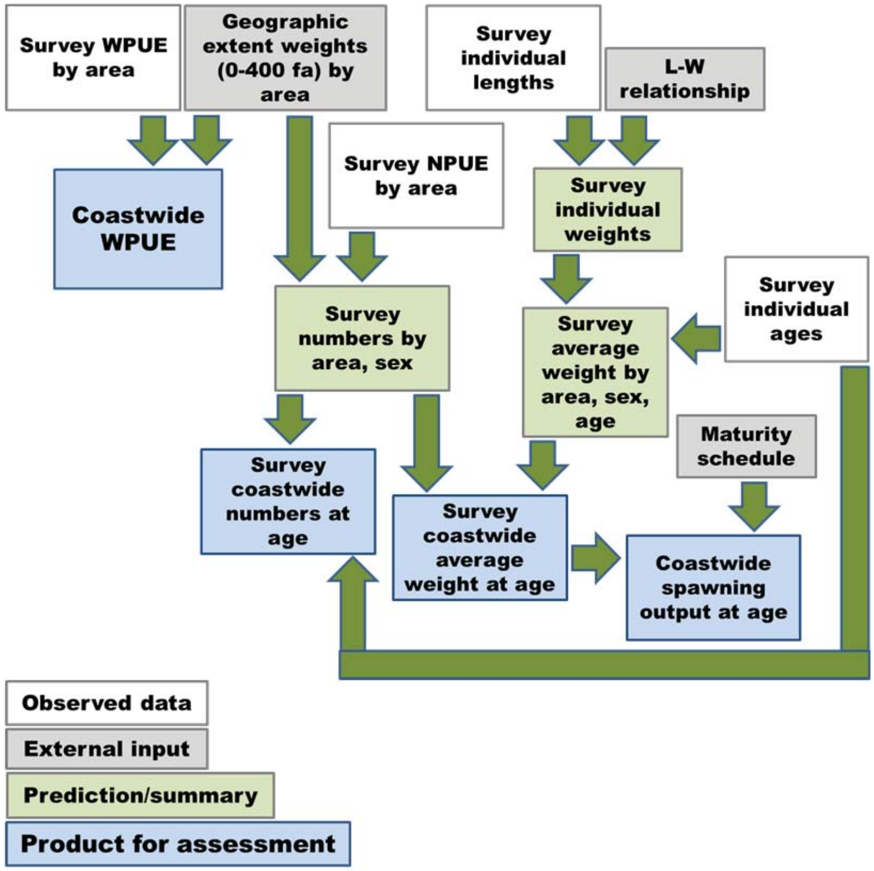

Figure 1. General schematic of the processing of the setline survey data.

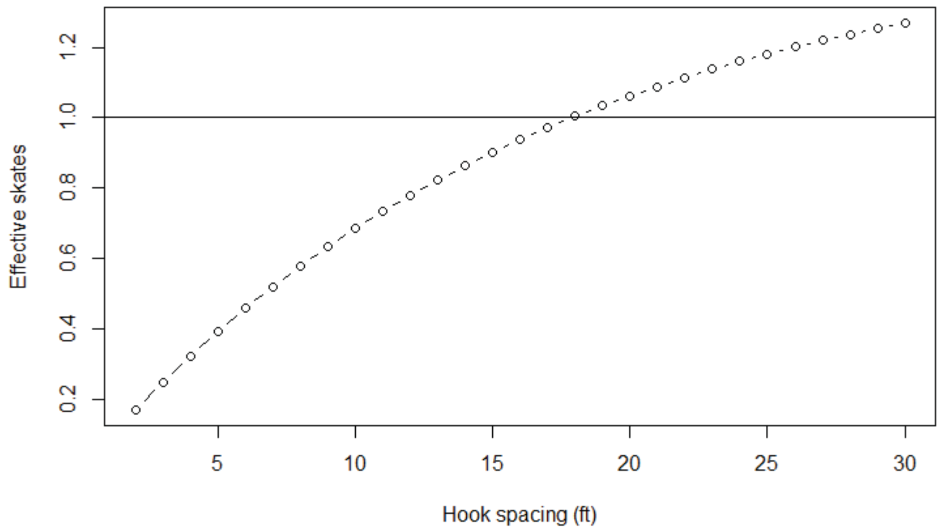

Figure 2. Relationship between hook spacing and the number of effective skates for set line survey and commercial fishery WPUE calculations (From: Hamley and Skud, 1978).

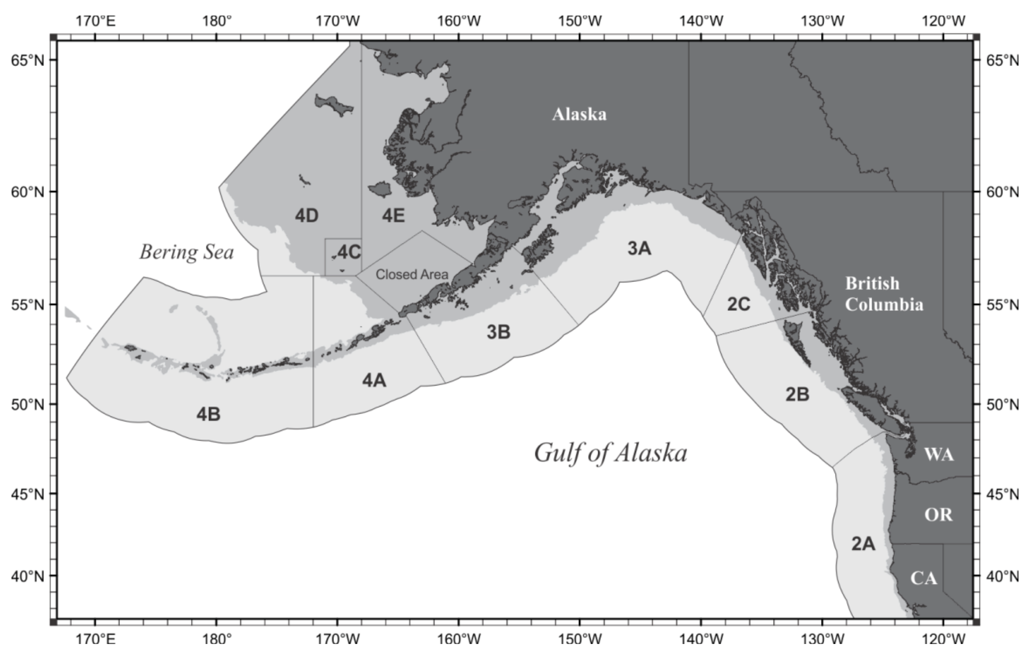

Figure 3. The IPHC's regulatory areas. Shaded region indicates the Exclusive Economic Zone (EEZ) of the United States and Canada.

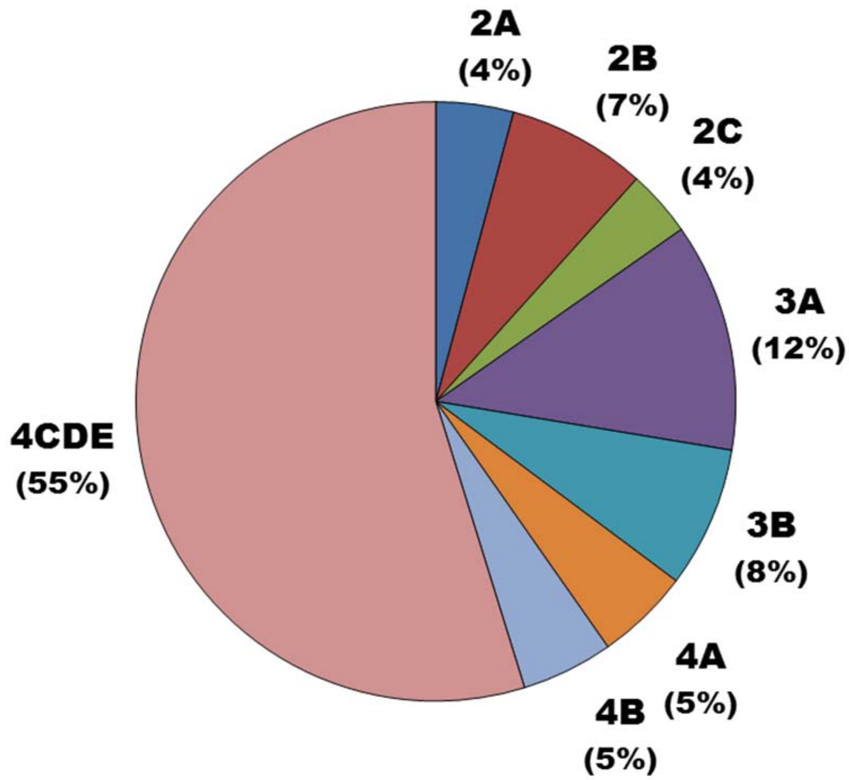

Figure 4. Relative spatial extent of each regulatory area.

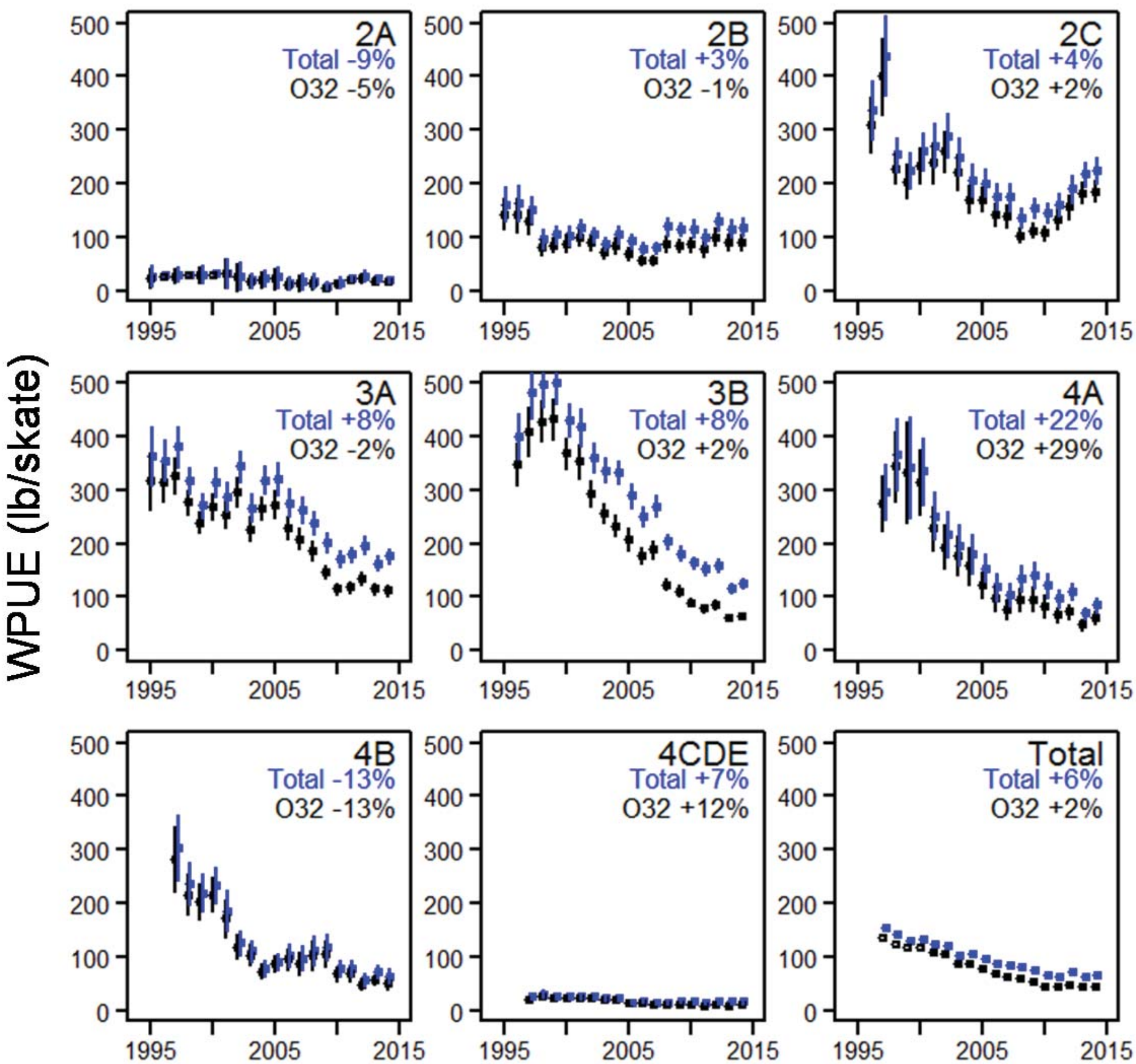

Figure 5. Recent setline survey WPUE (lbs/skate) for all (blue, upper series) and legal-sized fish (black, lower series) by regulatory area and year through 2014. Percentages for each area indicate the change from 2013 to 2014. Total WPUE values have been offset slightly on the x-axis to make the points easier to distinguish.

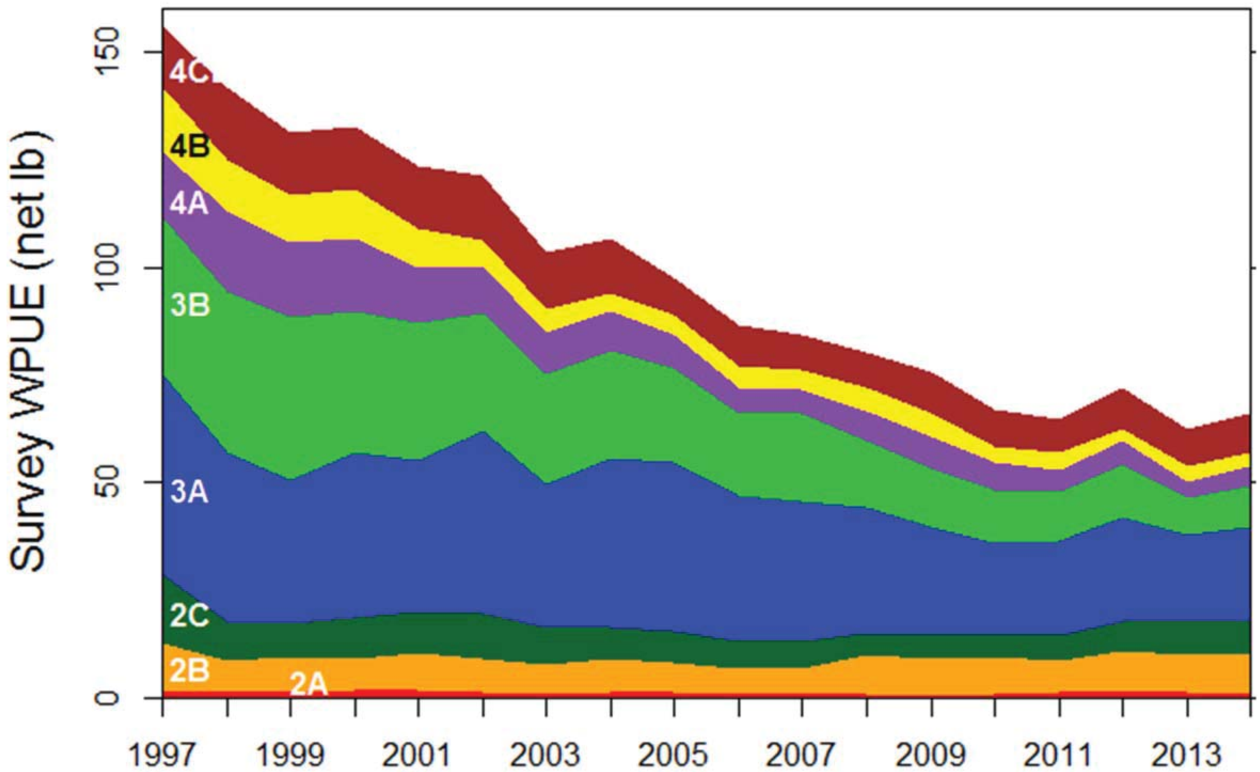

Figure 6. Weighted contributions of the regulatory areas to the coastwide survey total WPUE.

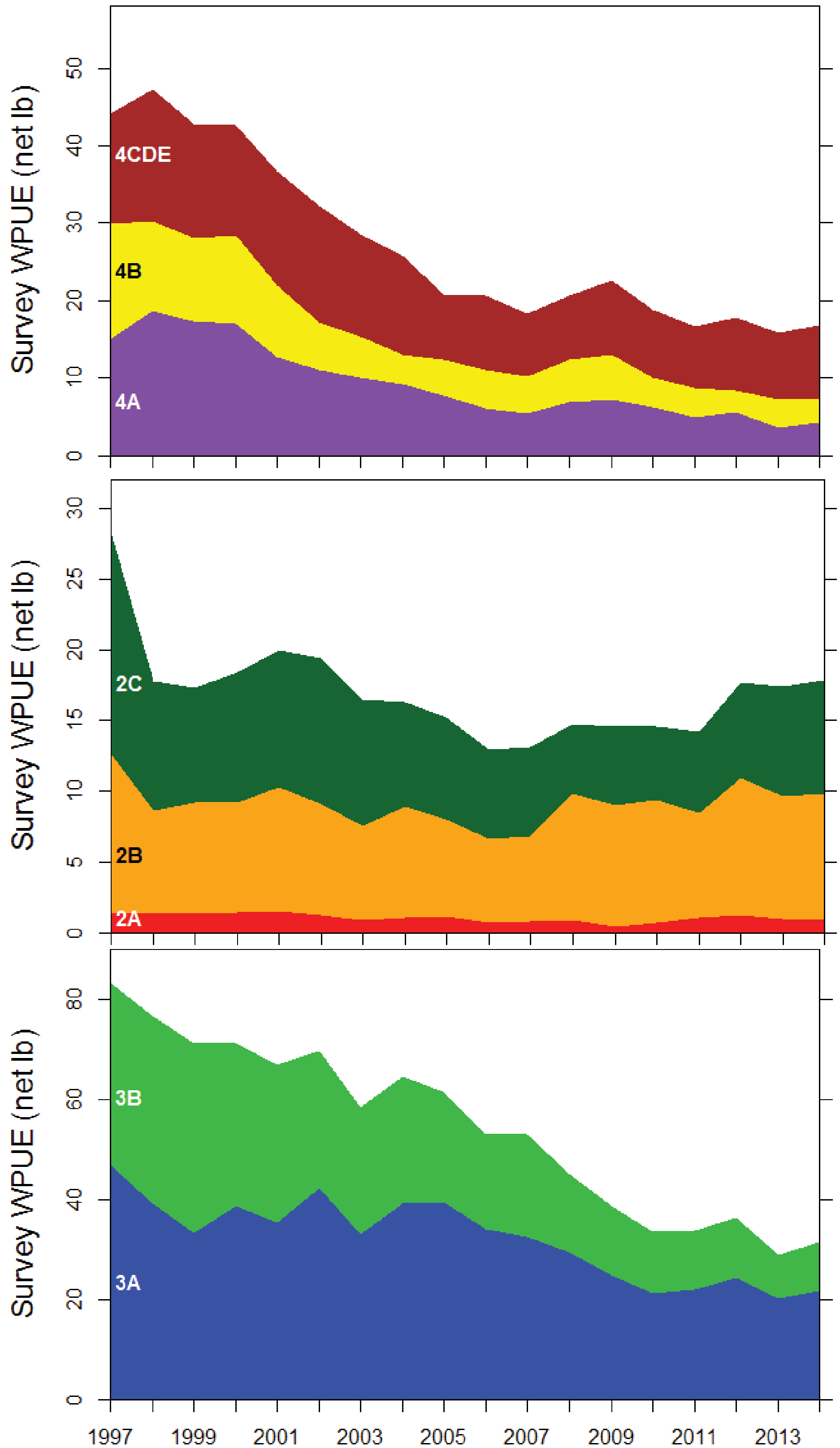

Figure 7. Weighted contributions of the individual regulatory Areas within the survey WPUE for Area 2 (lower panel), Area 3 (middle panel) and Area 4 (upper panel). Note that the y-axes differ among the panels.

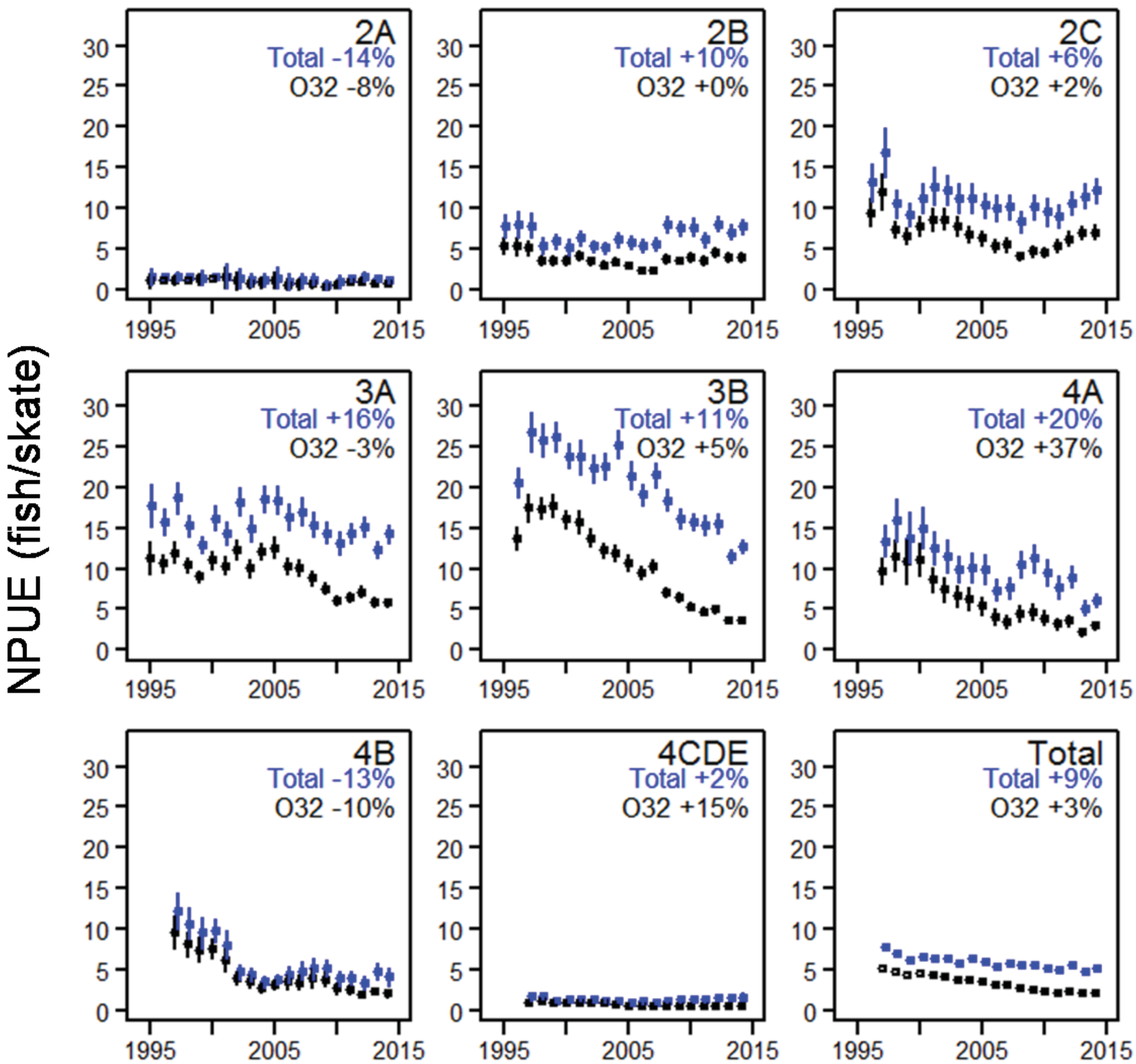

Figure 8. Recent setline survey NPUE (fish/skate) for all (blue, upper series) and legal-sized fish (black, lower series) by regulatory area and year through 2014. Percentages for each area indicate the change from 2013 to 2014. Total NPUE values have been offset slightly on the x-axis to make the points easier to distinguish.

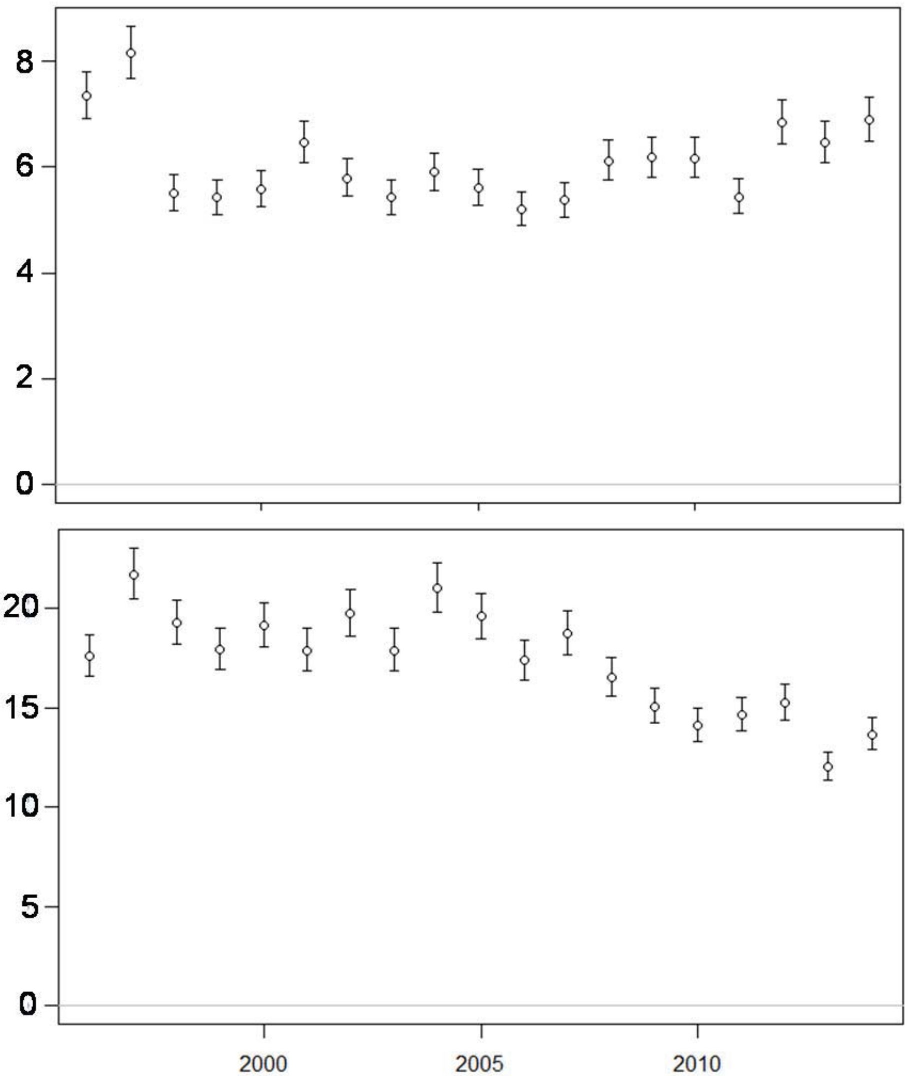

Figure 9. Recent aggregate setline survey total NPUE by geographic region (Area 2, upper panel; Area 3, lower panel).

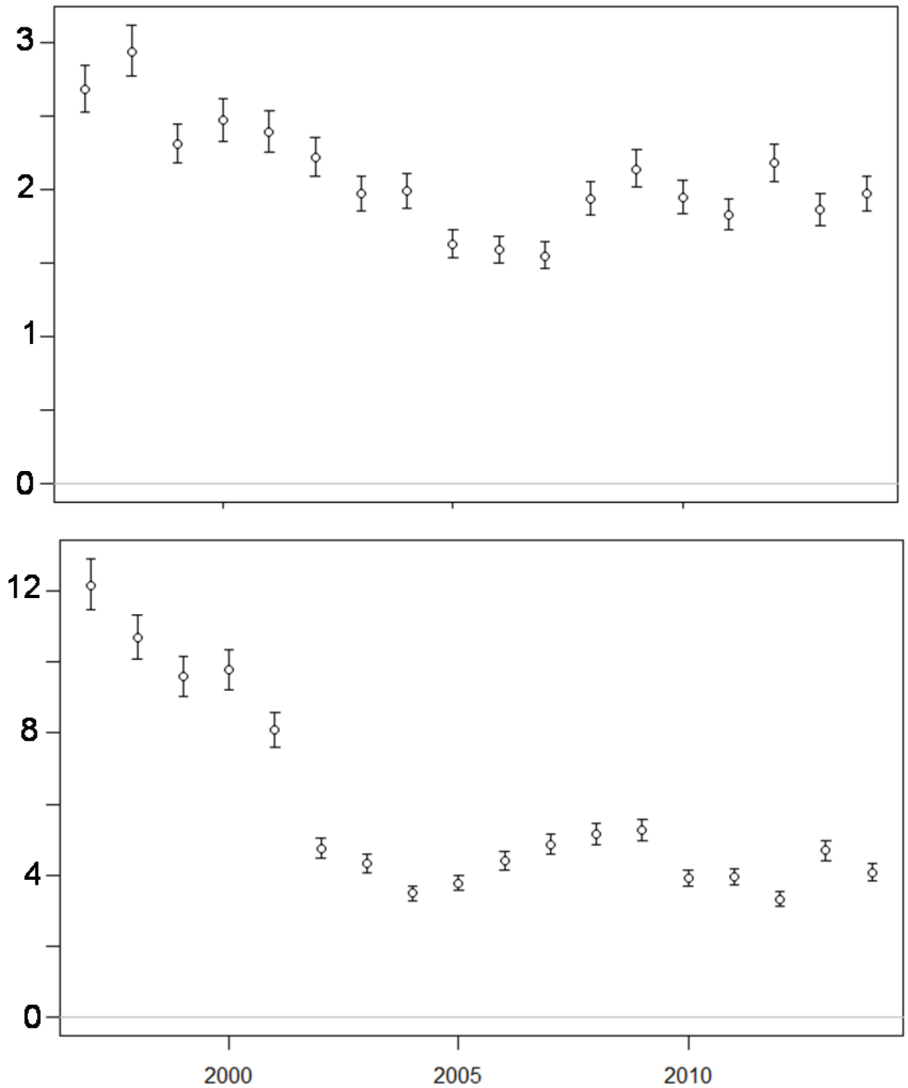

Figure 10. Recent aggregate setline survey total NPUE by geographic region (Area 4, upper panel; Area 4B, lower panel).

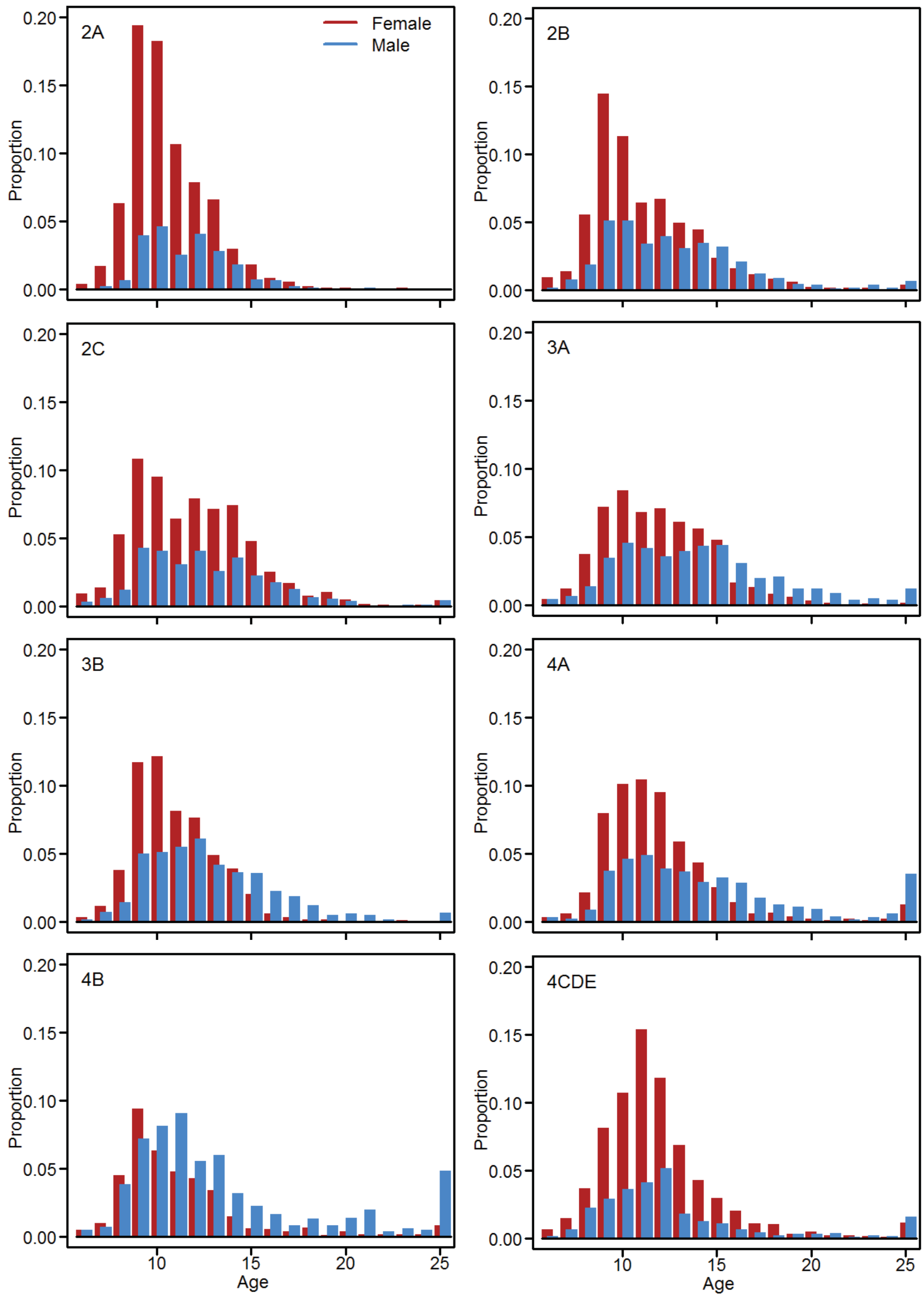

Figure 11. Age distributions from the 2014 setline survey by regulatory area.

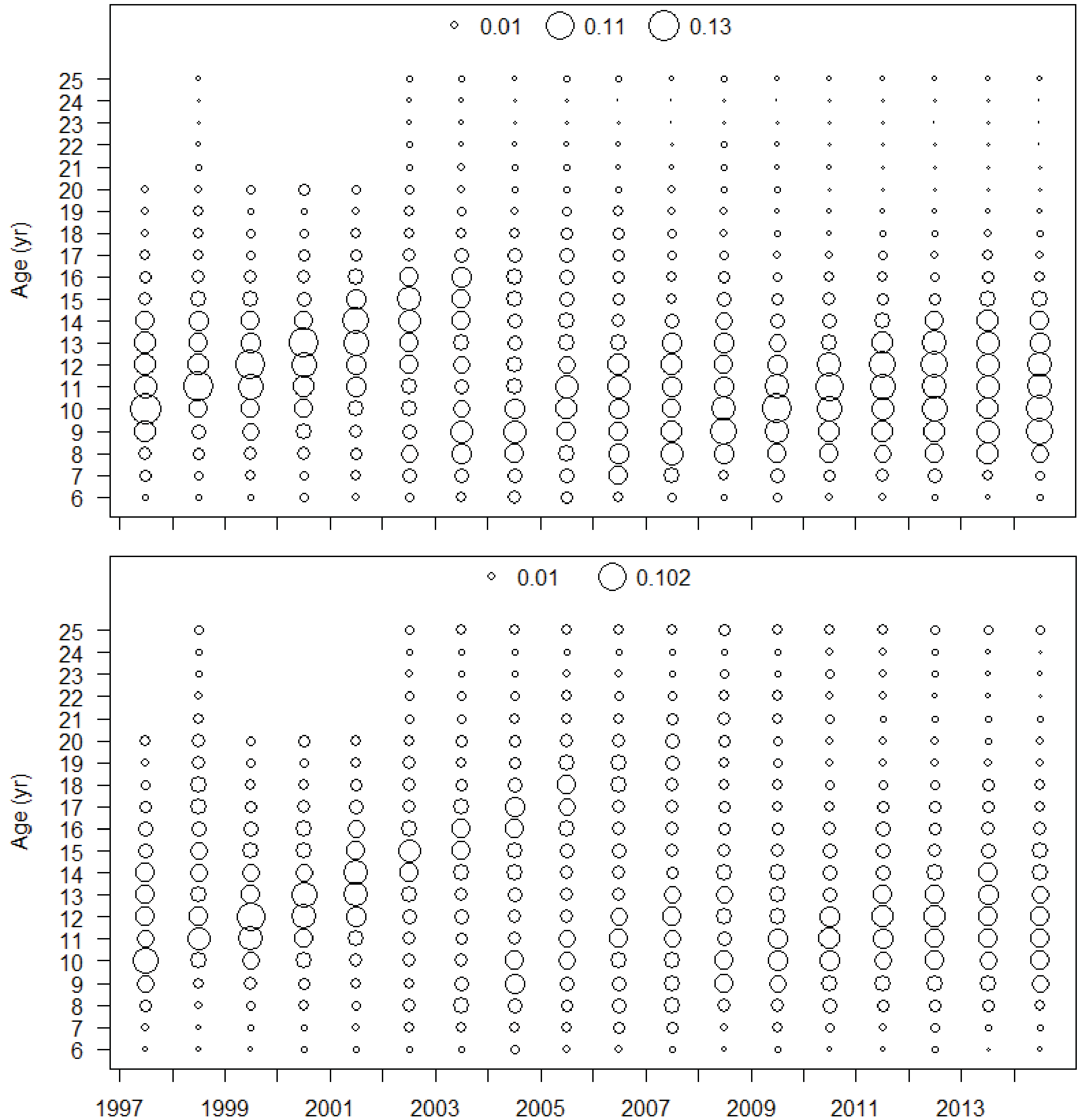

Figure 12. Recent coastwide proportions-at-age for females (upper panel) and males (lower panel) from the setline survey. Proportions sum to 1.0 across both sexes within each year.

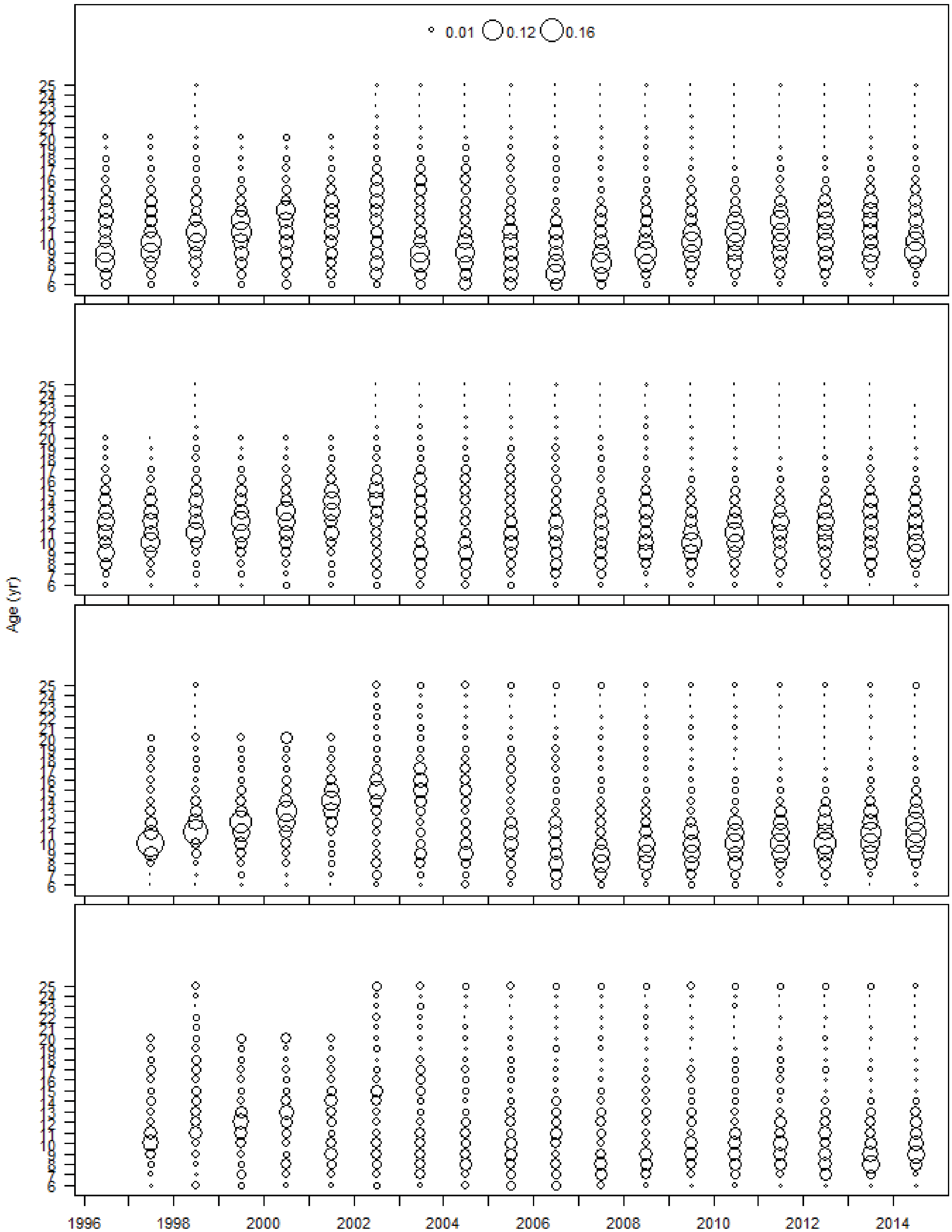

Figure 13. Recent proportions-at-age for female halibut captured by the setline survey by geographic region: Area 2 (upper panel), Area 3 (second panel from top), Area 4 (third panel) and Area 4B (bottom panel) halibut captured by the setline survey. Proportions sum to 1.0 across both sexes within each year.

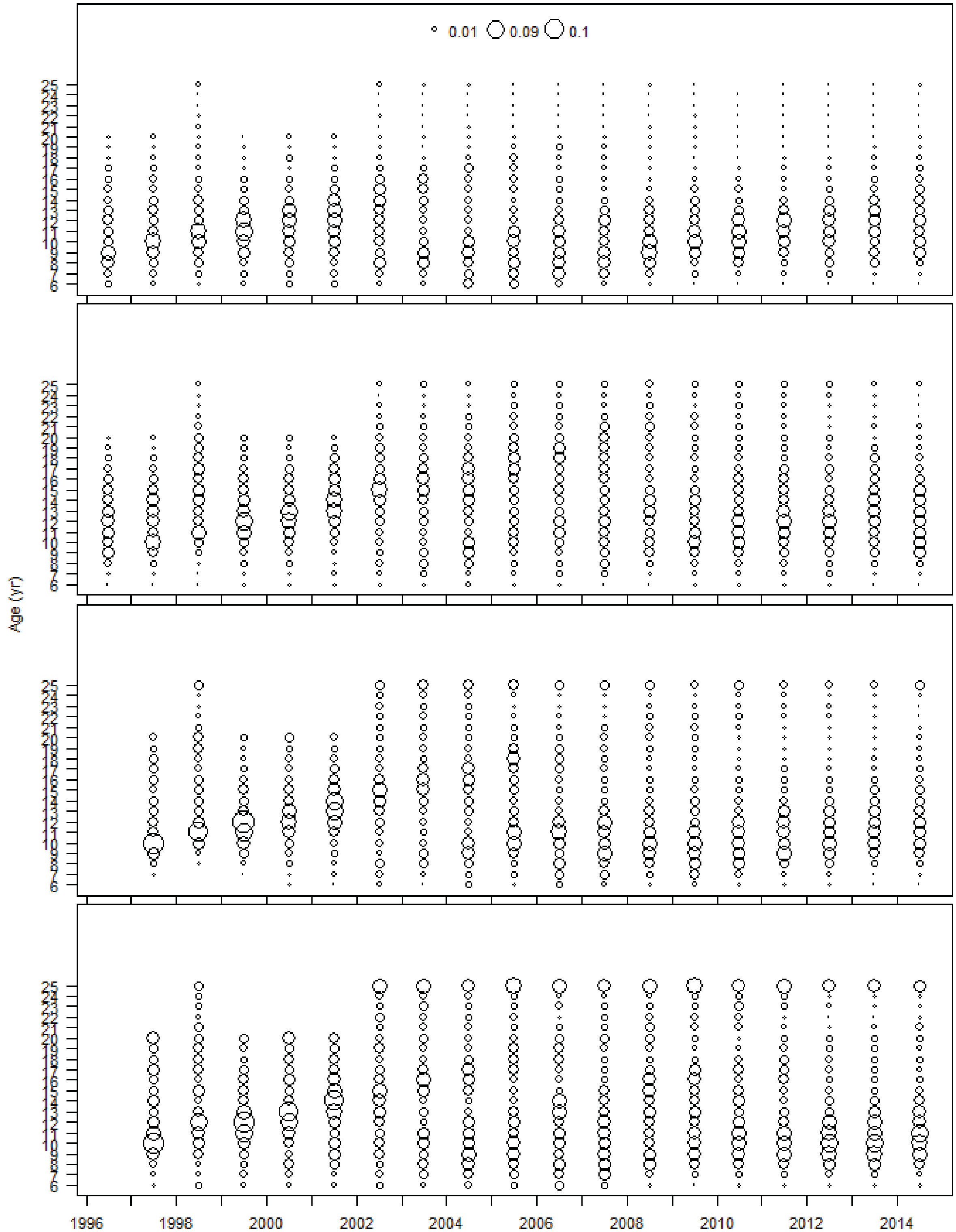

Figure 14. Recent proportions-at-age for male halibut captured by the setline survey by geographic region: Area 2 (upper panel), Area 3 (second panel from top), Area 4 (third panel) and Area 4B (bottom panel) halibut captured by the setline survey. Proportions sum to 1.0 across both sexes within each year.

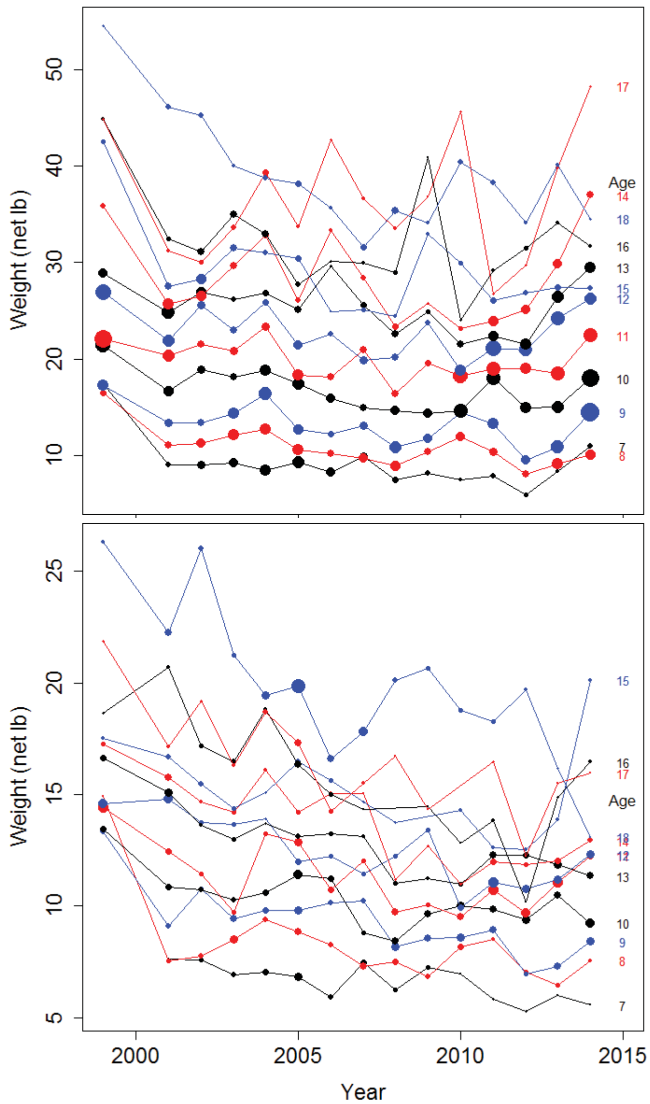

Figure 15. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 2A captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

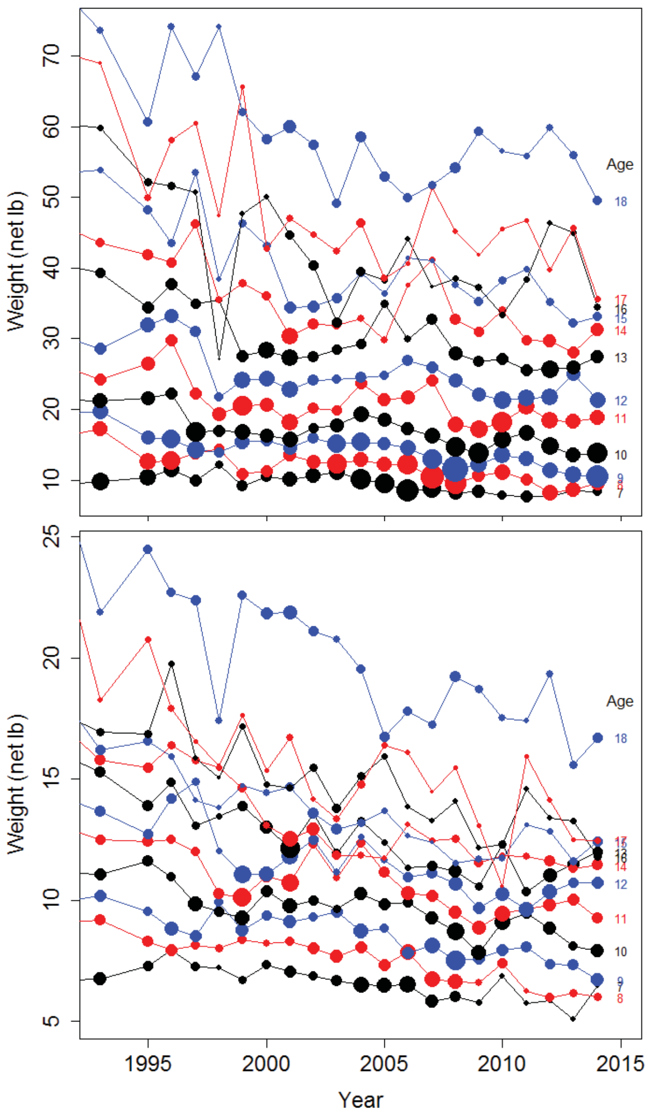

Figure 16. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 2B captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

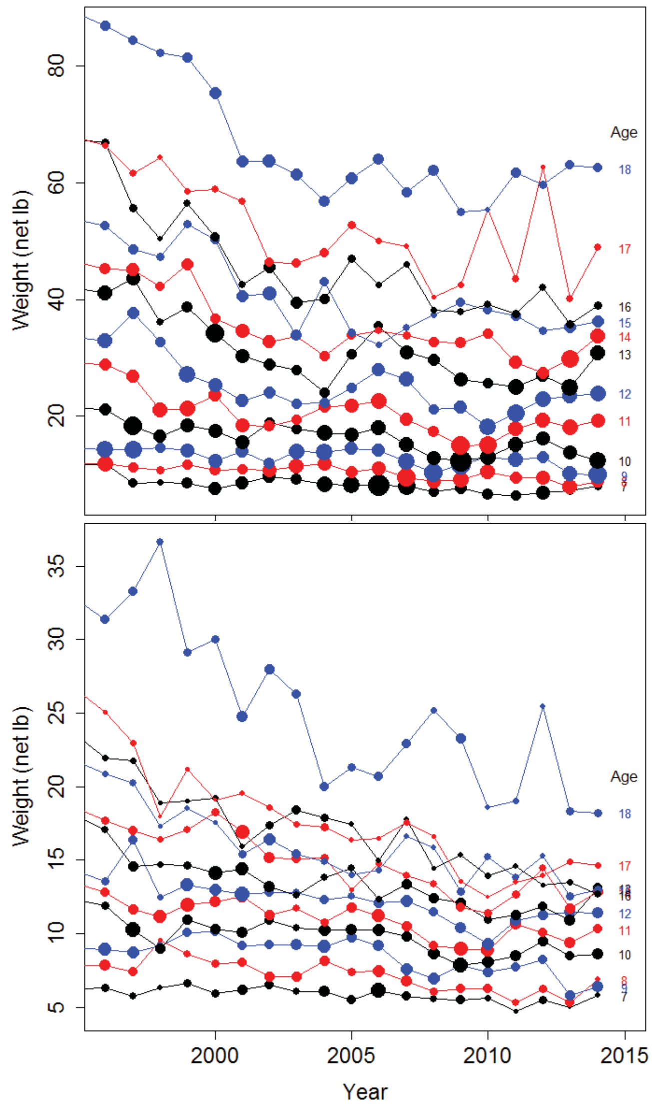

Figure 17. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 2C captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

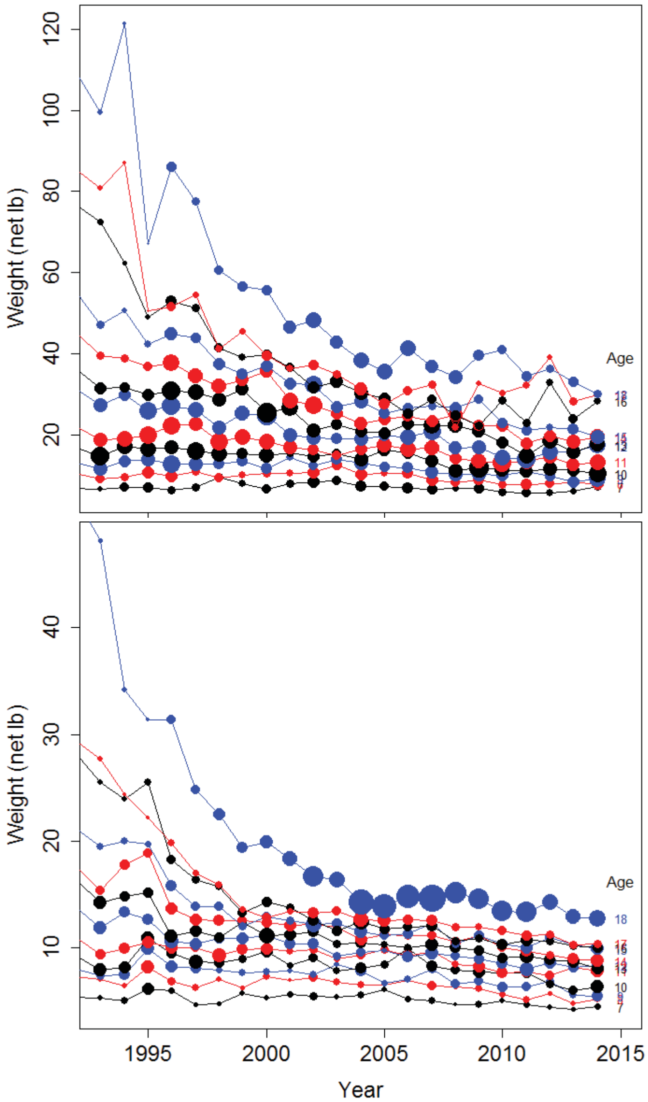

Figure 18. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 3A captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

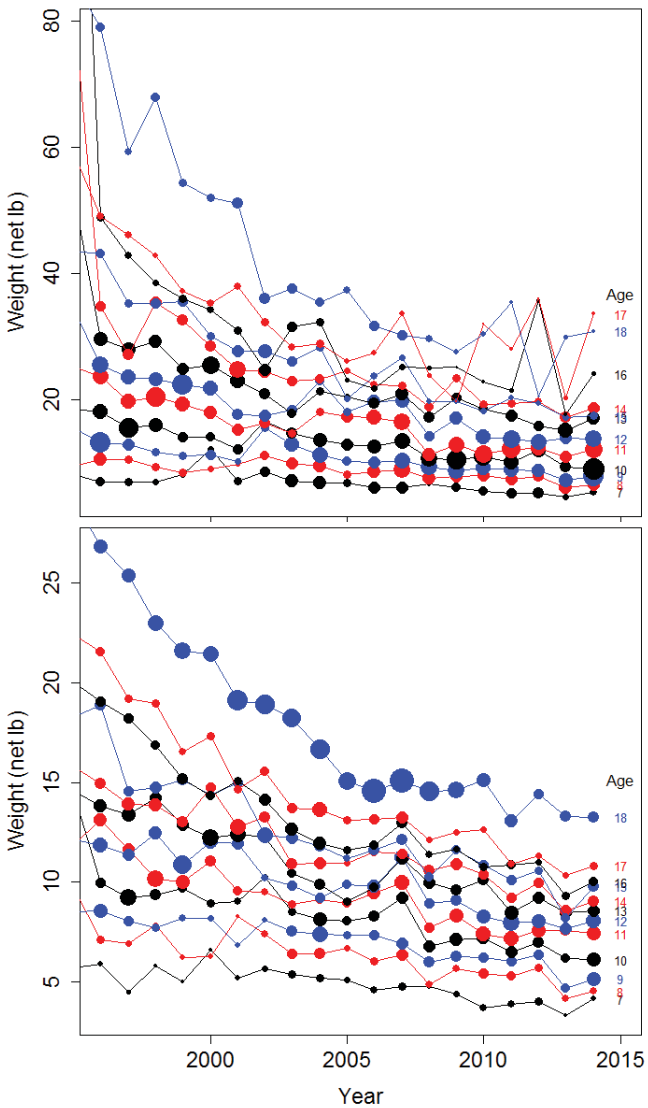

Figure 19. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 3B captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

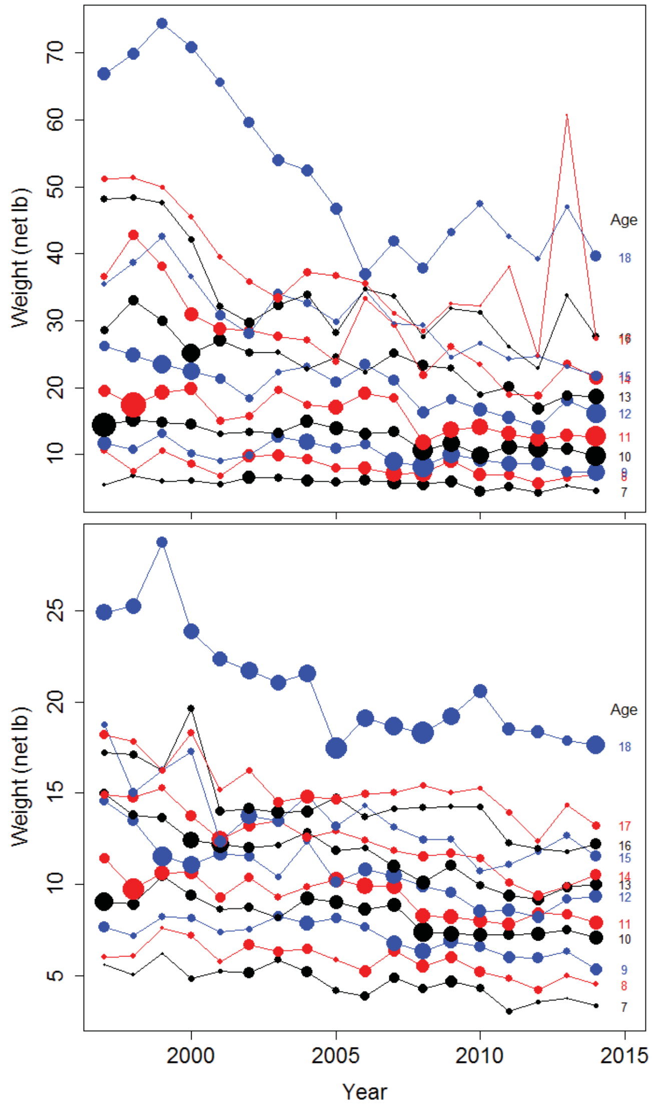

Figure 20. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 4A captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

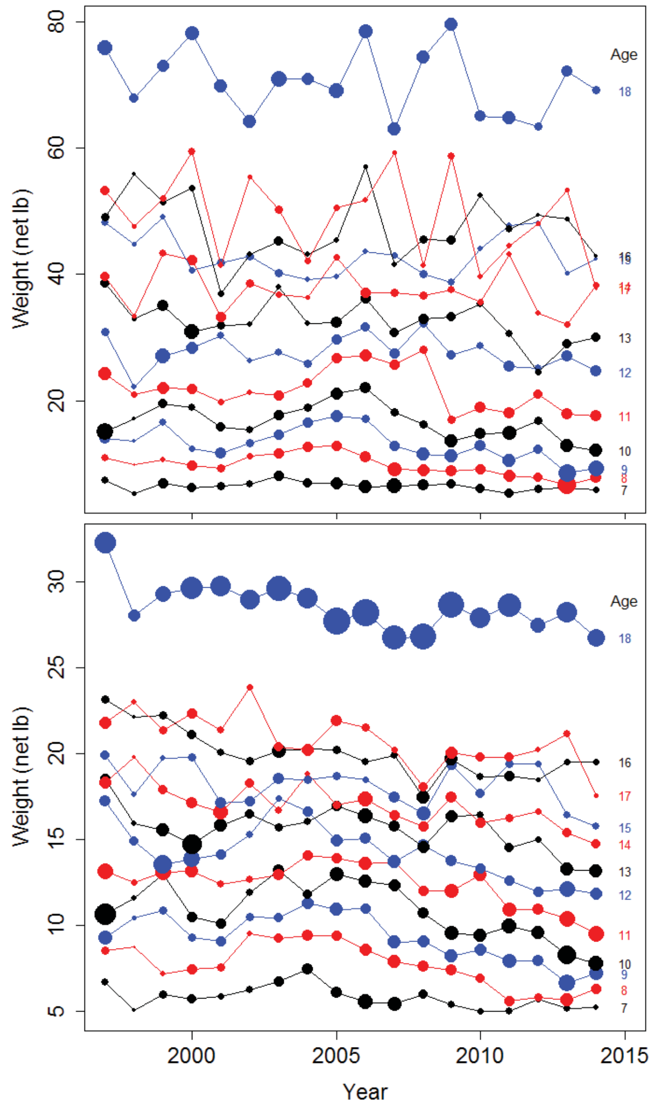

Figure 21. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Area 4B captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

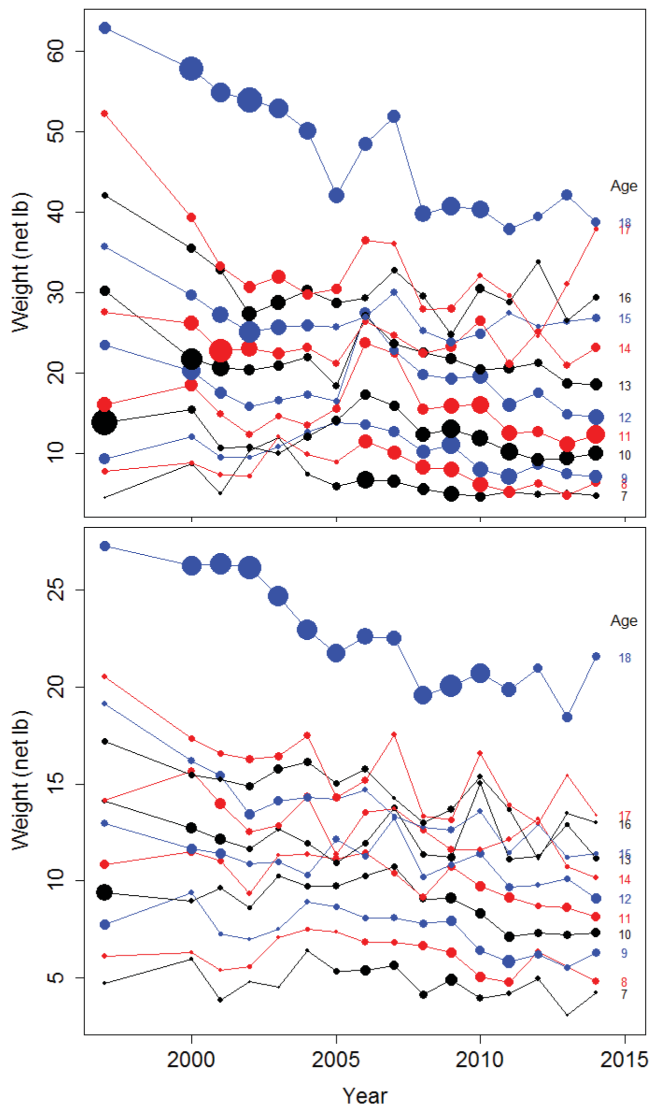

Figure 22. Trends in weight-at-age for female (upper panel), and male (lower panel) halibut from regulatory Areas 4C, 4D and 4E captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

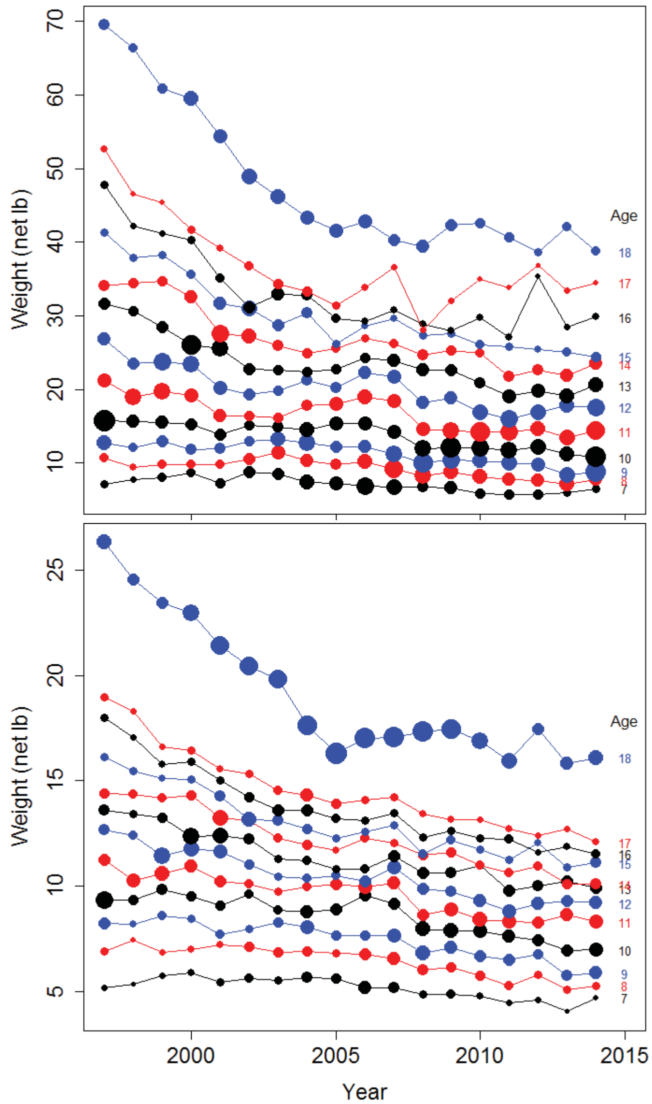

Figure 23. Weighted coastwide trends in weight-at-age for female (upper panel), and male (lower panel) halibut from all regulatory areas captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

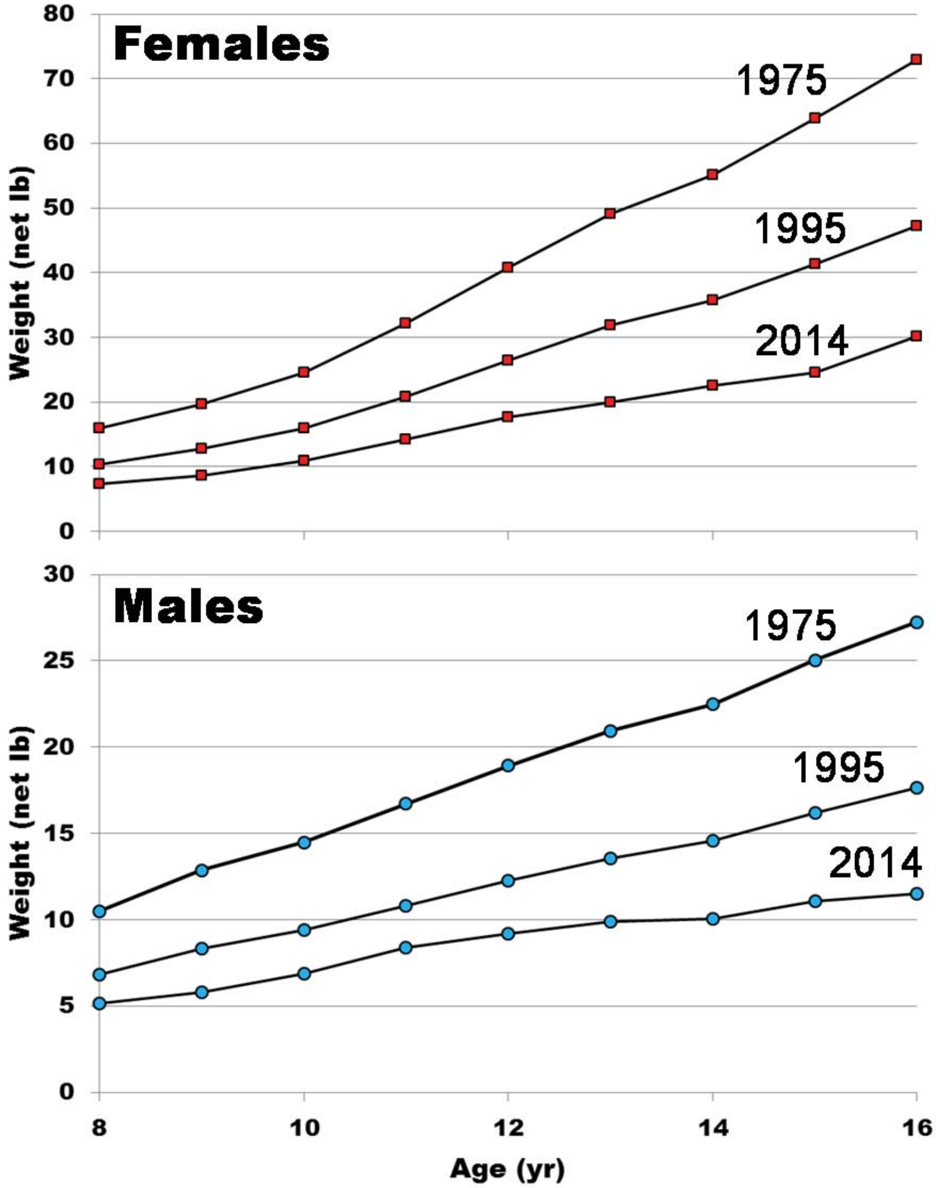

Figure 24. Coastwide aggregate estimated average weight-at-age trends from setline survey and fishery data over the last four decades.

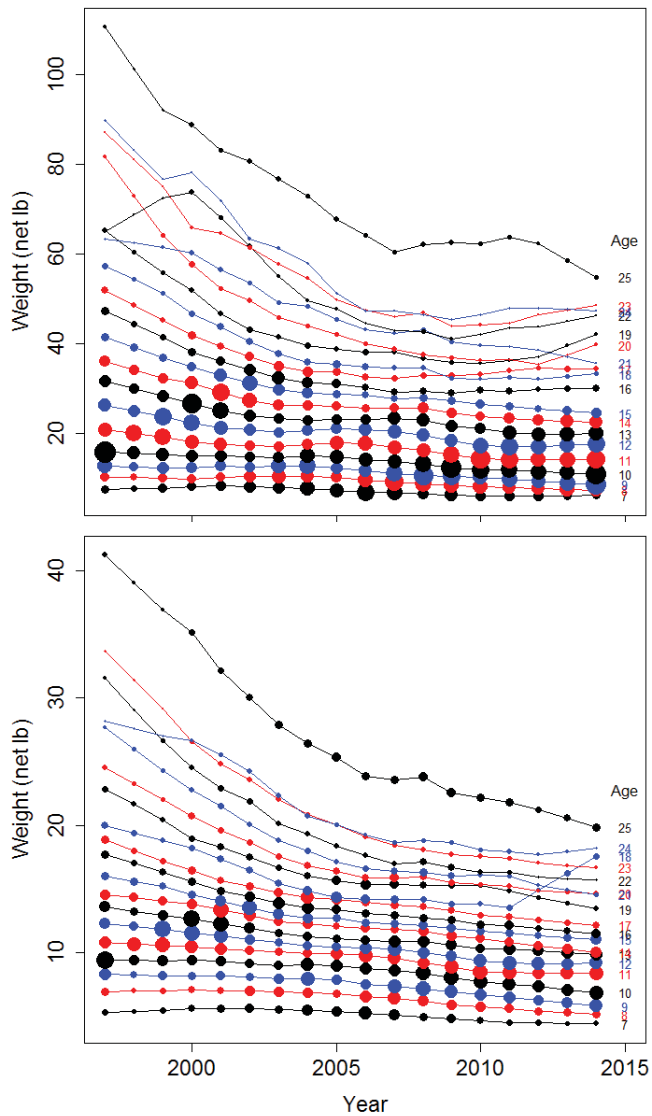

Figure 25. Weighted and smoothed coastwide trends in weight-at-age for female (upper panel), and male (lower panel) halibut from all regulatory areas captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 25 and greater have been aggregated.

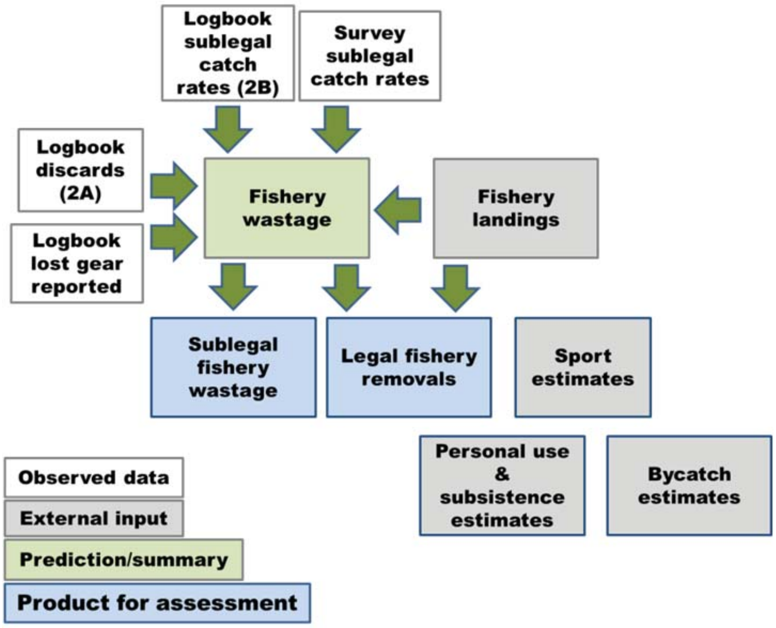

Figure 26. Relationships among estimates halibut mortality by source.

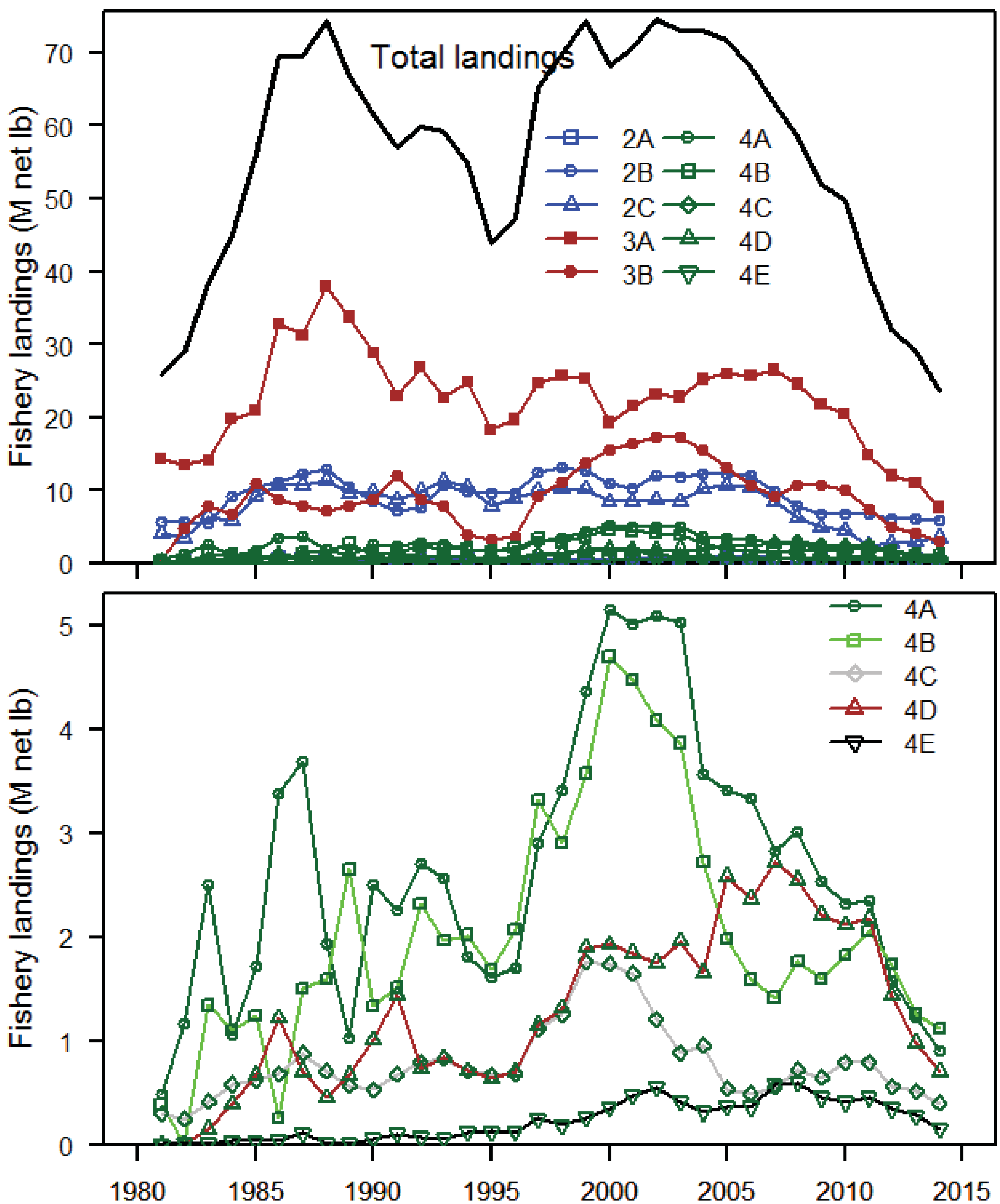

Figure 27. Recent landings of halibut by the directed commercial fishery by regulatory area (upper panel), and within Areas 4A to 4E for better resolution of the trends (lower panel).

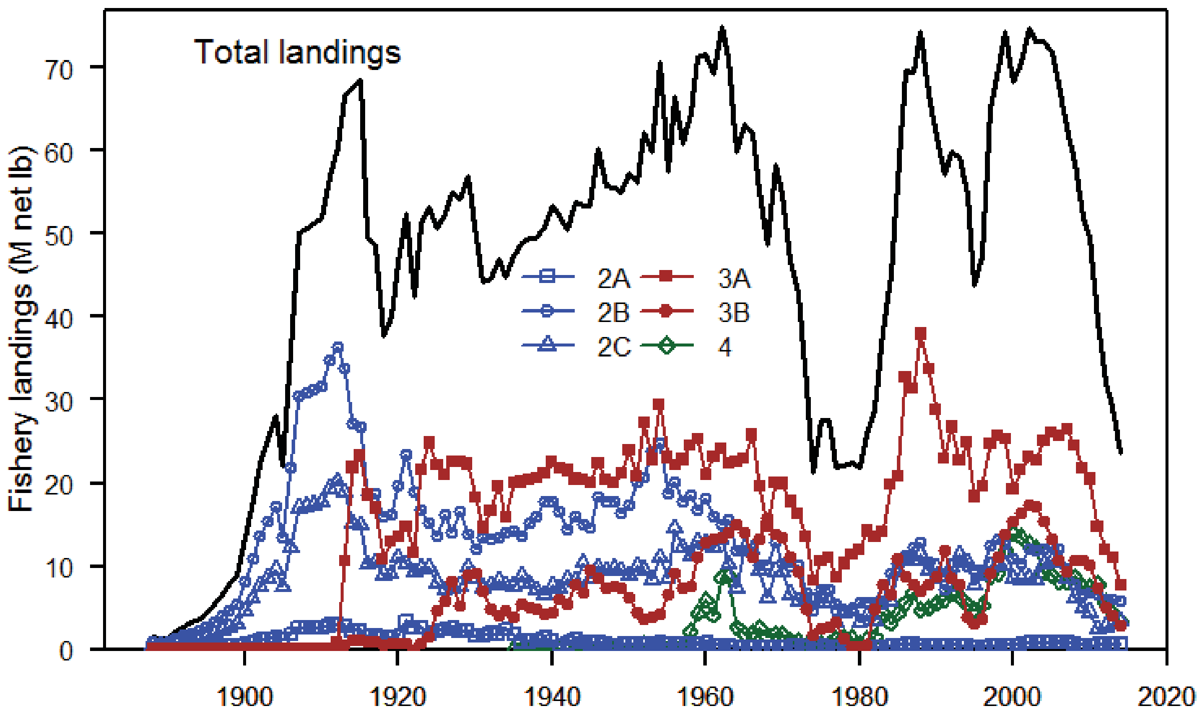

Figure 28. Landings of halibut by the directed commercial fishery by regulatory area.

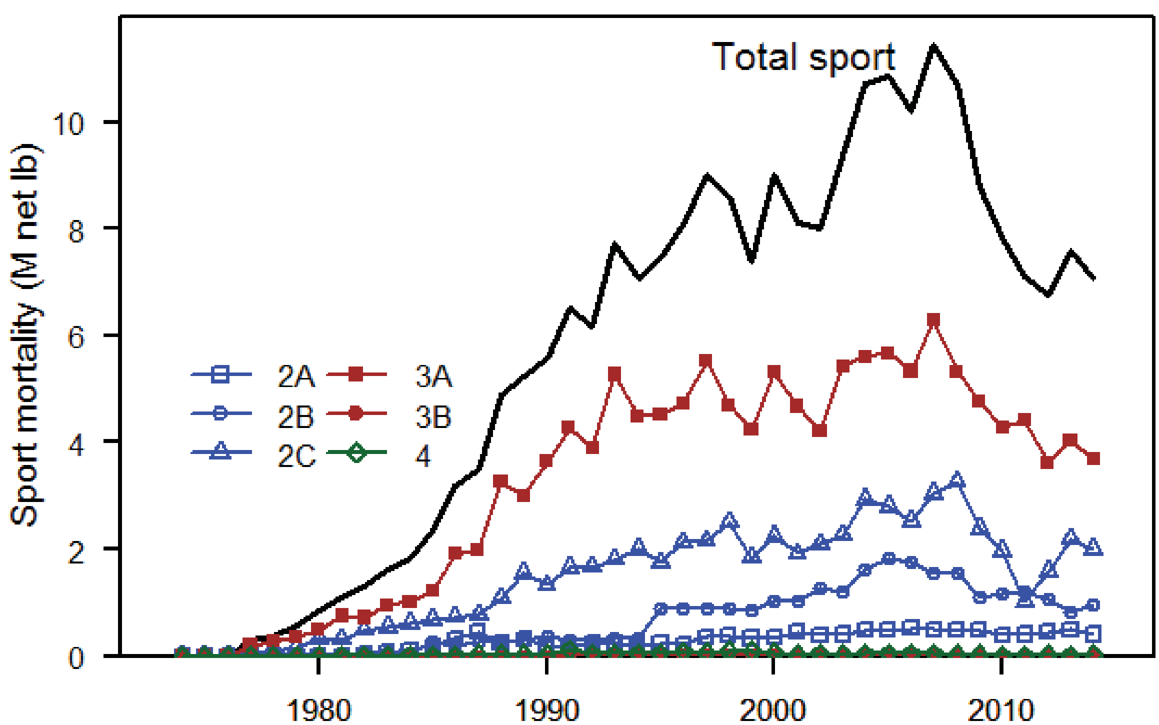

Figure 29. Sport (recreational) removals of halibut by regulatory area.

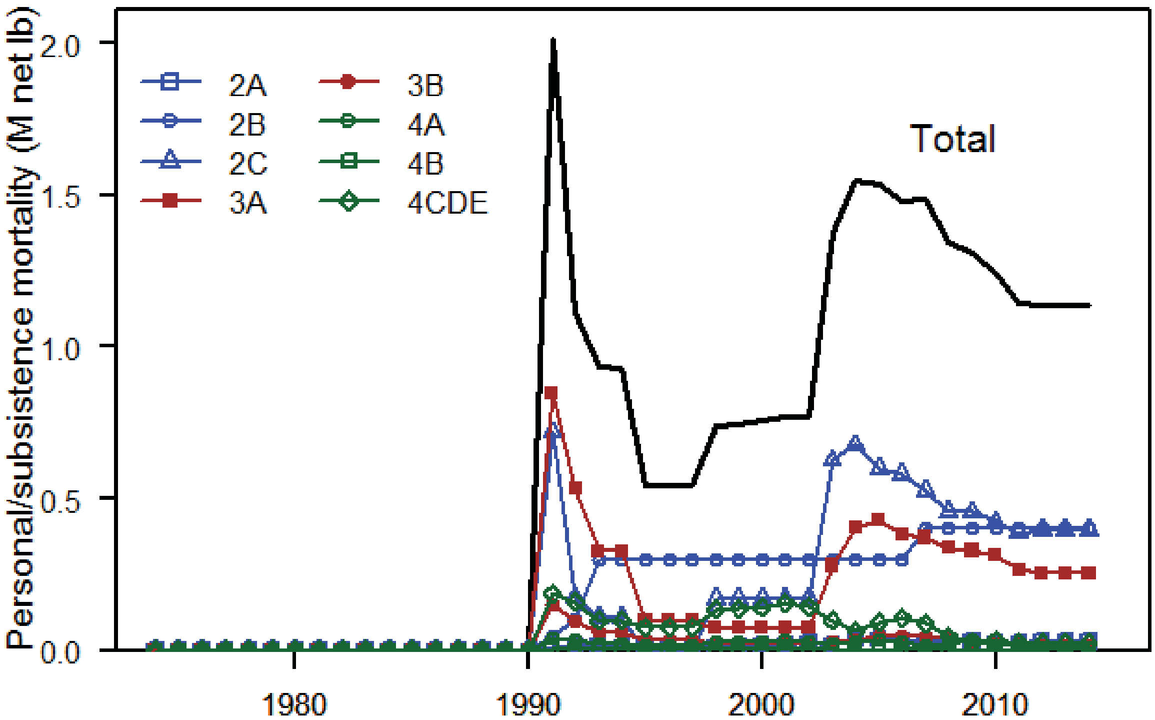

Figure 30. Estimated personal use or subsistence removals by regulatory area.

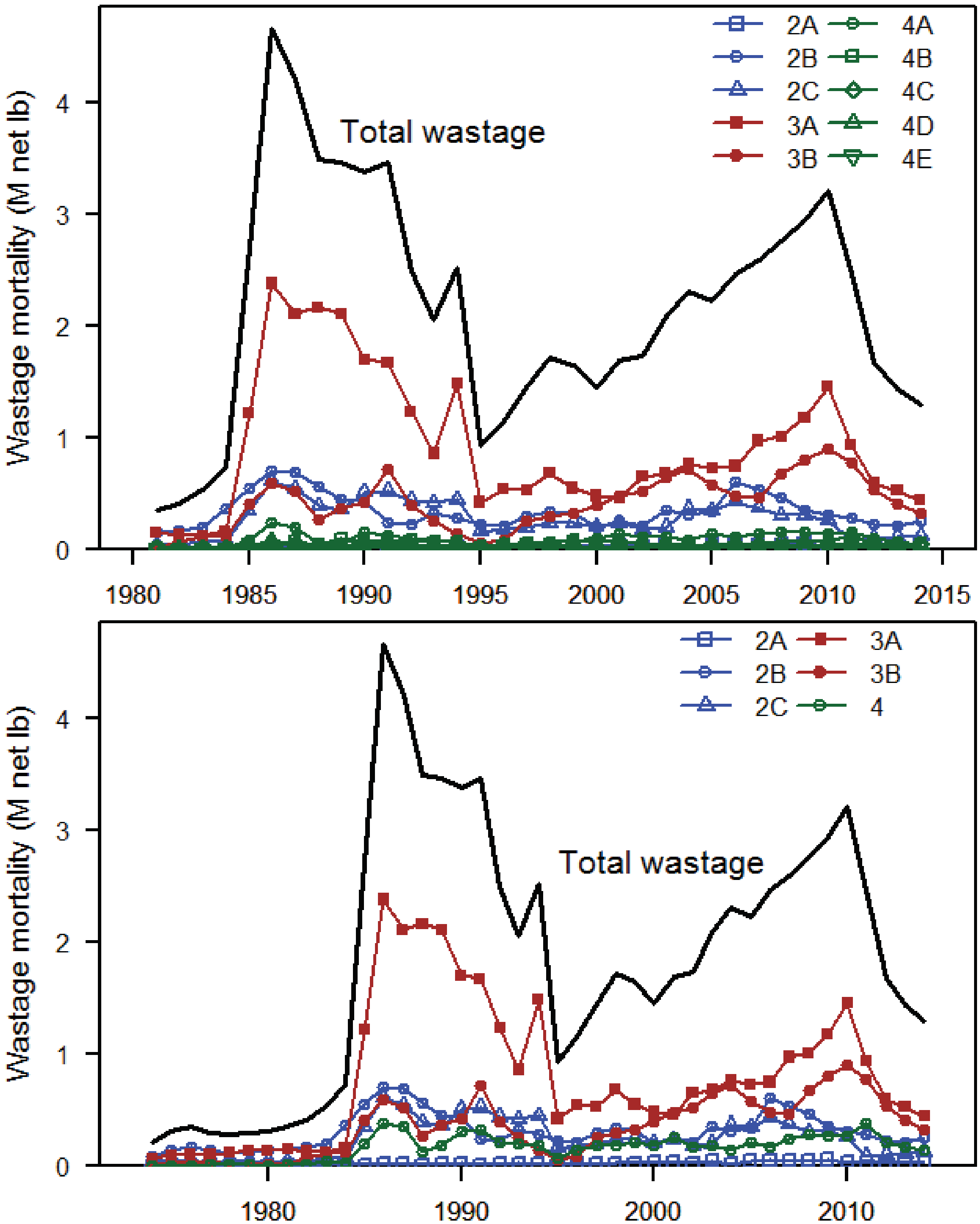

Figure 31. Wastage in the commercial fishery by regulatory area, 1981-2014 (upper panel), and 1974-2014, with all of Area 4 combined (lower panel).

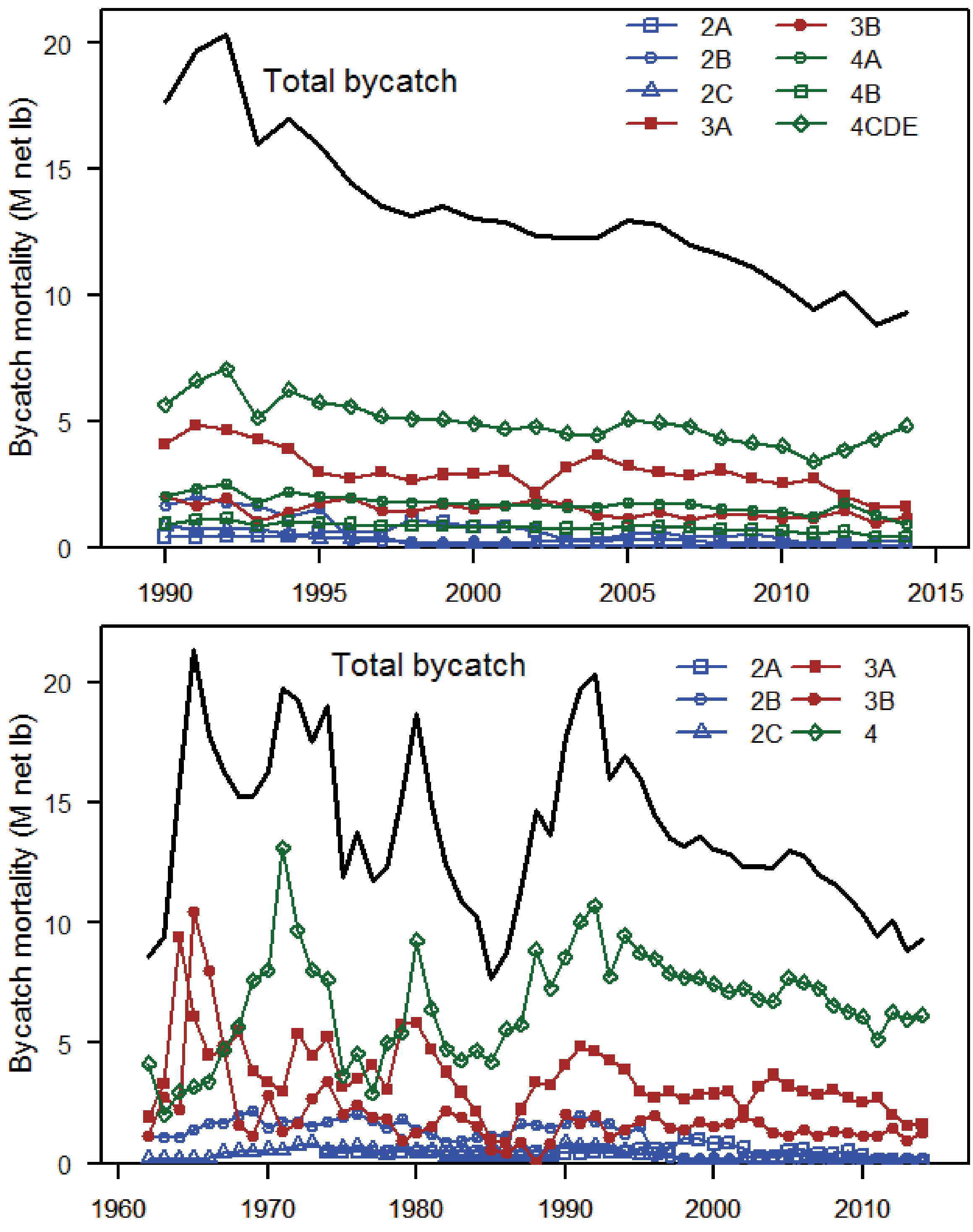

Figure 32. Halibut bycatch estimates by regulatory area, 1990-2014 (upper panel), and 1962-2014, with all of Area 4 combined (lower panel).

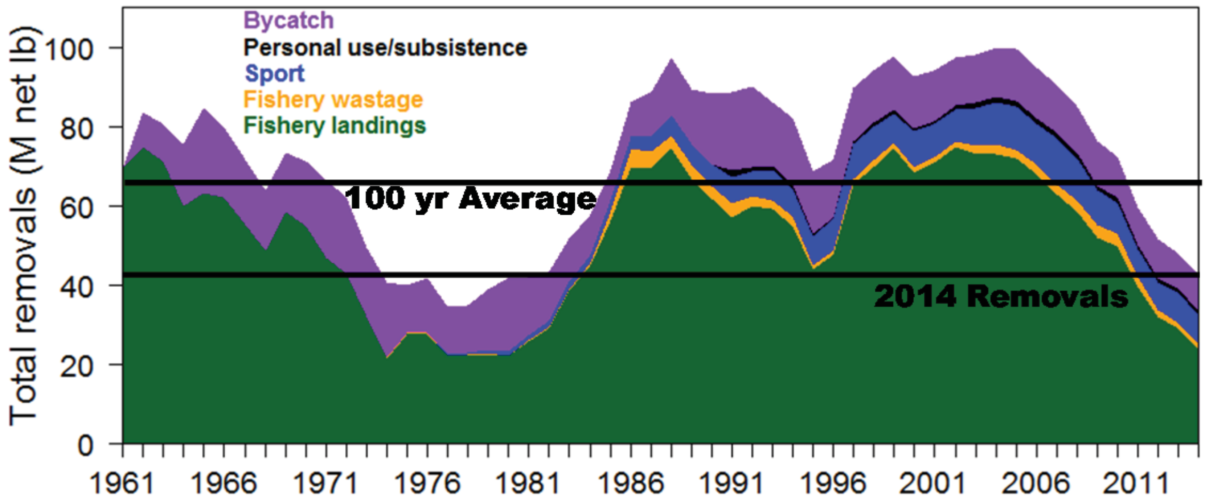

Figure 33. Total halibut removals by source since 1961.

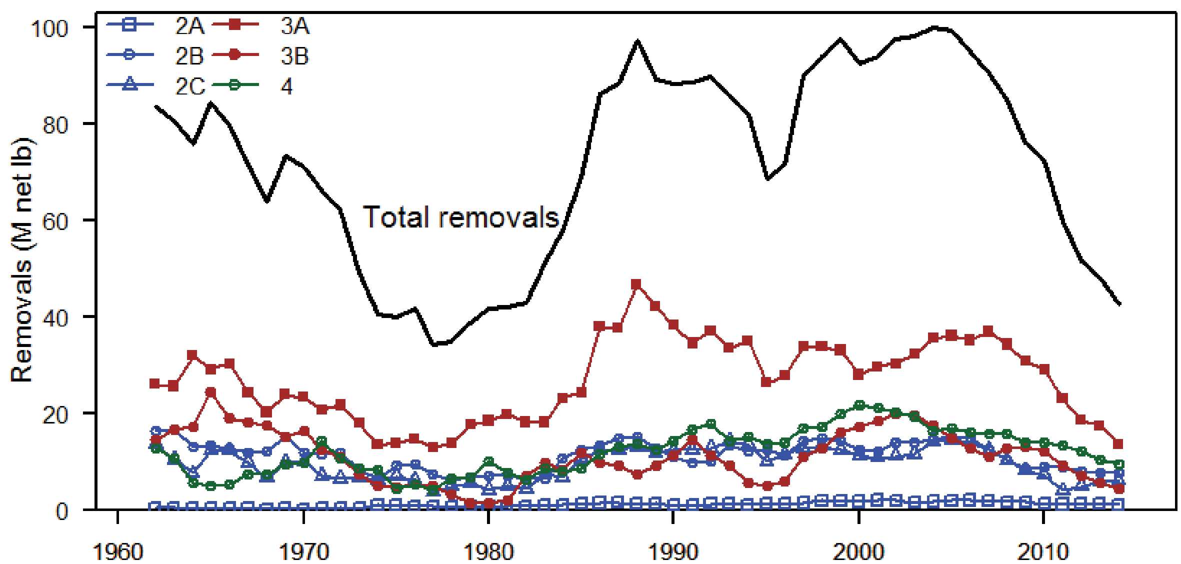

Figure 34. Total halibut removals by regulatory area since 1962.

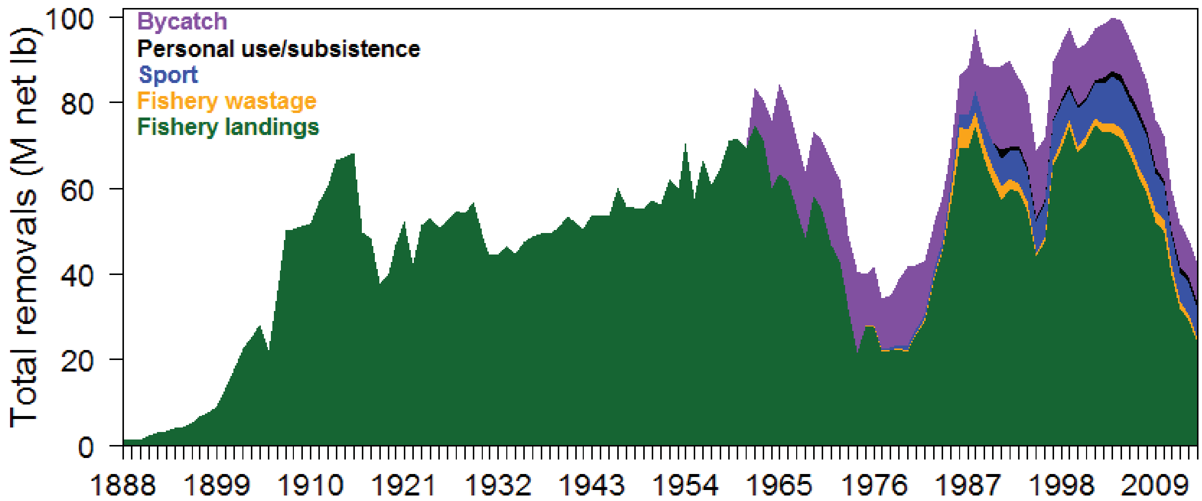

Figure 35. Total estimated halibut removals by source since 1888.

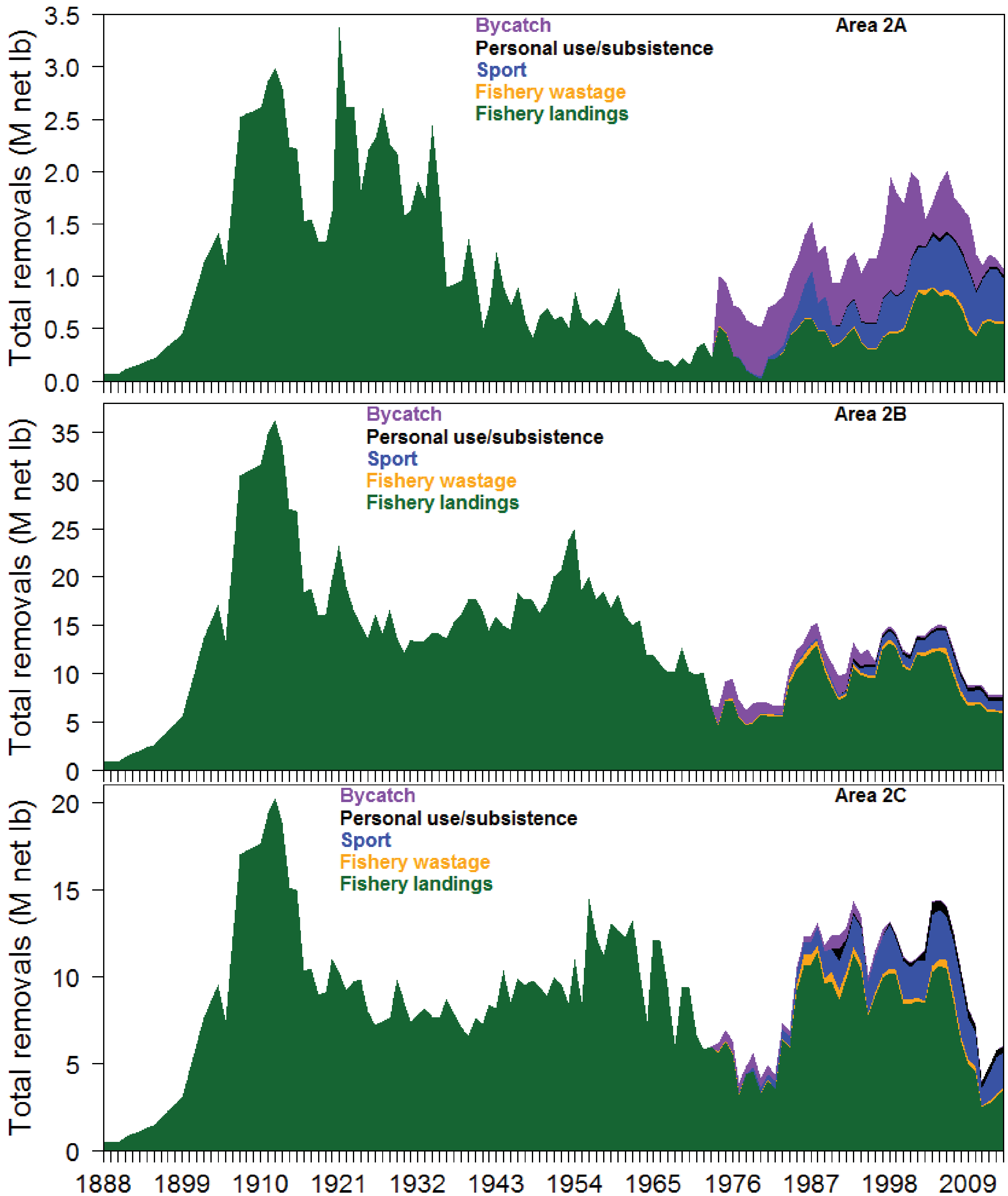

Figure 36. Total estimated halibut removals by source in Areas 2A, 2B, and 2C since 1888. Note that the y axes differ in scale.

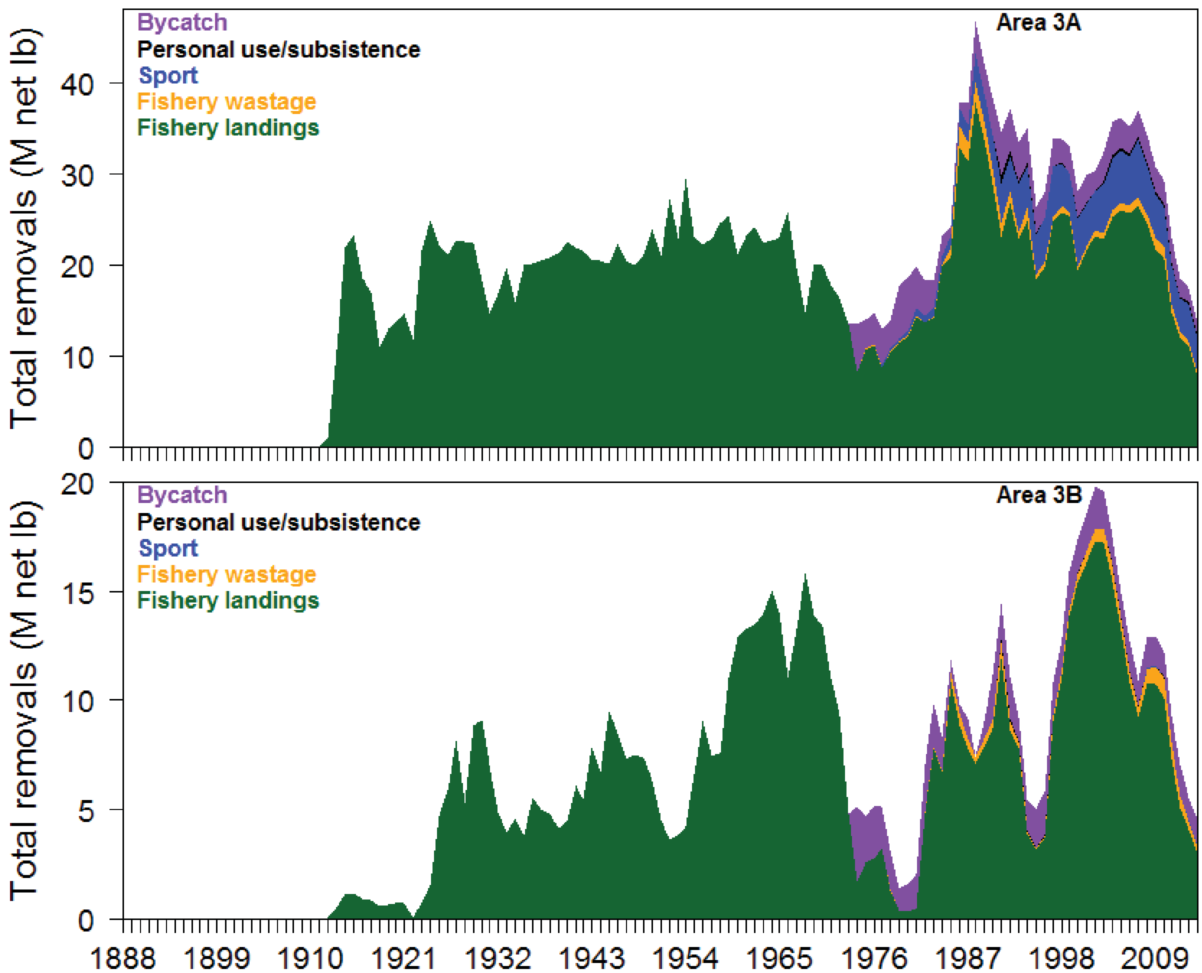

Figure 37. Total estimated removals by source in Areas 3A, and 3B since 1888. Note that the y-axes differ in scale.

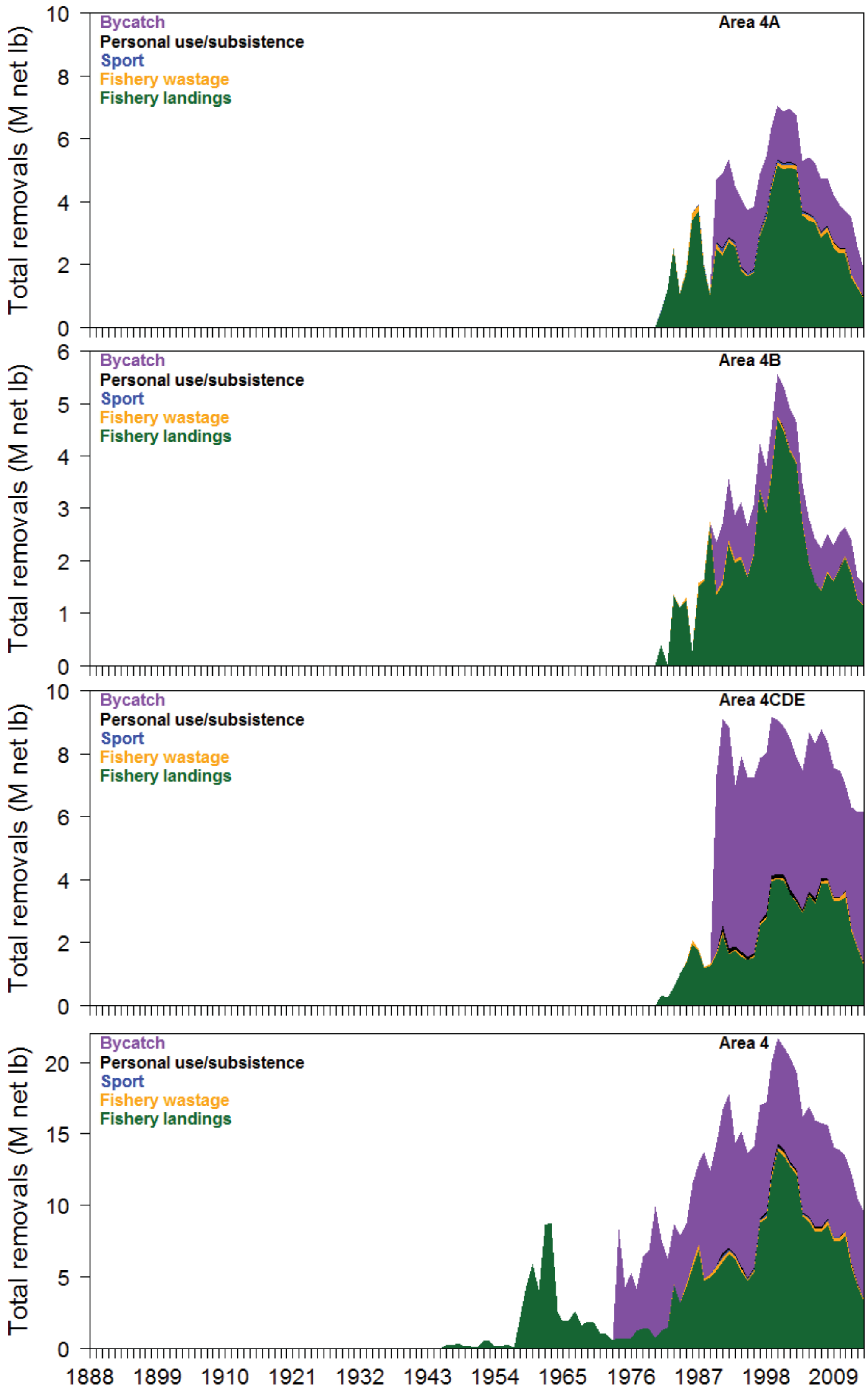

Figure 38. Total estimated removals by source in Areas 4A, 4B, 4CDE, and all of Area 4 combined since 1888. Note that the y-axes differ in scale.

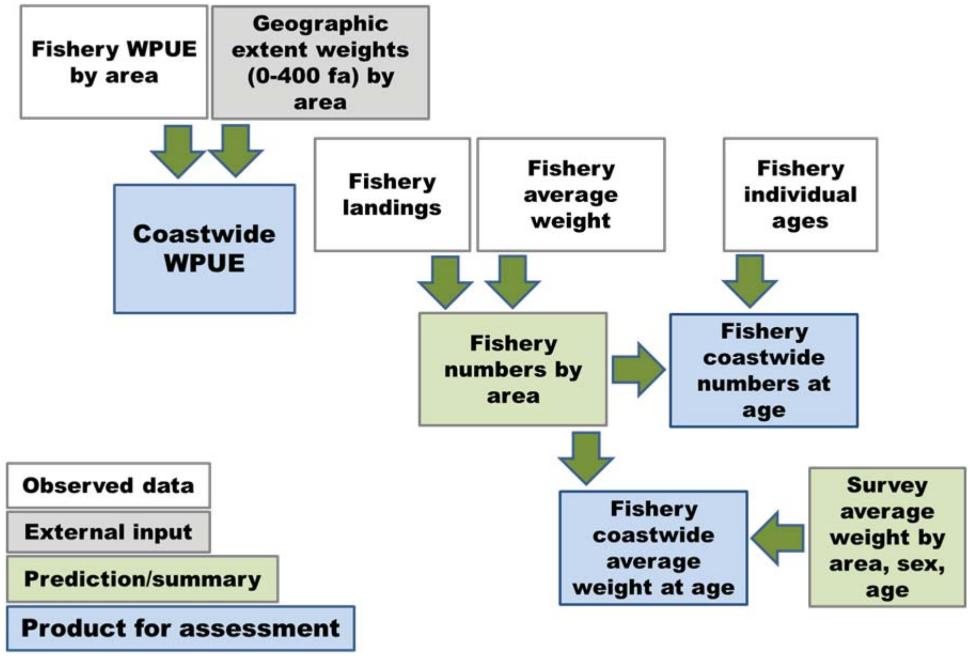

Figure 39. Relationships among fishery-dependent catch-rate and biological data sources.

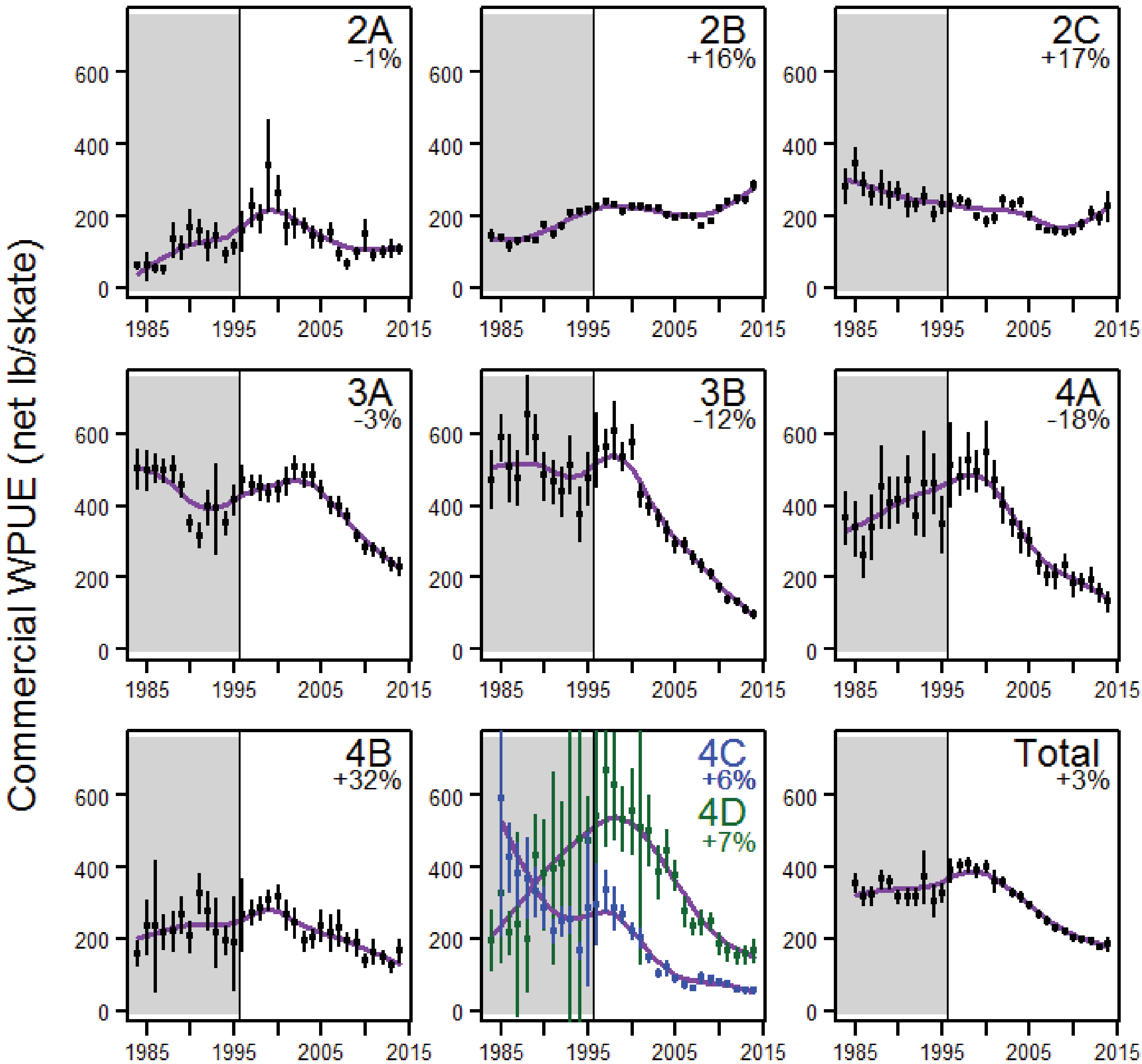

Figure 40. Commercial WPUE summarized by regulatory area and year. Percentages for each Area indicate the change from 2013 to 2014; lines represent a smoother for trend visualization purposes only.

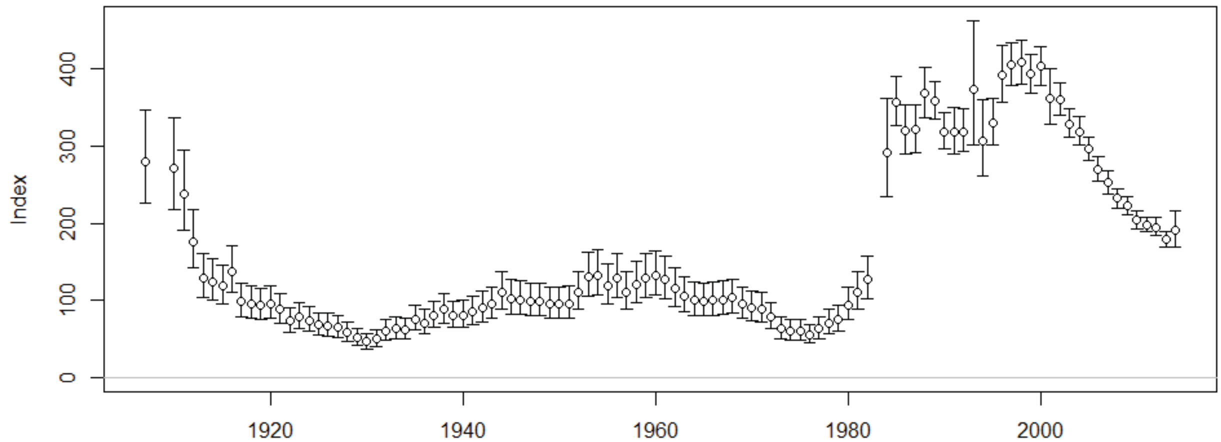

Figure 41. Coastwide commercial WPUE from historical records of effort and catch, as well as more recent direct logbook processing. The large change between 1982 and 1984 coincides with the adoption of circle hooks.

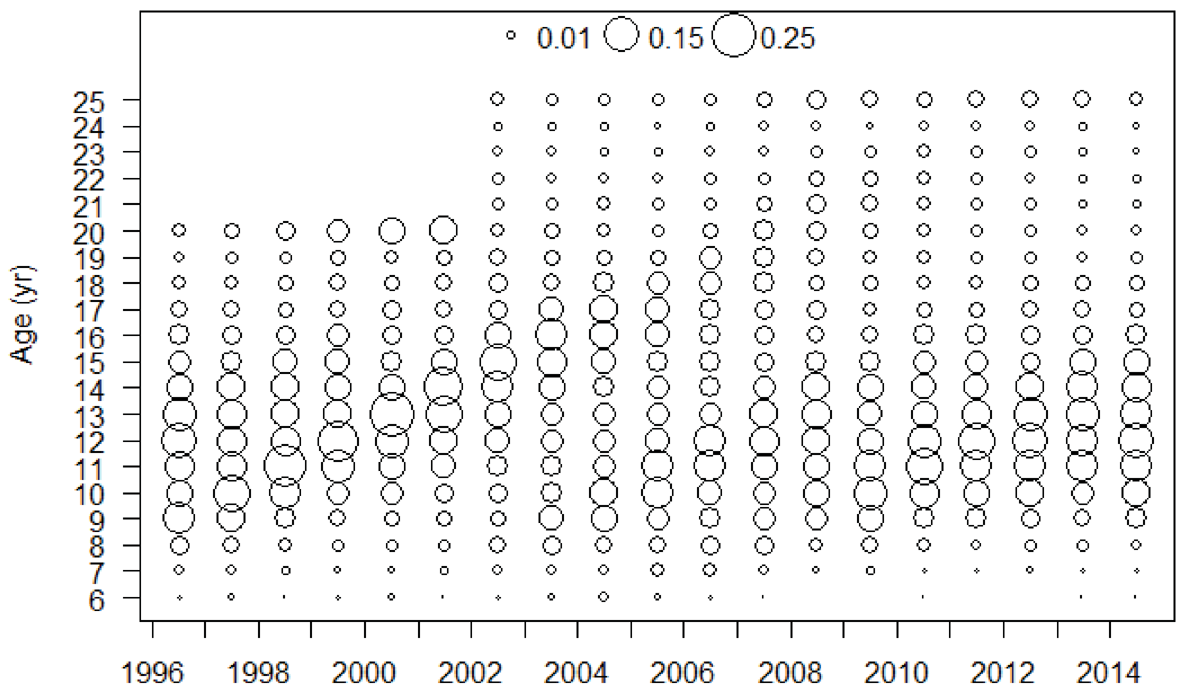

Figure 42. Estimates of recent commercial fishery numbers-at-age.

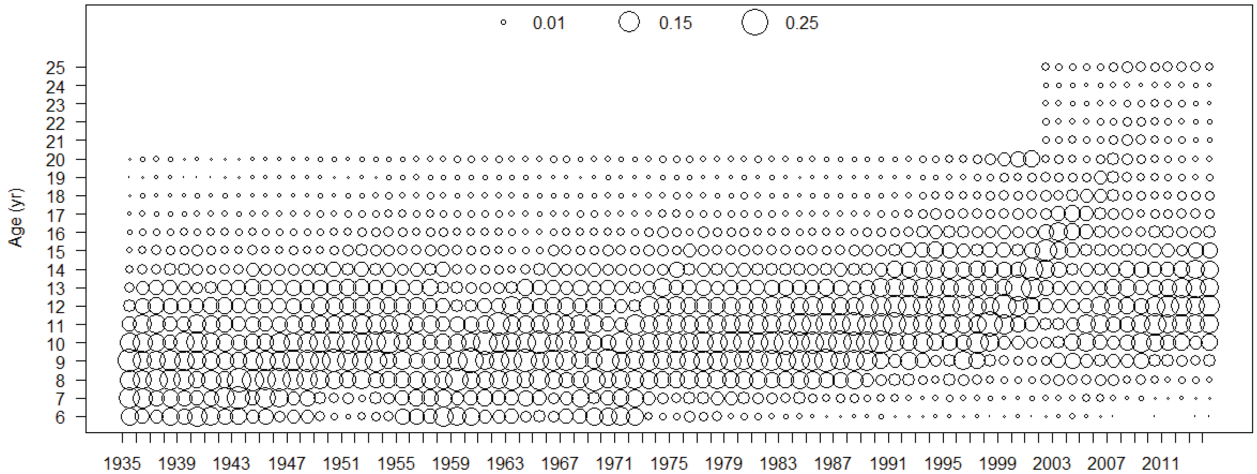

Figure 43. Coastwide commercial fishery proportions-at-age from the retained catch (male and female halibut combined). Note that the current 32 inch minimum size limit was implemented in 1973.

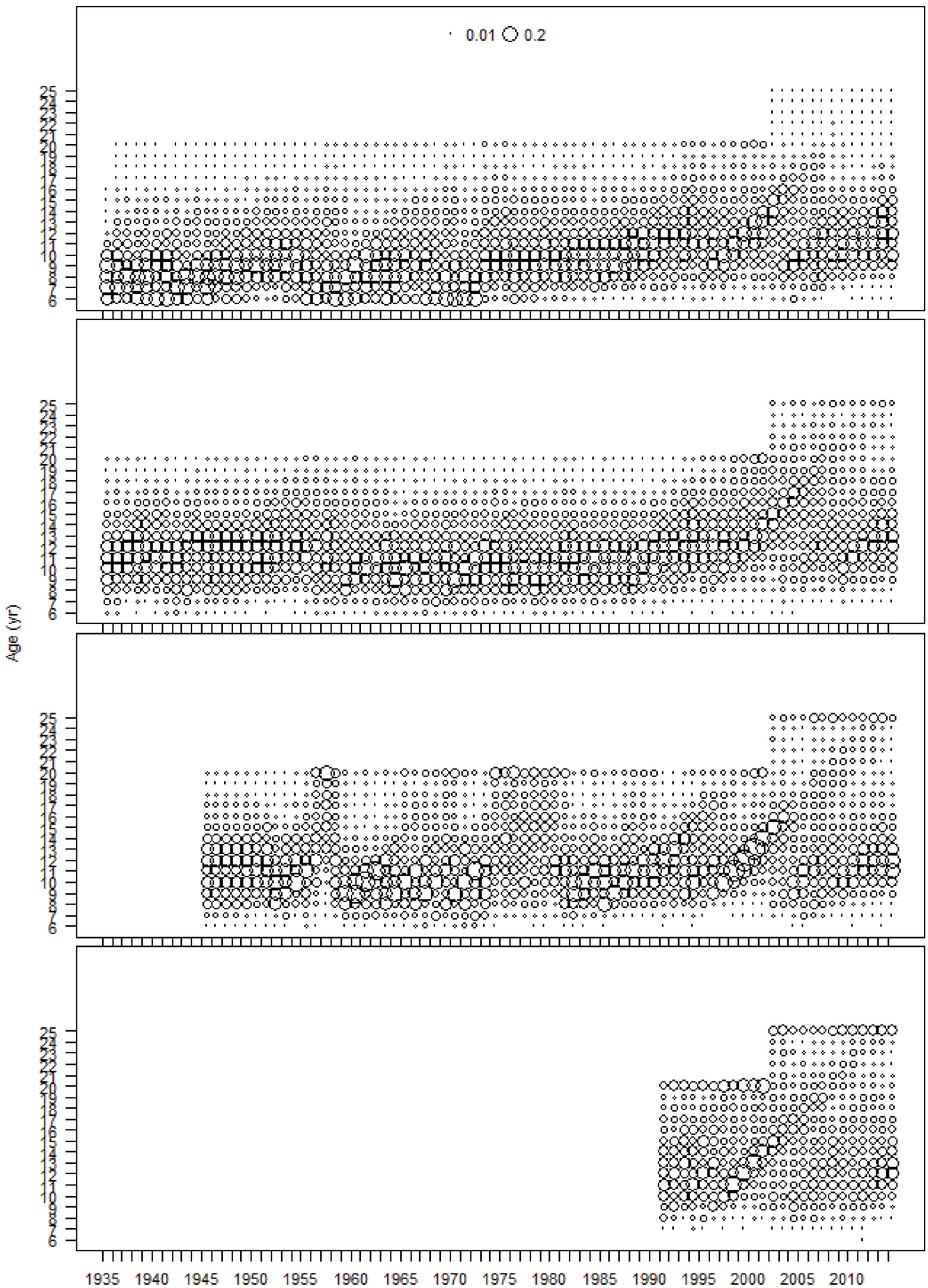

Figure 44. Commercial fishery proportions-at-age by geographic region from the retained catch (male and female halibut combined): Area 2 (top panel), Area 3 (second panel from top), Area 4 (third panel) and Area 4B (bottom panel).

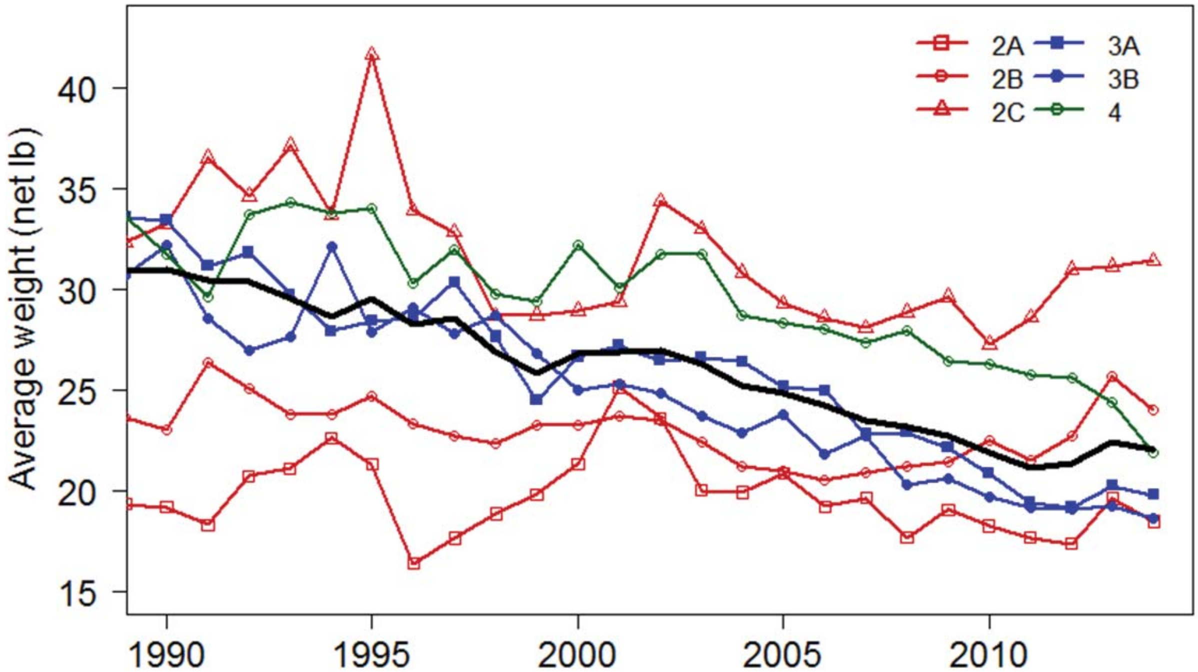

Figure 45. Recent average halibut weight by regulatory area in the directed fishery landings; thick black line indicates the coastwide average.

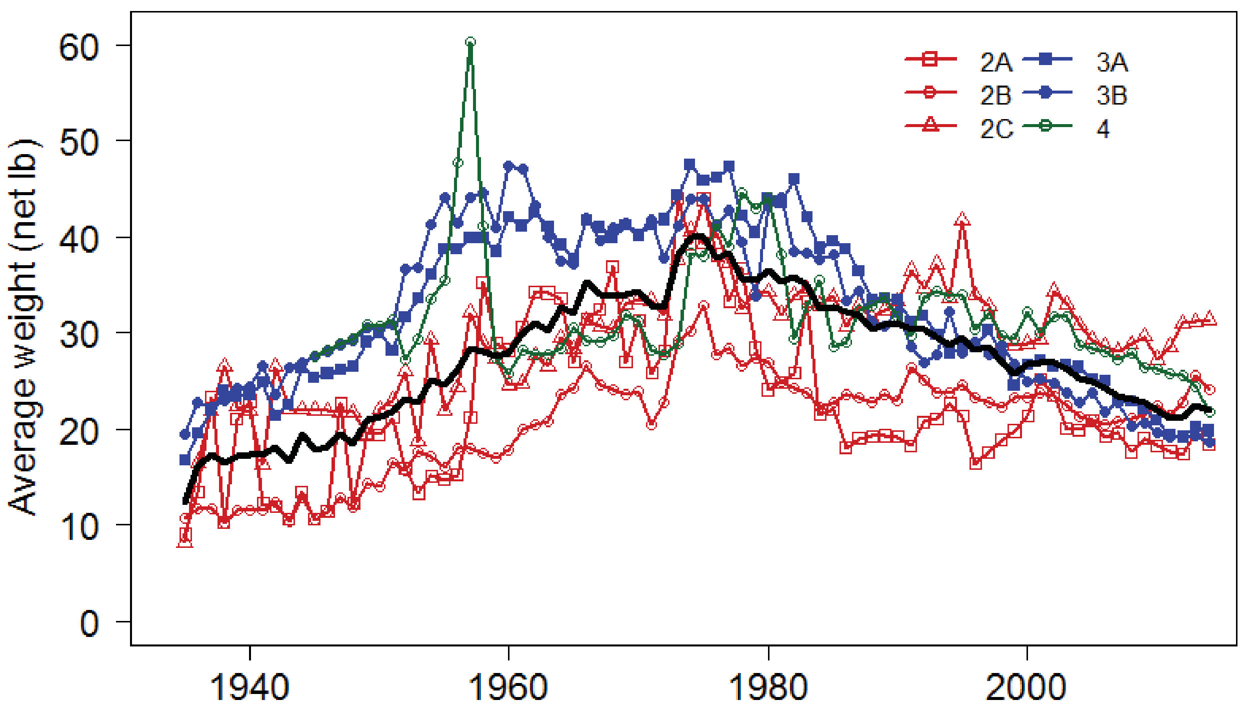

Figure 46. Historical trends in average individual halibut weight in the commercial fishery landings; thick black line indicates the coastwide average. The current 32-inch minimum size limit went into effect in 1974.

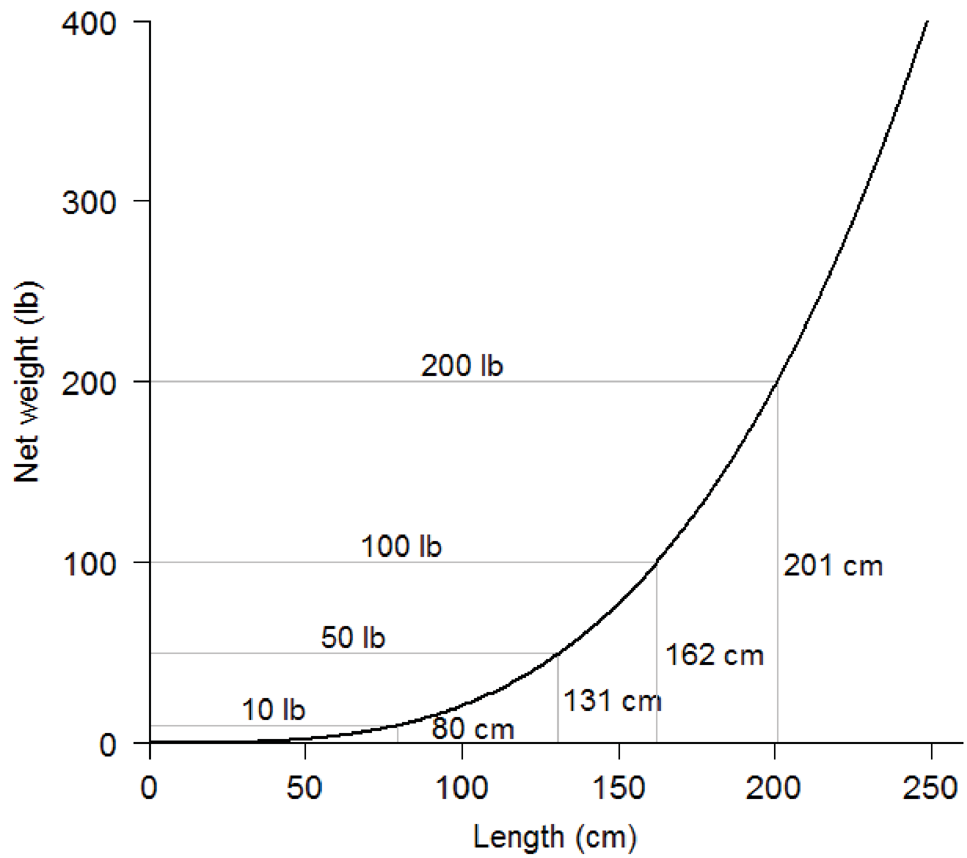

Figure 47. The conversion relationship for length in centimeters to net weight in pounds.

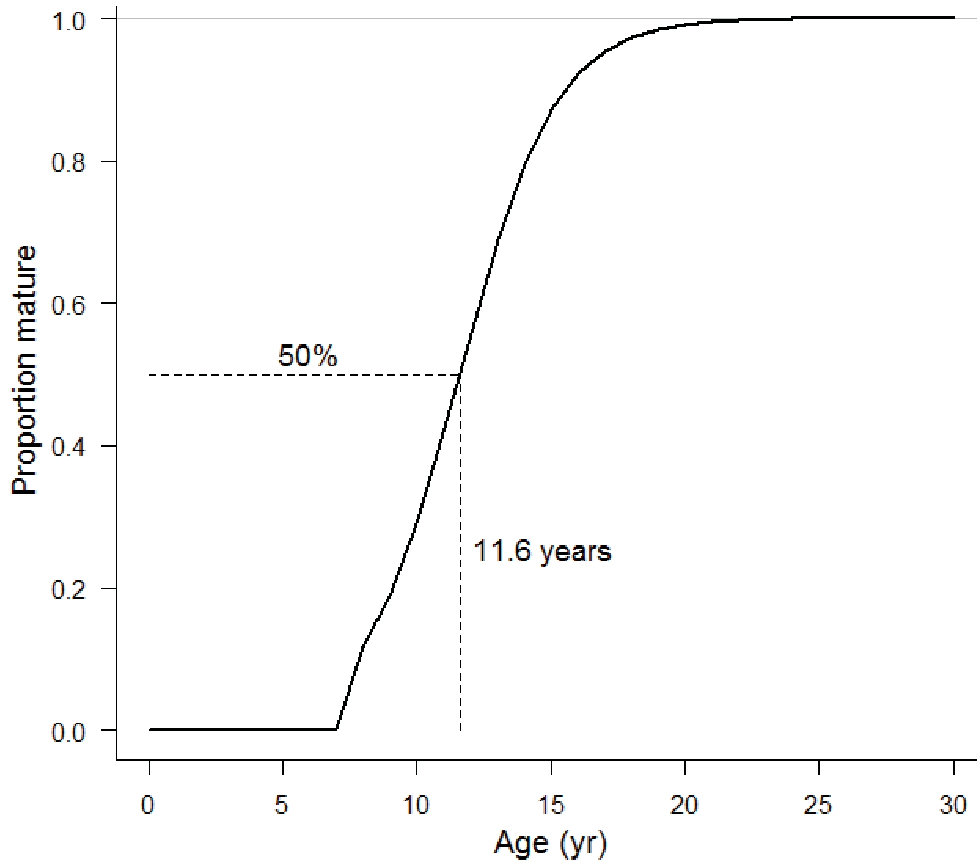

Figure 48. The maturity ogive used in recent halibut assessments. Note that this is a logistic curve, trimmed to be equal to zero below age-8.

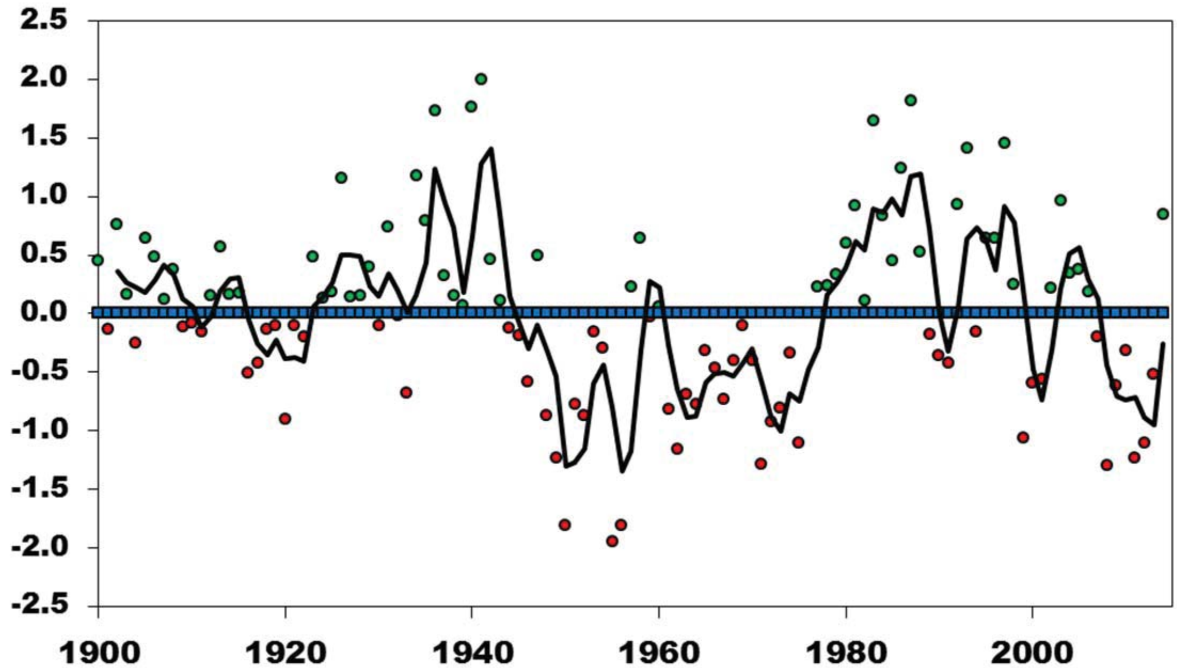

Figure 49. Time series of annual average PDO conditions (deviations from the long-term mean). Monthly means were obtained from (http://jisao.washington.edu/pdo/).

Assessment of the Pacific halibut stock at the end of 2013

Ian J. Stewart and Steven Martell

Abstract

This stock assessment reports the status of the Pacific halibut resource in the northeastern Pacific Ocean. A thorough exploration of all data sources was completed and reviewed by the Scientific Review Board (SRB) during 2013. This included the historical record to the early 1900's, as well as updated 2013 information from the survey and commercial fishery. Halibut removals from all sources have totaled 6.9 billion pounds, ranging annually from 34 to 100 million pounds over the last 100 years. After a peak in 2004, annual removals have decreased each year due to management actions in response to declining survey and commercial catch rates and stock assessment estimates. Total removals in 2013 were estimated to be 46 million pounds, down from 52 million pounds in 2012. The 2013 setline survey WPUE decreased by 12% relative to 2012. Observed age distributions continue to indicate a relatively stable stock, but with no evidence of strong recruitments in recent years. Individual size-at-age remains low relative to levels observed in the past several decades, although comparable to those estimated for the early portion of the 20th century. The 2013 SRB meeting produced a number of important recommendations that have been incorporated into the 2013 assessment. The extensive evaluation of data sources, allowed for the development of two additional stock assessment models in 2013, one comparable with the 2012 model, and the other including the full historical time-series. These models produced results that were very close in scale to those from the 2012 stock assessment for the most recent years, corroborating the final results from 2012. This effort provided estimates of historical trends which generated much needed context for both the recent declines in the stock, and current abundance levels. All three of these models were included in an "ensemble" analysis, an approach endorsed by the SRB, which integrated the uncertainty within each model and among models into the final decision table.

The 2013 stock assessment results indicate that the Pacific halibut stock has been declining continuously over much of the last decade, primarily as a result of recruitment strengths that are much smaller than those observed through the 1980s and 1990s, as well as decreasing size-at-age. In the last few years, female spawning biomass is estimated to have stabilized near 200 million pounds. The 2014 estimate of exploitable biomass consistent with the IPHC's current harvest policy is 170.29 million pounds. The long time-series model provided several alternative reference points for comparison: the stock is currently estimated to be at 38% of the long-term average equilibrium spawning biomass, and 34% of the current stock size projected in the absence of fishing. It is also estimated to be considerably larger (187%) than the spawning biomass estimate from the late 1970s. As in 2012, forecast projections were conducted for a range of alternative management actions; and probabilities of various risk metrics are reported in a decision-making table framework. The application of the current harvest policy results in the Blue Line of the decision table with a coastwide TCEY of 33.49 million pounds.

Introduction

This stock assessment reports the status of the Pacific halibut resource in the northeastern Pacific Ocean, including the territorial waters of the United States and Canada. As in recent assessments, the resource is modeled as a single stock extending from northern California to the Aleutian Islands and Bering Sea, including all inside waters of the Strait of Georgia and Puget Sound. Potential connectivity with the western Pacific Ocean resource is considered slight and is unaccounted for.

The halibut fishery has been closely managed for nearly 100 years, and much is known about the history of fishery removals, population trends, and biological characteristics. The 2013 assessment is the first in recent years to make use of the historical time-series. It also introduces a new approach to the annual stock assessment that does not rely on a single model, but instead focuses on understanding how estimates of stock dynamics and status compare among multiple approaches.

Data sources

A thorough exploration of data sources for the entire historical record, as well as updated 2013 information was completed and reviewed by the Scientific Review Board (SRB) during 2013 (Stewart 2014; Cox et al. 2014). Briefly, halibut removals (including all sources of mortality: target fishery landings and discards, bycatch in non-target fisheries, research, sport, and personal use) have totaled 6.9 billion pounds, ranging annually from 34 to 100 million pounds over the last 100 years (Table 3 and Fig. 33 in Stewart 2014); all weights in this document are reported as 'net' weights, head and guts removed; this is approximately 75% of the round weight). The average removal over this period has been 64 million pounds. Annual removals were above the 100-year average from 1985 through 2010. After a peak in 2004, annual removals have decreased each year due to management actions in response to declining survey and commercial catch rates and stock assessment estimates. Total removals in 2013 were estimated to be 46 million pounds, down from 52 million pounds in 2012. The 2013 setline survey WPUE decreased by 12% relative to 2012, back to the level observed in 2011. Commercial catch-rates also declined (by 8%) at the coastwide level. Survey and fishery age distributions continue to indicate a relatively stable stock, with no evidence of strong recruitments in recent years. Individual size-at-age remains low relative to levels observed in the past several decades, although comparable to those estimated for the early portion of the 20th century.

Assessment

The stock assessment for Pacific halibut has evolved through many different modeling approaches over the last 30 years (Clark 2003). These changes have reflected improvements in fisheries analysis methods, changes in model assumptions, and responses to recurrent retrospective biases (Stewart and Martell, *In press*). The 2012 stock assessment resolved the most recent retrospective bias (Stewart et al. 2013), and produced estimates of stock size that were considerably lower than previous analyses. This type of annual change, although necessary, is undesirable from a management perspective, and the 2013 stock assessment presents an approach that could make the process much more robust to model changes in the future.

Ensemble approach

The IPHC's Scientific Review Board (SRB) met to evaluate the stock assessment data and modeling conducted since the 2012 assessment on 1-3 October, 2013. This meeting produced a number of important recommendations that have been incorporated into the 2013 assessment and will be used to structure the work planned for 2014.

The re-analysis of all data sources, particularly the historical series, provided the basis for several new avenues of stock assessment modeling. The first was to recreate the existing stock assessment model 'from scratch', using independently coded software (Stock Synthesis; a widely used modeling platform developed at the National Marine Fisheries Service; Methot and Wetzel, 2013). This model was based on fully reprocessed and orthogonal data sources. Although similar in structure to the 2012 assessment model, alternative approaches to many of the technical aspects of the model (e.g., selectivity) that are more consistent with stock assessments for other North Pacific groundfish species were applied. This effort corroborated the results of the 2012 stock assessment in terms of recent stock size estimates; however it suggested somewhat larger biomass in the late 1990s and early 2000s.

A second extension included developing an assessment model that could accommodate all of the historical information from the commercial fishery and setline survey, accounting for changes in the fishery, introduction of size limits, spatial expansions, transition from "J" to circle hooks, and many other technical details of these series. A broader understanding of stock dynamics has been significantly hindered by the narrow view possible from the extremely short time-series in recent assessments. This analysis allowed for a re-evaluation of the link between environmental conditions in the North Pacific and halibut recruitment success (Clark and Hare 2006), and exploration of the fixed value for natural mortality used since 1998 (Clark and Parma 1999). With a comprehensive time-series of stock size estimates, this model also allowed for a comparison of alternate reference point calculations. Importantly, this model provided a second independent comparison with the results from 2012, using almost 100 years of additional data. The long time-series model, like the alternate short-time-series model, produced results that were very close in scale to those from the 2012 stock assessment for the most recent years. The long time-series model also provided much needed insight into the historical series as well as context for the recent declines in the stock and current abundance levels.

The focus in recent assessment cycles has been primarily centered on the technical aspects of a single stock assessment model, rather than on the more general goals of understanding the dynamics of the halibut resource, gaining perspective on where the stock is relative to past status, and evaluating how management actions influence the stock trends. Changes in annual assessment models, due to technical improvements (e.g., the retrospective bias), different interpretations or assumptions about biological data (e.g., natural mortality), and other modifications have led to variable yield estimates, unproductive debate about technical details during management deliberations, and a reduction in confidence about the annual assessment results. A solution to this dilemma, called "ensemble modeling", was endorsed by the SRB, and draws from the field of weather and hurricane forecasting (e.g., Hamill et al. 2012). This approach recognizes that there is no "perfect" assessment model, and that robust risk assessment can only be achieved via the inclusion of multiple models in the estimation of management quantities and the uncertainty about these quantities. This approach was actually used for the 2012 assessment, albeit in a crude manner, by including alternate models using differing values of natural mortality. However, this was identified at the time as only a preliminary means to address the uncertainty in management quantities pending further analysis.

For the 2013 stock assessment, an ensemble of all three alternative models now available for the halibut stock was used to produce the stock estimates and decision table results. As in 2012, arbitrary but reasonable weights were assigned to each alternative model: for 2013 each of the three models were assigned equal probabilities. The result are combined estimates of stock size and reference points that are substantially more robust to current or future technical changes to any one of the underlying models and a decision table provided in exactly the same manner as in 2012. This approach can be transparently improved in the future as additional models become available.

Comparison with the 2012 stock assessment

Comparison with previous stock assessments indicates that the 2013 results are very close to those from 2012, which lie inside the 50% interval of the ensemble (Fig. 1). When the 2012 stock assessment model was enhanced with the re-processed and newly available data, the point estimates for 2014 were also quite similar to the current results (Table 1). This 'bridge' comparison suggests that the 2013 assessment provides additional (improved estimates of uncertainty and historical perspective), but not conflicting information with the recent trends presented last year. The differences among the models contributing to the ensemble are most pronounced prior to the early 2000s (Fig. 2), and these differences are represented in the increased uncertainty in the 2013 results.

Biomass, recruitment and reference point results

Ensemble

The results of the 2013 stock assessment indicate that the Pacific halibut stock has been declining continuously over much of the last decade as a result of recruitment strengths that are much smaller than those observed through the 1980s and 1990s. Recruitments after 2007 do not yet have information available in the fishery or survey data, and therefore remain highly uncertain. Observed decreases in size-at-age have also been an important contributor to recent stock declines. In the last few years, the estimated female spawning biomass appears to have stabilized near 200 million pounds (Table 2 and Fig. 3). The 2014 estimate of exploitable biomass consistent with the IPHC's current harvest policy is 170.29 million pounds.

Long time-series model

The long time-series model provides, for the first time in recent years, historical estimates that are integrated with the current stock assessment results. This model was able to recreate the population age structure, and match the patterns in survey and commercial catch rates observed during the historical period (Fig. 4). Using the estimates produced from the long time-series model, halibut recruitment is estimated to be 37% higher, on average, during favorable Pacific Decadal Oscillation (PDO) regimes, a standard indicator of productivity in the North Pacific (Table 3). This is very consistent with the results of Clark and Hare (2002, 2006). Historically, these regimes have lasted approximately 30 years with positive conditions prior to 1947, poor conditions from 1947-1977, positive conditions from 1978-2006 and now poor conditions from 2007 to the present. Recruitment during the period from 1977 to 2006 was estimated to have been far higher than observed during any portion of the historical record (Fig. 5), leading to much larger stock sizes (Fig. 6), and therefore fishery yields available during this period.

There are number of useful reference levels against which to compare the current stock estimates. For the two shorter time-series models, the same calculation of the threshold 30% relative spawning biomass as has been used in recent assessments (spawning biomass per recruit, assuming average recruitment levels from a poor productivity regime) was used to populate the decision table. The longer time-series model also provides a comparable estimate to these values, suggesting the stock is at approximately 38% of the average condition expected in a poor recruitment period with relatively poor size-at-age (Fig. 7). This model also suggests the stock remains substantially higher than spawning biomass values estimated during the historical period (i.e., in the late 1920s and early 1930s just after the commission was formed, and again in the late 1970s at the end of a long period of poor recruitment; Table 3). Another comparison possible with the long time-series model is achieved by projecting the historical stock dynamics in the absence of fishery removals (assuming the same recruitment variability and the observed size-at-age), and comparing the relative trends. This analysis suggests that stock increases in the 1980s and 1990s as well as the recent stock declines would likely have occurred even in the absence of anthropogenic removals: changes in average recruitment and size at-age have been largely dictating stock trends (Fig. 8). The spawning biomass is currently estimated to be at 34% of the level projected from that analysis.

An additional analysis possible with the long time-series model is the evaluation of trends in surplus production, or the amount of biomass produced each year in excess of that needed to maintain the standing stock. Surplus production represents the change in stock size from one year to the next, plus the removals during that year. Specifically, if the stock stays at exactly the same level for two years, the removals were exactly equal to the surplus production. During the early 1900s, removals exceeded the annual surplus production and the halibut stock was 'fished-down' from previous very lightly exploited levels (Fig. 9). During much of the 20th century removals were very close to the annual surplus production, which increased as size-at-age increased. Estimated surplus production declined in the 1970s in response to poor recruitment over previous decades, then increased dramatically during the 1980s following substantially increased recruitment (and despite declining size-at-age). Although annual removals exceeded annual surplus production in the early 2000s, previous year's production was still available for harvest. In the last few years, surplus production is estimated to have declined back to levels near or slightly below the long-term average observed for the stock (Fig. 9).

Major sources of uncertainty

This stock assessment includes uncertainty associated with estimation of model parameters, treatment of the data (e.g., short and long time-series, overlap among sources) structuring of selectivity (length vs. age-based), natural mortality (fixed in the short time-series models vs. estimated in the long time-series model), and other differences among the three models included in the ensemble. The relative uncertainty in management quantities can be seen in the distribution for exploitable biomass, a quantity created for the current harvest policy that is used to generate the harvest rates and for apportionment. The distribution for the 2014 value is very broad, such that the small differences between the estimate from the 2013 assessment and the 2012 model (Table 1) are statistically insignificant (Fig. 10). Although this is a substantial improvement over the 2012 assessment, there are other important sources of uncertainty that are not included.

During 2012, natural mortality was identified as the most influential fixed parameter in the Pacific halibut stock assessment. Alternate values of natural mortality were therefore used to create three models from which the decision table was constructed. The fixed values used were 0.1, 0.15 (the value used in the primary assessment model) and 0.2. This approach was necessary, because the 2012 assessment model was unable to resolve a reasonable estimated value. This was not necessary for the 2013 stock assessment, as alternate values of natural mortality are included in the models contributing to the ensemble. Specifically, using the larger data sets, the long time-series model produces an estimate of female natural mortality of 0.2 (+/- 0.03; it contains sufficient data for estimation), and the value of 0.15 is retained in the 2012 and short time-series models.

An important unaddressed source of uncertainty is the spatial structure of the assessment model. The SRB endorsed the staff's plans to develop additional alternative models using both implicit and explicit spatial structure for future stock assessments, and these efforts may provide alternate models for inclusion into the ensemble approach.

The recent trends of reduced recruitment appear consistent with the transition from a positive to a negative PDO regime, however the correlation between halibut recruitment and environmental conditions remains poorly understood, and there is no guarantee that it will continue in the future. Therefore, recruitment variability remains a significant source of uncertainty in current stock estimates (due to the substantial lag between birth year and direct observation in the fishery and survey data) as well as short-term stock projections. Long-term projections would be entirely dominated by currently unobserved recruitment dynamics, as well as potential changes in size-at-age. The current low size-at-age is also a major driver of stock trends; unfortunately, the mechanisms involved are poorly understood. However, the historical record suggests that size-at-age changes relatively slowly; therefore, although highly uncertain, near-term future values are unlikely to be dramatically different than those currently observed.

Future expansion of the ensemble approach will continue to improve uncertainty estimates, and create assessment results that are robust to changes in individual models, data sets and other sources of historical changes in stock assessment results from year to year.

Sensitivity analyses

A wide range of sensitivity analyses were conducted during the 2013 process, but only a few of particular interest reported here. Because all three models tended to behave in a similar manner to changes in various assumptions, and because only the long-time-series model could be used to investigate certain processes, it is used for all analyses reported below.

The most influential source of uncertainty uncovered among sensitivity analyses conducted for 2013 was the sex-ratio of the commercial catch. There is no direct information available (due to dressing of fish at sea prior to observation by IPHC port samplers), and so the 2013 assessment relies on indirect estimates from the sex-ratios observed in the setline survey. These indirect estimates are either directly applied to estimate the size and age composition of the catch following the methods of Clark and Hare (2006) as has been done in recent assessments, or informing the model parameters defining the relative selectivity for the commercial fishery. Results were found to be very sensitive to this choice: a +/- 10% change in the relative selectivity for males vs. females (and therefore the sex-ratio of the catch) resulted in a 50 million pound range in the estimate of spawning biomass (Fig. 11). Efforts are underway to evaluate methods for direct sampling via collaboration with industry such that this assumption can be explored further in future assessments. Future assessments may be able to include alternative models to represent this uncertainty within the ensemble.

Three sensitivity analyses were conducted to investigate the relative importance of uncertainty in several sources of halibut removals. These analyses were based on questions posed during the 2012 assessment and management process, or due to new information regarding methods for generating removals estimates. The first of these sensitivity analyses tested the influence of alternate levels of bycatch in non-target fisheries. Bycatch estimates are, for most regulatory areas, based on less than complete monitoring of all fishing activities, and therefore there is uncertainty associated with estimation, as well as the applicability of these estimates to fishing activity that went unmonitored (Williams, 2014). This sensitivity analysis explored the influence on the coastwide stock assessment of significantly higher (doubled) and lower (halved) levels of bycatch. There was little difference in the relative trends estimated for both alternatives; however doubling the bycatch did increase the estimated spawning stock estimate for 2014 by just over eight million pounds (Fig. 12). Additional sensitivity analyses to changes in bycatch that are non-constant over time might have different effects. The historical record of industrial fishing in the northeast Pacific Ocean suggests several temporally-restricted scenarios of bycatch mortality that may be plausible; these and others will be explored in the future. Area-specific changes and potential effects on the application of the harvest policy within specific areas could also be the subject of future analyses.

Estimates of recreational removals have historically not included any estimates of mortality associated with captured and subsequently discarded halibut (Williams 2014). During 2013, estimates of recreational discards were produced for the fishery in Areas 2C and 3A (S. Meyer, ADFG; letter to the IPHC, 13 November, 2013). That analysis indicated that additional mortality on the order of 2-3% of the retained catch might be reasonable given the regulations currently in place. With no direct estimates for other regulatory areas, and little comparability among regulations currently and historically in place, it is difficult to hypothesize what magnitude of total coastwide recreational wastage might be plausible. Therefore, a simple sensitivity of adding 5% to all recreational removals in all years was conducted. This revealed that for the coastwide stock assessment there was no appreciable change in the estimated spawning biomass time-series (Fig. 13). Further evaluation into proxy estimates for each regulatory area, as well as sensitivity of harvest policy application to recreational wastage will be explored in future analyses.

The final sensitivity analysis reported here investigates the magnitude of directed commercial fishery wastage. As outlined in Gilroy and Stewart (2014), methods for estimating commercial wastage were improved for 2013; however, estimates remain indirect except for Area 2B which applies logbook-reported U32 discards beginning in 2006. Because of the indirect nature of the wastage estimates, the true level of uncertainty remains unknown. For this reason, a model run using doubled values of the estimated wastage was conducted. The results of this analysis indicated little difference in either the relative trend or scale of the coastwide assessment estimates (Fig. 14). As for the other sensitivity analyses, area-specific effects could be more pronounced given the harvest policy calculations and non-uniform estimates of wastage.

Retrospective analyses

A retrospective analysis using the long time-series model revealed little pattern in recent spawning biomass estimates as data are sequentially removed from the model (Fig. 15). Importantly, even the estimates deviating by the greatest degree from the current time-series were still contained in the estimated confidence intervals. This was not the case for assessment results conducted from 2006 through 2011 which included a very strong retrospective bias (Hare, 2012; Fig. 1).

Forecasts and decision table

As in 2012, stock projections were conducted using the coastwide stock assessment (all three models in the ensemble), summaries of the 2013 fishery, and other sources of mortality, as well as the results of apportionment calculations and harvest policy application. The steps included: 1) apportioning the coastwide estimate of exploitable biomass according to the survey catch rates in each regulatory area, adjusted for hook competition and survey timing (Webster and Stewart 2014), 2) applying the area-specific harvest rates to estimate the total CEY, and all other removals associated with a given level of harvest, and 3) calculating the total mortality and projecting the stock trends one and three years into the future.

The current harvest policy for Pacific halibut utilizes a ramp from target harvest rates down to no fishing between 30% and 20% relative spawning biomass (Fig. 16). Target harvest rates are 21.5% in Areas 2A, 2B, 2C and 3A, and 16.125% to Areas 3B, 4A, 4B, and 4CDE. Because the harvest policy is defined at the area-specific level, the results of apportionment calculations (Webster and Stewart 2014) are needed evaluate the harvest intensity, even though the assessment is conducted at a coastwide scale. Specifically, in order to compare the coastwide harvest rate estimated in the stock assessment to a target level, exploitable biomass must be apportioned to area, and then area-specific catch limits aggregated back to the coastwide level (Fig. 17). Using this method, harvest rates are estimated to have been above target levels for the last decade, although mortality reductions in the most recent three years (2010-2013) have brought the realized rate much closer to the target (Fig. 18). This calculation is based on the 2013 stock assessment results, and therefore does not correspond to the estimates and targets available as historical management decisions were being made.

The decision table (Table 4) provides a comparison of the relative risk, using a number of different stock and fishery metrics (columns) for a range of harvest levels in 2014 (rows). The decision table for 2013 is very similar in format to that reported in 2012, with a few changes to improve the clarity of the results. These changes include reporting probabilities as “times out of 100”, integrating one- and three-year projection for all quantities into a single table, organizing all row descriptions clearly outside the table contents, and more clearly delineating the metrics associated with the current harvest policy from those relating only to stock trend.

The block of columns entitled Stock Trend (a-d) provides an evaluation of the risks of various harvest levels to the short term trend in spawning biomass, without reference to a particular harvest policy. The remaining columns portray these risks relative to the spawning biomass reference points (e-h) and fishery performance (i-m) consistent with the current harvest policy. The 2014 alternative harvest levels (rows) provided include: no mortality (useful to evaluate the stock trend due solely to population processes), no directed mortality (but accounting for bycatch and non-scaling sport and personal use removals), the Blue Line (consistent with the current harvest policy and, historically, IPHC staff advice), the *status quo* removals (O26 mortality at the same level estimated in 2013), as well as a number of arbitrary values intended to foster the evaluation of the relative change in risk probability across a range of total mortality levels. As in 2012, additional alternatives will be produced during management deliberations such that all potential alternatives for 2014 can be evaluated in terms total mortality and associated risk.

The stock is projected to increase slightly in the absence of any mortality during 2014, and all levels of harvest above 30 million pounds of total mortality resulted in declines in the current stock size by 2015 (Table 4; Fig. 19), although there is considerable uncertainty associated with these projections. There is estimated to be only a 1/100 chance of greater than a 5% decline in spawning biomass from 2014 to 2015 for the Blue Line removals. The *status quo* removals correspond to an 8/100 chance of at least a 5% decline in spawning biomass, and 60 million pounds of total mortality a 38/100 chance. There is a higher probability of stock decline over the three year projections due to the delayed effects of recent recruitment, trends in size-at-age and compounding removals. As the stock stabilizes to biomass levels consistent with more recent recruitment levels (following the decline from much higher levels), it is reasonable to expect a greater response in stock trend to annual management decisions.

The metrics directly based on the current harvest policy (stock status, fishery trend, and fishery status), show a relatively small chance (<26/100) that the stock will decline below the 30% or 20% reference points in both the one- and three-year projections and under all alternatives presented. For removals in excess of the Blue Line, there is a greater than 50/100 probability that the fishery CEY would be smaller in 2015 and 2017 than if the current harvest policy were applied. The Blue Line removals correspond exactly to the application of the current harvest policy, and therefore the coastwide harvest rate target (Fig. 18). Because of the small decrease in the estimate of exploitable biomass relative to the value estimated in 2012, repeating the *status quo* removals would result in a slightly higher harvest rate than realized in 2013. A total mortality of 40 million pounds corresponds to an intermediate harvest rate, still above the Blue Line, but representing a reduction from 2013 (Fig. 18).

Future research

Based on data and model exploration completed during 2013, and recommendations from the SRB, future research will focus on the following topics:

1) Development of methods for sampling the sex-ratio of the commercial catch. The current assessment assumes that the setline survey sex-ratio is indicative of the commercial catch, but there are currently no direct observations to test this assumption. The results of the stock assessment are sensitive to the sex-ratio, and therefore this source of uncertainty is a high priority for future data collection.

2) Continued expansion of the ensemble of models used in the stock assessment. Specifically, implicit and explicit spatial models will be developed that will allow for incorporation of the uncertainty due to spatial processes such as migration and recruitment distribution among regulatory areas.

3) Bayesian methods for fully integrating parameter uncertainty may provide improved uncertainty estimates within models contributing to the ensemble.

4) Further investigation of the factors contributing to recruitment strength and observed size-at-age in order to better project trends in these quantities.

5) Exploration of methods for estimating wastage and bycatch in the assessment model as a function of effort, in order to better capture these sources uncertainty.

6) Analysis of projection methods for weight-at-age to determine if alternatives to recent trend might provide better estimates of likely future values and the uncertainty associated with these values.

7) Integration of the assessment results in the decision table with ongoing developments in the harvest policy arising through the MSE process.

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Table 1. Comparison of 2014 biomass point estimates (millions of net pounds) using the 2012 assessment model and from the 2013 ensemble analysis.

Quantity	2012 Assessment model	2013 Ensemble
2014 Exploitable biomass	176	170
2014 Spawning biomass	198	197

Table 2. Median population estimates (million lb) from the 2013 ensemble.

Year	Spawning biomass	Exploitable biomass
1997	570.3	796.8
1998	573.2	749.5
1999	563.2	739.7
2000	531.2	683.1
2001	489.0	597.8
2002	441.6	527.6
2003	390.5	458.6
2004	347.5	403.1
2005	307.7	353.7
2006	274.3	308.6
2007	248.9	268.4
2008	229.1	235.2
2009	206.3	202.7
2010	197.6	185.3
2011	193.5	174.6
2012	193.6	168.9
2013	194.9	168.4
2014	196.8	170.3

Table 3. Time-series of population estimates (million lb, recruits in millions) from the long time-series model.

Year	Age-8+ biomass	Spawning biomass	Age-0 recruits	Year	Age-8+ biomass	Spawning biomass	Age-0 recruits
1888	1,160.8	477.7	70.5	1933	324.9	52.8	34.2
1889	1,159.9	477.1	67.9	1934	339.6	56.6	31.1
1890	1,158.6	476.7	70.3	1935	338.7	60.9	54.9
1891	1,156.7	476.1	72.8	1936	351.6	66.4	48.8
1892	1,154.3	475.1	71.1	1937	382.6	72.9	40.1
1893	1,150.3	473.7	69.0	1938	395.7	78.2	54.4
1894	1,145.7	471.8	66.0	1939	405.0	83.3	48.6
1895	1,143.5	469.8	65.8	1940	400.4	86.2	43.8
1896	1,164.6	469.0	67.6	1941	400.1	88.1	55.5
1897	1,181.6	468.5	61.9	1942	398.3	89.7	44.4
1898	1,201.2	469.0	57.5	1943	431.2	92.3	49.2
1899	1,224.7	471.6	51.8	1944	453.5	94.9	49.2
1900	1,245.1	476.0	46.4	1945	465.0	98.2	25.8
1901	1,258.0	480.1	39.5	1946	494.1	103.1	31.3
1902	1,261.6	482.5	33.6	1947	510.6	106.7	22.3
1903	1,260.8	483.4	31.0	1948	518.5	111.2	24.8
1904	1,259.5	482.8	29.6	1949	547.9	117.6	26.4
1905	1,246.7	479.3	29.4	1950	558.2	122.2	29.8
1906	1,232.8	477.8	29.8	1951	568.0	125.4	48.2
1907	1,198.7	467.5	31.0	1952	588.0	131.2	24.6
1908	1,145.4	448.7	31.5	1953	562.1	133.1	27.9
1909	1,081.1	424.8	32.9	1954	563.4	139.3	31.2
1910	1,010.4	398.6	31.5	1955	546.3	140.8	33.1
1911	938.5	370.5	31.3	1956	551.5	146.1	22.0
1912	862.1	337.2	31.4	1957	553.3	145.7	35.7
1913	786.8	301.3	31.8	1958	564.9	145.3	27.0
1914	711.9	262.7	32.2	1959	622.8	147.5	18.1
1915	644.4	225.8	31.8	1960	604.0	141.5	21.0
1916	583.1	191.4	32.4	1961	606.0	140.6	34.8
1917	546.2	169.4	31.5	1962	606.0	137.9	17.6
1918	513.2	151.1	29.1	1963	597.5	132.0	22.8
1919	493.2	140.5	27.1	1964	588.3	131.0	21.6
1920	473.6	130.9	26.4	1965	587.5	127.1	20.7
1921	451.4	120.5	27.5	1966	562.8	122.4	21.6
1922	427.1	109.4	31.4	1967	518.5	116.6	25.7
1923	413.3	103.4	38.1	1968	493.9	114.0	29.8
1924	394.7	95.2	45.7	1969	503.8	113.6	35.0
1925	375.2	87.1	47.1	1970	470.7	108.2	43.9
1926	356.0	80.4	42.3	1971	449.8	102.8	39.4
1927	333.8	73.3	30.5	1972	434.3	98.9	56.1
1928	310.0	65.5	37.6	1973	425.1	97.3	66.9
1929	290.3	58.5	48.7	1974	413.4	95.4	45.7
1930	276.3	51.5	38.0	1975	429.7	99.6	61.0
1931	280.3	48.7	37.5	1976	451.9	102.4	64.5
1932	301.3	49.7	30.1	1977	487.7	108.0	104.8

Table 3. Continued.

Year	Age-8+ biomass	Spawning biomass	Age-0 recruits
1978	547.5	118.1	58.8
1979	595.1	131.0	108.3
1980	676.8	148.4	136.9
1981	785.7	172.8	67.5
1982	853.6	200.7	68.2
1983	941.8	231.1	143.8
1984	995.9	252.7	106.7
1985	1,142.8	280.3	68.7
1986	1,180.4	302.6	59.6
1987	1,279.7	316.5	342.8
1988	1,465.0	344.8	52.1
1989	1,455.6	362.3	93.2
1990	1,431.2	379.4	66.5
1991	1,543.4	400.3	52.5
1992	1,561.4	416.7	54.0
1993	1,482.5	420.1	32.1
1994	1,403.1	420.8	88.9
1995	1,966.8	491.9	88.7
1996	1,947.3	529.9	48.9
1997	1,973.5	570.4	44.6
1998	1,886.4	573.4	73.6
1999	1,749.2	565.2	101.9
2000	1,591.9	534.1	72.1
2001	1,410.8	492.4	54.5
2002	1,334.8	444.4	70.8
2003	1,267.6	392.7	42.0
2004	1,154.1	349.5	69.4
2005	1,038.9	309.5	63.6
2006	979.0	276.2	33.9
2007	973.5	250.6	30.6
2008	927.7	231.1	36.7
2009	845.6	207.6	47.6
2010	809.6	197.3	48.1
2011	744.2	189.8	47.9
2012	725.1	185.2	47.7
2013	702.2	181.8	47.5
2014	667.5	183.1	47.6

Table 4. Decision table of yield alternatives (rows) and risk metrics (columns). Values in the table represent the probability, in "times out of 100" of a particular risk.

				Stock Trend				Stock Status				Fishery Trend				Fishery Status
				Spawning biomass				Spawning biomass				Fishery CEY from the harvest policy				Harvest rate
				in 2015		in 2017		in 2015		in 2017		in 2015		in 2017		in 2014
2014 Alternative	Total removals (M lb)	Fishery CEY (M lb)	Harvest rate	is less than 2014	is 5% less than 2014	is less than 2014	is 5% less than 2014	is less than 30%	is less than 20%	is less than 30%	is less than 20%	is less than 2014	is 10% less than 2014	is less than 2014	is 10% less than 2014	is above target
No removals	0.0	0.0	0.0%	5/100	<1/100	23/100	4/100	3/100	<1/100	1/100	<1/100	0/100	0/100	0/100	0/100	0/100
FCEY = 0	11.4	0.0	5.0%	31/100	<1/100	32/100	18/100	3/100	<1/100	2/100	<1/100	0/100	0/100	0/100	0/100	<1/100
	20.0	8.5	10.1%	33/100	<1/100	37/100	24/100	4/100	<1/100	3/100	<1/100	<1/100	<1/100	<1/100	<1/100	<1/100
	30.0	18.2	15.9%	39/100	<1/100	66/100	41/100	4/100	<1/100	5/100	<1/100	5/100	2/100	8/100	4/100	7/100
Blue Line	36.4	24.5	19.7%	56/100	1/100	82/100	63/100	5/100	<1/100	6/100	1/100	43/100	20/100	74/100	47/100	50/100
	40.0	28.0	21.8%	68/100	1/100	87/100	73/100	5/100	<1/100	8/100	1/100	85/100	52/100	96/100	84/100	92/100
	45.0	32.8	24.7%	82/100	4/100	93/100	83/100	6/100	1/100	10/100	1/100	>99/100	95/100	>99/100	99/100	>99/100
status quo	48.5	36.1	26.7%	88/100	8/100	95/100	87/100	6/100	1/100	13/100	1/100	>99/100	>99/100	>99/100	>99/100	>99/100
	55.0	42.6	30.5%	95/100	23/100	98/100	94/100	6/100	1/100	19/100	2/100	>99/100	>99/100	>99/100	>99/100	>99/100
	60.0	47.5	33.5%	98/100	38/100	99/100	97/100	7/100	1/100	26/100	2/100	>99/100	>99/100	>99/100	>99/100	>99/100
				a	b	c	d	e	f	g	h	i	j	k	l	m

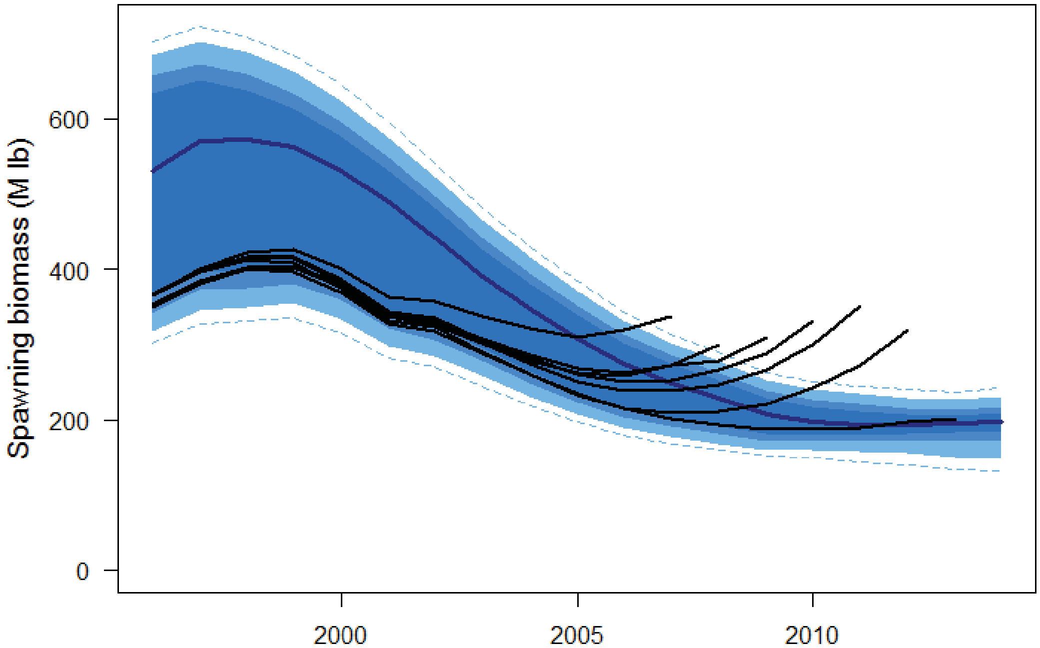

Figure 1. Retrospective analysis among recent stock assessments. The black lines denote previous assessments ending in 2006, 2007, 2008, 2009, 2010, 2011 and 2012. The dark blue line indicates the median (or "50:50 line"; with equal probability of the estimate falling above or below that level) from the 2013 assessment; colored bands moving away from the median indicate the intervals containing 50/100, 75/100, and 95/100 estimates; dashed lines indicating the 99/100 interval.

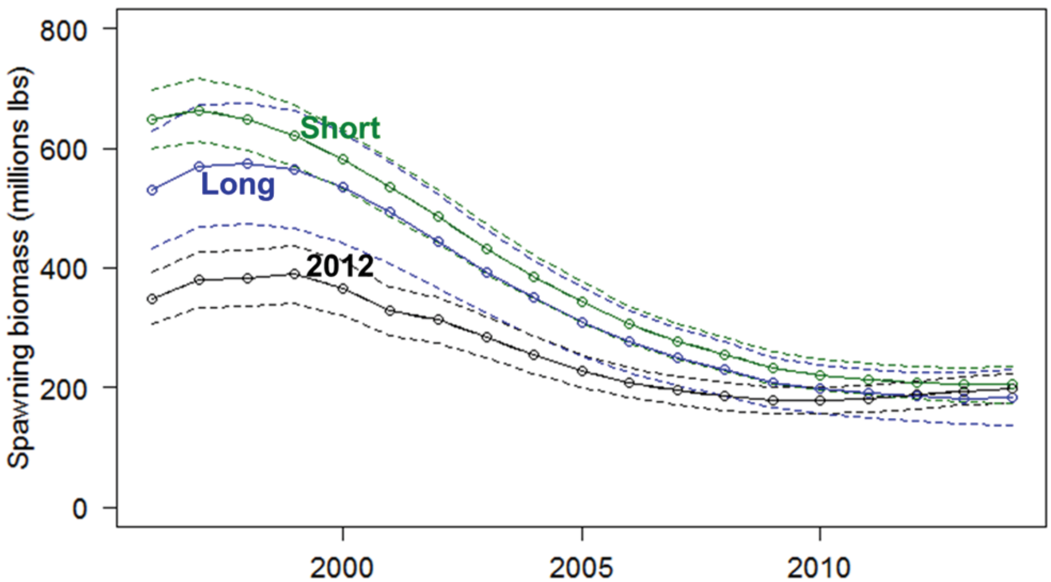

Figure 2. Comparison of models included in the 2013 stock assessment.

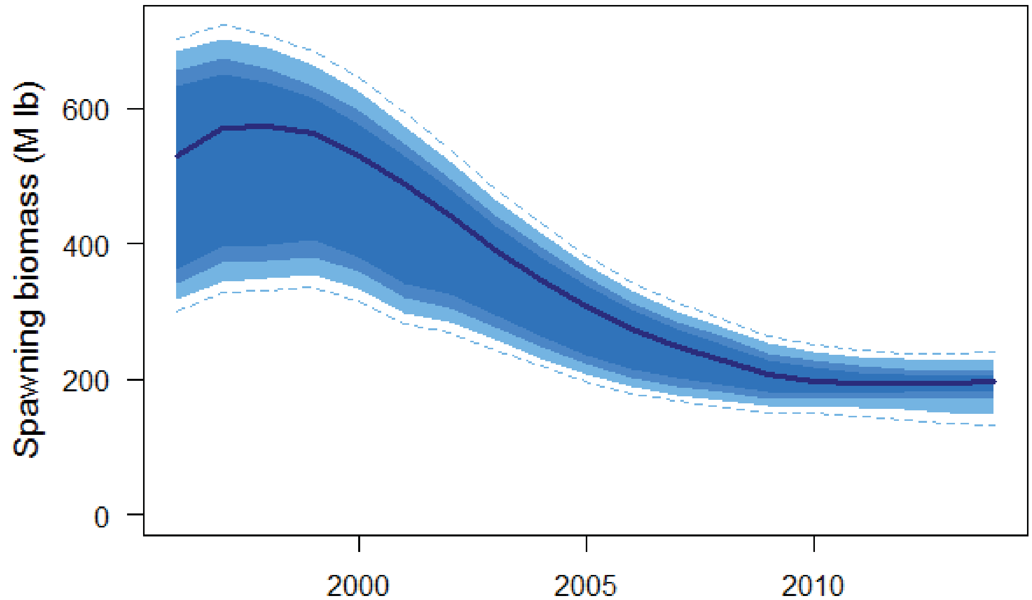

Figure 3. Trend in spawning biomass estimated in the 2013 stock assessment. The dark line indicates the median (or "50:50 line") with an equal probability of the estimate falling above or below that level; colored bands moving away from the median indicate the intervals containing 50/100, 75/100, and 95/100 estimates; dashed lines indicating the 99/100 interval.

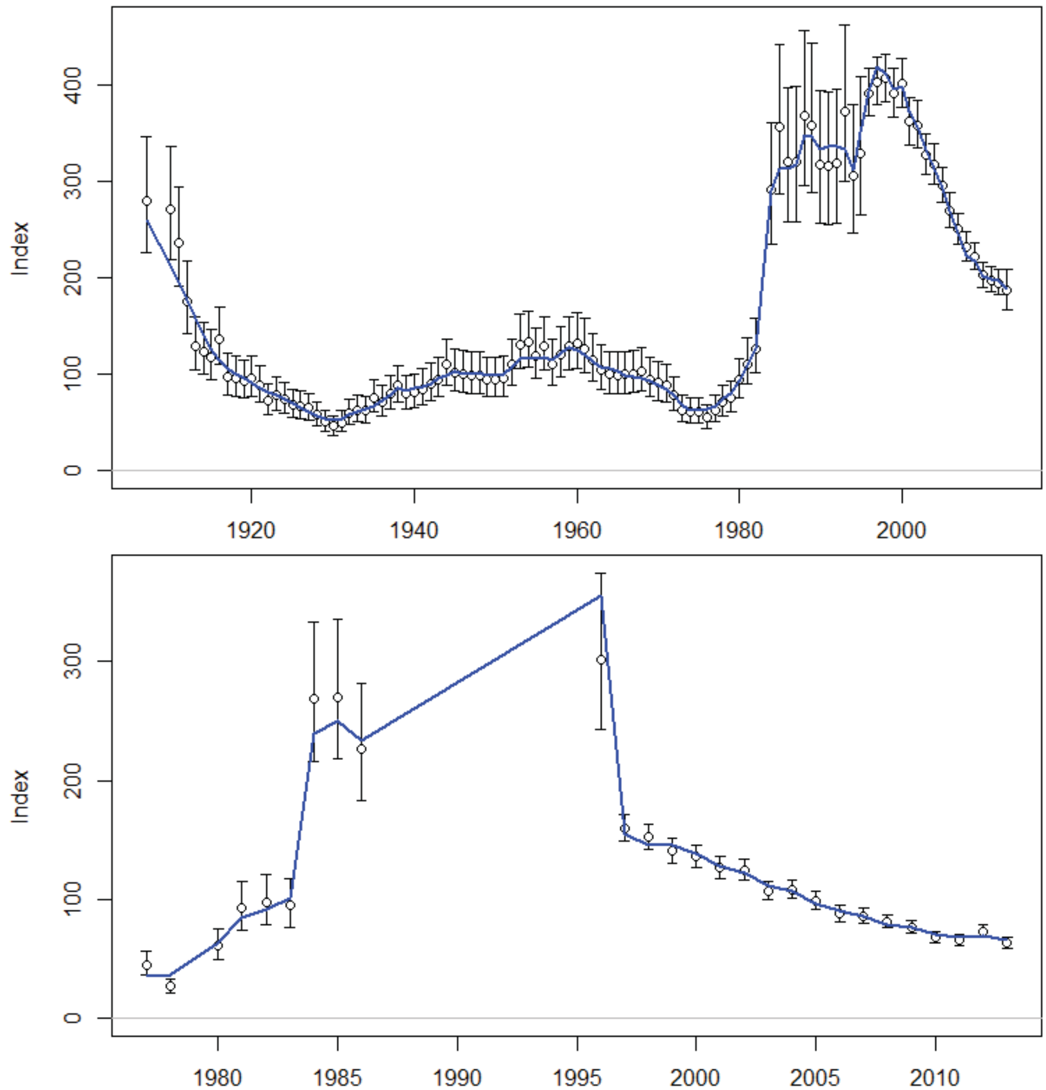

Figure 4. Observed (points with 95% confidence intervals) and predicted (lines) fishery (upper panel) and survey (lower panel) catch-rates. Note that the abrupt change in scale from 1983-1984 is due to the introduction of circle hooks to the fishery and survey.

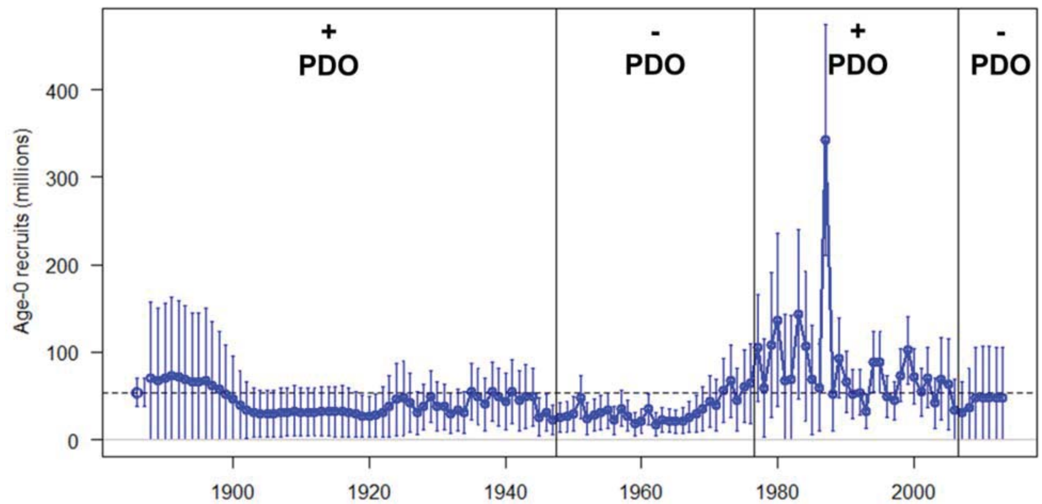

Figure 5. Trend recruitment strengths (by birth year) estimated by the long time-series model. Dashed horizontal line indicates the average level in the absence of fishing and under poor recruitment conditions. Vertical lines indicate the Pacific Decadal Oscillation (PDO) regimes estimated from environmental data. Note that estimates after 2008 are highly uncertain, as they are not yet informed by any direct observations.

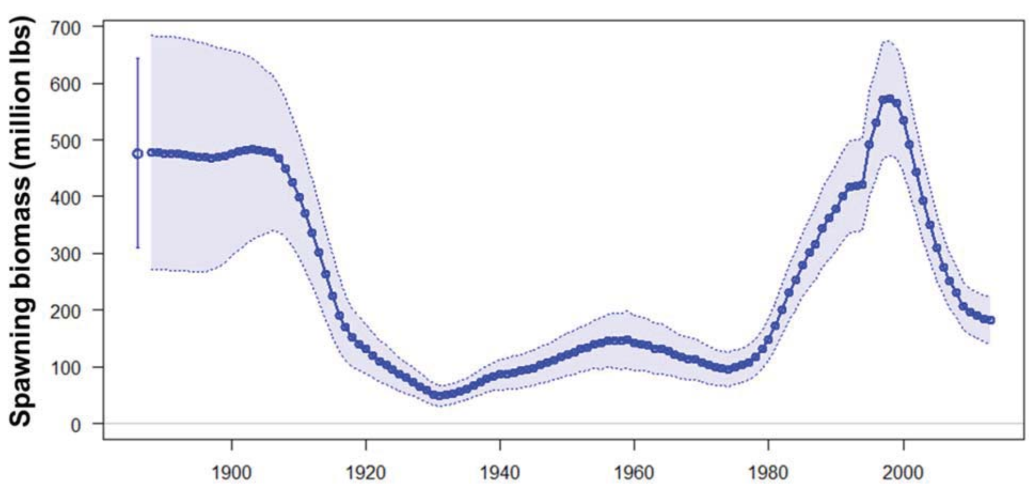

Figure 6. Spawning biomass estimates from the long time-series model.

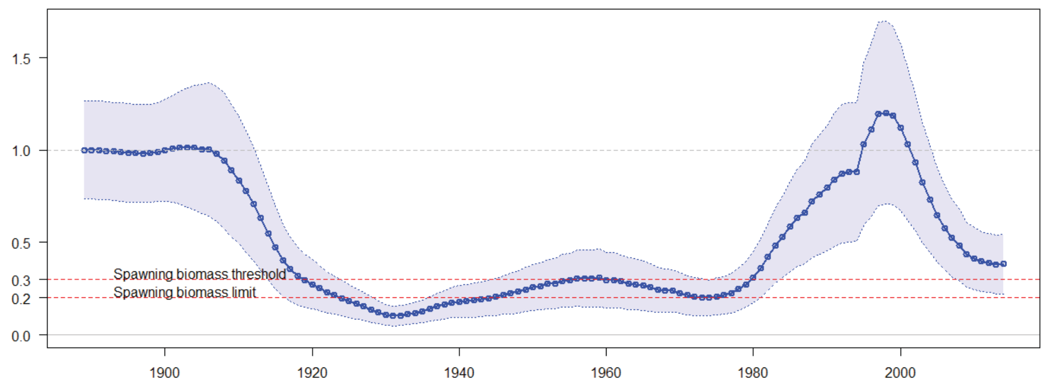

Figure 7. Time-series of relative spawning biomass estimates from the long time-series model.

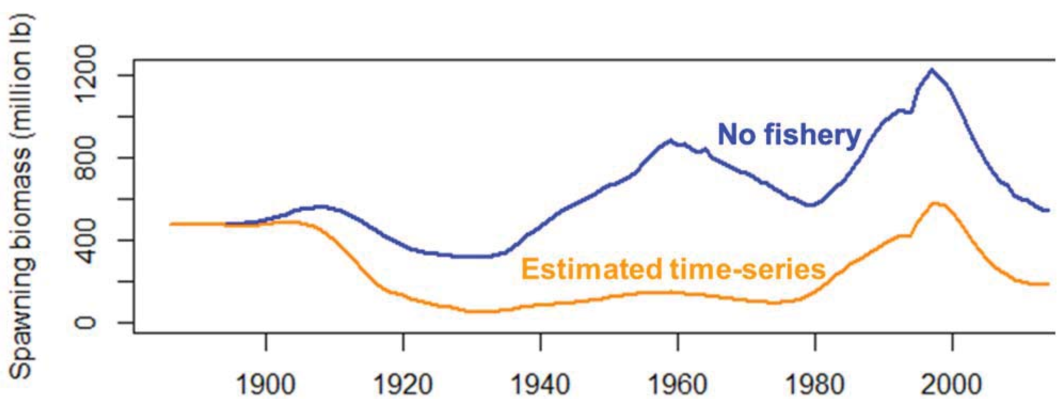

Figure 8. Estimated spawning biomass time-series from the long time-series model (lower, orange line) and recreated time-series in the absence of fishery removals (upper, blue line).

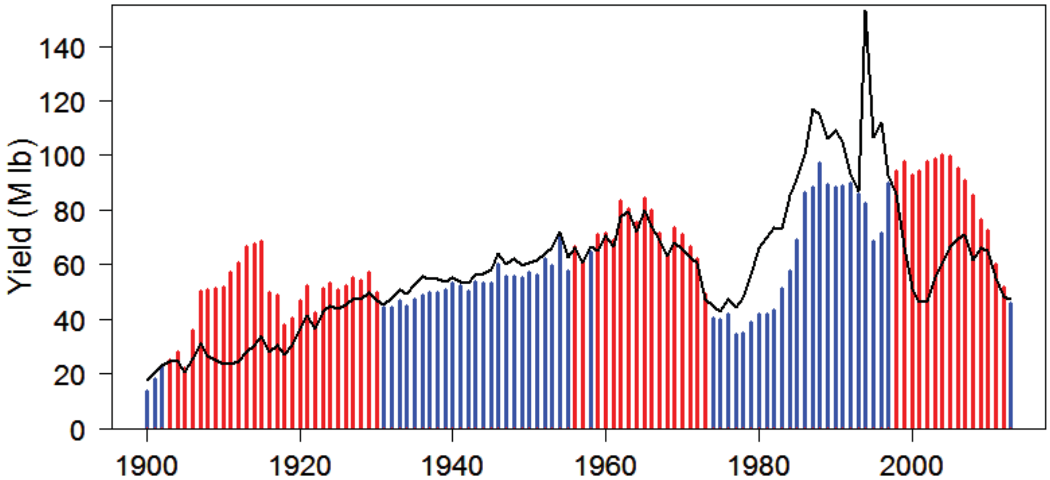

Figure 9. Time-series of removals (vertical bars) corresponding to levels above (red) and below (blue) the annual surplus production calculated based on the change in spawning biomass.

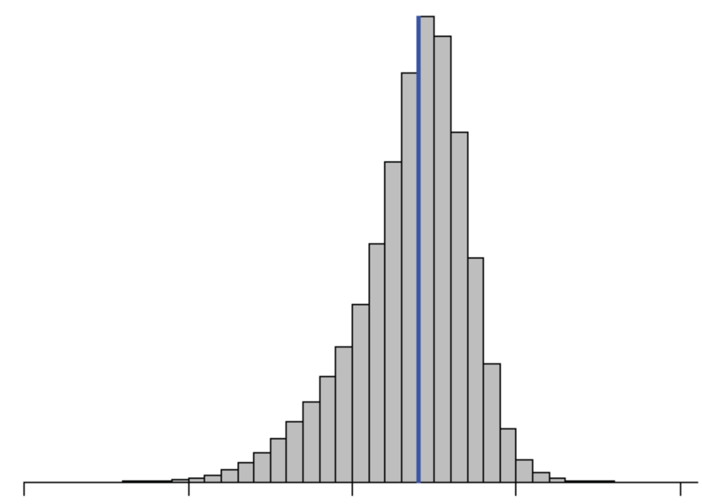

Figure 10. Distribution of 2014 exploitable biomass estimates including only model and estimation uncertainty, not uncertainty in the selectivity ogive generating the calculation.

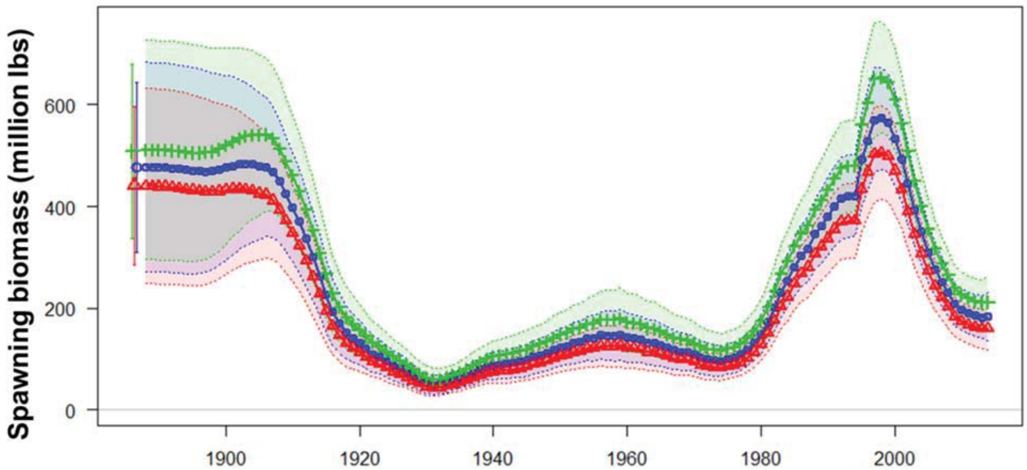

Figure 11. Sensitivity analysis to the assumption regarding relative selectivity of male and female halibut.

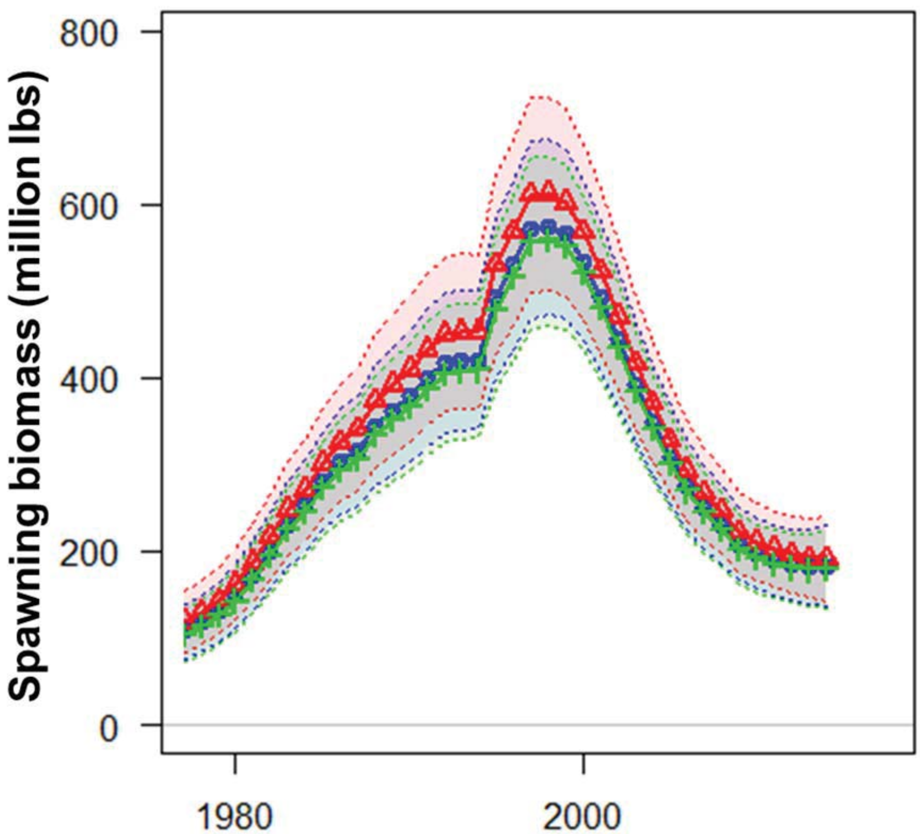

Figure 12. Sensitivity analysis to higher (doubled) and lower (halved) levels of bycatch from non-target fisheries.

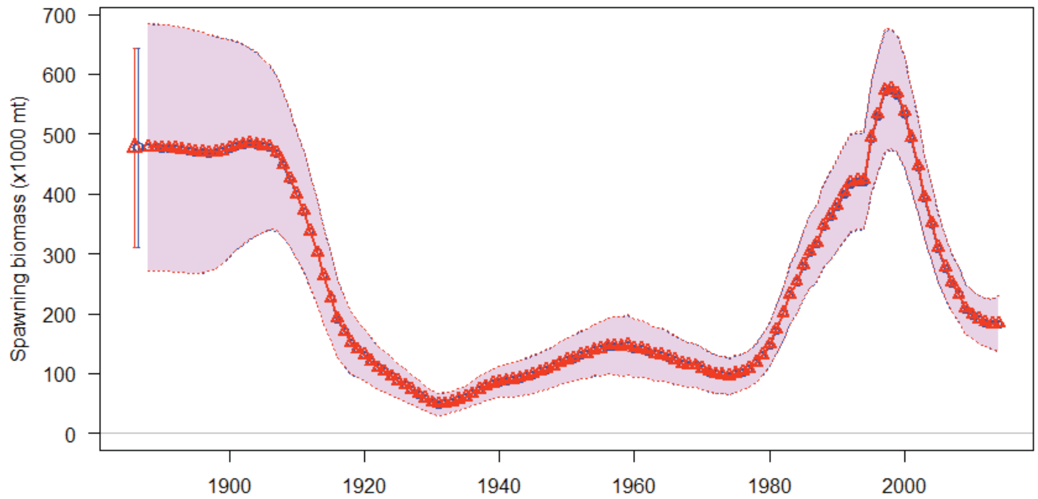

Figure 13. Sensitivity analysis to an increase in recreational mortality of 5%.

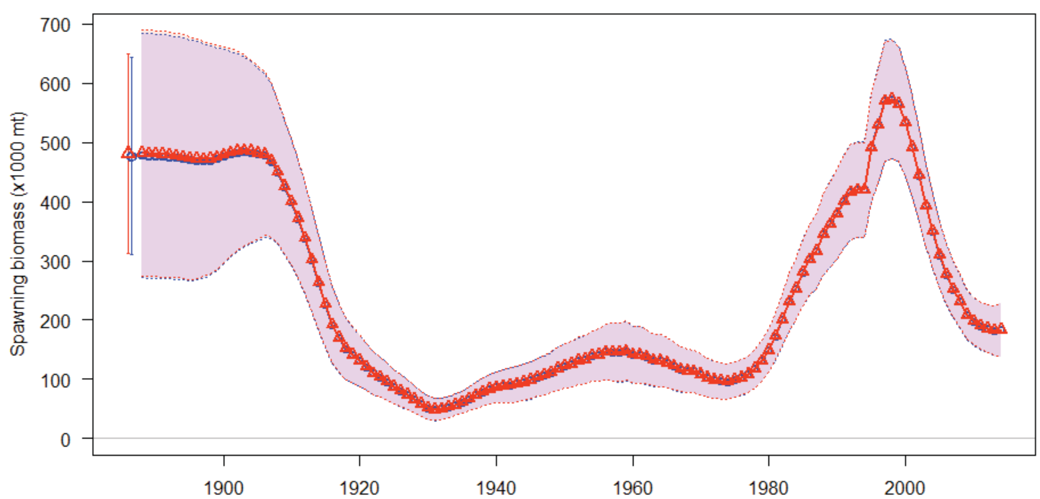

Figure 14. Sensitivity analysis to a doubling of the wastage estimated for the directed commercial fishery.

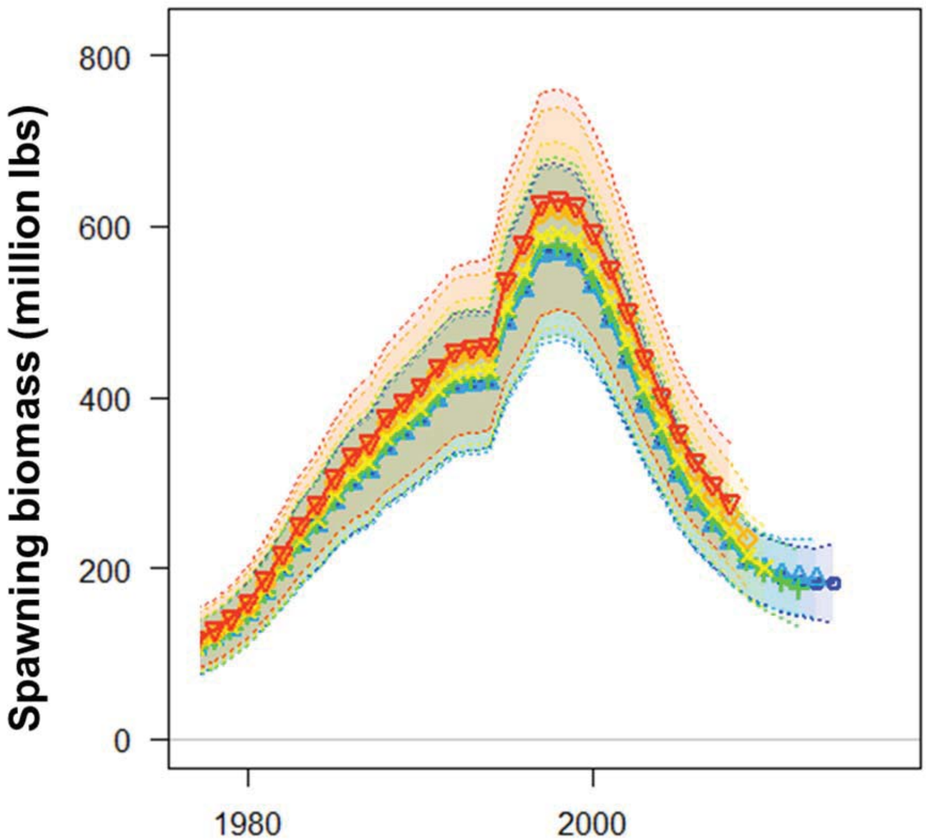

Figure 15. Results of the retrospective analysis on spawning biomass estimates using the long time-series model. Dashed lines and shaded regions indicate within-model 95% uncertainty intervals.

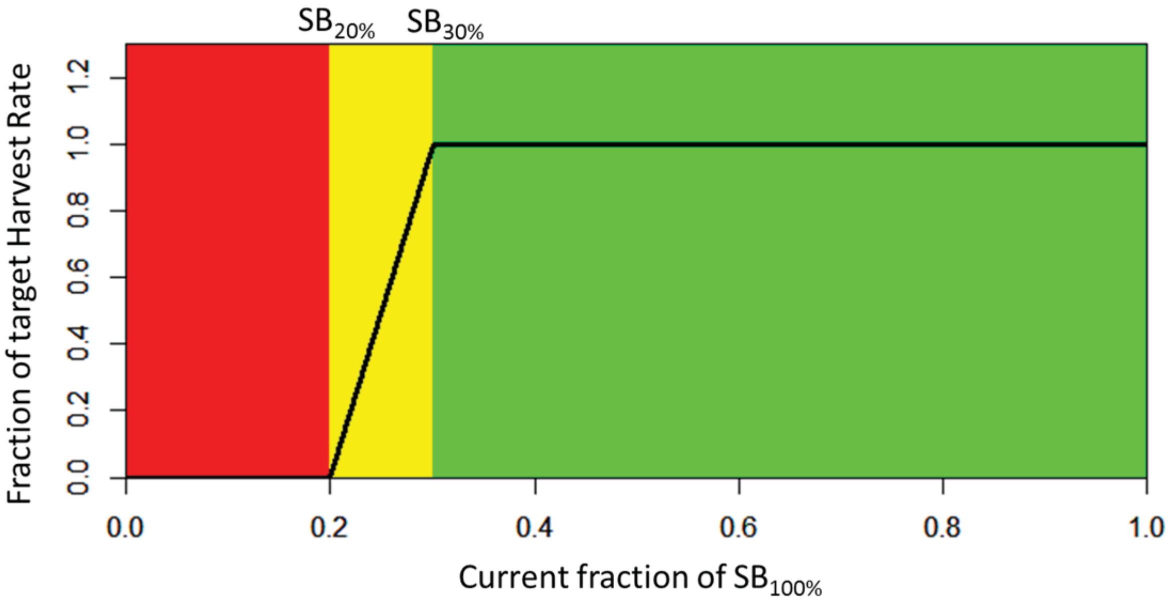

Figure 16. Illustration of the current IPHC harvest control rule for determining the relative target harvest rate as a function of relative spawning biomass, consistent with the IPHC's overall harvest policy.

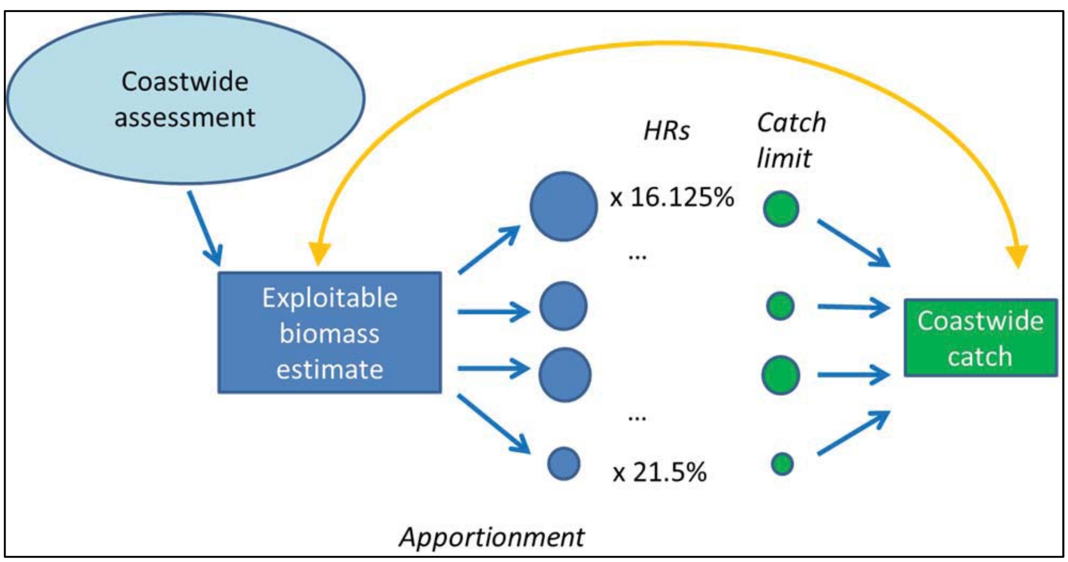

Figure 17. Illustration of the method for calculating the coastwide harvest rate consistent with the IPHC's harvest policy.

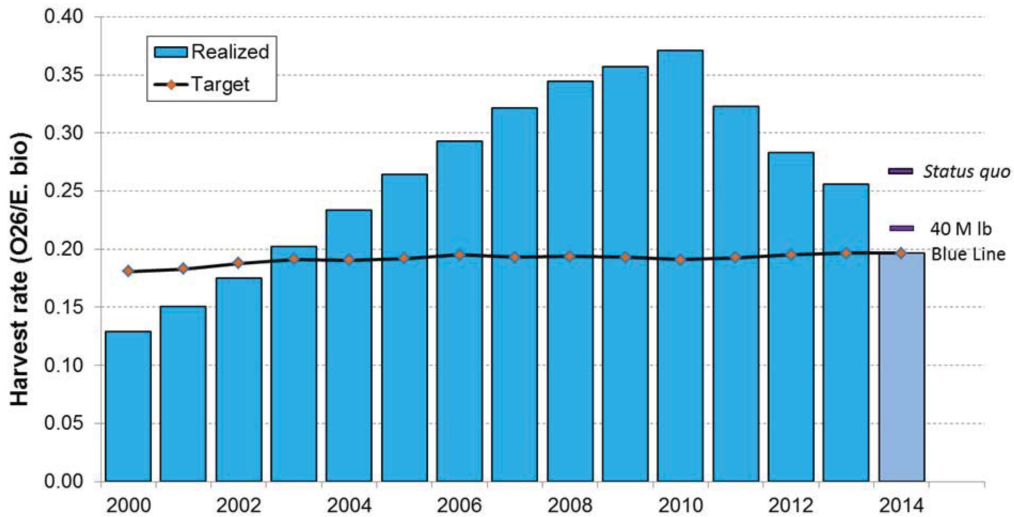

Figure 18. Time series of estimated coastwide harvest rates (bars) and hindcast harvest rate targets (line). Hindcast annual harvest rate targets correspond to the current estimate of exploitable biomass, not the estimate in that year. Values for 2014 represent alternatives from the decision table.

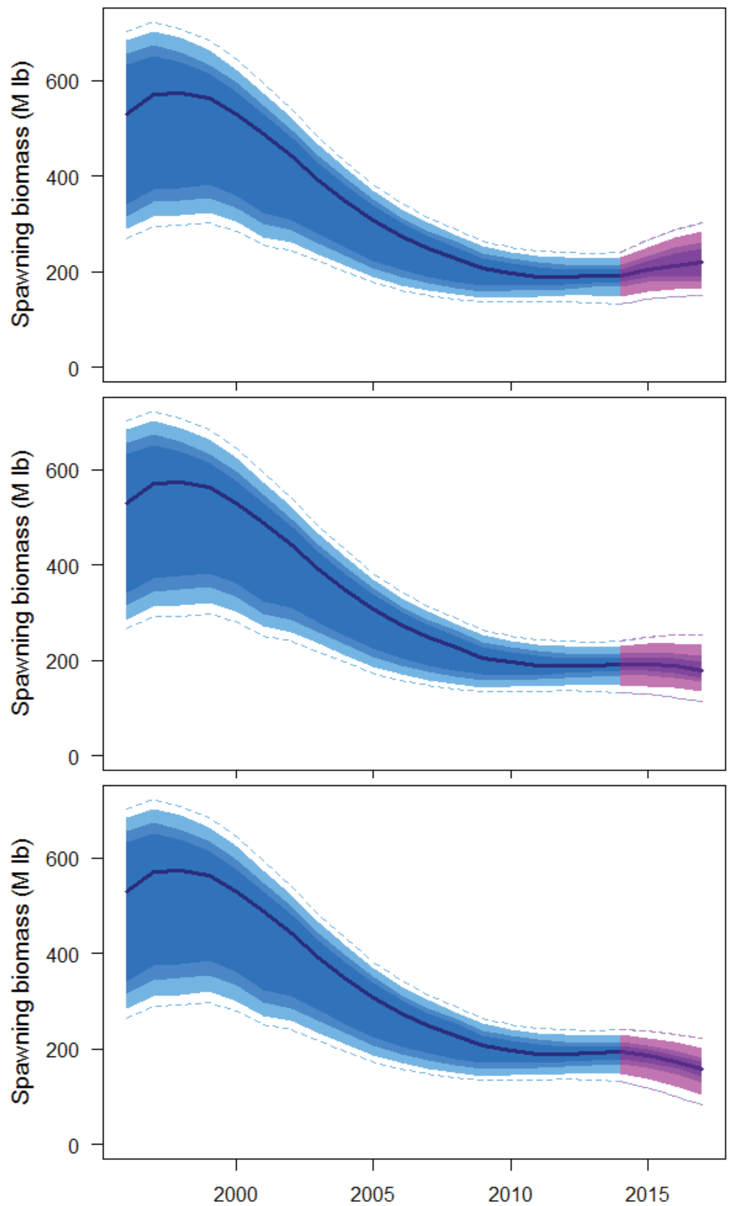

Figure 19. Three-year projections under alternative levels of mortality: no removals (upper panel), Blue Line removals (middle panel) and 60 million lbs removals (lower panel).

Overview of data sources for the Pacific halibut stock assessment and related analyses

Ian J. Stewart

Introduction

This document provides a summary of the data sources available for the Pacific halibut stock assessment, apportionment, harvest policy, management strategy analysis (MSE), and related analyses. It serves as background for the 2013 stock assessment, and also as an ongoing effort to provide transparent documentation and access to the data and processing methods employed. For each data source, a narrative is provided which includes the source, steps taken to filter and analyze the data, and the key quantities available for subsequent analysis. Data sources are described within the categories of: fishery-independent, fishery-dependent, and auxiliary sources of information.

Also provided in this document is a brief synopsis of changes to various data sources and processing explored during 2013, as well as a list of data sources or analyses that are currently not directly used, but are potentially available for future analysis. The latter includes some comment on avenues for additional data collection and/or analysis.

Fishery-independent data

Fishery independent data are generated each year by the IPHC's setline survey, covering most of the range of Pacific halibut habitat from the northern Bering Sea and Aleutian Islands to California, and depths of 20-275 fathoms (Soderlund et al. 2012, Henry et al. 2013). The setline survey generates catch rate information, as well as biological samples from individual fish sampled randomly from the catch including: sex, length, age, maturity, and presence of prior hooking injury. These data are reprocessed each year for use in the stock assessment as new observations become available (Fig. 1).

Survey WPUE (Weight-Per-Unit-Effort)

The catch-rate information from the setline survey serves as the primary source of trend information (along with commercial catch-rates) for the stock assessment. The area-specific setline survey indices of abundance (weight-per-unit-effort, WPUE) are calculated based on the catch in weight relative to the amount of gear deployed at each station. Survey effort for a particular station is standardized to an effective skate (*ES*) that is 1,800 feet long, with 100 hooks (and therefore an 18-foot average spacing), based on the number of skates fished (*S*), the average number of hooks fished per skate (N_h), and the hook-spacing (H_s; Fig. 2) based on the relationship given by Hamley and Skud (1978):

$$ES = S \cdot \left(\frac{N_h}{100}\right) \cdot 1.52 \cdot (1 - e^{-0.06 \cdot H_s})$$

Because the hook spacing is standardized for all recent survey operations, the only variability in this relationship occurs due to changes in the number of hooks (N_h) as a result of missing or extra hooks on a particular skate or skates. The weight of each halibut caught is estimated from the individual length observations via the weight-length relationship (see Auxiliary inputs section below). The sum of the catch weight is divided by the number of effective skates to obtain a station-level WPUE. These observations are then combined within a regulatory area (Fig. 3).

The area-specific WPUE is summarized via a simple arithmetic mean observed value (and SE) of WPUE for all stations (s) sampled within a regulatory area (a) during each year's (y) survey (Fig. 4):

$$\bar{I}_{a,y} = \sum_{s=1}^{Nstation} \frac{WPUE_{s,a,y}}{N_{a,y}}$$

These annual area-specific means are then weighted by the geographic extent of suitable depths occupied by Pacific halibut within each regulatory area (g_a, 0-400 fathoms) relative to the entire coast (Fig. 4). The weighted values are then summed to generate a coast-wide index of abundance:

$$I_y = \sum_{a=1}^{Areas} \bar{I}_{a,y} * \frac{g_a}{\sum_{a=1}^{Areas} g_a}$$

Due to anomalies in survey coverage, a number of calibrated expansions, corrections, and modifications are made to the WPUE for specific areas and years in order to make the coast-wide time-series as consistently representative as possible. By regulatory area these include:

<u>Area 2A</u>: In 1997, Area 2A stations followed a random stratified design instead of the grid-based design used in other areas and year. Therefore, the observed average WPUE values are calculated separately for each stratum, and strata are area-weighted within the regulatory area. In 1998 and 2000, survey catches for 2A are interpolated from adjacent years as there was no survey effort in that area. For all years other than 2011, Area 2A catch rates are expanded based on the ratio of catch rates observed in the additional stations (Puget Sound and outside waters) added in 2011. The 2012 Area 2A observations are also adjusted to the extra stations in Puget Sound fished in 2011, but the outside stations were fished as they had been in 2011, so no additional adjustment is necessary. In 2013, the Area 2A survey was expanded to cover a portion of northern California. An expansion has been developed for historical catch rates based on the survey catches in this area in 2013 (See Webster et al. 2014). In addition, the geographic extent of the 0-400 fathom area in northern California was added to the Area 2A calculations (unlike Puget Sound, for which the area had already been included prior to its initial survey in 2011).

<u>Area 2B</u>: In 1996-1998 and 2000, Area 2B had incomplete sampling coverage. Therefore, the values are scaled via an externally calculated ratio (0.89; Webster and Hare 2012) to the observed catches over the entire sampled area relative to the unsampled area in that year.

<u>Area3A</u>: Prior to 1996, only the western portion of area 3A was surveyed in some years. These values are adjusted by a scalar of 0.81 to reflect the lower catch rates in that region relative to the eastern portion of Area 3A.

Area 4A: In 1999, Area 4A values are scaled by a factor of 0.76 to account for incomplete spatial coverage.

The processing of survey WPUE calculations for the Bering Sea (Areas 4C, 4D, and 4E) is extensive. It consists of several expansions in order to estimate halibut density in large regions that are not covered by the annual setline survey. An expanded setline survey, conducted in 2006, in addition to the annual NMFS Bering Sea bottom trawl survey form the basis for these expansions. The specific methods have been revised for 2013, and are described in a separate summary document in this volume (Webster; 2014).

After these expansions have been applied, the coastwide survey legal-size (above the 32 inch minimum size limit) WPUE index is estimated to have declined by 12% from 2012 to 2013 (Fig. 5). This decline is largely driven by downward trends in areas 3A and 3B, and occurs despite increases in 2C and 4B (Fig. 5).

Sublegal halibut (below the 32-inch minimum size limit) are captured by both the commercial fishery and setline survey. Previous stock assessments have removed the sublegal halibut from the WPUE calculation, in large part to make the index more comparable to the catch rates observed in the commercial fishery. However, there is trend information in the catch of these smaller fish, and the total WPUE for all halibut is most consistent with the age-frequency data available for the survey, which also contains fish of all sizes. The total WPUE index provides a very similar trend to the legal-sized WPUE (Table 1, Figs. 6-7). When the regulatory area contributions are grouped, the declines in Areas 3 and 4 are particularly contrasting with the trend in Area 2 (Fig. 8)

Prior to 1997, survey coverage was sparse enough to preclude even a more complex approach to estimate coastwide catch rates. However, data are available for at least several regulatory areas in a number of earlier years. These data represent only Areas 2B, 2C, and 3A (the geographic 'core' of the stock) for the years 1982-1996, and only Areas 2B and 3A for the years 1977-1981. In 1984, among other changes to the station design and coverage, the setline survey (following the commercial fishery the year before) converted their standard gear to include circle hooks; this had a pronounced effect on observed catch rates (Fig. 9).

Survey age distributions

Otoliths are collected randomly from halibut captured by the setline survey, with sampling rates adjusted annually by regulatory area to achieve a similar number of samples from each area in each year. All otoliths collected during survey activities are read each year by IPHC age-readers. Because the survey catch is sampled randomly at the same rate for all stations within a given regulatory area and year, the raw frequency of ages is an appropriate estimate of the aggregate for the area. Age distributions differ between male and female halibut and among regulatory areas, with older fish comprised of primarily males, and occurring in much greater numbers in the western and northern regulatory areas (Fig. 10).

In order to weight these area-specific distributions, an estimate of the number of halibut in each area is required. This is obtained via calculating the numbers-per-unit-area (NPUE), following identical rules to the calculation of WPUE, and then weighting these values by the same geographic proportions used for WPUE. The relative numbers in each regulatory area then provide a weighting for combining the age-frequency distributions into a coastwide aggregate (Fig. 11). In recent years, the strength of the 1987 year class has been particularly evident in these data. The age frequencies in 2013 do not show any signs of strong incoming cohorts, nor much deviation from the recent observed age-structure.

Ages have been aggregated at age 20 (all ages 20 and older combined) for all data (survey and fishery) collected prior to 2002 when the break-and-bake ageing method was adopted for all halibut age-reading by the IPHC (see section on ageing bias and imprecision below). Most ages read prior to 2002 used surface ageing methods.

During 2013, there were some additional ages (628) determined to be missing from the 2001 sampling that were re-aged using surface aging methods (for comparability with the rest of the year's samples) and added to the IPHC's database. In addition, 3,466 otoliths from 1998 were re-aged using break-and-bake methods in order to provide a comparison of surface ages with break-and-bake ages (see section on ageing bias and imprecision below). These otoliths will also be used to create an improved age distribution for 1998 for use in the 2013 assessment. This distribution will reflect the unbiased and more precise nature of the break-and-bake method. A comparison of the raw age-distributions (not weighted by regulatory area) from the two methods shows reasonable consistency, and does not alter the perception of the particularly dominant 1987 cohort (aged 11 years in 1998; Fig. 12).

As for the catch-rate data, there are some sparse age data available prior to 1997. These age data represent only Areas 2B, 2C, and 3A for the years 1982-1996, and only Areas 2B and 3A for the years 1980-1981. These earlier data do not reveal any particularly strong cohorts, nor do the cohort strengths appear appreciably different for male and female halibut (Fig. 13). However, the persistence of male halibut to older ages at a much higher rate can be clearly observed in the more recent survey data.

Survey weight-at-age

The survey collects individual length observations on all halibut captured, which are then converted to estimated weights via the length-weight relationship (see section below). Age estimates are also available for a random subsample of these lengths.

Ages consist of primarily surface ages prior to 2002, and exclusively break-and-bake ages from 2002 to the present. Prior analyses of weight-at-age attempted to correct for the potential bias of surface ages by converting the weights corresponding to surface ages to the 'true' weight at age given an estimated level of bias (and some assumption of the underlying age structure). Investigation of the data prior to 2002 revealed that many of the surface ages also had corresponding break-and-bake ages that were not being included in the analysis (see summary of ageing bias and precision below). Replacing all surface ages with break-and-bake ages (where available) in the weight-at-age calculations appears to adequately address the differences in the ageing methods for the recent data.

Because the sampling of ages is random within the survey catches for an area each year, the average weight-at-age by area, sex, and year is calculated. Where there are very few individuals in the population of a particular age, the number of survey age samples is also small (the age samples are not length-stratified). This pattern, in combination with incomplete survey sampling for some areas and years, results in a small number of missing weights-at-age within area and year combinations. These are simply interpolated from adjacent years. Because the survey captures few fish younger than age 7 or older than age 25, all fish outside this range are aggregated to these 'minus' and 'plus' groups. Although there has been a very strong trend of declining weight-at-age in recent years, there are marked differences in the magnitude of this decline among regulatory areas (Figs. 14-21). There also appear to be some patterns associated with specific cohorts; e.g., females in Area 2C born in the late-1990s (Fig. 16, upper panel). There do not appear to be consistent or strong trends from 2010-2013 in the area-specific data.

These different trends among areas require appropriate weighting of the areas to create a coastwide time-series that represents the entire stock. The estimates of numbers of fish by regulatory area generated from survey NPUE and geographic area are used to weight the individual regulatory area. At the coastwide level the stronger declines observed in the areas for which the greatest number of halibut are estimated to be present are evident, especially for the years prior to 2010 (Fig. 22).

For input to the stock assessment, a full matrix of weight-at-age by year and sex is required, despite the small number of fish present in the youngest and oldest ages. To complete the matrix, a linear ramp in weight-at-age is applied below age 7. For the plus group (25+), the average age is calculated; this average age is then used to extrapolate the weight-at-age for ages 25-30. This is necessary because the average weight-at-age for all 25+ halibut combined should not be attributed to exactly age 25: the average age must be >25 unless all fish are exactly 25.

Spawning output-at-age

Survey data are also used to define the population-level weight-at-age and spawning output. Unlike the survey index calculation, where interannual sampling variability is logically included, the true population level quantities should be smoother than the raw observations. In previous analyses, these quantities had been smoothed across ages within each year without regard for sample size, which induced significant correlation among ages, and spurious ‘dog-legs’ that extended over several adjacent ages. Reanalysis of these quantities indicated that applying a smoother across years within each age produced results more consistent with those expected for population level values. These summaries most clearly show the population-level decline in weight-at-age observed for both male and female halibut over the recent time-series available from the survey (Fig. 23). Survey observations of weight-at-age might include some bias relative to the population if size-based selectivity is operating on the distribution of lengths within each age. However, the matrix of population-level weight-at-age is most important in the assessment for those ages that are mature, for halibut mainly ages 11 and higher (see Maturity section below) which are less likely to experience significant bias.

Fishery-dependent data

Commercial fishery landings

An annual estimate of total mortality of halibut from all sources is required for all stock assessment and related analyses. Removals can be categorized into five major components: fishery landings, fishery wastage (a combination of sub-legal and legal-sized fish), sport (recreational), personal use or subsistence removals, and bycatch of halibut in fisheries targeting other species (Fig. 24).

Landings of halibut from the directed fishery are documented through the use of commercial fish tickets, reported to the IPHC (Gilroy et al. 2014). From 1981 to the present, these landings are fully delineated by regulatory area (including all of the portions of Area 4; Fig. 25). Prior to 1981, landings are available only in aggregated form for all of Regulatory Area 4. Landings from 1935 to 1980 are not currently included in the IPHC’s database; however previous analysts have left a number of ‘flat files’ which appear to correspond well with tables published in technical reports, and other IPHC documents. Because the raw data are not able to be reprocessed directly, the landings estimates prior to 1981 are more uncertain than those after 1981. Historical landings prior to 1935 were reconstructed within current regulatory areas from summaries by historical statistical areas (Bell et al. 1952). Reported landings of halibut begin in 1888; however, already over one million pounds were being landed per year at that time. The reconstruction by regulatory area of total landings included some use of ratios between Areas 2A and 2B among adjacent years for ambiguous records, therefore the area-specific distributions are therefore more uncertain than the total landings. Several patterns emerge from the longer time series of landings including: the period of substantially reduced fishing in the 1970s in all areas, and the sequential exploitation of Areas 2, 3 and 4 over the entire time series (Table 2, Fig. 26).

Sport (recreational) removals

Sport or recreational removals are reported to the IPHC by the various agencies in charge of managing these fisheries, including Alaska Department of Fish and Game, the Department of Fisheries and Oceans Canada, and the states of Washington, Oregon and California (Williams 2014). The scientific basis for data collection programs, analyses, and the quality of the subsequent estimates vary considerably by year and source. None of the current estimates include mortality of released fish, although analyses are underway for Alaska. It is generally assumed that there was little sport fishing for Pacific halibut prior to the mid-1970s. Sport removals have grown rapidly since that time, with peak harvests estimated at over 10 million pounds annually during the mid-2000s. They have been reduced in recent years as the IPHC has lowered stock-wide mortality (Fig. 27). Among regulatory areas, Area 3A represents over half of the total removals, with Areas 2C, 2B, and 2A each contributing somewhat less (in declining order).

Personal use or subsistence removals

Subsistence harvest estimates are provided to the IPHC by the DFO and NMFS; only those from Alaska are based on an active sampling program (Williams 2014). Estimates are not generated annually in all cases, and therefore some values are applied through intervening years until the next estimate is made available. There are currently no estimates available prior to 1991. The time-series created from these estimates is relatively noisy, but occurs on a scale much smaller (< 2 million pounds) than other critical inputs to the analyses (Fig. 28).

Commercial fishery wastage

‘Wastage’ describes all mortality of halibut that occurs during the directed fishery, but that does not become part of the landed catch. There are three main sources of wastage: 1) fish that are estimated to have been captured by fishing gear that was subsequently lost during fishing operations, 2) fish that are discarded for regulatory reasons (e.g., the vessel’s trip limit or harvester’s IFQ limit have been exceeded), and 3) fish that are captured and discarded because they are below the legal size limit of 32 inches. The methods applied to produce each of these estimates differ due to the amount and quality of information available. For a full description of the improved methods used to calculate wastage for the 2013 assessment see Gilroy and Stewart (2014).

Based on these methods, wastage in the commercial fishery is estimated to have been highest in the early 1980s, subsequently declining (particularly in Area 3A in 1995 when the derby fishery was converted to a quota system), and then increasing from 1995 to 2010 as the size-at-age of halibut declined and more fish at older ages remained below the minimum size limit (Fig. 29, upper panel). The estimates of wastage cannot be delineated within Regulatory Area 4 prior to 1981, but there is very little wastage estimated prior to that time (Fig. 29, lower panel).

Bycatch in non-target fisheries

The estimated bycatch from non-target fisheries by regulatory area is reported to the IPHC by the NMFS and DFO on an annual basis (Williams 2014). These estimates vary greatly in quality and precision depending upon year, fishery, type of estimation method, and many other factors. Bycatch is delineated among Areas 4A, 4B, and 4CDE only from 1990 to the present, during which time it has declined from a peak of over 20 million pounds to a value of approximately 7.9 million pounds in 2013 (Fig. 30, upper panel). Prior to 1991, available bycatch estimates are aggregated for all of Area 4. From the 1960s to 1990s, annual values were variable with a peak in the early 1960s corresponding to the peak of foreign fishing in (currently) Alaska waters, primarily Areas 3A and 3B. There was likely less bycatch prior to the development of the foreign fishery in U.S. waters in the early 1960s; however, bycatch estimates are only available from 1962 to the present (Fig. 30, lower panel).

Summary of total halibut removals

Recent aggregate total removals from all sources reveal that although the directed commercial fishery represents the majority of the anthropogenic mortality, other sources, including bycatch and sport removals, tend to contribute a larger proportion when the total is lower (Fig. 31). Recent total removals from all sources by regulatory area reveal that Area 3A has been the dominant contributor to total mortality throughout the last five decades, that Area 4 has increased in its proportion of the total, and that the other areas have been somewhat consistent (Table 3, Fig. 32).

The full time-series of estimated removals illustrates that all four of the major peaks in the commercial fishery mortality have been of similar magnitude (around 70 million pounds) but that each peak has been larger than the previous with regard to total mortality from all sources (Table 4, Fig. 33). When the removals by source are compared among regulatory areas, there are a number of differing patterns in magnitude and distribution (Figs. 34-36).

Fishery catch-rate and biological data

Directed commercial fishery data is processed similarly to the setline survey data (Fig. 37), with the important exception that there are no sex-specific biological observations available due to the dressing of halibut at sea.

Directed fishery WPUE

Commercial fishery logbook data is collected by port samplers, and reported directly to the IPHC by fishermen. The data that are included in the fishery WPUE analysis are: the regulatory area of fishing (regardless of the port of delivery), the type of fishing gear used (only fixed-hook data are used in Areas 2C, 3A, 3B, 4A, 4B, 4C, 4D; both fixed-hook and snap gear are used in Areas 2A and 2B), the year of fishing (some logbooks are not obtained by port samplers until the following year), the number of skates fished (excluding any gear that was lost), the spacing of the hooks, the number of hooks on each skate, and the pounds of legal-sized halibut captured and landed. Only sets specifically targeting Pacific halibut are included in the analysis and all sets with hook-spacing of less than four feet are assumed to be non-halibut targeting, except in Area 2A.

For each regulatory area and year combination, the sum of the recorded landings is divided by the sum of the effective skates (the calculation of effective skates is identical to that applied to the survey data). Due to the small number of fixed-hook sets in regulatory Areas 2A and 2B, snap gear is included in the calculation for these areas. This is done by dividing the snap gear effort by a factor of 1.35 (Clark 2002). There are too few logs available on an annual basis from Area 4E to include that regulatory area in the WPUE calculations.

The WPUE by regulatory area is combined into a coastwide total by multiplying the area-specific values by the geographic extent of the 0-400 fathom bathymetry in each area (as for survey WPUE). This is consistent with the concept that the commercial WPUE is also a 'survey' of the stock and therefore the estimates are a proxy for density, but diverges from the more common approach of weighting the commercial WPUE from each area by the catch in that area relative to the total. It may be preferable in the future to explore the use of catch- instead of geographic-weighting.

Logbook catch-rates from Areas 2A and 4C were not included in the coastwide total during previous analyses, but were added in 2013 in order to apply a consistent method to all areas, and to include as much of the data as possible. In addition, the geographic extent of each regulatory area was revised slightly to reflect improved bathymetric data and re-analysis by Ray Webster as part of the setline survey standardization analysis. Neither change resulted in a difference to the coastwide time-series that was large enough to detect after rounding the results to an appropriate number of significant digits.

As has been observed over several previous stock assessments, in 2013 there was a change in the 2012 WPUE relative to the dataset available for the 2012 annual stock assessment. Specifically, the final verified record of logbooks available approximately 10-12 months after the end of the annual fishing season (August to September of the following year) have tended to show a lower catch rate than the preliminary data available in November and used in the stock assessment each year. The final 2012 logbook data indicated a 2% decline from 2011 to 2012 in the total WPUE series, as compared to a 0% change in the preliminary data available during November of 2012. Area-specific differences were variable, but generally larger for regulatory areas with few logbook records (e.g., Areas 2A, 4C). These differences reflect the inclusion of logbooks that were not collected by port samplers during the year of fishing (and subsequently mailed in to the IPHC, or collected by port samplers during the 2013 fishing season), as well as logbooks that had been collected but were not available for analysis in 2012 (the fishing season extended until early November; the stock assessment data were finalized the day the fishery closed). A potential contributing factor could be the combination of a decline in WPUE during the fishing season, and a higher probability of logs from later in the season being unavailable at the time of the assessment. Given this pattern, the variance of the terminal year of the WPUE series should be routinely inflated to reflect this additional uncertainty, and the interpretation of small changes tempered by previous trends.

Commercial WPUE series are quite variable among regulatory areas, with Areas 2A, 2B and 2C increasing trends in recent years, and Areas 3A through 4 the greatest declines. Sustained higher catch rates during the 1980s and 1990s are evident in many areas (Table 5, Fig. 38).

Effort data for years prior to 1981 do not currently exist in the IPHC's database. For historical data, as is the case for other sources of information, there exist flat files from previous analysts that include effort and landed catch by regulatory area. These data have been used for other analyses, and date back to 1929. Prior to 1935, records of effort are reported in various technical and other

IPHC reports, and there are a number of differing time-series available. For this summary, total catch and total effort were tabulated from Chapman (1962) for the years 1921-1934, and from Thompson and Bell (1931), although there are differing series in at least Skud (1975) and several others. The oldest historical records do include even earlier years, but have not been included here pending more detailed investigation. It would be preferable to access and process the historical log data directly from data stored in a database with meta-data, but this is not possible at present.

The most dramatic change in the commercial WPUE time series corresponds to the transition from "J" to circle hooks in 1984, although there have been many other changes in the definition of effort over the time series (See synopsis in: Leaman et al. 2012). Changes in catch rates prior to the 1980s also reflect the areas over which fishing was conducted; given the geographic patterns in landings (Fig. 26) it is quite clear that these have shown a strong pattern of moving south to north over much of the time-series. Despite these caveats, it is clear that catch rates were quite low around the time of the formation of the Halibut Commission (in fact, this was the motivation for the original convention), and again in the late 1970s (Table 5, Fig. 39). Additional uncertainty throughout the historical series is reflected by increased CVs (fixed at 0.1) for all years prior to 1996.

Fishery age distributions

Recent fishery ages are created from otoliths collected by port samplers in proportion to the landings in the ports that are annually staffed by the IPHC (Erikson and MacTavish 2013). Because of this method, the raw ages can be directly aggregated within each area and year to estimate the age composition of the catch. Because port samplers also collect individual lengths, the average weight within each area can also be directly estimated via the length-weight relationship. Dividing the total commercial catch for each regulatory area and year by the average fish weight gives an estimate of the number of fish captured. To aggregate the proportions-at-age from each area into a coastwide total, each area is weighted by the numbers of fish in the catch relative to the total number of fish captured over all areas. For the period included in recent stock assessments, the coastwide age distribution displays a very similar pattern to that of the setline survey ages: a very strong 1987 cohort moving through the stock (Fig. 40).

Commercial fishery ages prior to 1991 have been summarized by several previous analysts, in some cases processed originally by one analyst and then subsequently by another (Clark et al. 2000). For this summary, a file produced for the analysis by Clark et al. (2000) was obtained, which included proportions at age by regulatory area from 1935 to 1990. Additional work could be done to verify which of these proportions can and can't be recreated from the current IPHC database. Weighting of the area-specific proportions followed the method applied to the more recent data, first obtaining an average individual weight (in this case by multiplying the proportions at age by the estimated average weight at age from the historical records), and then dividing the total landings by that weight to get an estimate of the number of fish in the landings by year and area. Again following the survey analysis methodology, the numbers in the landings by area were used to weight the proportions-at-age for a coastwide total.

The resultant fishery age-frequency distributions reveal that halibut in the commercial landings from the 1930s to 1973 (when the current minimum size limit was implemented) have been predominantly age 6 to 14 (Fig. 41). Several strong cohorts can be observed in the data, but none more conspicuous than the 1987 cohort.

Fishery weight-at-age

Both lengths and otoliths are collected by port samplers, and the lengths can be converted into individual weight estimates. No sex information is available from port samples. The average weight of a landed halibut has shown relatively flat trends over Areas 2A, 2B, and 2C, steep declines in Areas 3A and 3B and somewhat less pronounced declines in area 4 (Fig. 42). Several areas showed an increase in average weight in 2013 resulting in an increase at the coastwide level. These observations accurately reflect the fishery landings, but combine the relative influences of weight-at-age, age- and sex-structure, as well as selectivity relative to the underlying population.

Historical observations of average weight are more problematic. Specifically, from 1963-1990 the IPHC did not collect individual lengths from the commercial landings. It was thought at the time that otoliths measurements could be used to adequately estimate the body size of the fish (Southward 1962), and therefore the weight. Subsequent investigation of the relationship between otolith measurements and individual length (Clark 1992) resulted in the resumption of length sampling in 1991. For this reason, the weights-at-age for most of the historical period should be considered much more uncertain than recent observations. In addition, there has yet been no detailed evaluation of surface ageing bias or precision for the period prior to the 1990s (although this work is currently underway at the IPHC). Despite these considerations, there is a clear pattern of increasing fish size in the landings from the 1930s through the 1970s, followed by a subsequent decline to the present (Fig. 43). Also clearly visible is the effect of the implementation of the 32 inch minimum size limit in 1973.

Following the same method applied to the age-composition data (weighting the historical weight-at-age for each regulatory area by the number of fish in the landings for that area), a coastwide weight-at-age can be constructed for the entire time-series. Unfortunately, this series is not sex-specific due to the dressing of fish at sea prior to sampling by port samplers. However, there are similar trends for the best represented ages (8-16) over the historical period. One way to investigate these patterns is to divide the time series of weight-at-age for each age relative to the first year in which we have a coastwide estimate from survey data (1997). Only legal-sized fish from the survey catch are included in these weights-at-age in order to make them comparable to fishery landings. These deviations show very similar temporal patterns, despite expected differences on an absolute scale (Fig. 44).

As a proxy for sex-specific weights-at-age for the time-series, the survey weights-at-age from 1997 were scaled by the time series of annual deviations calculated from the fishery data. This implicitly assumes that male and female halibut have experienced similar trends in size-at-age; recent data that are available by sex support this assumption.

Auxiliary inputs

Several additional sources of information are included in the stock assessment or related analyses and treated as data, even though they represent the products of analyses themselves. These are briefly summarized here but considerable additional background material exists.

Weight-length relationship

The weight-length relationship for Pacific halibut was developed in 1926, re-evaluated in 1991 (Clark), and has been applied as standard practice for al years of IPHC management. The relationship between fork length (L_f), and individual net (headed and gutted) weights (W_n) is given by:

$$W_n = 0.00000692 \cdot L_f^{\,3.24}$$

This relationship reflects the slightly greater than cubic increase in weight with increasing length (Fig. 45).

Maturity schedule

The maturity schedule for Pacific halibut has been investigated several times historically, and maturity-at-age found to be very stable despite long-term changes in length- and weight-at-age (Clark and Hare 2006). Estimates of the age at which 50% of female halibut are sexually mature average 11.6 years among regulatory areas, with very few fish mature at ages less than five and nearly all fish mature by about age-17. The maturity schedule used for stock assessment has not been updated in recent years, and it is represented by a logistic fit that is truncated below age 8 (Fig. 46).

Ageing bias and imprecision

Ages are often treated and referred to as 'data', however they represent estimates of age based (most commonly) on the counting the rings formed annually on otoliths. These estimates are therefore subject to both bias and imprecision depending on the method employed to obtain them. Halibut tend to be relatively easy to age (compared to longer-lived groundfish), and historical estimates of the imprecision of the standard method of 'break-and-bake' ageing showed that the method was very precise (Clark 2004a, b, Clark and Hare 2006). Validation of the method relative to actual age has been performed via analysis of radiocarbon levels observed in known-age otoliths, and the relationship has since been used as the standard for North Pacific groundfish species (Piner and Wischniowski 2004).

Prior to 2002, surface ageing was employed as the primary tool for ageing Pacific halibut, and this method is known to be biased for older individuals and less precise than other methods when applied to many marine species. Previous analyses of the properties of surface ages were based on comparison of an extensive data set of duplicate surface and break-and-bake ages (each otoliths read at least twice) that had been collected opportunistically (Clark 2004b, Clark and Hare 2006). This comparison also included some broken-and-burned ages, which are quite similar, but not identical to those generated by the break-and-bake method. Specifically, as readers found otoliths that were difficult to surface age, they had the option to break-and-bake them, thus the comparisons represented a nonrandom sample biased toward the most difficult ages to read. This work found a modest amount of bias for the surface aging method for ages less than 13-15, but rapidly increasing bias and imprecision with further increases in age.

In order to provide an updated and rigorous test of the properties of surface ageing methods employed by the IPHC, a re-ageing of 4,362 systematically selected otoliths from the setline survey collection from 1998 was conducted. For all of these ages, the original surface age and a break-and-bake age are available for direct comparison without regard to the difficulty of reading. The dataset produced by this effort was analyzed with an updated version of a widely available software program for this purpose that has been simulation tested (Punt et al. 2008) and applied as part of many Pacific coast groundfish stock assessments. Briefly, the program estimates a latent age structure in the sample, and estimates the degree of bias and imprecision (assuming at least one method is unbiased) for each ageing method via the joint probability of possible combinations of individual age reads. Based on the newly available 1998 data set, the degree of imprecision estimate for the break-and-bake method is virtually identical to the one previously estimated by Clark (2004; Fig. 47).

However, the estimated properties of surface ages showed a similar level of imprecision, but notably reduced degree of bias when compared to the previous analysis (Fig. 48). This is consistent with the previous dataset including mainly otoliths that were considered difficult to read, and the updated analysis representing a random sample from an entire year's data. These results indicate a reduced degree of bias is likely for ages above 15 years old, and therefore greater accuracy in weight-at-age and age-frequency distributions calculated from surface ages.

Pacific Decadal Oscillation

Previous research identified a strong correlation between the environmental conditions in the northeast Pacific Ocean, specifically the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) and recruitment of halibut to the commercial fishery during the 1900s. A description of ongoing PDO research as well as access to the time-series of estimates can be found at: http://jisao.washington.edu/pdo/. For Pacific halibut, the positive 'phase' of the PDO (years up to and including 1947 and 1977-2006) and subsequent recruitment of juveniles into the commercial fishery appears to be correlated (Clark et al. 1999, Clark and Hare 2002). Although compelling, that analysis utilized only recruitment estimates prior to the mid-1990s. Pending a fully updated investigation into the correlation between recruitment and the PDO, it may still be of qualitative value to monitor the recent trends in the PDO time series. Inspection of the most recent PDO values indicates that since 2006 annual deviations have been negative (Fig. 49). This represents the longest period of negative annual values observed since the late 1940s.

Conclusions

Despite the heterogeneous nature of the various datasets, there is a considerable quantity of historical data available for Pacific halibut, perhaps more than for any other single groundfish species in the region. The IPHC has the benefit of an extremely long time-series of data collection, a high degree of cooperation from the commercial fleet, and therefore a unique resource for historical fishery and biological patterns in the northeast Pacific Ocean. The data themselves, after accounting for important known changes in fishery and survey activities, are remarkably coherent and potentially highly informative for stock assessment, harvest policy, and Management Strategy Evaluation (MSE) analyses.

Summary of notable changes to data processing made for 2013

This document does not attempt to describe all previous data sources and processing methods used for stock assessment. It is intended to provide an overview of what might be considered current 'best practices'. Some of the more important changes to previously employed methods are outlined here along with the rationale for the changes made.

- Previous analyses have required sex-specific age-composition information from the commercial fishery. These were constructed via the estimation of an age-specific logistic function describing the sex-ratio-at-length from the setline survey data, and then the application of these estimated curves to the commercial fishery length-at-age observations (Clark and Hare 2006). Because it is difficult to propagate uncertainty through these calculations, treatment of fishery age-data may be more appropriately conducted using aggregate age-frequency data for both sexes combined. See future analyses section below.
- As noted above, there is no compelling reason to discard the sublegal catch information when constructing the setline survey WPUE time-series. Use of total WPUE includes all available information and avoids artificially partitioning the survey catch rate data at the legal-size limit.
- Several improvements have been incorporated into the current calculations of commercial fishery wastage. These include use of logbook-reported discards in Area 2A, use of logbook-reported sublegal catches in Area 2B and re-estimating the appropriate filtering of survey catch rates for comparison with commercial catch rates in Areas 2A, 2B (prior to 2006), and 2C, where historically used percentages were consistently biased (Gilroy and Stewart 2013).
- As described above, weighting the area-specific weights-at-age for the survey and fishery observations by the catch of each in numbers is necessary to generate a coastwide aggregate. These changes, as well as the use of smoothing over years (not ages) of weight-at-age observations for the survey data, are now applied. The projection of weight-at-age through the historical time-series using the trends observed in the fishery data is also new for 2013.
- The geographic extent of the bottom areas contained in 0-400 fathom depths have been updated based on more accurate bathymetric areas obtained in 2013.
- Areas 2A and 4C are now included in the coastwide fishery WPUE index.

Data sources for future analysis and potential research projects

This section represents a ‘laundry-list’ of potential extensions to current efforts, as well as new analyses that could benefit the halibut stock assessment or related analyses in the future. It is not a prioritized list, nor is it to be comprehensive: there are certainly other datasets not listed here but potentially available for analysis. A number of the projects are already underway.

- New approaches are needed for sampling the sex of commercial fish that have been dressed at sea. The IPHC has already begun investigating the potential for genetic sampling to be used on a broad scale.
- Extended analysis of the previously documented relationship between halibut recruitment and the Pacific Decadal Oscillation could inform ongoing harvest policy, MSE, and stock assessment efforts.
- Reevaluation of the historical length-weight relationship to determine whether recent changes in length-at-age are also accompanied by changes in weight-at-length. A pilot study on this topic was begun by IPHC port samplers in 2013.
- A renewed analysis of improved methods for commercial CPUE standardization, with a focus on integrating more of the fishery logbooks. In recent years there have been many improvements in the statistical methods available for CPUE standardization (e.g., Maunder

and Punt 2004). The current approach used is relatively simple, and only includes the fixed-gear logbooks, except for in Areas 2A and 2B where a fixed calibration between gears is applied. Potential collaboration with the University of Washington on this research is under consideration by the IPHC.

- A historical investigation on the factors influencing observed size-at-age, and ageing of additional samples from key periods and areas to support this analysis is ongoing at the IPHC as part of a large collaborative North Pacific Research Board project.
- Historical re-aging efforts will also provide information on the bias and imprecision of historical surface ageing relative to the data that are available from the 1990s onward.
- There is the potential that trawl surveys, accessing juvenile halibut habitat and capturing much younger fish than those observed from longline sampling (fishery or survey), could provide information on recruitment strengths for halibut several years prior to currently available sources of data. The NMFS conducts annual trawl surveys in the Bering Sea (Sadoris and Lauth 2013), and biannual surveys in the Aleutian Islands (Sadoris et al. 2013) and Gulf of Alaska . The NMFS also conducts annual trawl surveys off the U.S. west coast (Keller et al. 2012) which also enumerate halibut catches. The DFO conducts both trawl and longline surveys off the B.C. coast which could be included in an analysis of juvenile or adult habitat.
- The NMFS conducts ichthyoplankton surveys in the southwest Bering Sea that could be investigated with regard to potential correlation of planktonic halibut with the distribution and/or abundance of Pacific halibut spawning biomass.
- Mapping of survey catch rates and biological observations is an ongoing project at the IPHC. This should provide greater ability to evaluate and interpret trends in the survey data in the future.
- The NMFS sablefish longline survey in the Gulf of Alaska, Aleutian Islands and Bering Sea edge conducts fishing operations in depths that overlap and exceed those occupied by the IPHC's setline survey. The IPHC has an ongoing project to evaluate the catch rate information from this survey and explore methods for calibrating and using it to adjusting estimates of deep-water abundance for areas and years where this might be possible.
- Recreational catch-rate and length/age-distribution data are available from Alaska Department of Fish and Game. Although these data do not include samples from all potential recreational removals, they could be investigated as inputs to the stock assessment or for comparison with predicted age distributions.
- Mortality associated with catch-and-release in the recreational fishery has not been included in existing estimates. Analyses have been conducted by ADFG, and future estimates for all areas would be improved by inclusion of this type of mortality.
- There is a vast quantity of archived historical data that is currently inaccessible until organized, keypunched and formatted into the IPHC's database with appropriate meta-data. Information on historical fishery landings, effort, and age samples would provide a much clearer (and more reproducible) perception of the historical period.
- Estimates of migration rates by size, and regulatory area are available from the extensive tagging programs that the IPHC has conducted. These data require careful interpretation, as there are many unknown factors (e.g., reporting rates) that could potentially confound the results. However, they may be useful in both a quantitative and qualitative context for establishing migration rates could be further explored in the context of the stock assessment, harvest policy and MSE analyses.

- Additional efforts could be made to reconstruct estimates of personal use or subsistence harvest prior to 1991.
- Standardizing the setline survey catch rates for use in the stock assessment currently includes only gear-related aspects of the data. Model-based estimators, potentially explicitly spatial, might be explored in order to determine the degree to which the time series may be influenced by spatial and other factors relating to exogenous variables.
- There are length-frequency data available for some portions of the bycatch of Pacific halibut captured in fisheries targeting other species. These data have not been included in the fitting of recent stock assessments, although this could be explored. These data have been used to partition the bycatch into U26, and O26 components for apportionment. Such data could be transformed into predicted ages via an annual age-length key and treated as age data for the stock assessment. However, the values themselves are poorly estimated (high variance and not all contributing sources have length-frequency observations available for appropriate weighting), therefore the accuracy of these values would be suspect. Specifically, the representativeness of the samples relative to the total estimated bycatch would need to be evaluated.

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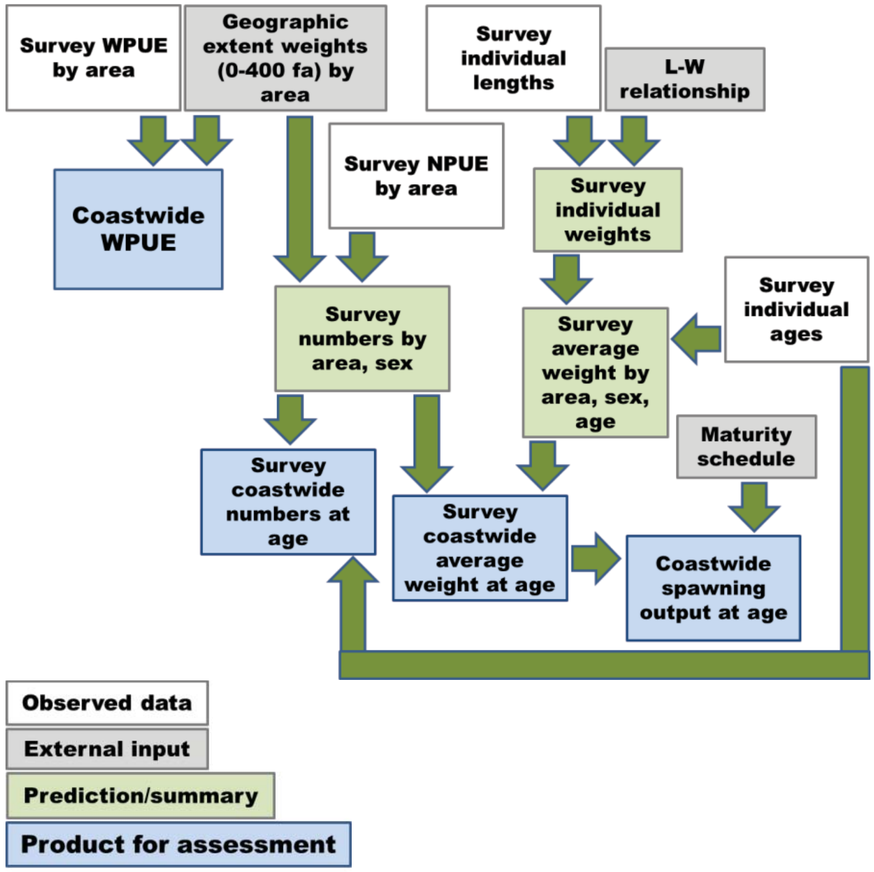

Figure 1. General schematic of the processing of the setline survey data.

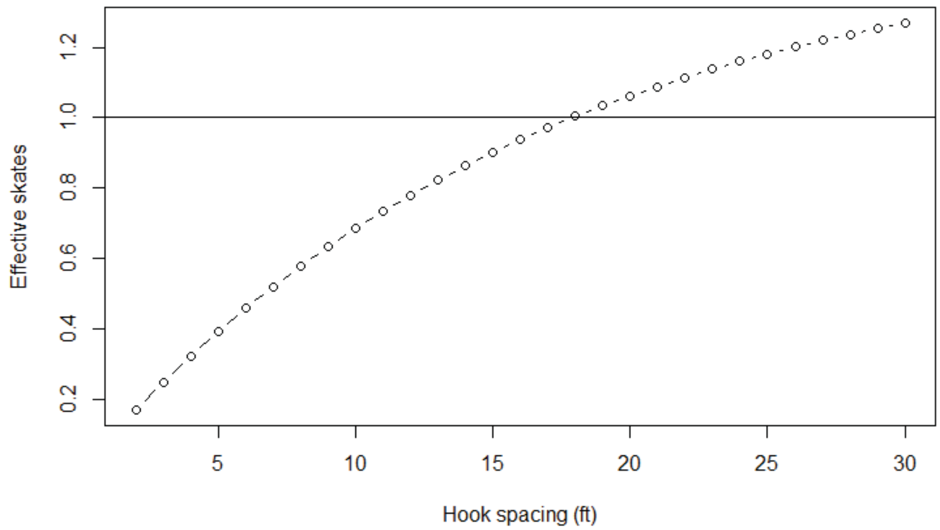

Figure 2. Relationship between hook spacing and the number of effective skates for setline survey and commercial fishery WPUE calculations (From: Hamley and Skud, 1978).

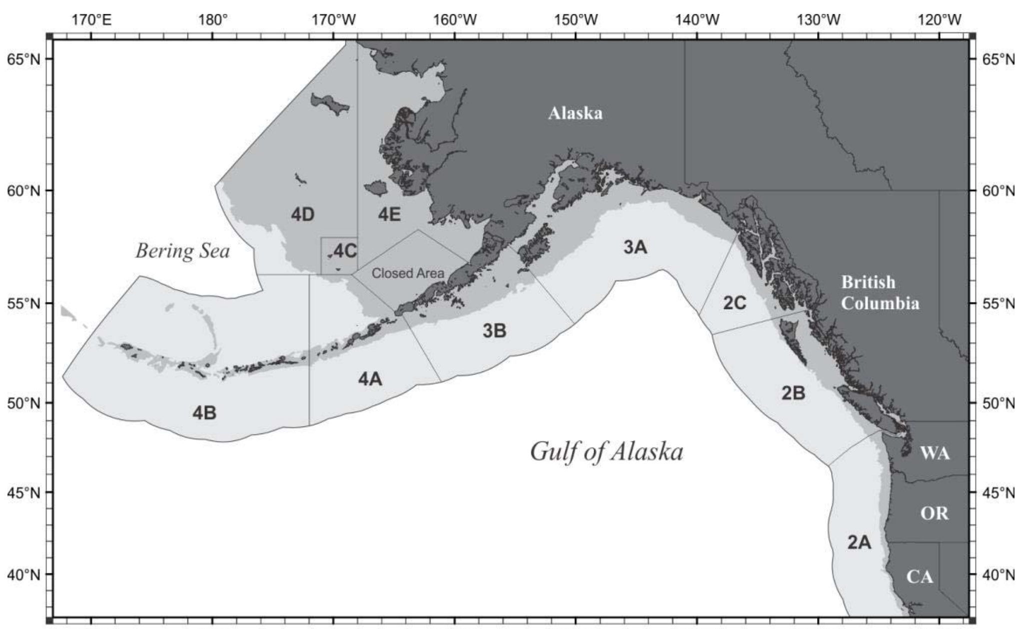

Figure 3. The IPHC's regulatory Areas. Shaded region indicates the Exclusive Economic Zone (EEZ) of the United States and Canada.

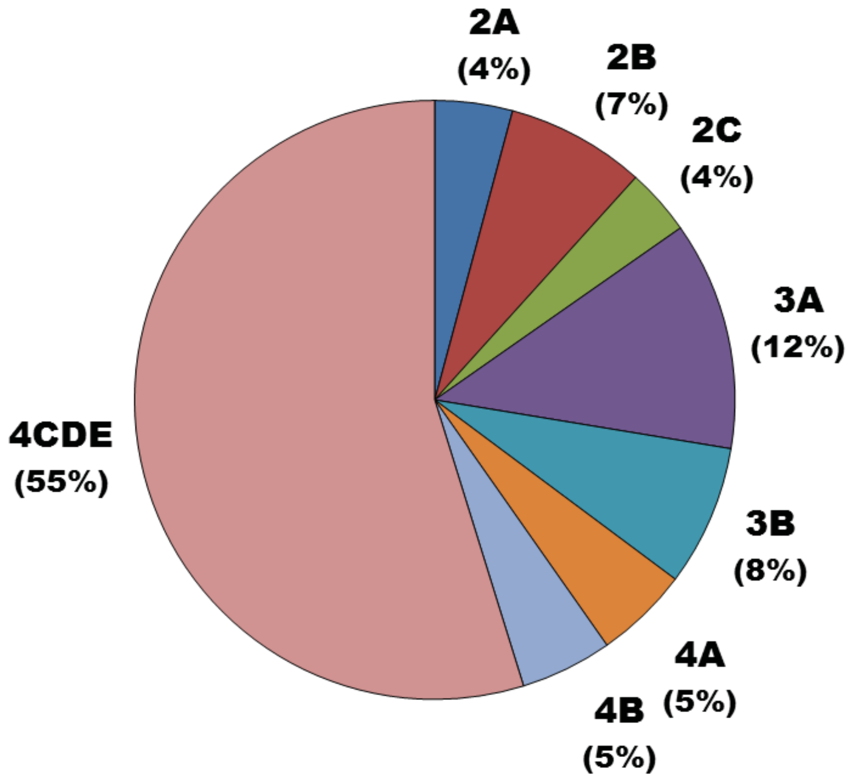

Figure 4. Relative spatial extent of each regulatory Area.

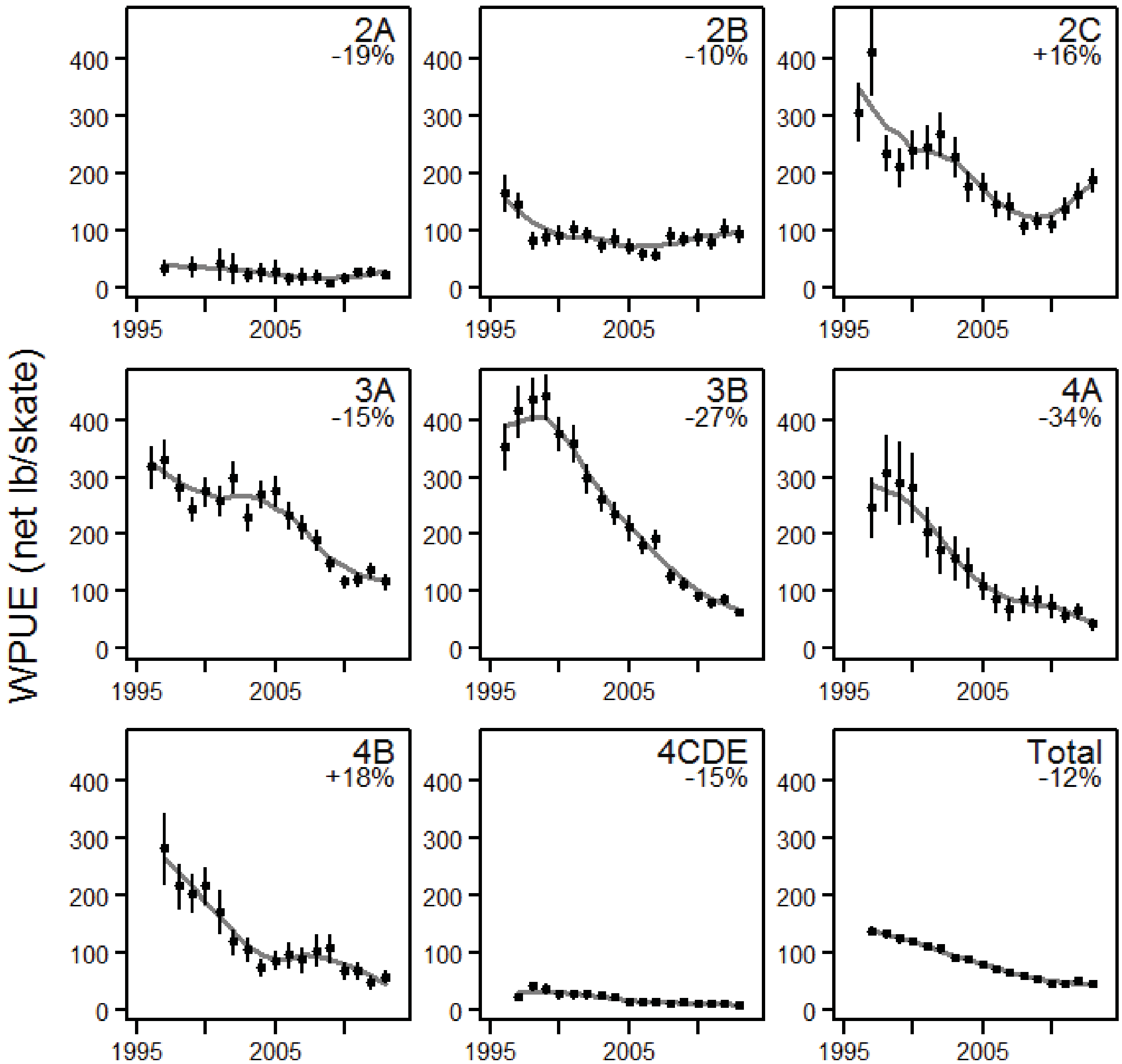

Figure 5. Recent setline survey WPUE for legal-sized fish only by area and year through 2013. Percentages for each area indicate the change from 2012 to 2013; lines represent a smoother for visualization purposes only. Indices include all expansions for incomplete survey coverage.

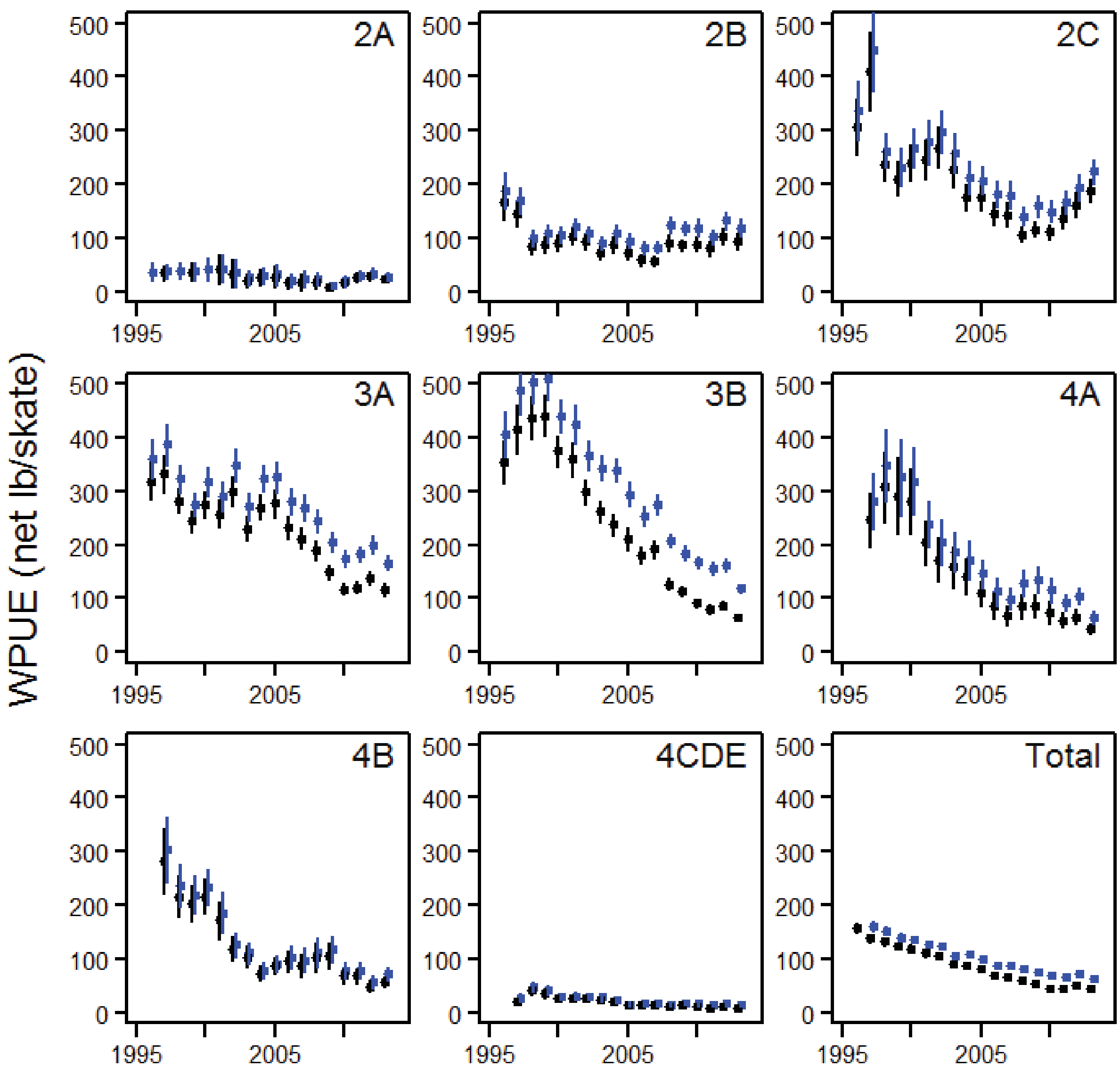

Figure 6. Setline survey total WPUE (blue; slightly larger values) and legal-size WPUE (black) by area and year through 2013. Total WPUE values have been offset slightly on the x-axis to make the points easier to distinguish.

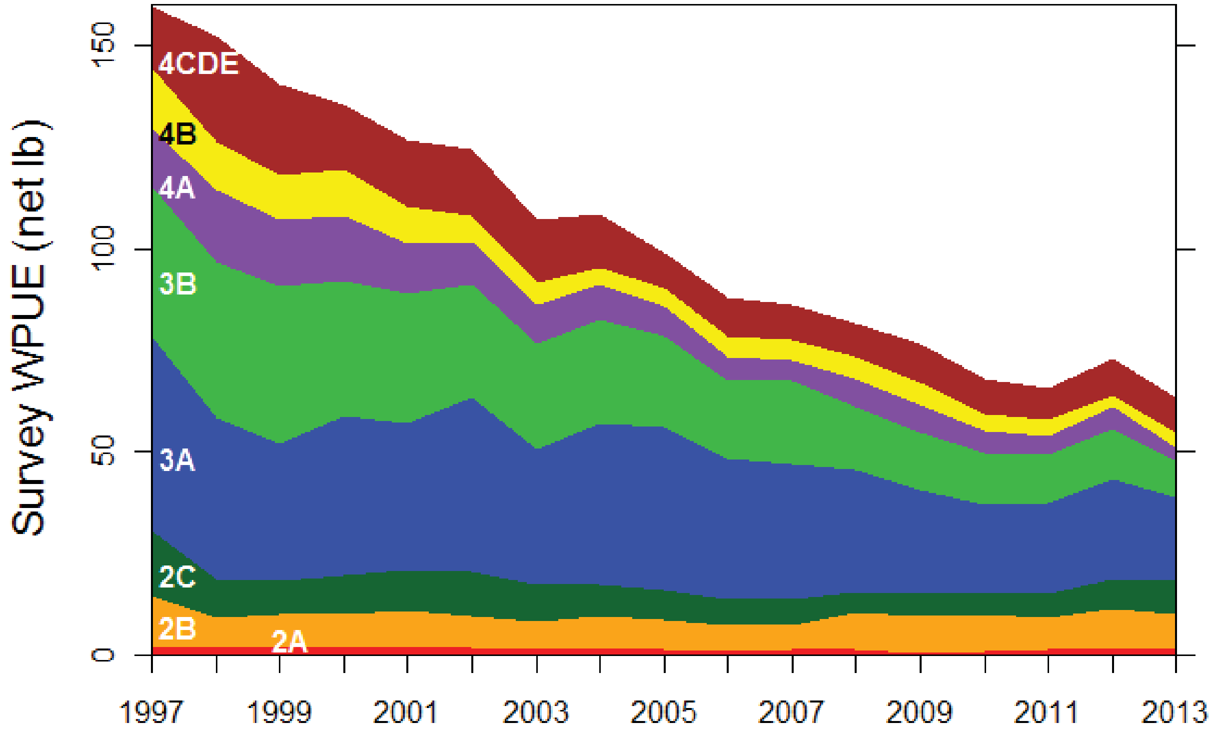

Figure 7. Weighted contributions of the regulatory areas to the coastwide survey total WPUE.

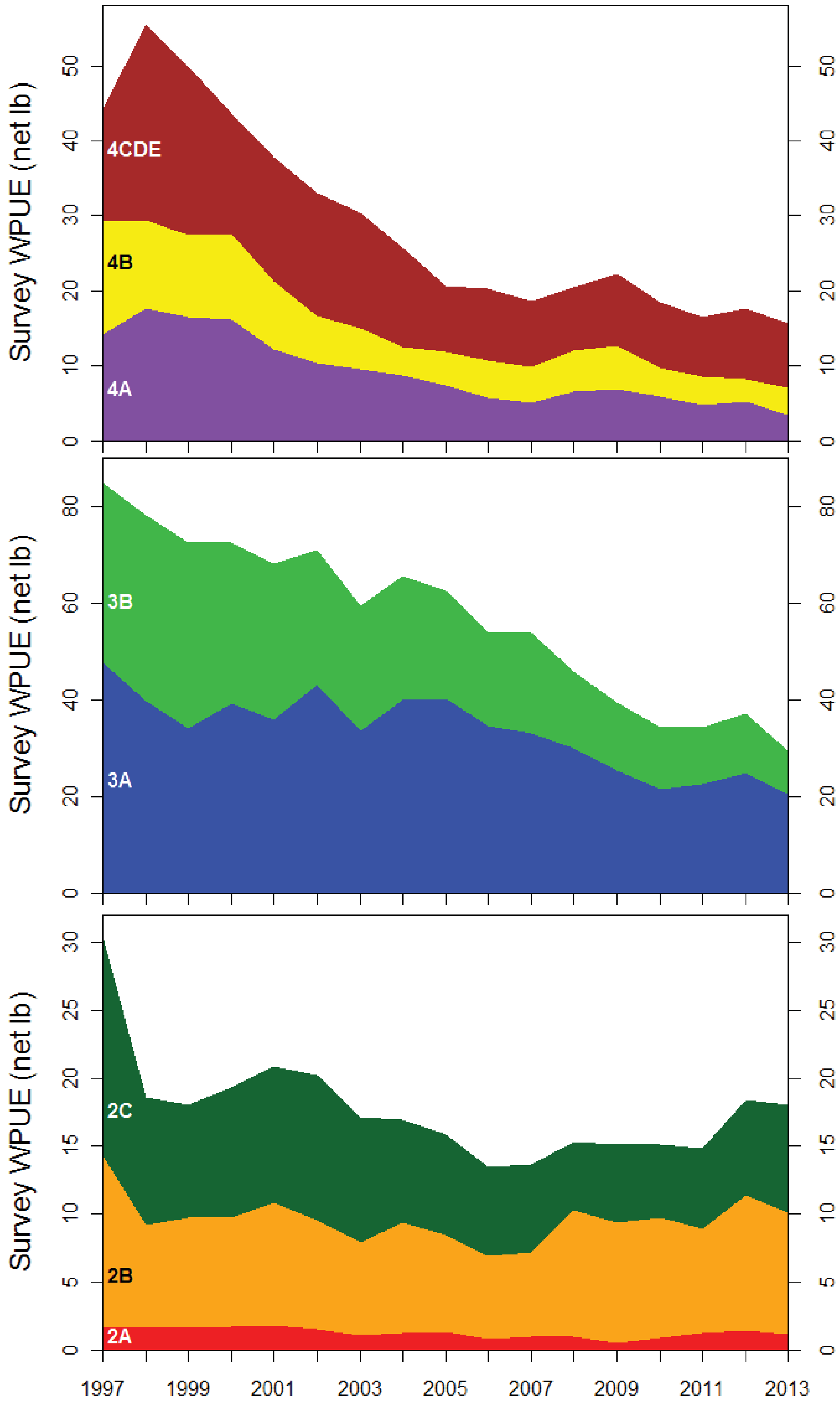

Figure 8. Weighted contributions of the individual regulatory Areas within the survey WPUE for Area 2 (lower panel), Area 3 (middle panel) and Area 4 (upper panel). Note that the y-axes differ among the panels.

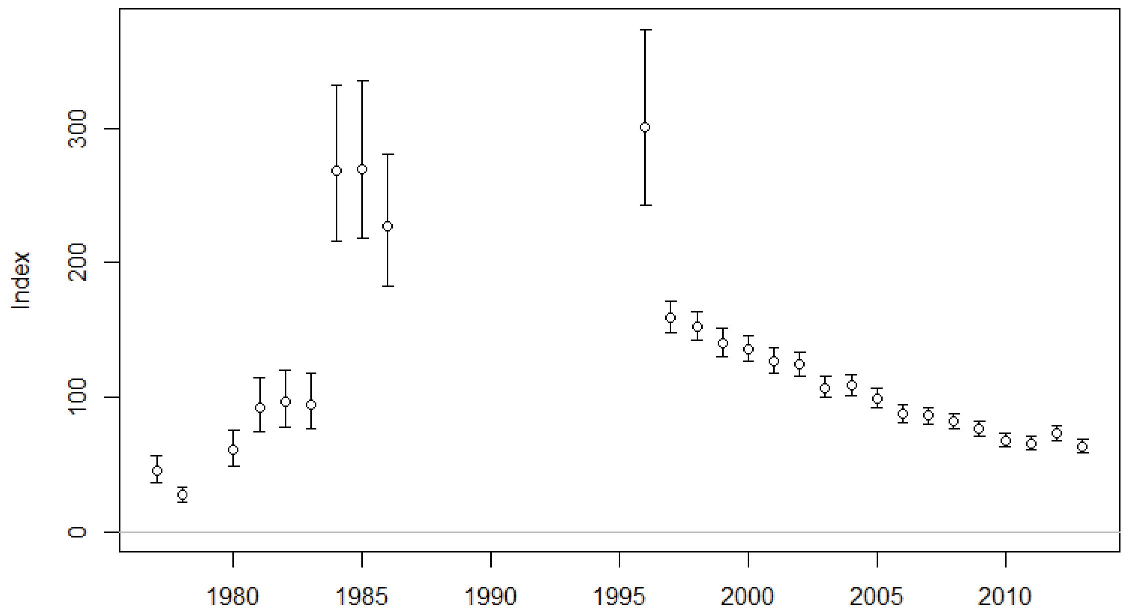

Figure 9. Aggregate setline survey total WPUE. This index contains only regulatory Areas 2B and 3A until 1981, Areas 2B, 2C, and 3A from 1982-1996, and all regulatory Areas from 1997-2013. The increase between 1983 and 1984 coincides with the adoption of circle hooks.

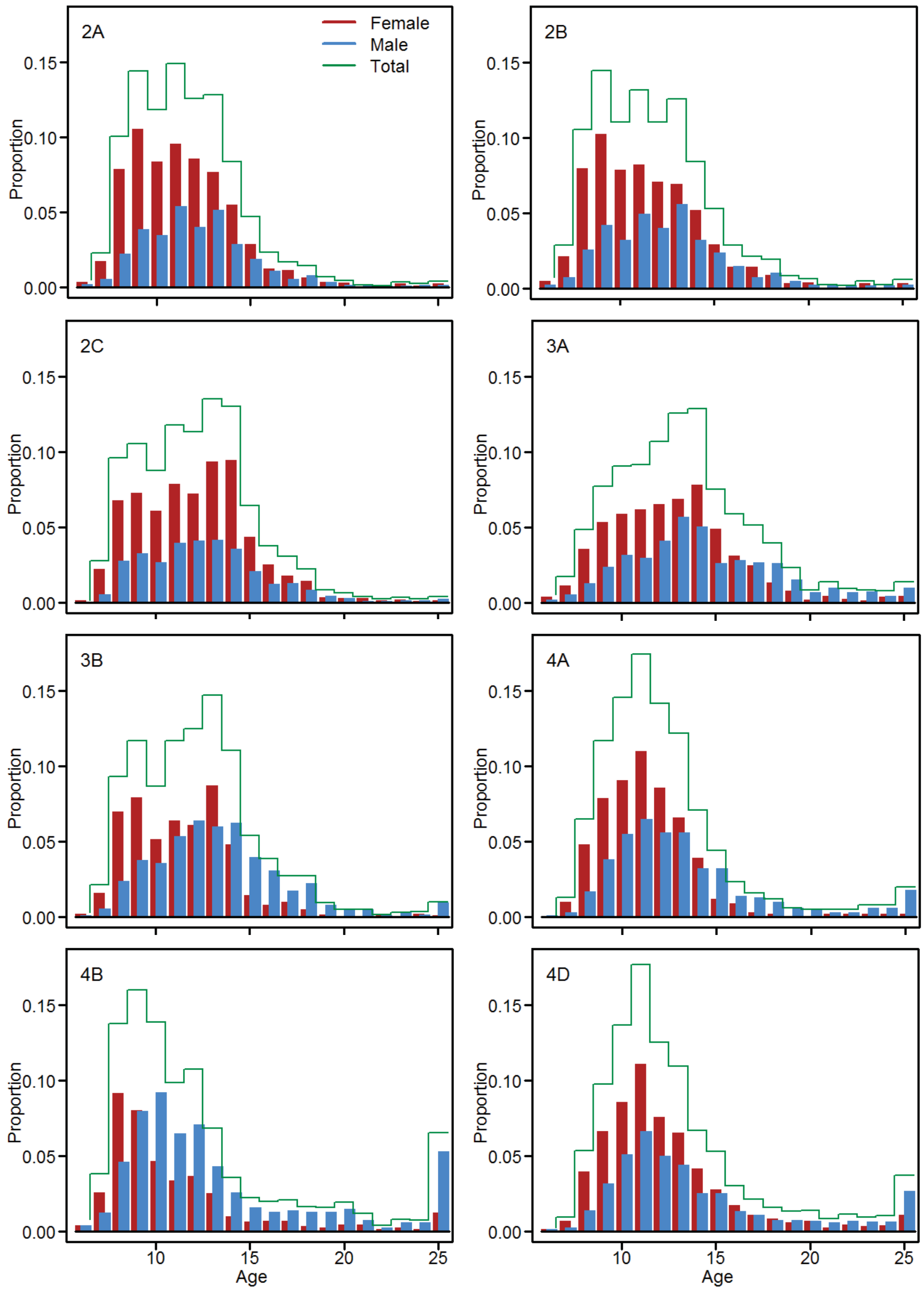

Figure 10. Age distributions from the 2013 setline survey by regulatory Area.

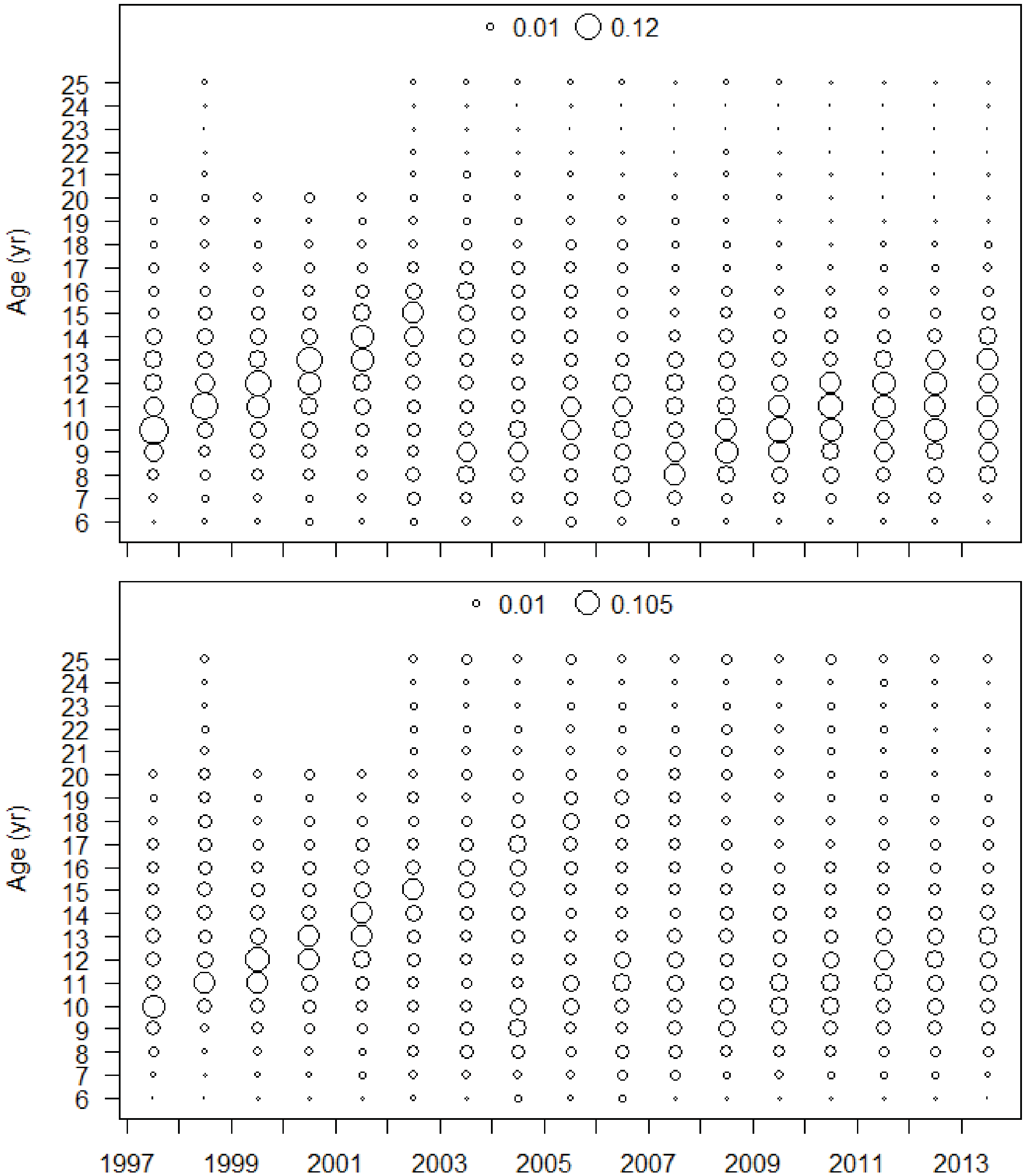

Figure 11. Recent coastwide proportions-at-age for females (upper panel) and males (lower panel) from the setline survey. Proportions sum to 1.0 across both sexes.

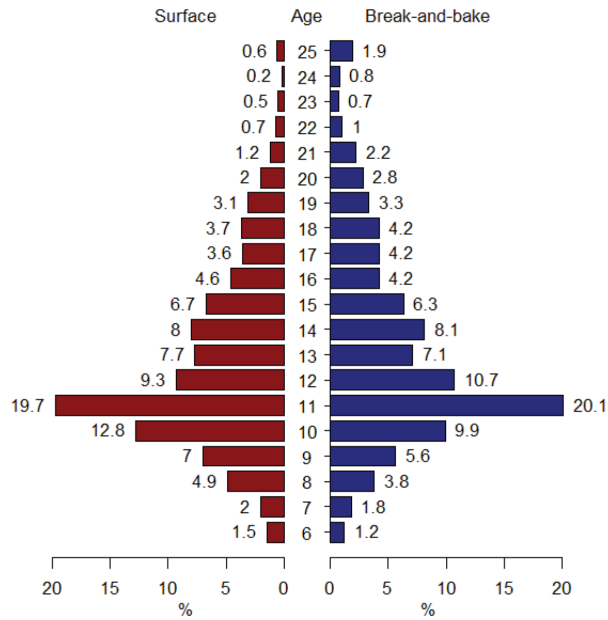

Figure 12. Comparison of raw age-frequency distributions from the 1998 otoliths re-aged in 2013. Age categories 6 and 25 represent aggregates of all ages less and greater than those values.

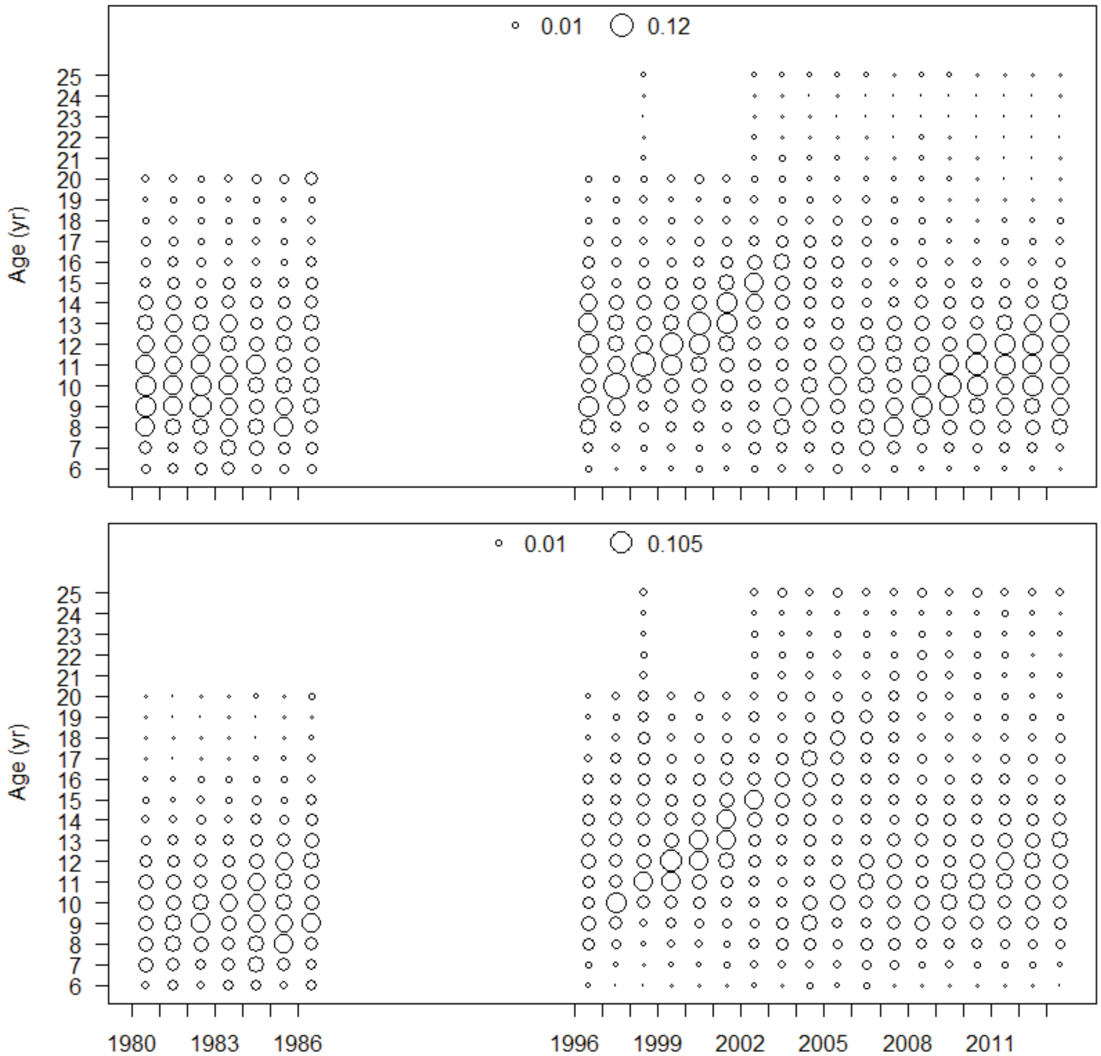

Figure 13. Proportions-at-age for female (upper panel) and male (lower panel) halibut captured by the setline survey. Years prior to 1997 represent reduced and variable spatial coverage.

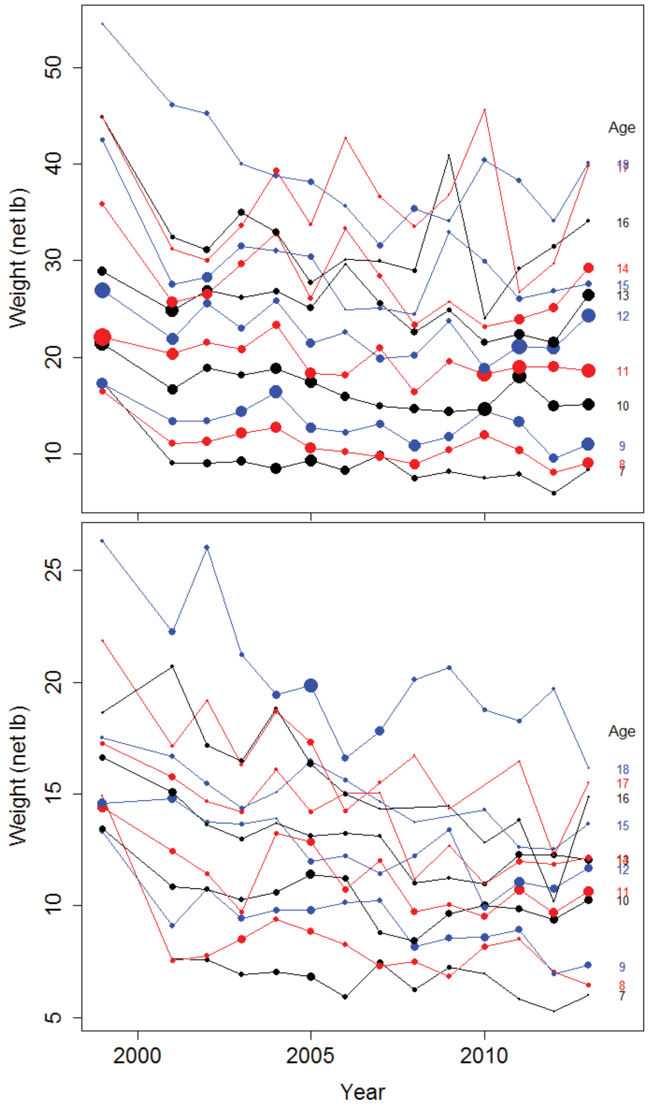

Figure 14. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 2A captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

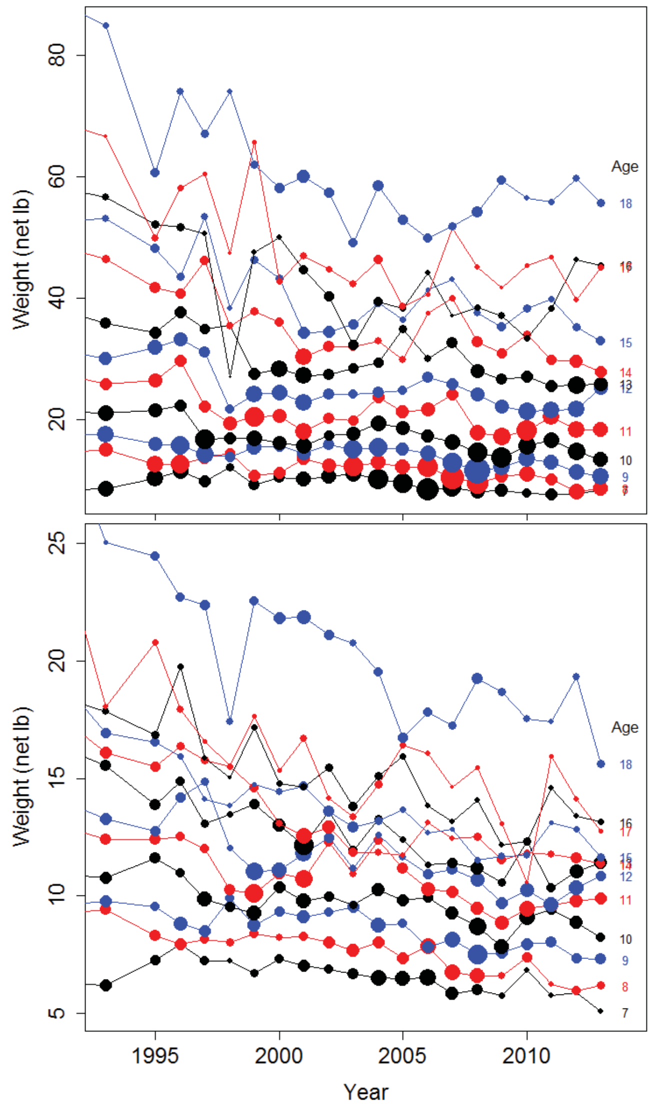

Figure 15. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 2B captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

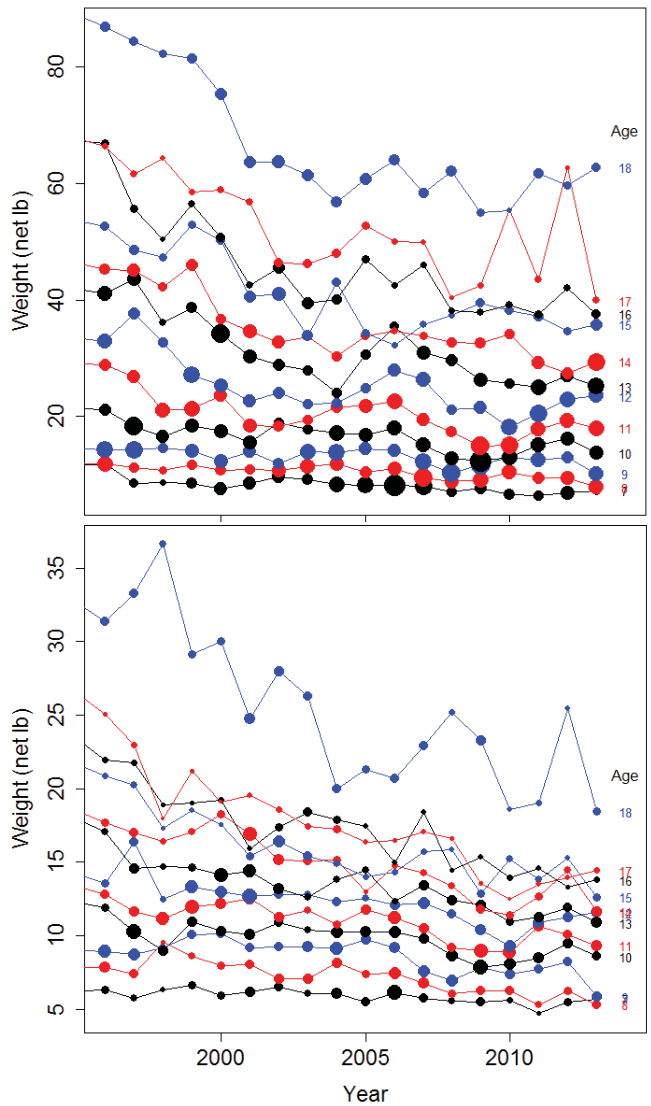

Figure 16. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 2C captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

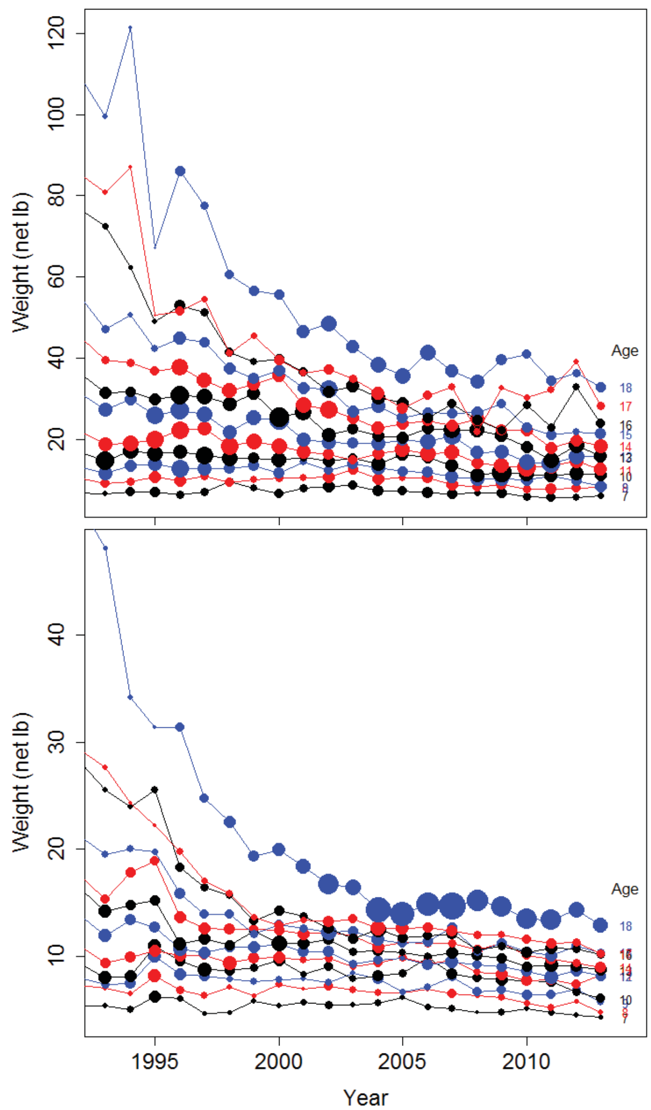

Figure 17. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 3A captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

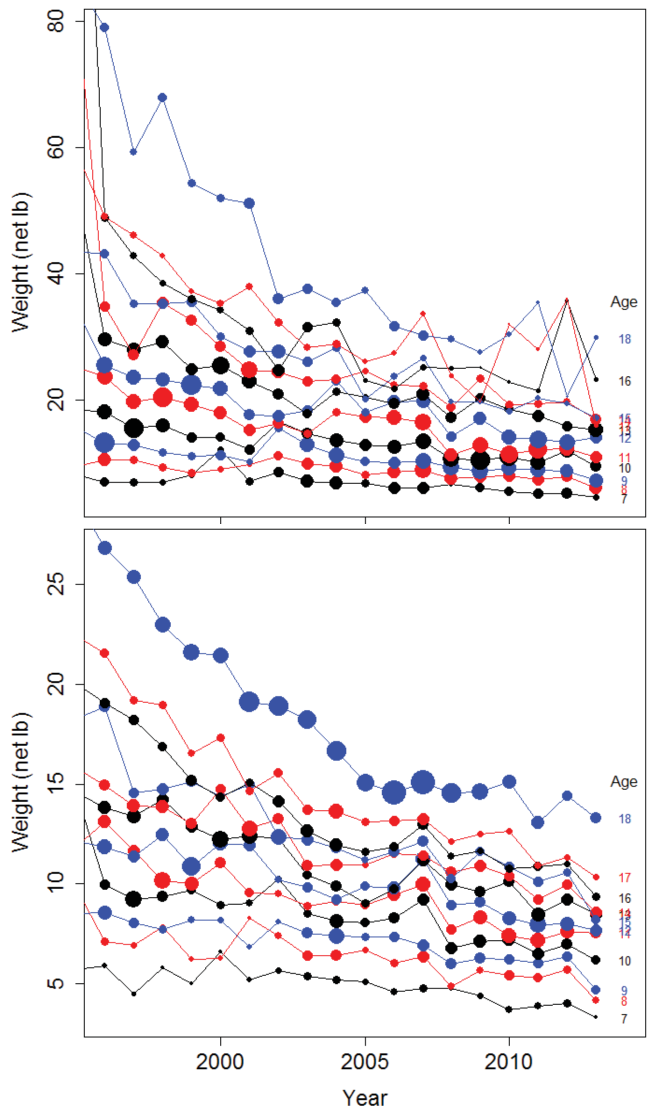

Figure 18. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 3B captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

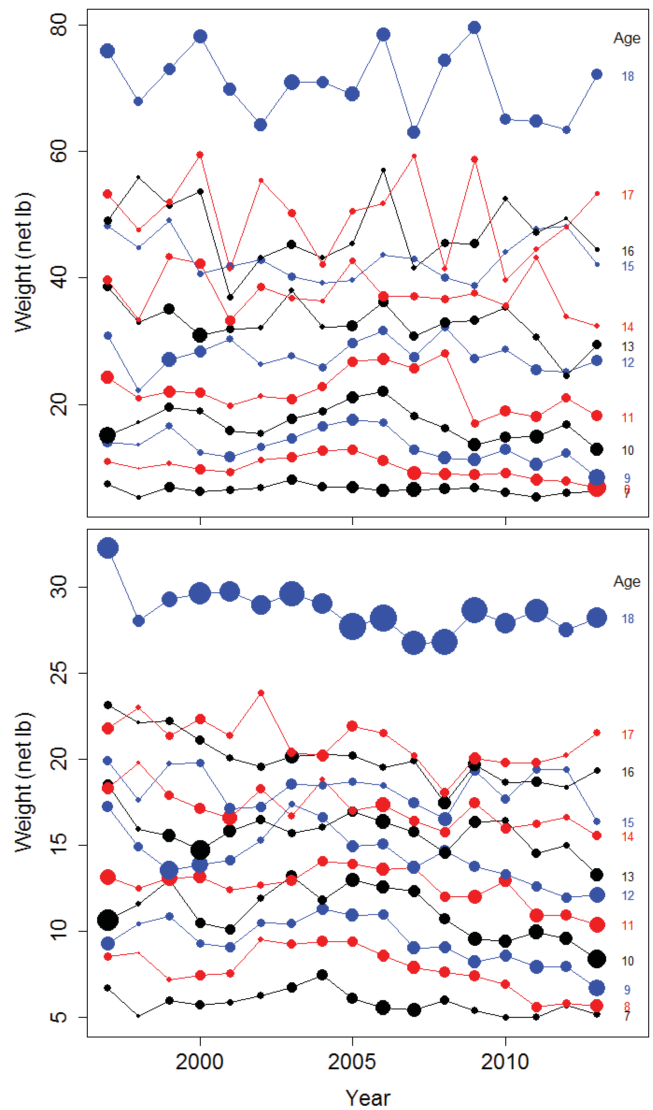

Figure 19. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 4A captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

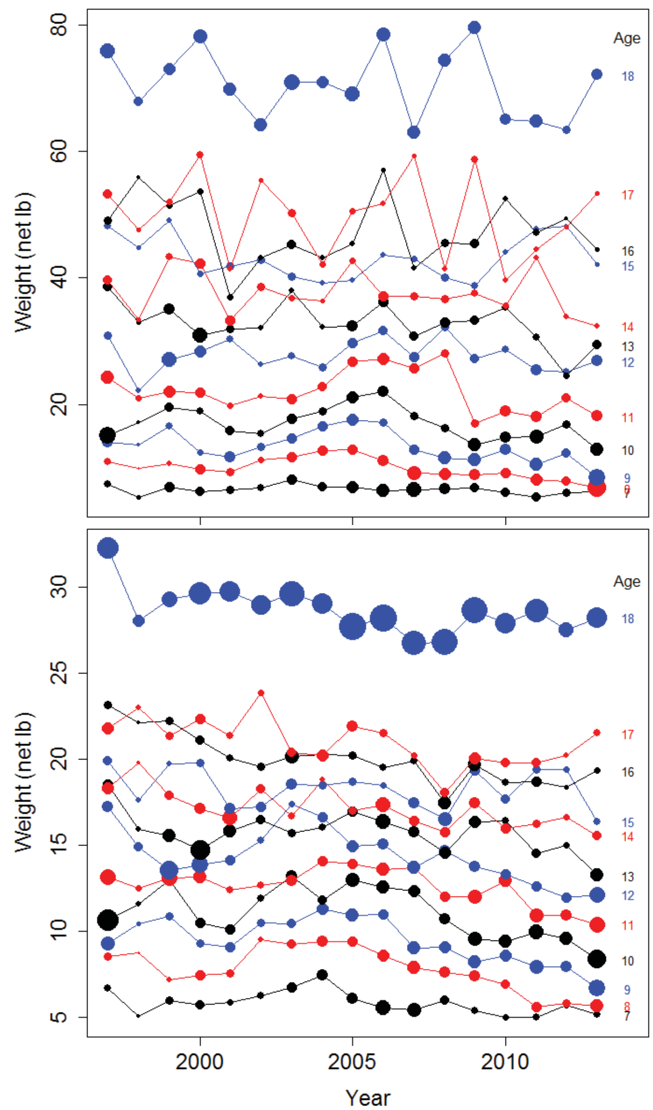

Figure 20. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Area 4B captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

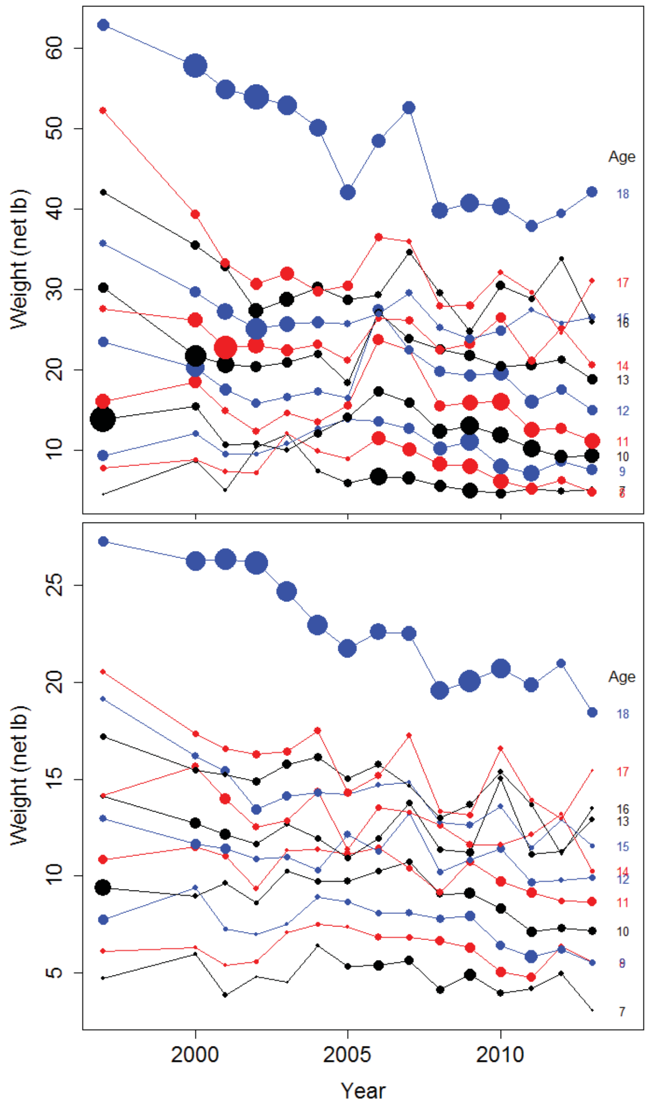

Figure 21. Trends in weight at age for female (upper panel), and male (lower panel) halibut from regulatory Areas 4C, 4D and 4E captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

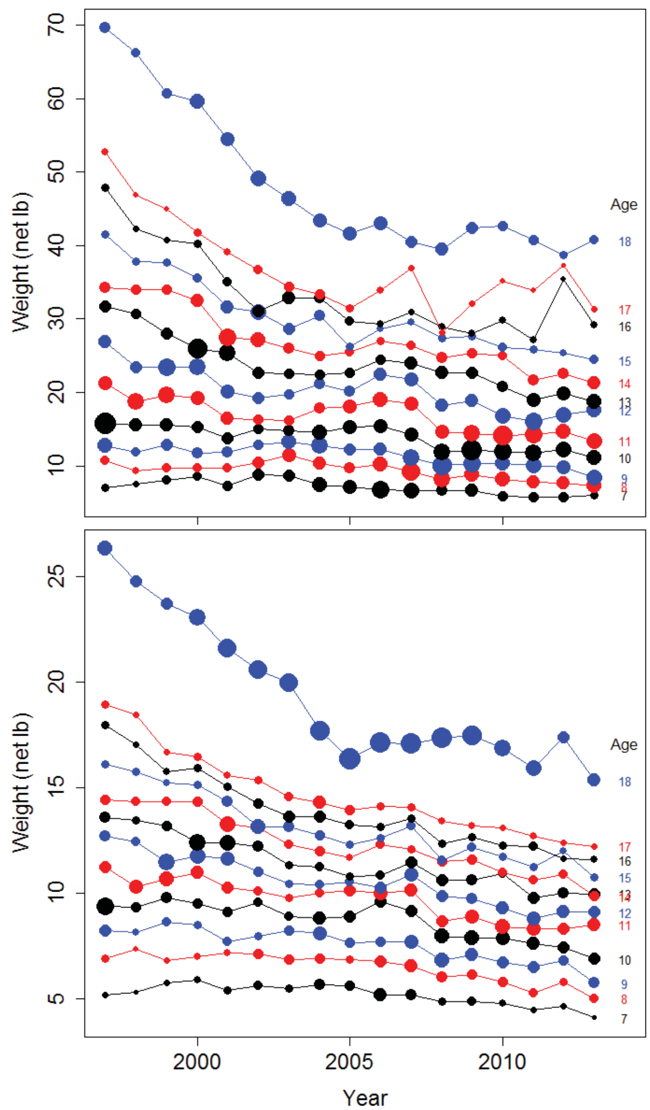

Figure 22. Weighted coastwide trends in weight at age for female (upper panel), and male (lower panel) halibut from all regulatory Areas captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 18 and greater have been aggregated for clarity.

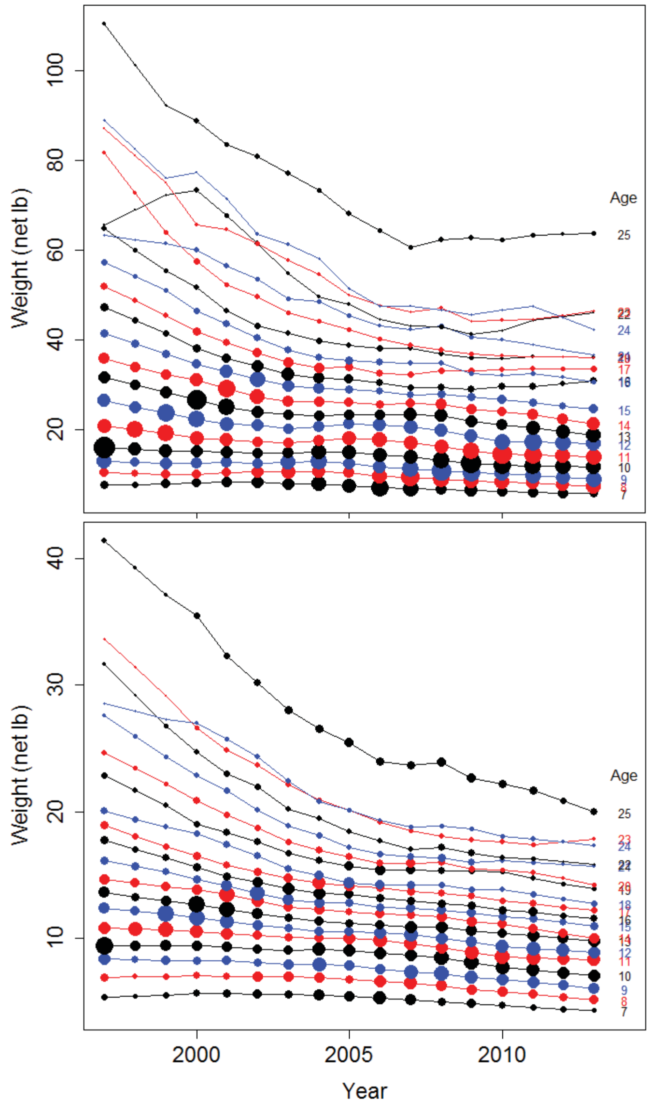

Figure 23. Weighted and smoothed coastwide trends in weight-at-age for female (upper panel), and male (lower panel) halibut from all regulatory Areas captured by the setline survey. The size (area) of the points is proportional to the number of fish contributing to each observation; ages 25 and greater have been aggregated.

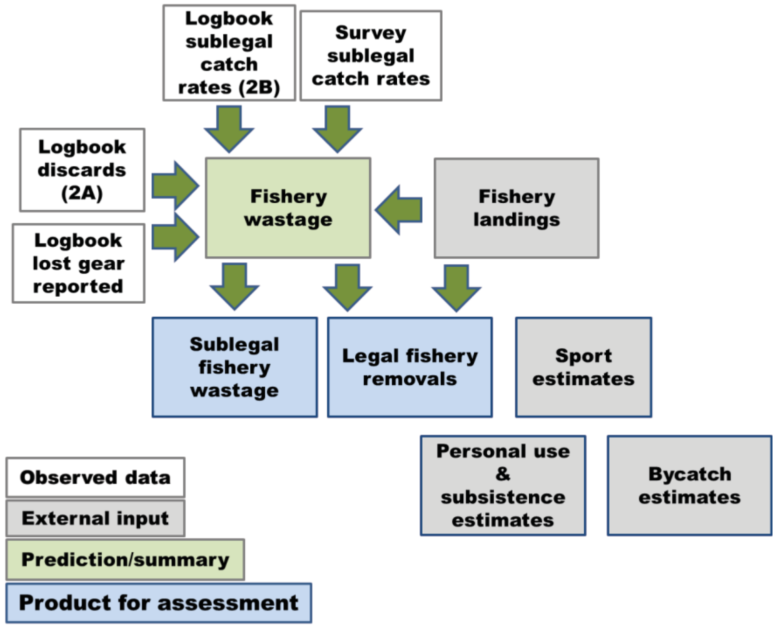

Figure 24. Relationships among estimates halibut mortality by source.

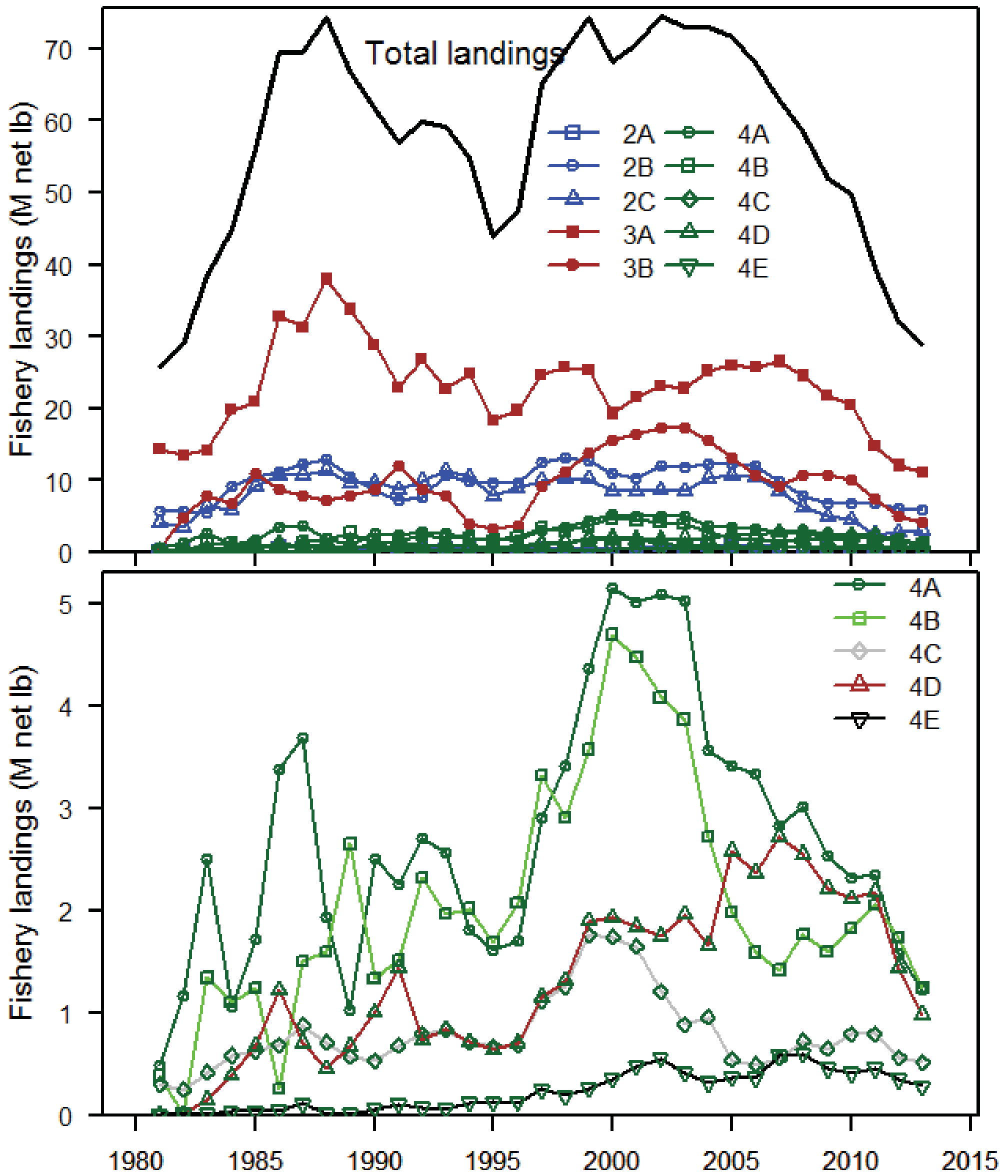

Figure 25. Recent landings of halibut by the directed commercial fishery by regulatory area (upper panel), and within regulatory Areas 4A to 4E for better resolution of the trends (lower panel).

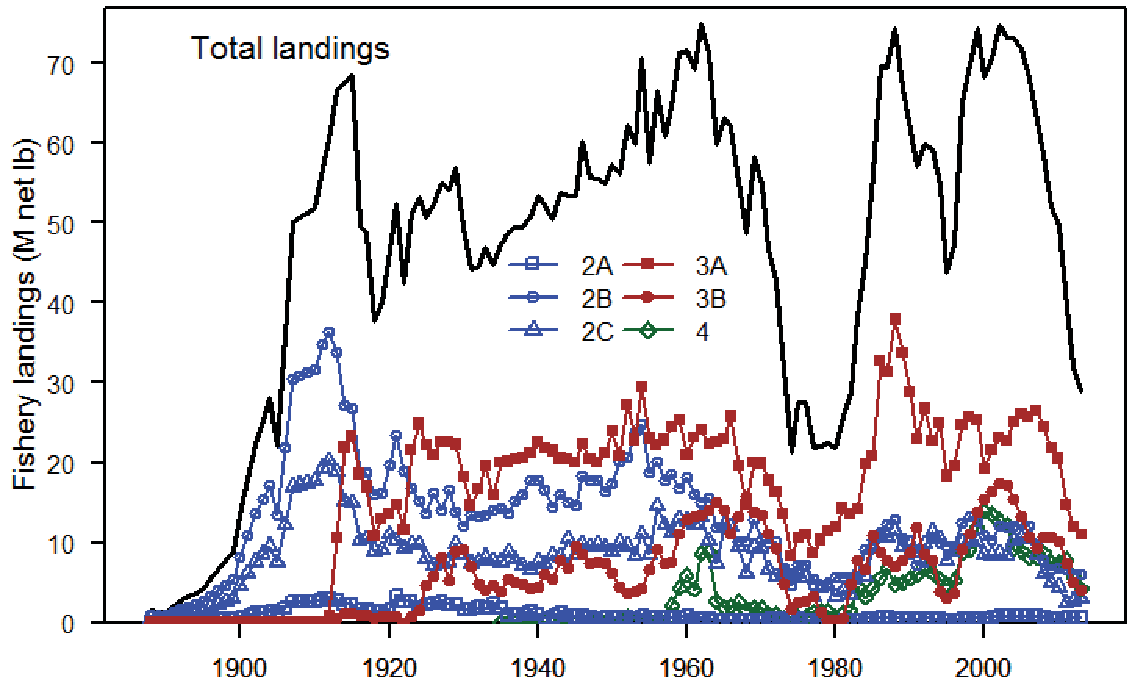

Figure 26. Landings of halibut by the directed commercial fishery by regulatory Area.

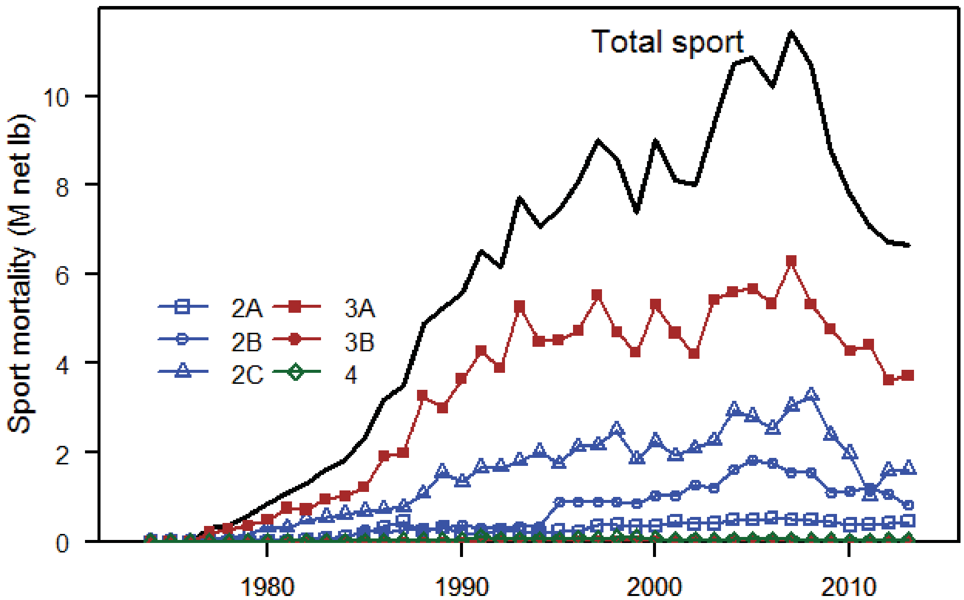

Figure 27. Sport (recreational) removals of halibut by regulatory Area.

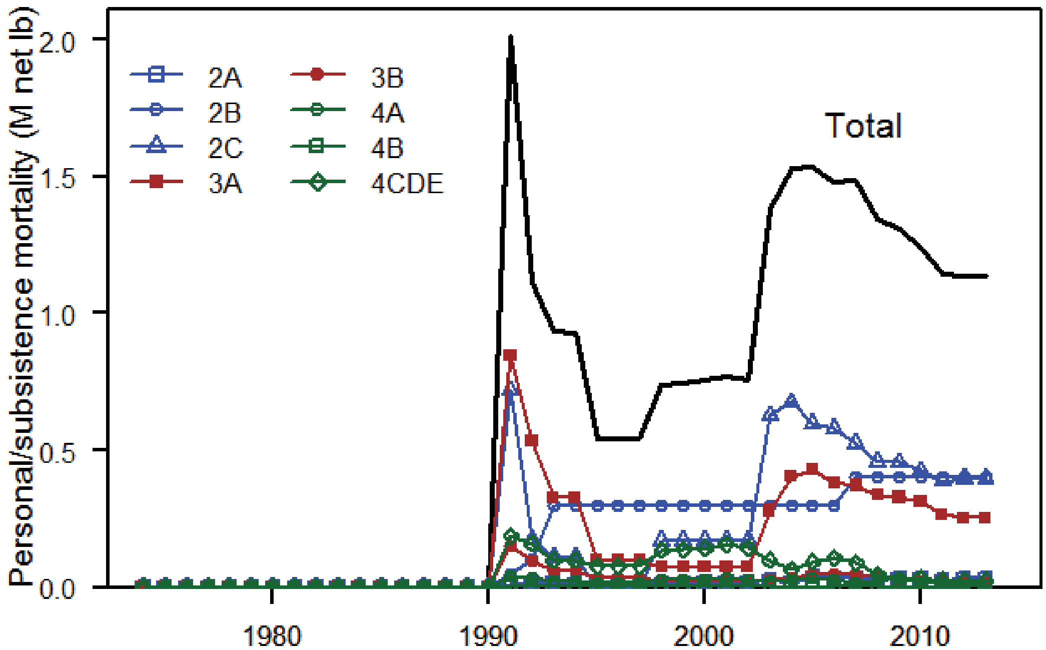

Figure 28. Estimated personal use or subsistence removals by regulatory Area.

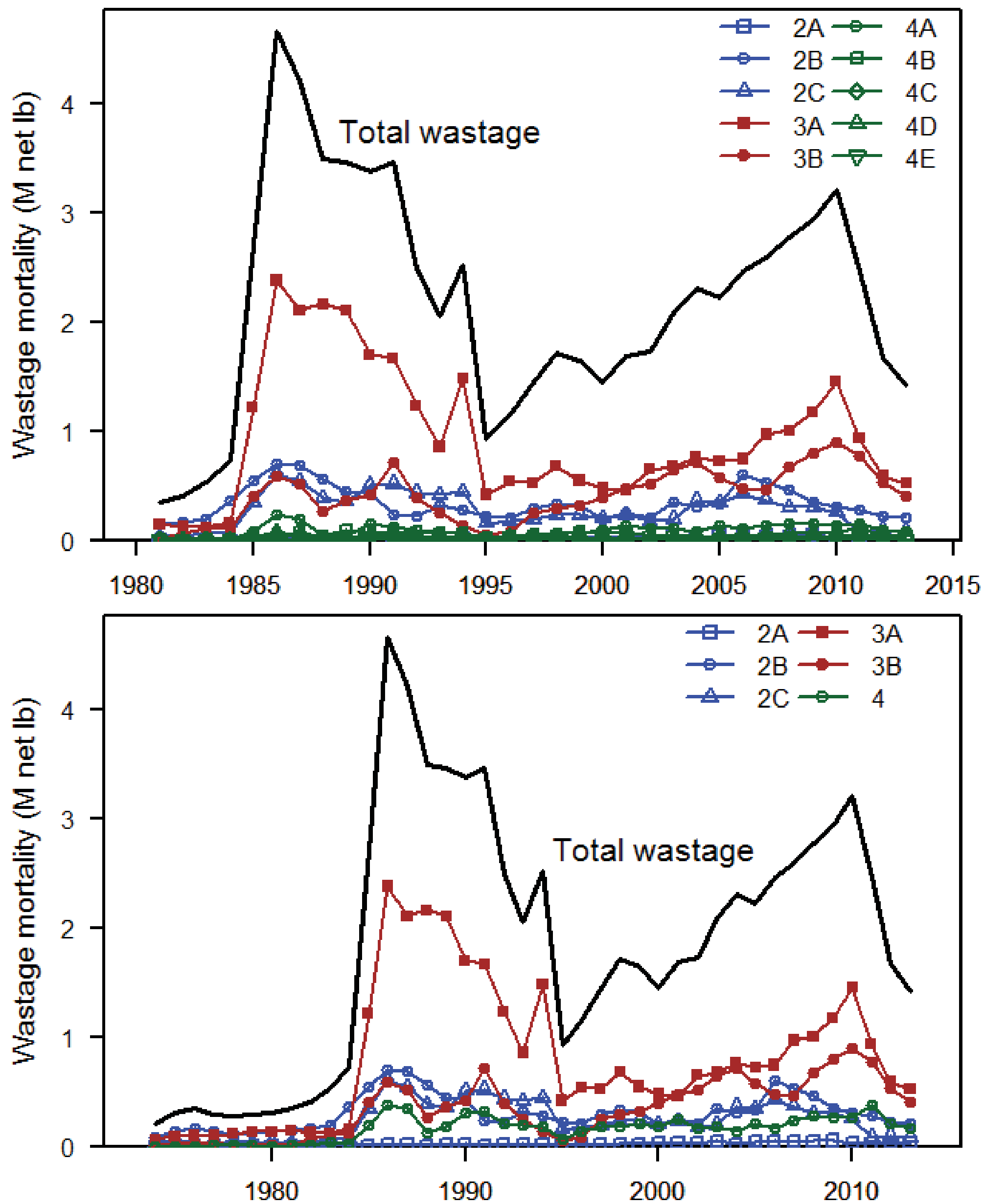

Figure 29. Wastage in the commercial fishery by regulatory Area, 1981-2013 (upper panel), and 1974-2013, with all of Area 4 combined (lower panel).

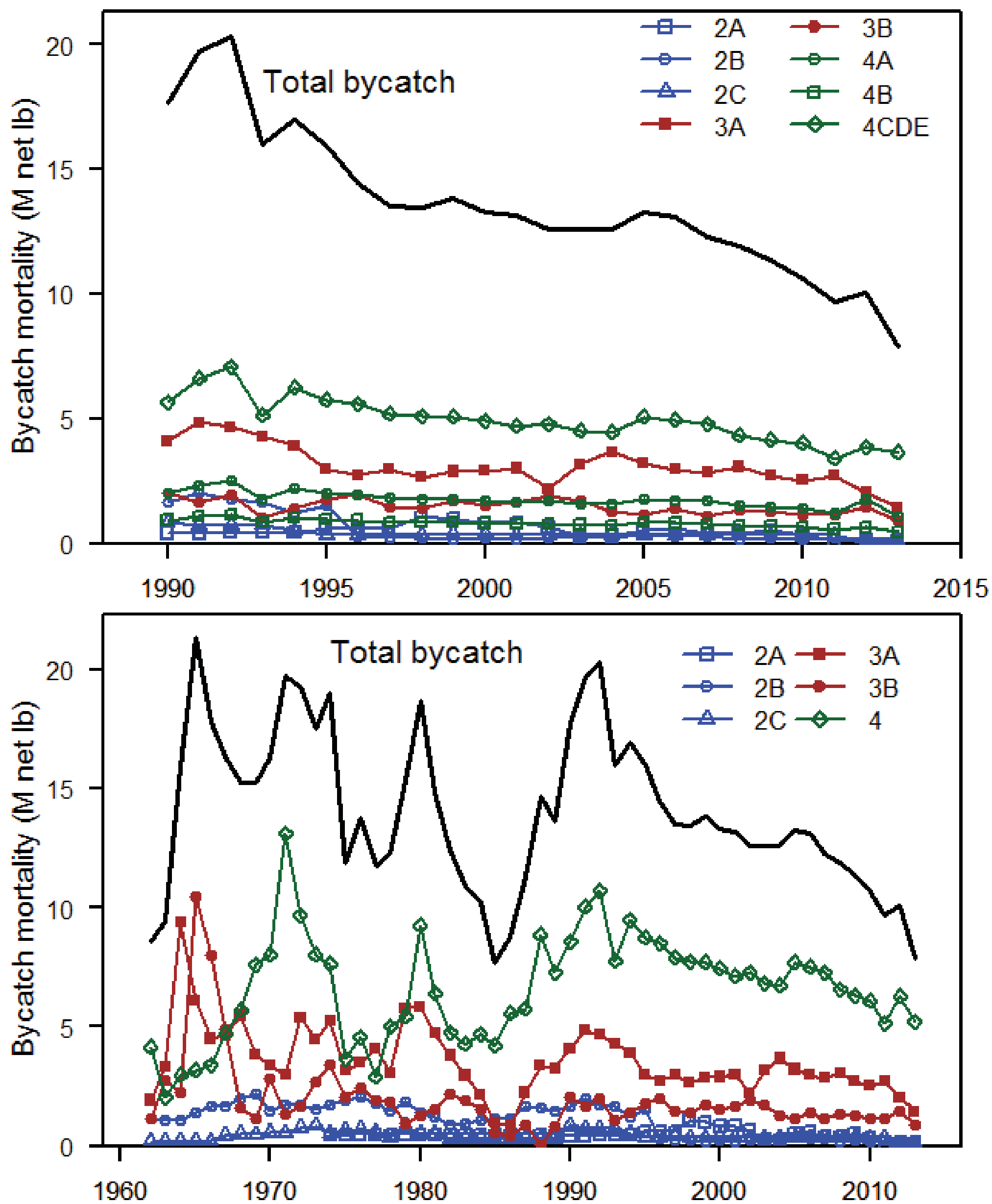

Figure 30. Halibut bycatch estimates by regulatory Area, 1990-2013 (upper panel), and 1962-2012, with all of Area 4 combined (lower panel).

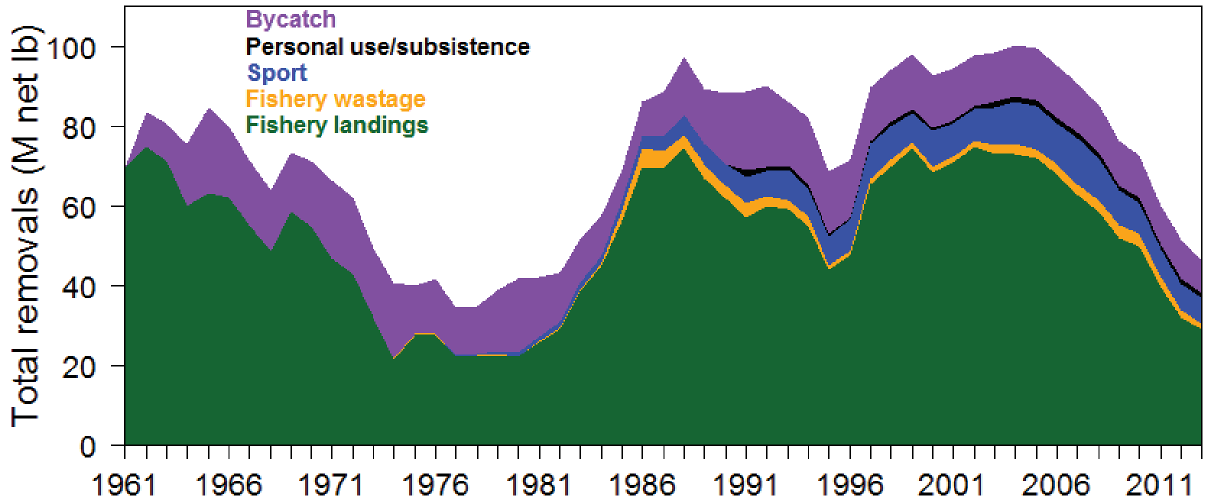

Figure 31. Total removals by source since 1961.

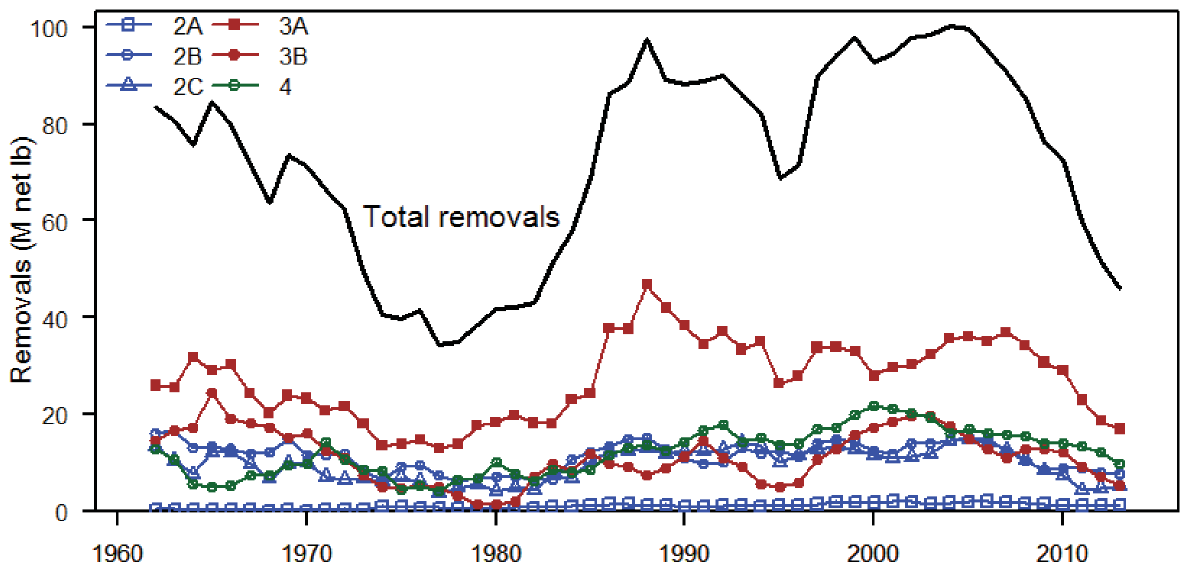

Figure 32. Total removals by regulatory Area since 1962.

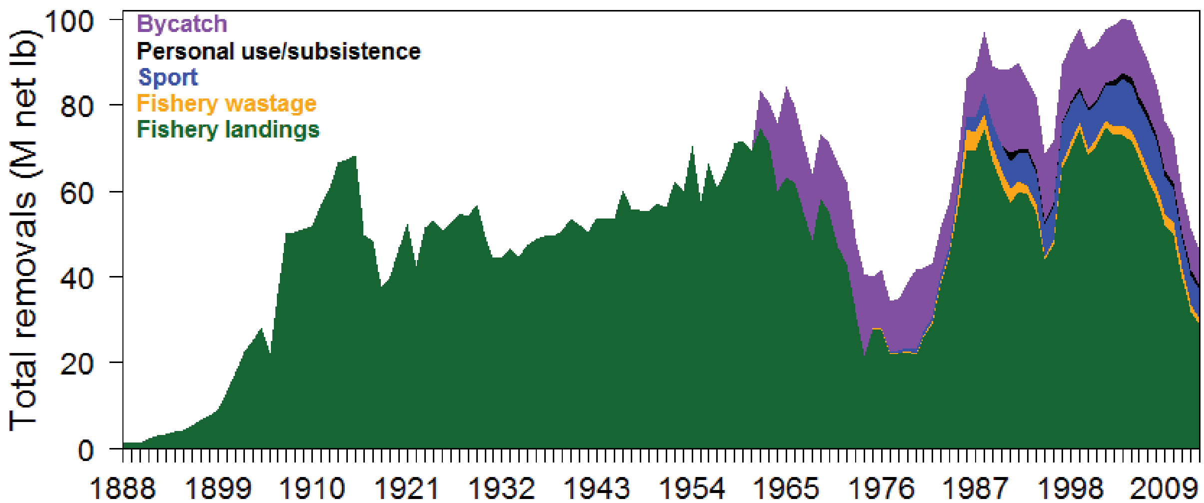

Figure 33. Total estimated removals by source since 1888.

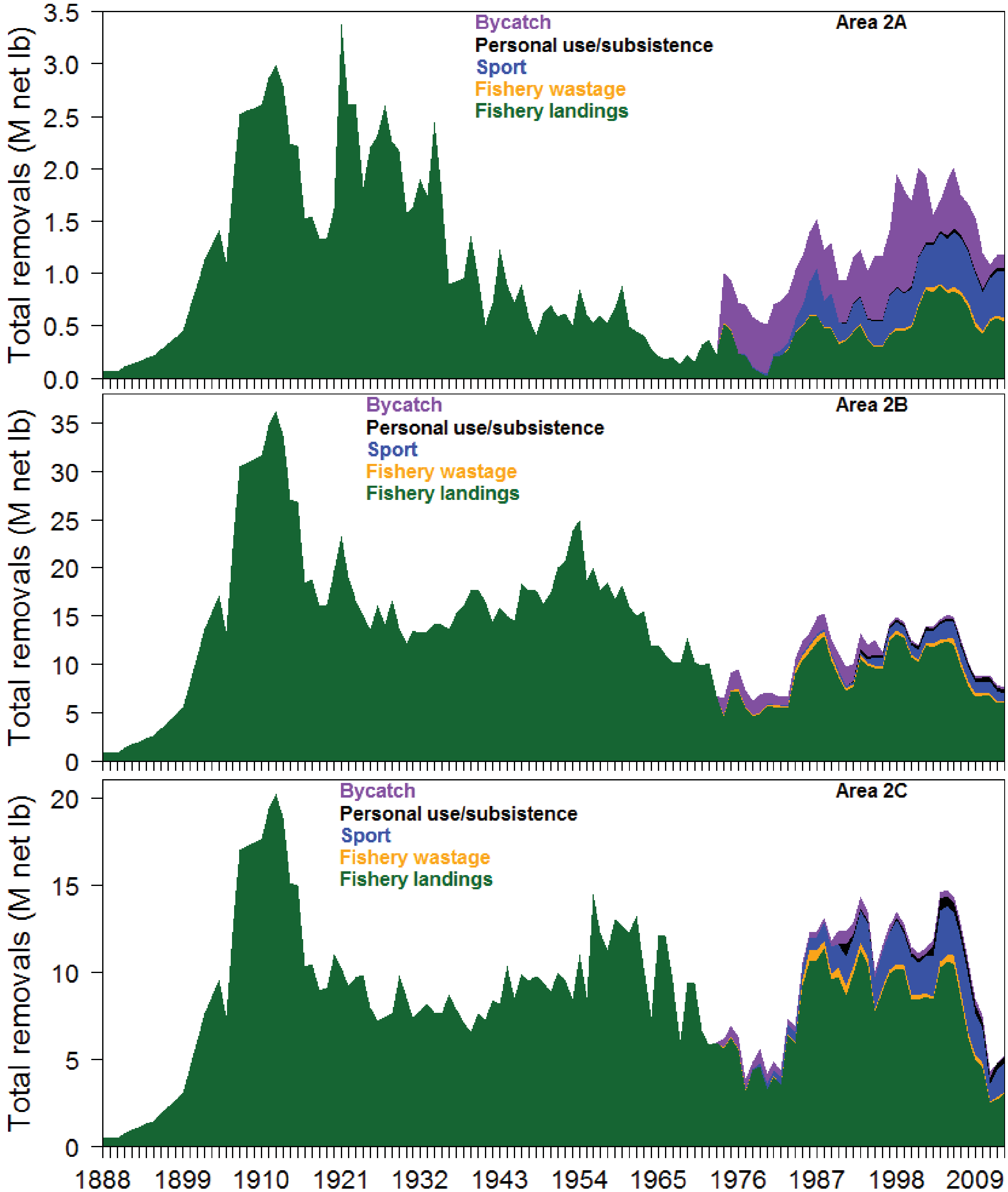

Figure 34. Total estimated removals by source in Areas 2A, 2B, and 2C since 1888. Note that the y axes differ in scale.

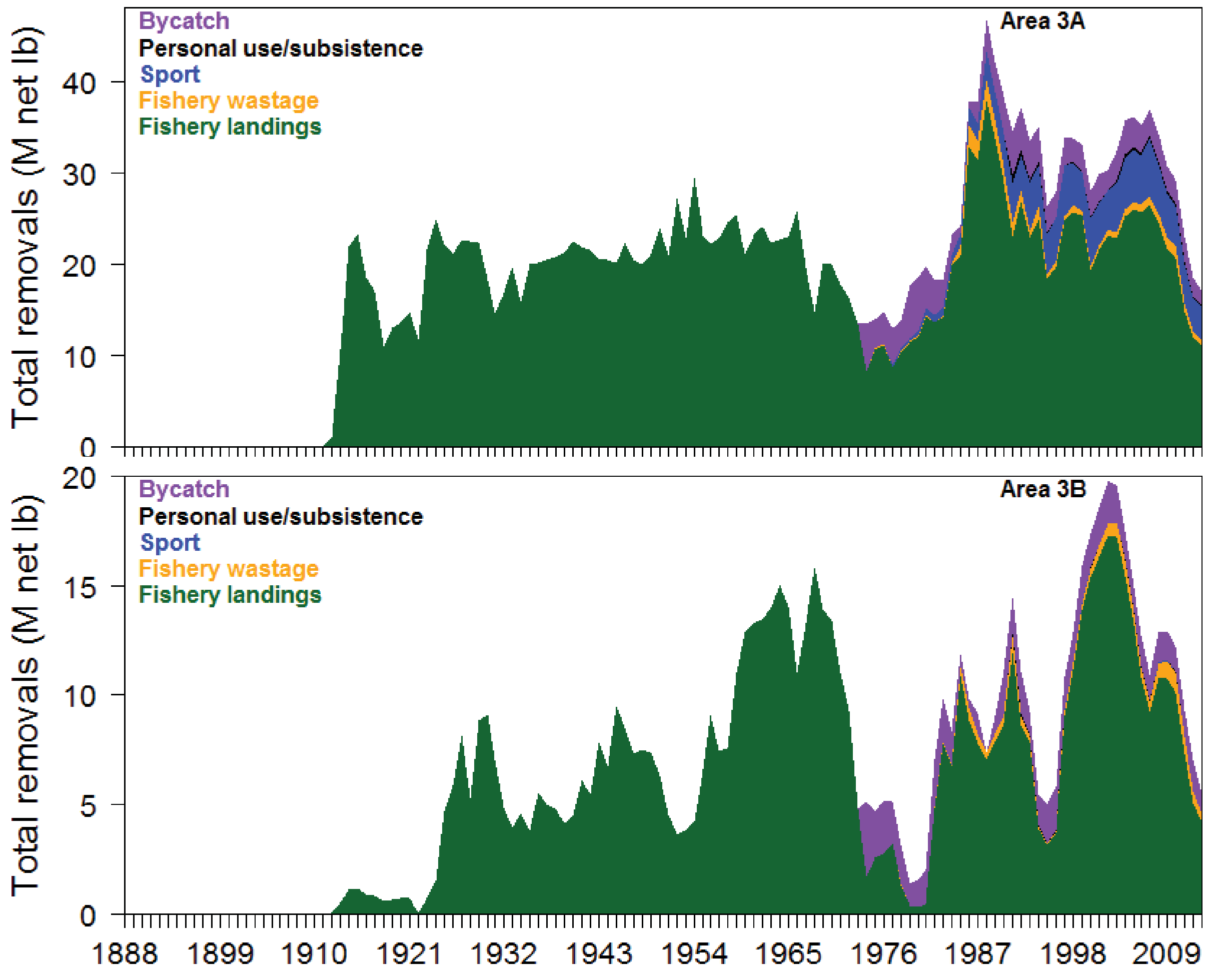

Figure 35. Total estimated removals by source in Areas 3A, and 3B since 1888. Note that the y-axes differ in scale.

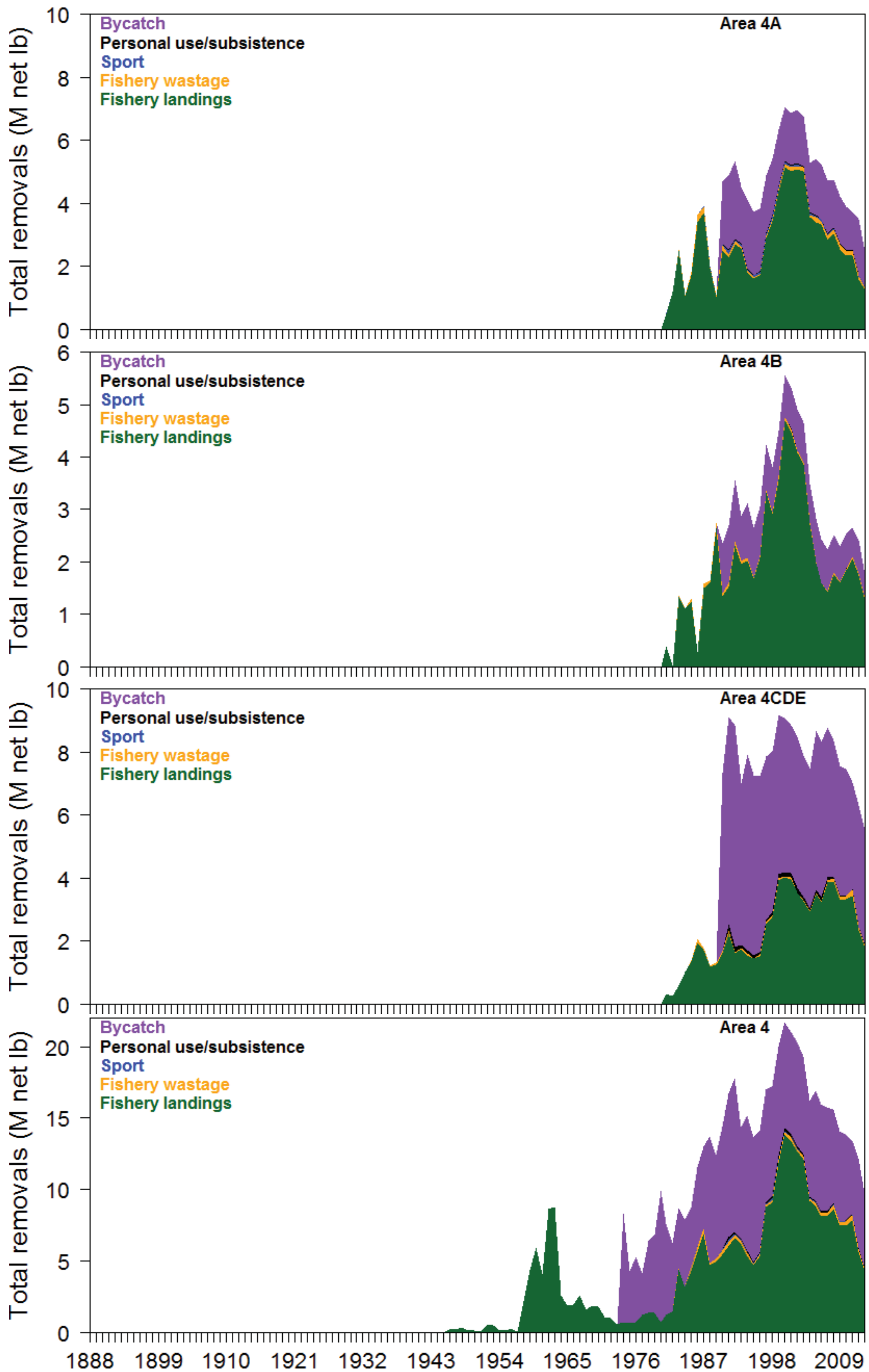

Figure 36. Total estimated removals by source in Areas 4A, 4B, 4CDE, and all of Area 4 combined since 1888. Note that the y-axes differ in scale.

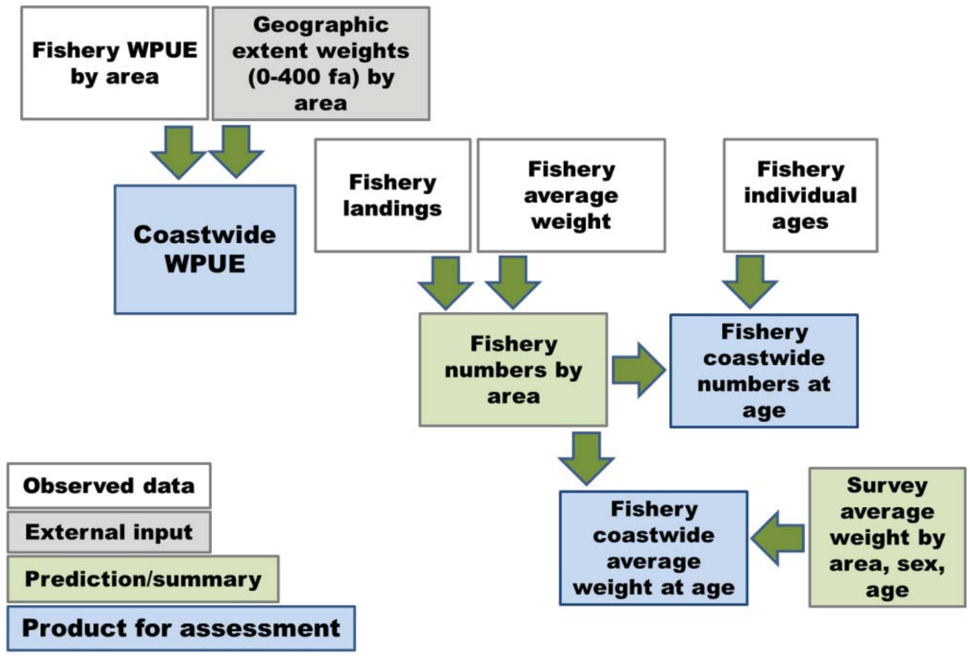

Figure 37. Relationships among fishery-dependent catch-rate and biological data sources.

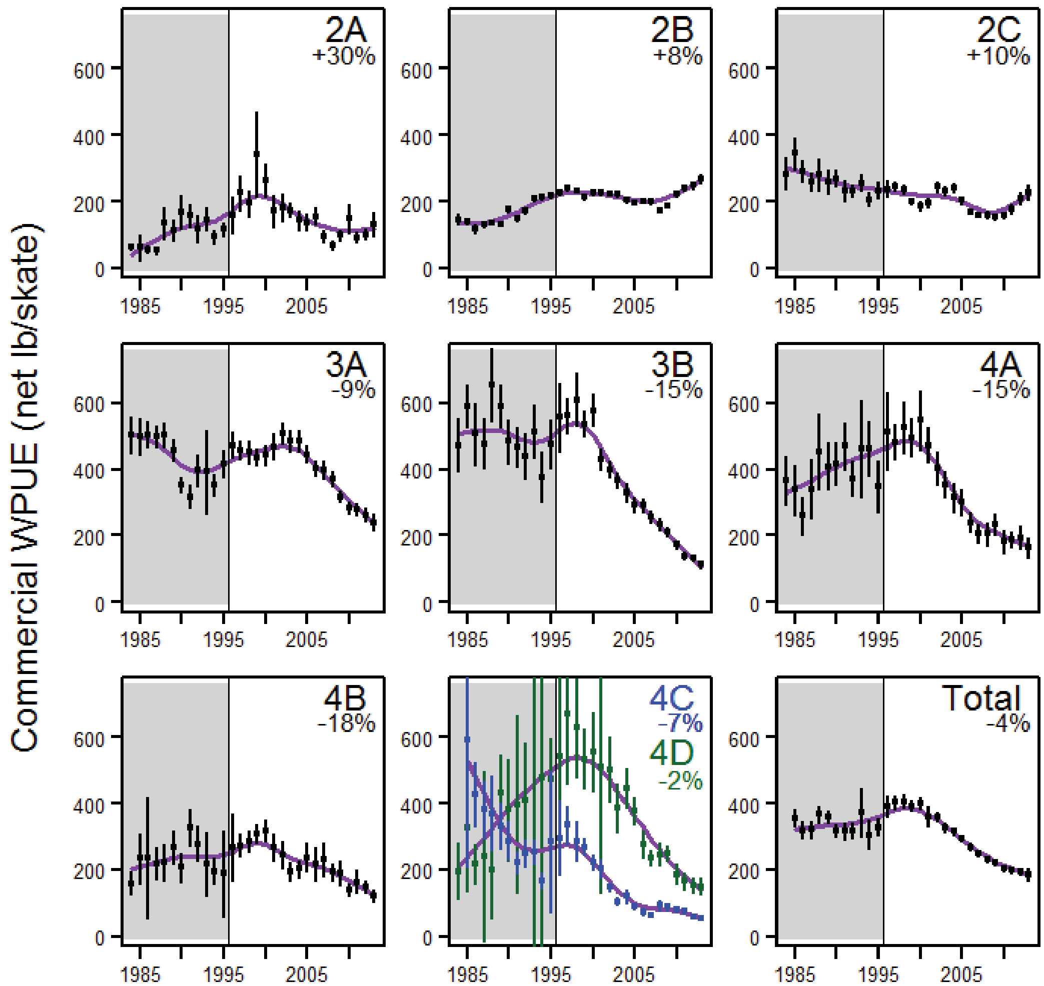

Figure 38. Commercial WPUE summarized by regulatory area and year. Percentages for each Area indicate the change from 2012 to 2013; lines represent a smoother for visualization purposes only.

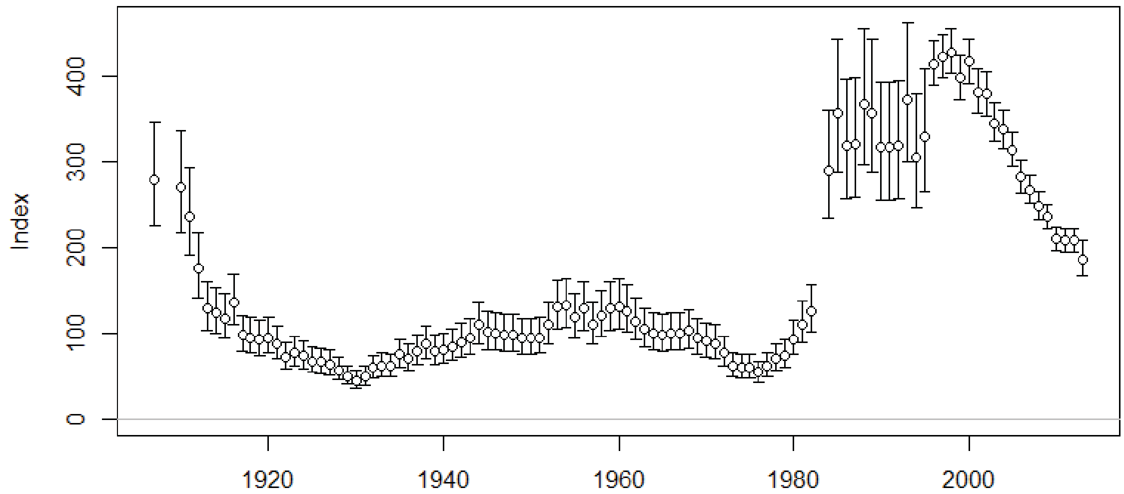

Figure 39. Coastwide commercial WPUE from historical records of effort and catch, as well as more recent direct logbook processing. The large change between 1982 and 1984 coincides with the adoption of circle hooks.

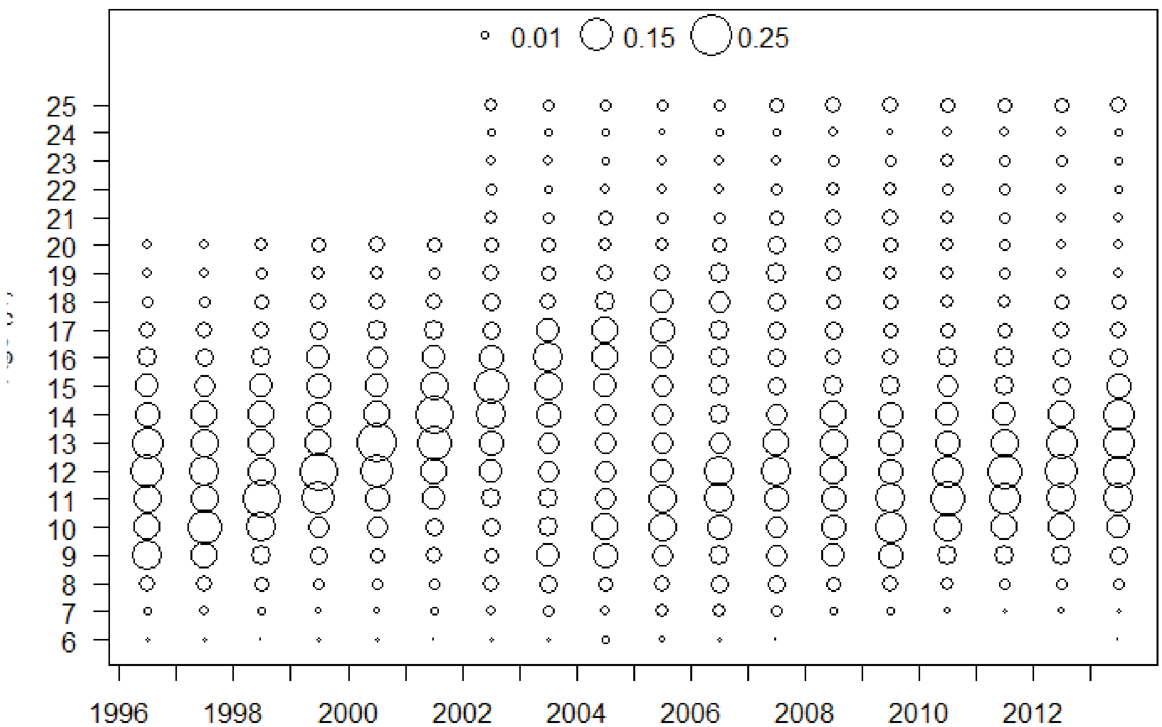

Figure 40. Estimates of recent commercial fishery numbers-at-age.

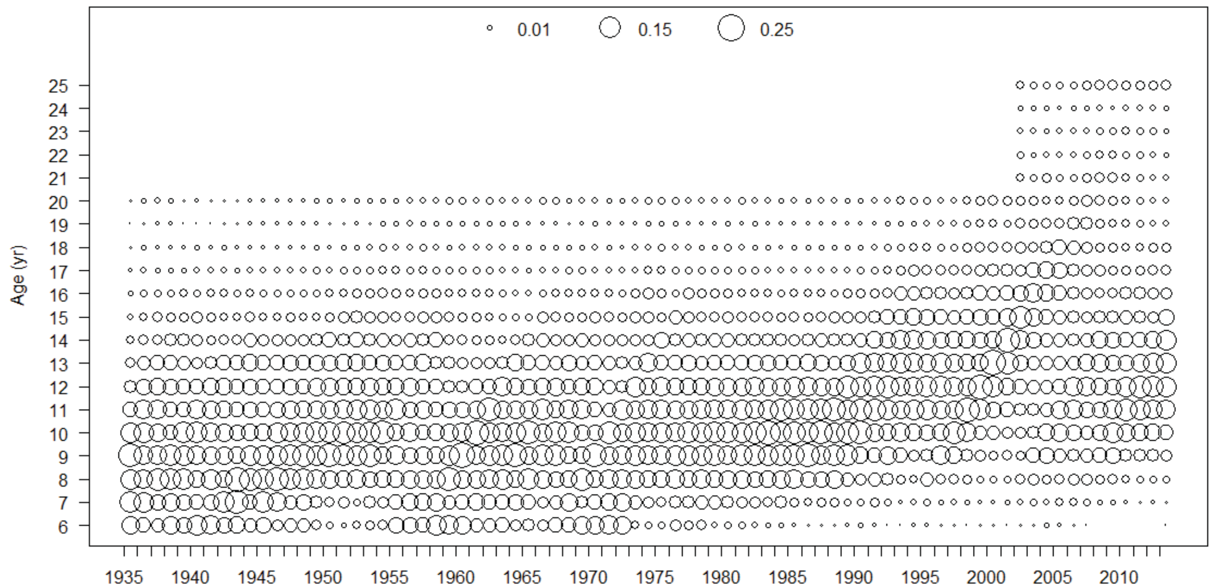

Figure 41. Commercial fishery proportions-at-age from the retained catch (male and female halibut combined). Note that the current 32 inch minimum size limit was implemented in 1973.

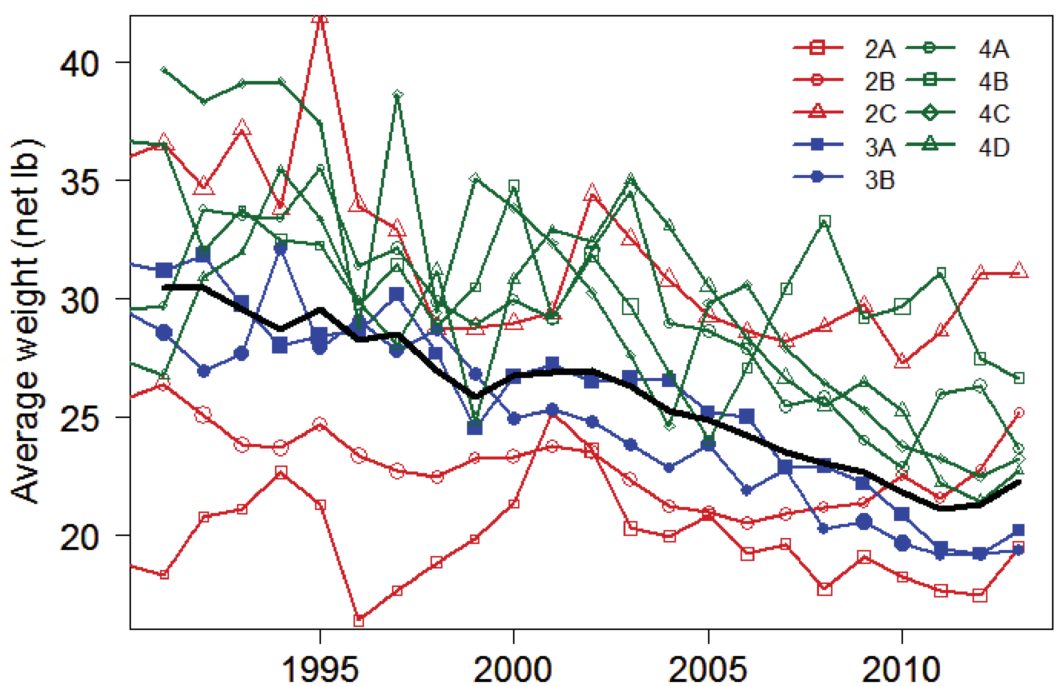

Figure 42. Recent average halibut weight in the directed fishery landings.

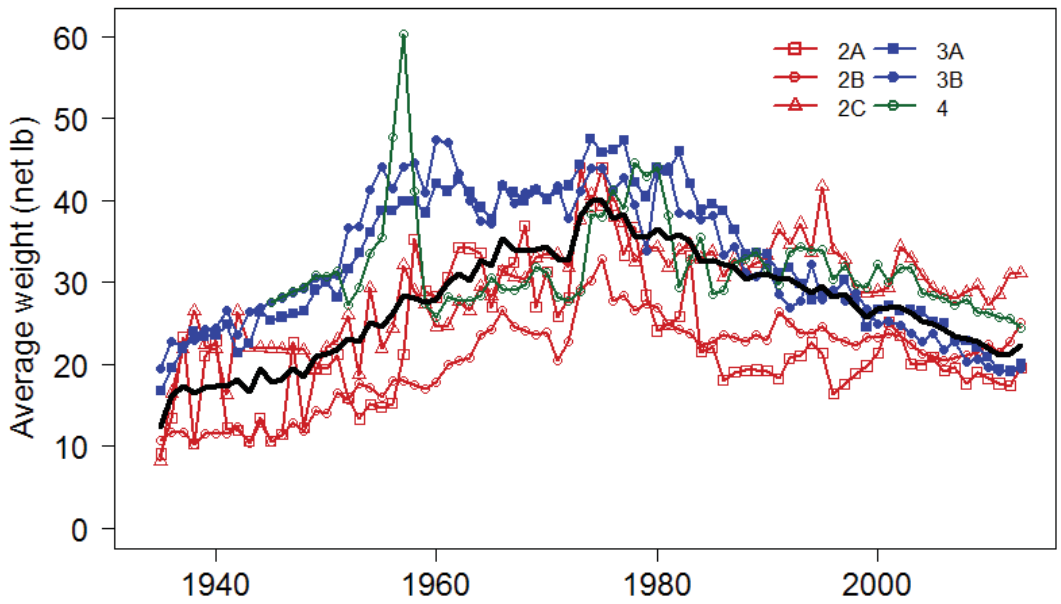

Figure 43. Trends in average individual halibut weight in the commercial fishery landings. The current 32-inch minimum size limit went into effect in 1974.

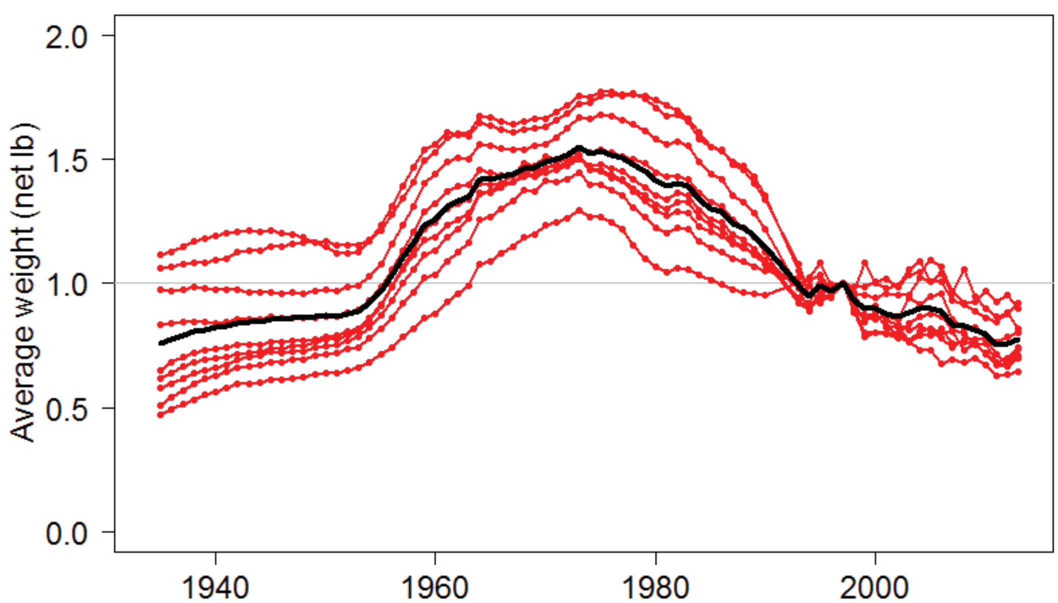

Figure 44. Trends in average individual halibut weight as deviations from 1997 in the commercial fishery landings for halibut aged 8-16 years old (red lines). The black line represents the average trend among the nine ages included. The current 32-inch minimum size limit went into effect in 1974.

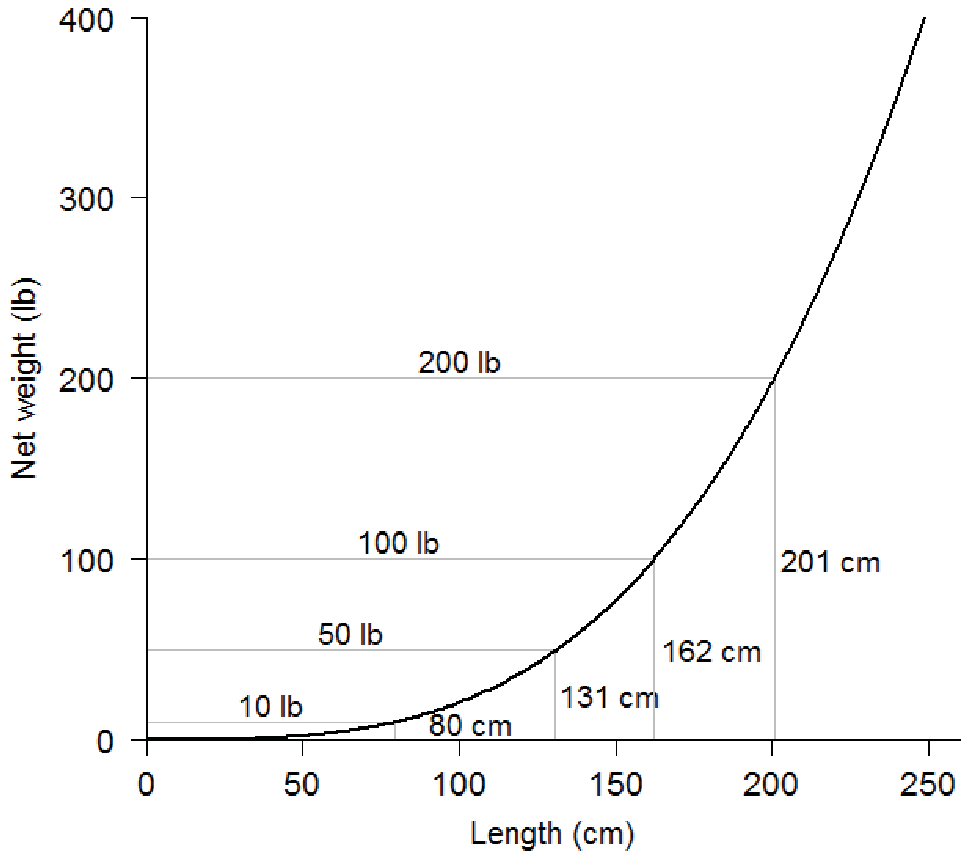

Figure 45. The conversion relationship for length in centimeters to net weight in pounds.

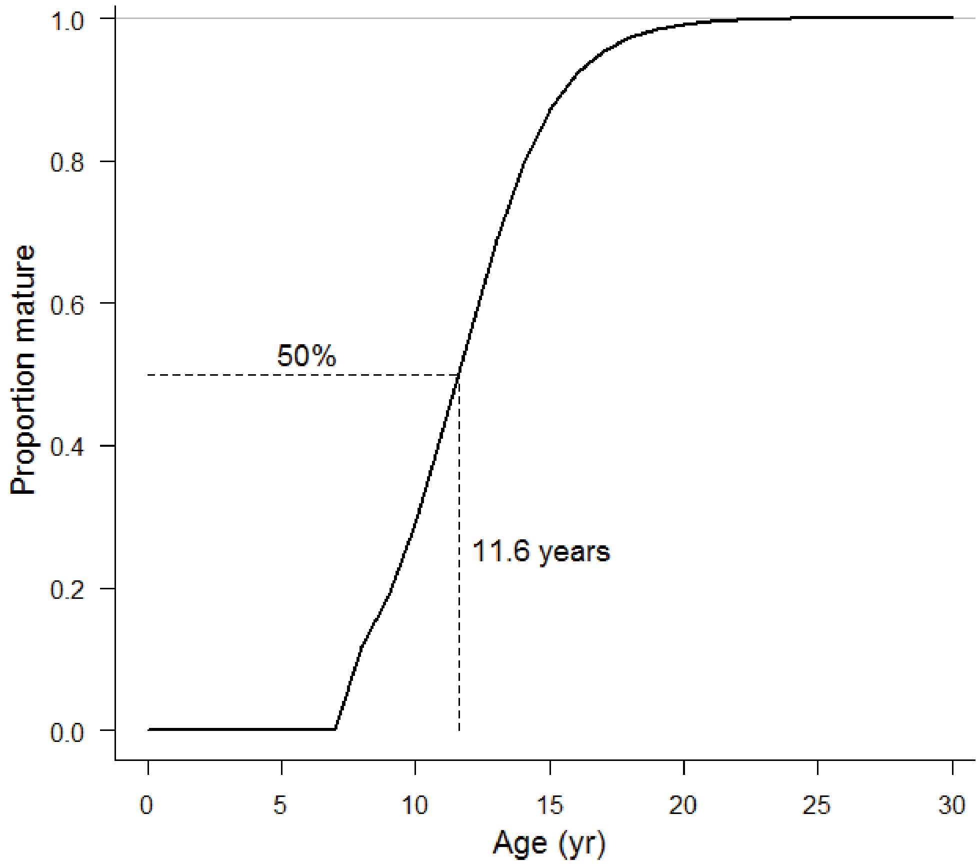

Figure 46. The maturity ogive used in recent halibut assessments. Note that this is a logistic curve, trimmed to be equal to zero below age-8.

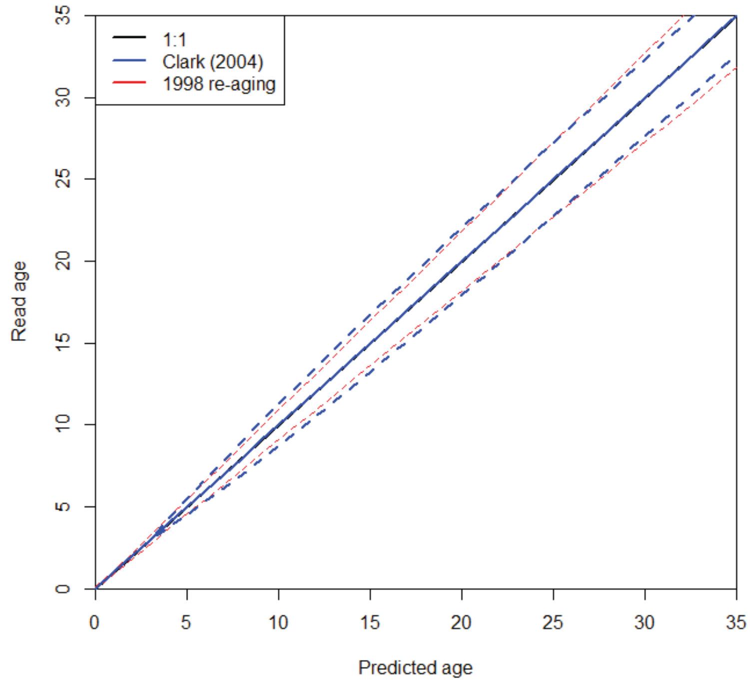

Figure 47. Re-estimated level of imprecision for break-and-bake ages based on the otoliths re-read in 2013, compared with the previously available estimate. Dashed lines indicate 95% prediction intervals for the distribution of individual ages.

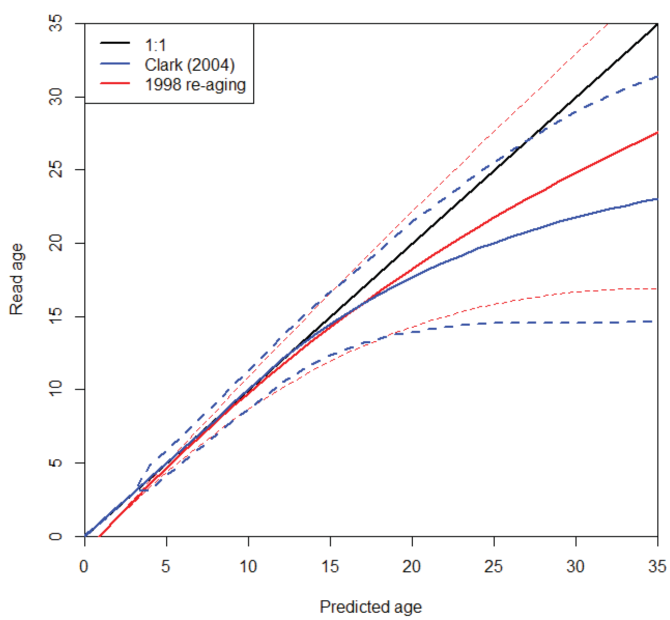

Figure 48. Re-estimated levels of imprecision and bias for surface ages based on the otoliths re-read in 2013, compared with the previously available estimate. Dashed lines indicate 95% prediction intervals for the distribution of individual ages.

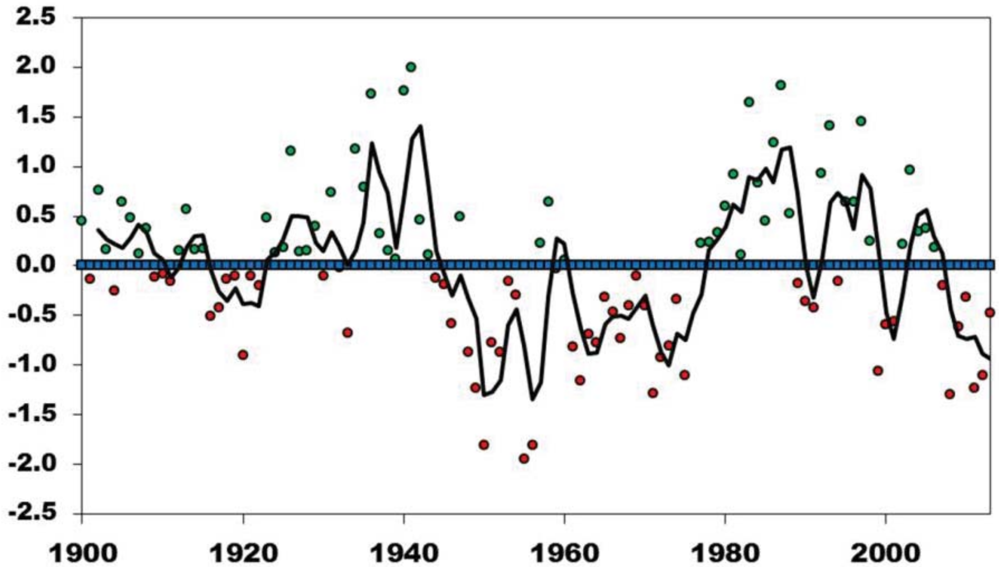

Figure 49. Time series of annual average PDO conditions (deviations from the long-term mean). Monthly means were obtained from (http://jisao.washington.edu/pdo/).

Table 1. Time-series of expanded setline survey WPUE by regulatory Area (O32; net lb/skate). Years prior to 1984 are based on surveys conducted with "J" hooks.

Year	2A	2B	2C	3A	3B	4A	4B	4CDE	Total
1977	NA	13.7	NA	58.4	NA	NA	NA	NA	NA
1978	NA	19.1	NA	26.9	NA	NA	NA	NA	NA
1979	NA	NA	NA	41.0	NA	NA	NA	NA	NA
1980	NA	25.5	NA	76.2	NA	NA	NA	NA	NA
1981	NA	16.5	NA	131.4	NA	NA	NA	NA	NA
1982	NA	20.6	113.7	130.3	NA	NA	NA	NA	NA
1983	NA	18.0	142.2	119.0	NA	NA	NA	NA	NA
1984	NA	57.4	259.6	361.2	NA	NA	NA	NA	NA
1985	NA	41.7	260.5	377.5	NA	NA	NA	NA	NA
1986	NA	37.8	282.6	305.1	NA	NA	NA	NA	NA
1987	NA	NA	NA	NA	NA	NA	NA	NA	NA
1988	NA	NA	NA	NA	NA	NA	NA	NA	NA
1989	NA	NA	NA	NA	NA	NA	NA	NA	NA
1990	NA	NA	NA	NA	NA	NA	NA	NA	NA
1991	NA	NA	NA	NA	NA	NA	NA	NA	NA
1992	NA	NA	NA	NA	NA	NA	NA	NA	NA
1993	NA	95.7	NA	261.1	NA	NA	NA	NA	NA
1994	NA	NA	NA	255.1	NA	NA	NA	NA	NA
1995	30.0	159.4	NA	300.9	NA	NA	NA	NA	NA
1996	32.6	166.0	307.1	318.1	353.0	NA	NA	NA	NA
1997	35.2	144.3	411.1	331.4	415.4	246.2	281.9	21.9	137.5
1998	36.1	83.4	235.7	281.9	436.1	307.3	216.6	40.7	132.4
1999	37.0	88.2	210.1	243.4	440.6	291.1	203.3	36.3	123.6
2000	39.3	91.9	240.5	274.3	375.2	281.4	216.5	26.4	118.6
2001	41.5	101.8	245.4	257.5	358.9	203.9	171.4	26.5	110.3
2002	33.3	92.6	268.7	299.8	297.8	172.7	119.3	26.6	106.6
2003	22.1	73.1	228.8	229.9	261.8	157.8	104.1	24.7	89.3
2004	27.0	86.3	176.1	270.1	237.0	141.1	73.4	21.1	87.4
2005	28.1	72.2	175.7	276.7	211.3	109.7	86.3	13.2	79.9
2006	16.3	58.9	146.9	232.8	181.6	87.3	95.5	14.2	69.6
2007	18.8	57.6	143.2	212.3	191.8	68.4	87.4	12.9	65.7
2008	18.5	90.2	107.3	189.5	126.3	85.4	103.5	11.1	59.7
2009	8.1	86.6	116.6	149.1	113.6	86.1	106.8	13.0	54.7
2010	16.8	89.2	111.3	117.2	91.5	74.7	68.4	11.1	45.9
2011	26.8	80.2	137.5	120.7	79.9	59.3	68.1	9.3	44.4
2012	28.5	103.9	161.7	137.7	87.2	65.5	48.5	10.8	49.9
2013	23.0	93.6	188.3	116.9	64.0	43.0	57.3	9.1	44.0

Table 2. Time-series of fishery landings by regulatory Area (million lb, net wt.).

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1888	0.07	0.89	0.50	0.00	0.00	NA	NA	NA	NA	1.47
1889	0.07	0.79	0.44	0.00	0.00	NA	NA	NA	NA	1.29
1890	0.07	0.84	0.47	0.00	0.00	NA	NA	NA	NA	1.37
1891	0.11	1.30	0.73	0.00	0.00	NA	NA	NA	NA	2.13
1892	0.14	1.69	0.94	0.00	0.00	NA	NA	NA	NA	2.77
1893	0.16	1.96	1.09	0.00	0.00	NA	NA	NA	NA	3.22
1894	0.19	2.29	1.28	0.00	0.00	NA	NA	NA	NA	3.76
1895	0.21	2.59	1.45	0.00	0.00	NA	NA	NA	NA	4.25
1896	0.27	3.31	1.84	0.00	0.00	NA	NA	NA	NA	5.42
1897	0.33	4.02	2.24	0.00	0.00	NA	NA	NA	NA	6.59
1898	0.39	4.73	2.64	0.00	0.00	NA	NA	NA	NA	7.77
1899	0.45	5.45	3.04	0.00	0.00	NA	NA	NA	NA	8.94
1900	0.68	8.17	4.56	0.00	0.00	NA	NA	NA	NA	13.41
1901	0.90	10.90	6.08	0.00	0.00	NA	NA	NA	NA	17.87
1902	1.13	13.62	7.60	0.00	0.00	NA	NA	NA	NA	22.34
1903	1.27	15.37	8.57	0.00	0.00	NA	NA	NA	NA	25.21
1904	1.41	17.12	9.55	0.00	0.00	NA	NA	NA	NA	28.08
1905	1.11	13.41	7.48	0.00	0.00	NA	NA	NA	NA	22.00
1906	1.81	21.95	12.24	0.00	0.00	NA	NA	NA	NA	36.00
1907	2.52	30.48	17.00	0.00	0.00	NA	NA	NA	NA	50.00
1908	2.55	30.86	17.21	0.00	0.00	NA	NA	NA	NA	50.62
1909	2.58	31.23	17.42	0.00	0.00	NA	NA	NA	NA	51.23
1910	2.61	31.61	17.63	0.00	0.00	NA	NA	NA	NA	51.85
1911	2.87	34.71	19.36	0.00	0.00	NA	NA	NA	NA	56.93
1912	3.00	36.29	20.24	0.86	0.04	NA	NA	NA	NA	60.43
1913	2.79	33.80	18.85	10.58	0.52	NA	NA	NA	NA	66.54
1914	2.24	27.11	15.12	21.87	1.08	NA	NA	NA	NA	67.43
1915	2.22	26.84	14.97	23.31	1.15	NA	NA	NA	NA	68.48
1916	1.53	18.46	10.30	18.56	0.92	NA	NA	NA	NA	49.76
1917	1.55	18.78	10.47	16.96	0.84	NA	NA	NA	NA	48.60
1918	1.32	16.02	8.93	10.88	0.54	NA	NA	NA	NA	37.69
1919	1.34	16.22	9.05	12.90	0.64	NA	NA	NA	NA	40.14
1920	1.62	19.73	11.01	13.59	0.67	NA	NA	NA	NA	46.62
1921	3.39	23.37	10.22	14.75	0.73	NA	NA	NA	NA	52.46
1922	2.61	19.02	9.22	11.63	0.02	NA	NA	NA	NA	42.49
1923	2.62	16.71	9.72	21.60	0.67	NA	NA	NA	NA	51.32
1924	1.82	15.14	9.86	24.82	1.50	NA	NA	NA	NA	53.14
1925	2.20	13.65	7.99	22.16	4.66	NA	NA	NA	NA	50.66
1926	2.32	16.12	7.17	21.01	5.85	NA	NA	NA	NA	52.47
1927	2.62	14.09	7.42	22.62	8.20	NA	NA	NA	NA	54.95
1928	2.27	16.63	7.58	22.54	5.25	NA	NA	NA	NA	54.26
1929	2.18	13.77	9.85	22.27	8.86	NA	NA	NA	NA	56.92
1930	1.58	12.12	8.53	18.19	9.09	NA	NA	NA	NA	49.51
1931	1.63	13.53	7.39	14.61	7.06	NA	NA	NA	NA	44.22
1932	1.90	13.25	7.74	16.71	4.89	NA	NA	NA	NA	44.49
1933	1.75	13.37	8.15	19.67	3.97	NA	NA	NA	NA	46.91
1934	2.45	14.12	7.68	15.88	4.58	NA	NA	NA	NA	44.72
1935	1.77	14.21	7.58	19.96	3.82	0.00	NA	NA	NA	47.34
1936	0.90	13.67	8.75	20.09	5.52	0.00	NA	NA	NA	48.92
1937	0.92	15.29	7.87	20.47	5.00	0.00	NA	NA	NA	49.54
1938	0.95	16.00	7.15	20.66	4.79	0.00	NA	NA	NA	49.55
1939	1.36	17.67	6.56	21.16	4.15	0.00	NA	NA	NA	50.90
1940	0.98	17.81	7.62	22.50	4.48	0.00	NA	NA	NA	53.38

Table 2. Continued.

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1941	0.51	16.53	7.25	21.84	6.10	0.00	NA	NA	NA	52.23
1942	0.72	14.37	8.35	21.50	5.46	0.00	NA	NA	NA	50.39
1943	1.24	15.97	8.15	20.51	7.83	0.00	NA	NA	NA	53.70
1944	0.90	15.07	10.38	20.36	6.73	0.00	NA	NA	NA	53.44
1945	0.73	14.58	8.49	20.07	9.52	0.01	NA	NA	NA	53.40
1946	0.90	18.37	9.90	22.40	8.50	0.20	NA	NA	NA	60.27
1947	0.57	17.67	9.50	20.44	7.33	0.19	NA	NA	NA	55.70
1948	0.41	17.67	9.75	19.93	7.50	0.30	NA	NA	NA	55.56
1949	0.62	16.34	9.45	21.12	7.38	0.12	NA	NA	NA	55.03
1950	0.70	17.46	8.84	23.86	6.30	0.08	NA	NA	NA	57.23
1951	0.59	20.04	9.97	20.86	4.54	0.05	NA	NA	NA	56.05
1952	0.62	20.63	9.56	27.27	3.62	0.56	NA	NA	NA	62.26
1953	0.50	23.80	8.41	22.84	3.81	0.48	NA	NA	NA	59.84
1954	0.85	24.90	11.04	29.46	4.21	0.13	NA	NA	NA	70.58
1955	0.61	18.65	8.54	23.06	6.57	0.09	NA	NA	NA	57.52
1956	0.53	20.06	14.51	22.11	9.12	0.26	NA	NA	NA	66.59
1957	0.60	17.69	12.25	22.85	7.43	0.04	NA	NA	NA	60.85
1958	0.52	18.49	11.20	24.52	7.60	2.18	NA	NA	NA	64.51
1959	0.67	16.83	13.03	25.36	11.00	4.31	NA	NA	NA	71.20
1960	0.89	18.16	12.72	21.05	12.90	5.90	NA	NA	NA	71.61
1961	0.50	16.08	12.29	23.07	13.28	4.07	NA	NA	NA	69.27
1962	0.45	15.03	13.24	24.04	13.48	8.62	NA	NA	NA	74.86
1963	0.41	15.52	10.24	22.31	13.98	8.77	NA	NA	NA	71.24
1964	0.28	11.86	7.43	22.56	15.04	2.62	NA	NA	NA	59.78
1965	0.21	11.97	12.07	22.98	14.07	1.88	NA	NA	NA	63.18
1966	0.18	11.04	12.04	25.77	11.05	1.94	NA	NA	NA	62.02
1967	0.20	10.11	9.41	19.66	13.26	2.58	NA	NA	NA	55.22
1968	0.14	10.15	6.11	14.77	15.83	1.60	NA	NA	NA	48.59
1969	0.23	12.82	9.33	20.08	13.92	1.90	NA	NA	NA	58.27
1970	0.16	10.26	9.37	19.91	13.37	1.78	NA	NA	NA	54.84
1971	0.32	9.85	6.61	17.76	11.04	1.08	NA	NA	NA	46.65
1972	0.37	10.13	5.78	16.30	9.28	1.02	NA	NA	NA	42.88
1973	0.23	6.73	5.98	13.50	4.79	0.52	NA	NA	NA	31.74
1974	0.52	4.62	5.60	8.19	1.67	0.71	NA	NA	NA	21.31
1975	0.46	7.13	6.24	10.60	2.56	0.63	NA	NA	NA	27.62
1976	0.24	7.28	5.53	11.04	2.73	0.72	NA	NA	NA	27.54
1977	0.21	5.43	3.19	8.64	3.19	1.22	NA	NA	NA	21.88
1978	0.10	4.61	4.32	10.30	1.32	1.35	NA	NA	NA	22.00
1979	0.05	4.86	4.53	11.34	0.39	1.37	NA	NA	NA	22.54
1980	0.02	5.65	3.24	11.97	0.28	0.71	NA	NA	NA	21.87
1981	0.20	5.66	4.01	14.23	0.45	NA	0.49	0.39	0.31	25.74
1982	0.21	5.54	3.50	13.52	4.80	NA	1.17	0.01	0.25	29.01
1983	0.27	5.44	6.38	14.13	7.76	NA	2.50	1.34	0.58	38.39
1984	0.43	9.05	5.87	19.77	6.69	NA	1.05	1.10	1.01	44.97
1985	0.49	10.39	9.21	20.84	10.89	NA	1.72	1.24	1.33	56.10
1986	0.58	11.23	10.61	32.80	8.82	NA	3.38	0.26	1.95	69.63
1987	0.59	12.25	10.69	31.31	7.76	NA	3.69	1.50	1.69	69.47
1988	0.49	12.86	11.36	37.91	7.08	NA	1.93	1.59	1.17	74.39
1989	0.47	10.43	9.53	33.74	7.84	NA	1.03	2.65	1.26	66.95
1990	0.33	8.57	9.73	28.85	8.69	NA	2.50	1.33	1.59	61.60
1991	0.36	7.19	8.69	22.93	11.93	NA	2.26	1.51	2.22	57.08
1992	0.44	7.63	9.82	26.78	8.62	NA	2.70	2.32	1.59	59.89
1993	0.50	10.63	11.29	22.74	7.86	NA	2.56	1.96	1.73	59.27

Table 2. Continued.

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1994	0.37	9.91	10.38	24.84	3.86	NA	1.80	2.02	1.55	54.73
1995	0.30	9.62	7.77	18.34	3.13	NA	1.62	1.68	1.44	43.88
1996	0.30	9.55	8.87	19.69	3.66	NA	1.70	2.07	1.51	47.34
1997	0.41	12.42	9.92	24.64	9.06	NA	2.91	3.32	2.52	65.20
1998	0.46	13.17	10.20	25.70	11.16	NA	3.42	2.90	2.75	69.76
1999	0.45	12.71	10.14	25.32	13.84	NA	4.37	3.57	3.92	74.31
2000	0.48	10.81	8.45	19.27	15.41	NA	5.16	4.69	4.02	68.29
2001	0.68	10.29	8.40	21.54	16.34	NA	5.02	4.47	3.97	70.70
2002	0.85	12.07	8.60	23.13	17.31	NA	5.09	4.08	3.52	74.66
2003	0.82	11.79	8.41	22.75	17.22	NA	5.02	3.86	3.26	73.14
2004	0.88	12.16	10.23	25.17	15.46	NA	3.56	2.72	2.92	73.11
2005	0.80	12.33	10.63	26.03	13.17	NA	3.40	1.98	3.48	71.82
2006	0.83	12.01	10.49	25.71	10.79	NA	3.33	1.59	3.23	67.98
2007	0.79	9.77	8.47	26.49	9.25	NA	2.83	1.42	3.85	62.87
2008	0.68	7.76	6.21	24.52	10.75	NA	3.02	1.76	3.88	58.57
2009	0.49	6.64	4.96	21.76	10.78	NA	2.53	1.59	3.31	52.05
2010	0.42	6.73	4.49	20.50	10.11	NA	2.33	1.83	3.32	49.72
2011	0.54	6.69	2.45	14.67	7.32	NA	2.35	2.05	3.43	39.51
2012	0.57	5.98	2.69	12.03	5.05	NA	1.58	1.74	2.34	31.99
2013	0.54	5.92	3.04	11.05	4.12	NA	1.23	1.24	1.78	28.91

Table 3. Time-series of total removals by regulatory Area (million lb, net wt.).

Year	2A	2B	2C	3A	3B	4	Total
1888	0.07	0.89	0.50	0.00	0.00	0.00	1.47
1889	0.07	0.79	0.44	0.00	0.00	0.00	1.29
1890	0.07	0.84	0.47	0.00	0.00	0.00	1.37
1891	0.11	1.30	0.73	0.00	0.00	0.00	2.13
1892	0.14	1.69	0.94	0.00	0.00	0.00	2.77
1893	0.16	1.96	1.09	0.00	0.00	0.00	3.22
1894	0.19	2.29	1.28	0.00	0.00	0.00	3.76
1895	0.21	2.59	1.45	0.00	0.00	0.00	4.25
1896	0.27	3.31	1.84	0.00	0.00	0.00	5.42
1897	0.33	4.02	2.24	0.00	0.00	0.00	6.59
1898	0.39	4.73	2.64	0.00	0.00	0.00	7.77
1899	0.45	5.45	3.04	0.00	0.00	0.00	8.94
1900	0.68	8.17	4.56	0.00	0.00	0.00	13.41
1901	0.90	10.90	6.08	0.00	0.00	0.00	17.87
1902	1.13	13.62	7.60	0.00	0.00	0.00	22.34
1903	1.27	15.37	8.57	0.00	0.00	0.00	25.21
1904	1.41	17.12	9.55	0.00	0.00	0.00	28.08
1905	1.11	13.41	7.48	0.00	0.00	0.00	22.00
1906	1.81	21.95	12.24	0.00	0.00	0.00	36.00
1907	2.52	30.48	17.00	0.00	0.00	0.00	50.00
1908	2.55	30.86	17.21	0.00	0.00	0.00	50.62
1909	2.58	31.23	17.42	0.00	0.00	0.00	51.23
1910	2.61	31.61	17.63	0.00	0.00	0.00	51.85
1911	2.87	34.71	19.36	0.00	0.00	0.00	56.93
1912	3.00	36.29	20.24	0.86	0.04	0.00	60.43
1913	2.79	33.80	18.85	10.58	0.52	0.00	66.54
1914	2.24	27.11	15.12	21.87	1.08	0.00	67.43
1915	2.22	26.84	14.97	23.31	1.15	0.00	68.48
1916	1.53	18.46	10.30	18.56	0.92	0.00	49.76
1917	1.55	18.78	10.47	16.96	0.84	0.00	48.60
1918	1.32	16.02	8.93	10.88	0.54	0.00	37.69
1919	1.34	16.22	9.05	12.90	0.64	0.00	40.14
1920	1.62	19.73	11.01	13.59	0.67	0.00	46.62
1921	3.39	23.37	10.22	14.75	0.73	0.00	52.46
1922	2.61	19.02	9.22	11.63	0.02	0.00	42.50
1923	2.62	16.71	9.72	21.60	0.67	0.00	51.32
1924	1.82	15.14	9.86	24.82	1.50	0.00	53.14
1925	2.20	13.65	7.99	22.16	4.66	0.00	50.66
1926	2.32	16.12	7.17	21.01	5.85	0.00	52.47
1927	2.62	14.09	7.42	22.62	8.20	0.00	54.95
1928	2.27	16.63	7.58	22.54	5.25	0.00	54.26
1929	2.18	13.77	9.85	22.27	8.86	0.00	56.93
1930	1.58	12.12	8.53	18.19	9.09	0.00	49.51
1931	1.63	13.53	7.39	14.61	7.06	0.00	44.22
1932	1.90	13.25	7.74	16.71	4.89	0.00	44.49
1933	1.75	13.37	8.15	19.67	3.97	0.00	46.91
1934	2.45	14.12	7.68	15.88	4.58	0.00	44.72
1935	1.77	14.21	7.58	19.96	3.82	0.00	47.34
1936	0.90	13.67	8.75	20.09	5.52	0.00	48.92
1937	0.92	15.29	7.87	20.47	5.00	0.00	49.54
1938	0.95	16.00	7.15	20.66	4.79	0.00	49.55
1939	1.36	17.67	6.56	21.16	4.15	0.00	50.90
1940	0.98	17.81	7.62	22.50	4.48	0.00	53.38

Table 3. Continued.

Year	2A	2B	2C	3A	3B	4	Total
1941	0.51	16.53	7.25	21.84	6.10	0.00	52.23
1942	0.72	14.37	8.35	21.50	5.46	0.00	50.39
1943	1.24	15.97	8.15	20.51	7.83	0.00	53.70
1944	0.90	15.07	10.38	20.36	6.73	0.00	53.44
1945	0.73	14.58	8.49	20.07	9.52	0.01	53.40
1946	0.90	18.37	9.90	22.40	8.50	0.20	60.27
1947	0.57	17.67	9.50	20.44	7.33	0.19	55.70
1948	0.41	17.67	9.75	19.93	7.50	0.30	55.56
1949	0.62	16.34	9.45	21.12	7.38	0.12	55.03
1950	0.70	17.46	8.84	23.86	6.30	0.08	57.23
1951	0.59	20.04	9.97	20.86	4.54	0.05	56.05
1952	0.62	20.63	9.56	27.27	3.62	0.56	62.26
1953	0.50	23.80	8.41	22.84	3.81	0.48	59.84
1954	0.85	24.90	11.04	29.46	4.21	0.13	70.58
1955	0.61	18.65	8.54	23.06	6.57	0.09	57.52
1956	0.53	20.06	14.51	22.11	9.12	0.26	66.59
1957	0.60	17.69	12.25	22.85	7.43	0.04	60.85
1958	0.52	18.49	11.20	24.52	7.60	2.18	64.51
1959	0.67	16.83	13.03	25.36	11.00	4.31	71.20
1960	0.89	18.16	12.72	21.05	12.90	5.90	71.61
1961	0.50	16.08	12.29	23.07	13.28	4.07	69.27
1962	0.45	16.21	13.45	25.96	14.65	12.76	83.47
1963	0.41	16.60	10.45	25.62	16.77	10.81	80.66
1964	0.28	12.96	7.64	31.93	17.30	5.59	75.70
1965	0.21	13.40	12.27	29.08	24.51	5.06	84.54
1966	0.18	12.70	12.25	30.28	19.03	5.34	79.79
1967	0.20	11.76	9.85	24.29	18.16	7.30	71.56
1968	0.14	12.11	6.63	20.25	17.41	7.28	63.81
1969	0.23	15.00	9.79	23.89	15.09	9.50	73.50
1970	0.16	11.73	9.93	23.30	16.21	9.80	71.13
1971	0.32	11.59	7.15	20.74	12.40	14.18	66.37
1972	0.37	11.88	6.54	21.71	10.98	10.69	62.16
1973	0.23	8.24	6.82	17.95	7.49	8.55	49.27
1974	1.00	6.43	6.17	13.50	5.10	8.33	40.54
1975	0.94	9.18	6.93	13.85	4.65	4.28	39.84
1976	0.72	9.51	6.28	14.64	5.20	5.29	41.63
1977	0.70	7.39	3.87	13.02	5.12	4.14	34.24
1978	0.59	6.20	4.82	13.75	3.17	6.38	34.90
1979	0.54	6.84	5.56	17.62	1.33	6.79	38.68
1980	0.52	7.16	4.12	18.44	1.53	9.95	41.72
1981	0.70	7.01	4.87	19.85	2.02	7.62	42.06
1982	0.74	6.60	4.33	18.16	7.04	6.21	43.08
1983	0.81	6.63	7.30	18.15	9.80	8.72	51.41
1984	1.03	10.55	6.86	23.10	8.30	7.89	57.73
1985	1.17	12.33	10.53	24.26	11.86	8.70	68.86
1986	1.40	13.27	12.25	37.92	9.82	11.56	86.22
1987	1.52	14.85	12.31	37.64	9.14	13.00	88.46
1988	1.22	15.28	13.13	46.69	7.40	13.70	97.42
1989	1.29	12.69	11.75	42.11	9.03	12.43	89.29
1990	0.95	11.07	12.42	38.29	11.15	14.36	88.25
1991	0.94	9.76	12.31	34.55	14.48	16.69	88.73
1992	1.15	9.98	12.83	37.11	11.12	17.78	89.97
1993	1.23	13.24	14.36	33.48	9.24	14.39	85.94

Table 3. Continued.

Year	2A	2B	2C	3A	3B	4	Total
1994	1.02	12.03	13.46	35.04	5.46	15.18	82.19
1995	1.17	12.56	10.02	26.33	5.00	13.67	68.75
1996	1.17	11.24	11.52	27.81	5.76	14.09	71.59
1997	1.41	14.12	12.67	33.74	10.82	16.97	89.72
1998	1.96	14.90	13.46	33.81	12.88	17.23	94.23
1999	1.80	14.38	12.75	33.05	15.93	20.01	97.92
2000	1.69	12.55	11.46	28.02	17.34	21.74	92.80
2001	2.01	12.03	11.07	29.75	18.53	21.04	94.42
2002	1.92	14.08	11.37	30.25	19.79	20.35	97.76
2003	1.56	13.90	11.84	32.32	19.64	19.29	98.54
2004	1.70	14.64	14.57	35.61	17.49	16.23	100.23
2005	1.90	15.15	14.70	36.08	14.93	16.93	99.70
2006	2.01	14.96	14.36	35.15	12.73	15.99	95.20
2007	1.75	12.58	12.76	36.96	10.89	15.74	90.68
2008	1.66	10.29	10.57	34.25	12.85	15.61	85.23
2009	1.54	8.71	8.44	30.74	12.93	14.08	76.43
2010	1.20	8.75	7.48	29.08	12.21	13.89	72.61
2011	1.08	8.83	4.29	23.00	9.30	13.40	59.91
2012	1.18	7.85	4.78	18.52	7.07	12.21	51.61
2013	1.18	7.58	5.15	16.98	5.44	9.68	46.01

Table 4. Time-series of estimated removals by source (million lb, net wt.).

Year	Commercial landings	Commercial wastage	Bycatch	Sport	Personal use	Total
1888	1.47	0.00	0.00	0.00	0.00	1.47
1889	1.29	0.00	0.00	0.00	0.00	1.29
1890	1.37	0.00	0.00	0.00	0.00	1.37
1891	2.13	0.00	0.00	0.00	0.00	2.13
1892	2.77	0.00	0.00	0.00	0.00	2.77
1893	3.22	0.00	0.00	0.00	0.00	3.22
1894	3.76	0.00	0.00	0.00	0.00	3.76
1895	4.25	0.00	0.00	0.00	0.00	4.25
1896	5.42	0.00	0.00	0.00	0.00	5.42
1897	6.59	0.00	0.00	0.00	0.00	6.59
1898	7.77	0.00	0.00	0.00	0.00	7.77
1899	8.94	0.00	0.00	0.00	0.00	8.94
1900	13.41	0.00	0.00	0.00	0.00	13.41
1901	17.87	0.00	0.00	0.00	0.00	17.87
1902	22.34	0.00	0.00	0.00	0.00	22.34
1903	25.21	0.00	0.00	0.00	0.00	25.21
1904	28.08	0.00	0.00	0.00	0.00	28.08
1905	22.00	0.00	0.00	0.00	0.00	22.00
1906	36.00	0.00	0.00	0.00	0.00	36.00
1907	50.00	0.00	0.00	0.00	0.00	50.00
1908	50.62	0.00	0.00	0.00	0.00	50.62
1909	51.23	0.00	0.00	0.00	0.00	51.23
1910	51.85	0.00	0.00	0.00	0.00	51.85
1911	56.93	0.00	0.00	0.00	0.00	56.93
1912	60.43	0.00	0.00	0.00	0.00	60.43
1913	66.54	0.00	0.00	0.00	0.00	66.54
1914	67.43	0.00	0.00	0.00	0.00	67.43
1915	68.48	0.00	0.00	0.00	0.00	68.48
1916	49.76	0.00	0.00	0.00	0.00	49.76
1917	48.60	0.00	0.00	0.00	0.00	48.60
1918	37.69	0.00	0.00	0.00	0.00	37.69
1919	40.14	0.00	0.00	0.00	0.00	40.14
1920	46.62	0.00	0.00	0.00	0.00	46.62
1921	52.46	0.00	0.00	0.00	0.00	52.46
1922	42.49	0.00	0.00	0.00	0.00	42.49
1923	51.32	0.00	0.00	0.00	0.00	51.32
1924	53.14	0.00	0.00	0.00	0.00	53.14
1925	50.66	0.00	0.00	0.00	0.00	50.66
1926	52.47	0.00	0.00	0.00	0.00	52.47
1927	54.95	0.00	0.00	0.00	0.00	54.95
1928	54.26	0.00	0.00	0.00	0.00	54.26
1929	56.92	0.00	0.00	0.00	0.00	56.92
1930	49.51	0.00	0.00	0.00	0.00	49.51
1931	44.22	0.00	0.00	0.00	0.00	44.22
1932	44.49	0.00	0.00	0.00	0.00	44.49
1933	46.91	0.00	0.00	0.00	0.00	46.91
1934	44.72	0.00	0.00	0.00	0.00	44.72
1935	47.34	0.00	0.00	0.00	0.00	47.34
1936	48.92	0.00	0.00	0.00	0.00	48.92
1937	49.54	0.00	0.00	0.00	0.00	49.54
1938	49.55	0.00	0.00	0.00	0.00	49.55
1939	50.90	0.00	0.00	0.00	0.00	50.90

Table 4. Continued.

Year	Commercial landings	Commercial wastage	Bycatch	Sport	Personal use	Total
1940	53.38	0.00	0.00	0.00	0.00	53.38
1941	52.23	0.00	0.00	0.00	0.00	52.23
1942	50.39	0.00	0.00	0.00	0.00	50.39
1943	53.70	0.00	0.00	0.00	0.00	53.70
1944	53.44	0.00	0.00	0.00	0.00	53.44
1945	53.40	0.00	0.00	0.00	0.00	53.40
1946	60.27	0.00	0.00	0.00	0.00	60.27
1947	55.70	0.00	0.00	0.00	0.00	55.70
1948	55.56	0.00	0.00	0.00	0.00	55.56
1949	55.03	0.00	0.00	0.00	0.00	55.03
1950	57.23	0.00	0.00	0.00	0.00	57.23
1951	56.05	0.00	0.00	0.00	0.00	56.05
1952	62.26	0.00	0.00	0.00	0.00	62.26
1953	59.84	0.00	0.00	0.00	0.00	59.84
1954	70.58	0.00	0.00	0.00	0.00	70.58
1955	57.52	0.00	0.00	0.00	0.00	57.52
1956	66.59	0.00	0.00	0.00	0.00	66.59
1957	60.85	0.00	0.00	0.00	0.00	60.85
1958	64.51	0.00	0.00	0.00	0.00	64.51
1959	71.20	0.00	0.00	0.00	0.00	71.20
1960	71.61	0.00	0.00	0.00	0.00	71.61
1961	69.27	0.00	0.00	0.00	0.00	69.27
1962	74.86	0.00	8.61	0.00	0.00	83.47
1963	71.24	0.00	9.42	0.00	0.00	80.66
1964	59.78	0.00	15.91	0.00	0.00	75.70
1965	63.18	0.00	21.36	0.00	0.00	84.54
1966	62.02	0.00	17.77	0.00	0.00	79.79
1967	55.22	0.00	16.34	0.00	0.00	71.56
1968	48.59	0.00	15.22	0.00	0.00	63.81
1969	58.27	0.00	15.23	0.00	0.00	73.50
1970	54.84	0.00	16.29	0.00	0.00	71.13
1971	46.65	0.00	19.72	0.00	0.00	66.37
1972	42.88	0.00	19.28	0.00	0.00	62.16
1973	31.74	0.00	17.53	0.00	0.00	49.27
1974	21.31	0.20	19.03	0.00	0.00	40.54
1975	27.62	0.31	11.91	0.00	0.00	39.84
1976	27.54	0.34	13.75	0.00	0.00	41.63
1977	21.88	0.29	11.78	0.29	0.00	34.24
1978	22.00	0.28	12.24	0.38	0.00	34.90
1979	22.54	0.30	15.28	0.56	0.00	38.68
1980	21.87	0.30	18.70	0.85	0.00	41.72
1981	25.74	0.35	14.86	1.11	0.00	42.06
1982	29.01	0.40	12.37	1.30	0.00	43.08
1983	38.39	0.53	10.88	1.62	0.00	51.41
1984	44.97	0.72	10.19	1.84	0.00	57.73
1985	56.10	2.70	7.70	2.36	0.00	68.86
1986	69.63	4.65	8.76	3.18	0.00	86.22
1987	69.47	4.20	11.28	3.51	0.00	88.46
1988	74.39	3.49	14.66	4.88	0.00	97.42
1989	66.95	3.46	13.65	5.23	0.00	89.29
1990	61.60	3.38	17.68	5.59	0.00	88.25
1991	57.08	3.46	19.67	6.51	2.01	88.74

Table 4. Continued.

Year	Commercial landings	Commercial wastage	Bycatch	Sport	Personal use	Total
1992	59.89	2.50	20.29	6.18	1.11	89.97
1993	59.27	2.05	15.96	7.73	0.93	85.94
1994	54.73	2.51	16.95	7.07	0.93	82.19
1995	43.88	0.93	15.93	7.46	0.54	68.75
1996	47.34	1.15	14.46	8.08	0.54	71.59
1997	65.20	1.45	13.51	9.03	0.54	89.73
1998	69.76	1.72	13.43	8.59	0.74	94.23
1999	74.31	1.65	13.84	7.38	0.75	97.92
2000	68.29	1.45	13.29	9.01	0.76	92.80
2001	70.70	1.69	13.16	8.10	0.77	94.42
2002	74.66	1.72	12.61	8.01	0.76	97.76
2003	73.14	2.08	12.58	9.35	1.38	98.54
2004	73.11	2.31	12.58	10.70	1.53	100.23
2005	71.82	2.22	13.26	10.86	1.54	99.70
2006	67.98	2.46	13.08	10.19	1.48	95.20
2007	62.87	2.59	12.27	11.46	1.49	90.68
2008	58.57	2.76	11.89	10.67	1.34	85.23
2009	52.05	2.94	11.38	8.75	1.31	76.43
2010	49.72	3.21	10.63	7.80	1.24	72.61
2011	39.51	2.46	9.71	7.09	1.14	59.91
2012	31.99	1.67	10.08	6.73	1.14	51.61
2013	28.91	1.41	7.89	6.66	1.14	46.01

Table 5. Time-series of fishery WPUE by regulatory Area (net lb/skate). Years prior to 1984 are based on fishing conducted with “J” hooks.

Year	2A	2B	2C	3A	3B	4A	4B	4C	4D	Total
1907	NA	NA	NA	NA	NA	NA	NA	NA	NA	280
1910	NA	NA	NA	NA	NA	NA	NA	NA	NA	271
1911	NA	NA	NA	NA	NA	NA	NA	NA	NA	237
1912	NA	NA	NA	NA	NA	NA	NA	NA	NA	176
1913	NA	NA	NA	NA	NA	NA	NA	NA	NA	129
1914	NA	NA	NA	NA	NA	NA	NA	NA	NA	124
1915	NA	NA	NA	NA	NA	NA	NA	NA	NA	118
1916	NA	NA	NA	NA	NA	NA	NA	NA	NA	137
1917	NA	NA	NA	NA	NA	NA	NA	NA	NA	98
1918	NA	NA	NA	NA	NA	NA	NA	NA	NA	96
1919	NA	NA	NA	NA	NA	NA	NA	NA	NA	93
1920	NA	NA	NA	NA	NA	NA	NA	NA	NA	96
1921	NA	NA	NA	NA	NA	NA	NA	NA	NA	88
1922	NA	NA	NA	NA	NA	NA	NA	NA	NA	73
1923	NA	NA	NA	NA	NA	NA	NA	NA	NA	78
1924	NA	NA	NA	NA	NA	NA	NA	NA	NA	74
1925	NA	NA	NA	NA	NA	NA	NA	NA	NA	68
1926	NA	NA	NA	NA	NA	NA	NA	NA	NA	67
1927	NA	NA	NA	NA	NA	NA	NA	NA	NA	65
1928	NA	NA	NA	NA	NA	NA	NA	NA	NA	58
1929	NA	NA	NA	NA	NA	NA	NA	NA	NA	51
1930	NA	NA	NA	NA	NA	NA	NA	NA	NA	46
1931	NA	NA	NA	NA	NA	NA	NA	NA	NA	50
1932	NA	NA	NA	NA	NA	NA	NA	NA	NA	60
1933	NA	NA	NA	NA	NA	NA	NA	NA	NA	63
1934	NA	NA	NA	NA	NA	NA	NA	NA	NA	62
1935	NA	NA	NA	NA	NA	NA	NA	NA	NA	76
1936	NA	NA	NA	NA	NA	NA	NA	NA	NA	71
1937	NA	NA	NA	NA	NA	NA	NA	NA	NA	80
1938	NA	NA	NA	NA	NA	NA	NA	NA	NA	88
1939	NA	NA	NA	NA	NA	NA	NA	NA	NA	80
1940	NA	NA	NA	NA	NA	NA	NA	NA	NA	81
1941	NA	NA	NA	NA	NA	NA	NA	NA	NA	85
1942	NA	NA	NA	NA	NA	NA	NA	NA	NA	90
1943	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1944	NA	NA	NA	NA	NA	NA	NA	NA	NA	110
1945	NA	NA	NA	NA	NA	NA	NA	NA	NA	102
1946	NA	NA	NA	NA	NA	NA	NA	NA	NA	101
1947	NA	NA	NA	NA	NA	NA	NA	NA	NA	99
1948	NA	NA	NA	NA	NA	NA	NA	NA	NA	99
1949	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1950	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1951	NA	NA	NA	NA	NA	NA	NA	NA	NA	96
1952	NA	NA	NA	NA	NA	NA	NA	NA	NA	110
1953	NA	NA	NA	NA	NA	NA	NA	NA	NA	131
1954	NA	NA	NA	NA	NA	NA	NA	NA	NA	133
1955	NA	NA	NA	NA	NA	NA	NA	NA	NA	119
1956	NA	NA	NA	NA	NA	NA	NA	NA	NA	129
1957	NA	NA	NA	NA	NA	NA	NA	NA	NA	110
1958	NA	NA	NA	NA	NA	NA	NA	NA	NA	121
1959	NA	NA	NA	NA	NA	NA	NA	NA	NA	129
1960	NA	NA	NA	NA	NA	NA	NA	NA	NA	132

Table 5. Continued.

Year	2A	2B	2C	3A	3B	4A	4B	4C	4D	Total
1961	NA	NA	NA	NA	NA	NA	NA	NA	NA	127
1962	NA	NA	NA	NA	NA	NA	NA	NA	NA	115
1963	NA	NA	NA	NA	NA	NA	NA	NA	NA	105
1964	NA	NA	NA	NA	NA	NA	NA	NA	NA	100
1965	NA	NA	NA	NA	NA	NA	NA	NA	NA	99
1966	NA	NA	NA	NA	NA	NA	NA	NA	NA	100
1967	NA	NA	NA	NA	NA	NA	NA	NA	NA	101
1968	NA	NA	NA	NA	NA	NA	NA	NA	NA	103
1969	NA	NA	NA	NA	NA	NA	NA	NA	NA	95
1970	NA	NA	NA	NA	NA	NA	NA	NA	NA	91
1971	NA	NA	NA	NA	NA	NA	NA	NA	NA	89
1972	NA	NA	NA	NA	NA	NA	NA	NA	NA	78
1973	NA	NA	NA	NA	NA	NA	NA	NA	NA	63
1974	59	64	57	65	57	NA	NA	NA	NA	61
1975	59	68	53	66	68	NA	NA	NA	NA	61
1976	33	53	42	60	65	NA	NA	NA	NA	55
1977	83	61	45	61	73	NA	NA	NA	NA	63
1978	39	63	56	78	53	NA	NA	NA	NA	71
1979	50	48	80	86	37	NA	NA	NA	NA	75
1980	37	65	79	118	113	NA	NA	NA	NA	94
1981	33	67	144	142	160	158	99	110	NA	111
1982	22	69	146	168	203	103	NA	91	NA	127
1983	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1984	63	147	284	502	474	366	161	NA	197	291
1985	62	139	345	500	592	337	234	594	330	357
1986	55	118	290	506	506	260	238	427	218	320
1987	53	130	260	498	478	342	220	384	241	321
1988	134	137	281	503	654	453	224	371	201	368
1989	113	133	258	457	590	409	268	333	432	358
1990	168	176	270	354	484	418	209	288	381	318
1991	158	149	233	319	466	471	329	223	399	317
1992	117	171	230	397	440	372	280	249	412	319
1993	147	208	256	393	514	463	218	257	851	373
1994	93	215	207	354	377	463	197	167	480	306
1995	116	219	234	417	476	349	189	286	475	330
1996	159	227	239	473	557	515	269	297	543	392
1997	226	241	246	458	563	483	275	335	671	404
1998	194	232	236	452	611	525	287	287	627	407
1999	342	213	199	437	538	497	310	271	535	392
2000	263	229	187	443	579	548	320	223	556	402
2001	171	227	196	469	431	474	270	203	511	362
2002	181	223	244	508	399	402	245	148	503	359
2003	173	221	233	485	365	355	196	105	388	328
2004	143	203	240	486	328	315	202	120	445	318
2005	137	195	203	446	293	301	238	91	379	296
2006	156	201	170	403	292	241	218	72	280	270
2007	96	198	160	398	257	206	230	65	237	251
2008	69	174	161	370	234	206	193	94	247	232
2009	98	188	155	318	211	234	189	88	249	222
2010	149	222	158	285	173	182	142	82	188	203
2011	92	240	175	280	140	189	165	75	166	198
2012	102	248	207	263	133	194	149	60	155	195
2013	132	269	227	240	113	164	122	55	151	187

Assessment of the Pacific halibut stock at the end of 2012

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Abstract

This stock assessment reports the status of the Pacific halibut resource in the northeastern Pacific, including the territorial waters of the United States and Canada. Annual removals were above the 100 year average of 64 million pounds from 1985 through 2010, dropping to 60 million pounds in 2011, and then 51 million pounds in 2012, in response to management measures intended to stabilize declining trends in the IPHC setline survey and stock assessment estimates. All data sources were updated through 2012. The 2012 setline survey showed an increase in WPUE (+12% relative to 2011), the first since the current geographically comprehensive survey began in 1997. Age distributions in 2012 from both the survey and fishery were very similar to those observed in 2011, indicating a relatively stable stock, but not showing any evidence of strong recruitments in recent years. Individual size-at-age continues to be low relative to the rest of the time-series, although there were signs of flattening in the declining trend for some ages for both males and females.

For 2012, there was a full review of the data, specific model equations and general approach used to assess the stock in recent years. This effort consisted of three parts: 1) investigate and address the cause of the retrospective pattern observed in recent assessments, 2) improve the way uncertainty is propagated through data processing, model estimation and into the results used for management, and 3) identify additional work needed to create a more stable and easily reviewed stock assessment for the future. This work culminated in a successful Scientific Review Meeting, 24-26 October, 2012. Allowing for time-varying availability in the assessment model removed the retrospective bias in recent status estimates and is consistent with observed geographic and demographic trends. This change to the assessment model resulted in a much more pronounced decline in the estimated stock trend in recent years, a large reduction in the scale of current population estimates, and also a decrease in the estimated average level of productivity.

The 2012 assessment indicated that the Pacific halibut stock has been declining continuously over much of the last decade as a result of decreasing size-at-age, as well as poor recruitment strengths. The population decline is estimated to have slowed and the stock trajectory is now relatively flat at 35% of the reference level, just above the harvest policy threshold (30%). Despite reductions in harvest levels in 2011 and 2012, the assessment estimates that, in retrospect, harvest rates have been well above the coastwide targets implied by the current harvest policy. The 2013 estimate of exploitable biomass is 186.49 million pounds, significantly smaller than the 2011 estimate of 260 million pounds. A bridge with the 2011 stock assessment results is provided, along with revised results from that model using the final data sets available through 2011 and through 2012 for direct comparison to the 2012 assessment results. Forecast projections were conducted for a range of alternative management actions, and probabilities of various risk metrics are reported in a decision-making table framework. The application of the current harvest policy, consistent with the approach used in recent stock assessments, results in the Blue line of the decision-making table indicating a coastwide TCEY of 36.63 million pounds and FCEY of 22.7 million pounds.

Introduction

Stock, management, and removals

This stock assessment reports the status of the Pacific halibut resource in the northeastern Pacific Ocean, including the territorial waters of the United States and Canada. As in recent assessments (Hare 2011), the resource is modeled as a single stock extending from northern California to the Aleutian Islands and Bering Sea, including all inside waters, the Strait of Georgia and Puget Sound. Potential connectivity with the western Pacific resource is considered slight and is not explicitly accounted for.

The halibut fishery has been managed for nearly 100 years, and much is known about the history of fishery removals, population trends and life-history characteristics. Total annual halibut removals (including all sources of mortality: target fishery landings and discards, bycatch in non-target fisheries, research, sport and personal use) have ranged from 34 to 100 million pounds over the last 100 years (Fig. 1; all weights in this document are reported as 'net' weights, head and guts removed; this is approximately 75% of the round weight). The average annual removal over this period has been 64 million pounds. Annual removals were above the 100 year average from 1985 through 2010, dropping to 60 million pounds in 2011 and then 51 million pounds in 2012 (Table 1).

After a peak in 2004, annual removals have decreased each subsequent year in response to management measures intended to stabilize declining trends in IPHC setline survey WPUE (Weight-Per-Unit-Effort, net lb/skate) and stock assessment estimates. These reductions have been proportionally greatest for the directed longline fishery (Fig. 2), although all components have seen reductions during this period. Management of halibut includes a complex set of regulations that vary among fishery sectors, regulatory areas and management bodies. The management of annual removals begins with the Total Constant Exploitation Yield (TCEY), which is defined as the target level of harvest of halibut exceeding 26 in. (66 cm) in fork length (O26). This value is obtained by applying regulatory area-specific harvest rates (based on current harvest policy) to the coastwide estimate of Exploitable biomass (frequently referred to as Ebio in previous assessments) after it has been apportioned among areas. Apportionment calculations consist of adjusting raw survey WPUE in each regulatory area to account for the fraction of the annual fishing mortality that occurred prior to the survey, competition for baits as measured by the proportion of hooks returning with baits, and the geographic extent of the area. These calculations and results are described in Webster and Stewart (2013). Over the last decade, management has followed this prescription quite closely, with the TCEY tracking the declines in each subsequent estimate of exploitable biomass (from the annual stock assessment results), available at the time of each decision (Fig. 3). Both the setline survey and commercial fishery logbook WPUE trends have shown a very similar trend when compared with assessment results (Fig. 3). The Fishery Constant Exploitation Yield (FCEY) is calculated by subtracting from the TCEY the removals associated with directed fishery wastage (sublegal fish discarded that are then assumed to die due to hooking mortality as well as mortality of all sizes from lost fishing gear), bycatch, sport and personal use fisheries (with the exceptions of Area 2A, where personal use and sport removals are included in the FCEY, and Area 2B where sport removals are included in the FCEY). Since 2004, reductions in the TCEY have translated into reductions in the total removals from all sources, as well as the FCEY. During this period, there has been an increase in the proportional contribution of other removals (Fig. 4).

Data sources

The data included in this assessment are comprised of fishery-dependent sources, fishery-independent sources, and auxiliary biological information (Table 2). These data represent the survey trends, biological characteristics associated with these trends (proportions-at-age by sex, length-at-age, and weight-at-age), removals from the stock from each source, as well as the biological characteristics of those removals. All raw observations undergo various processing steps to account for sampling methods, and then a process of aggregation to the coastwide level. Data are first summarized by regulatory area, and then weighted appropriately, such that inputs to the assessment represent total coastwide mortality, or the geographically-weighted average values for indices of abundance and biological summaries (length-, weight-, and age-composition data). Further, where different methods have been used in different years (e.g., ageing methods before and after 2002) these changes are also accounted for. The primary sources of information for this assessment and the methods used to process them remain unchanged from recent stock assessments, although guidance on potential improvements for the 2013 stock assessment is outlined in the report of the recent Scientific Review Meeting (Stewart et al. 2012).

Data through 2011 were updated to include additional observations either not available for the 2011 stock assessment (e.g., finalized 2011 catches, additional logbook information), or improved estimates over the time-series for all sources. All data sources were finalized on 7 November, 2012 in order to provide adequate time for analysis and modeling prior to the IPHC's interim meeting.

Fishery-independent data

The annual IPHC setline survey provides the primary source of fishery-independent data available for the stock assessment. Trend information included in the assessment model includes both WPUE and Numbers-Per-Unit-Effort (NPUE) for halibut over 32 in. (81.3 cm) in fork length (O32). Trends in these indices of abundance had been steadily declining through 2011 since 1997 when the current geographically comprehensive survey design was initiated (Table 3, Fig. 5). However, the 2012 setline survey indices of WPUE and NPUE were 12% and 9% higher than those from 2011. Despite the increase in the coastwide aggregate, this trend was not ubiquitous across all regulatory areas (Figs. 5 and 6). The largest WPUE increase was observed in area 2B (30%), with area 4B showing a large decline (29%).

Coastwide age distributions observed by the survey in 2012 were very similar to those observed in 2011, indicating a relatively stable stock, but not showing any clear evidence of strong recent recruitments (Fig. 8). The majority of the halibut encountered by the survey has consistently remained in the 7-15 year-old range for the recent decade (Fig. 9). Prior to that time, stronger recruitment around the 1987 cohort was quite dominant in the proportions-at-age. The average age observed in the survey increased until 2002 (following the aging of the 1987 cohort) and has since declined to 12.2 years in 2012 (Fig. 10). This is slightly older than the age at 50% maturity. Average individual weight has declined significantly from 21.2 lb in 1997 to 13.7 lb in 2012. This reflects not only the decline in the average age, but also a strong decline in both length- and weight-at-age (estimated from the weight-length relationship) over all ages observed and for both female and male halibut (Figs. 11 and 12). The apparent 'kink' in these size-at-age patterns is likely due to a change in ageing methods (described below), rather than an actual biological phenomenon. Some flattening of recent trends is evident in the 2012 length- and weight-at-age data, particularly for female halibut between ages 10-20, which are those ages making the greatest contribution to the spawning biomass.

NOAA trawl surveys provide direct calibration information used to extrapolate the setline survey estimates in the Bering Sea, and also indirect comparisons of stock trend for the assessment results. The trawl surveys capture a relatively high proportion of age-2 to age-5 halibut, much younger than frequently observed in the commercial fishery or setline survey, and therefore also potentially provide an index for recruitment.

The NOAA Bering Sea trawl survey conducted in 2012 observed a slight (1%) decrease in total biomass (estimated via density multiplied by area-swept), and a modest increase (17%) in the biomass thought to be available to the setline survey (Fig. 13). These differing trends appear to be caused by a decline in the number of small halibut, but an increase in the number of fish available to the survey (Fig. 14). No clear evidence for strong incoming recruitments can be seen in the annual size distributions from the Bering Sea, since the relatively strong 2005 cohort was first observed (Fig. 15).

Although there was a NOAA Aleutian Islands trawl survey conducted in 2012, there was insufficient time to process and analyze these data for this assessment document. Using data through 2012, different trends have been observed in Area 4B and 4A. Specifically, both total and exploitable numbers have declined in 4B, while total numbers have increased in 4A (Fig. 16 Since the exploitable numbers have also declined in 4A, there have apparently been some increases in smaller fish in that area. There was no NOAA trawl survey conducted in the Gulf of Alaska during 2012. Due to the spacing in the timing of the surveys, it is difficult to draw strong conclusions; however, the numbers of exploitable fish appear to have declined over the last decade (Fig. 17) consistent with setline survey and fishery observations.

Fishery-dependent data

Up-to-date estimates of commercial fishery landings from the stock are compiled from a variety of sources (Table 1). These commercial landings are inflated to account for lost gear, as well as discarded sublegal halibut and also include annual research catches. Because there are no direct observations of discarding for most of the directed fishery, a proxy method is required to infer the number and size of discarded fish. For all recent assessments, these quantities have been estimated via the ratio of legal to sublegal halibut captured by the setline survey for each year and area combination. Only the survey stations with the highest 33% of all catch-rates are included in this analysis, as the catch rates observed for these stations have been found to track the observed commercial rates quite well (Gilroy and Stewart, 2013). This approach makes the implicit assumption that temporal and spatial difference between survey and fishery catches do not result in significant demographic differences in availability and should be a point of future investigation.

Logbooks collected from the commercial fishery generate indices of both WPUE and NPUE. These indices indicate very similar trends to those observed in the setline survey (Table 3). Many of the general patterns observed in the logbooks are also similar to those from the setline survey, particularly the observed recent increasing trends throughout Area 2. However, unlike the survey WPUE, the coastwide commercial fishery WPUE was almost unchanged from 2011 to 2012, and there were somewhat more pronounced declines in Area 3 (Figs. 18 and 19).

The length- and age-frequency distributions of commercially landed halibut are sampled by IPHC port samplers. Because these fish have been gutted at sea the sex cannot be determined at the time of sampling. Sex-ratios observed in the setline survey generally show a tight relationship with size within a given age, due to the pronounced sexually dimorphic growth pattern of females attaining much larger sizes than males. Because of this consistency, the relationship between sex-ratio and size by age has historically been estimated from the survey and then applied to the fishery biological samples in order to infer the ages and lengths-at-age by sex. Although representing a very reasonable approach, this processing step has implications for calculation of uncertainty and was recommended for revisiting in the future by the Scientific Review Meeting (Stewart et al. 2013).

Age distributions for most years observed in the commercial fishery are very similar to those observed in the setline survey, but generally show fewer fish less than age-10 (due to a high proportion of these fish being sublegal). This was again the case in 2012 (Fig. 9). Also discernible in the commercial age-frequency distribution for 2012 are relatively fewer males (again, a greater proportion are sublegal) as well as slightly more of the oldest fish at age-25 or greater. These old fish were observed primarily in Areas 4A and 4B, with fish greater than age-20 almost entirely absent from Area 2 (Fig. 20). As in the survey data, recent age distributions have been relatively stable, with most of the commercial catch ranging from 8-15 years old (Fig. 21). The coastwide average weight and age of commercially caught fish are consistently greater than those observed in the survey (Fig. 10), but area-specific patterns are very pronounced. The average commercial landed fish weight has declined over the recent time-series; however, this trend has not been consistent across all regulatory areas. Specifically, average weight in Areas 2B, 2C and 4A has been increasing for the last several years, while in Areas 3, 4B and 4D there have been very strong and consistent declines (Fig. 22). The heaviest average fish observed in 2012 were found in Area 2C. Declines in length- and weight-at-age for both females and males appear to have been more pronounced in commercially caught fish than was observed in the survey data (Figs. 23 and 24). Note that for some ages there are very few observations and therefore historically fixed values are assigned; however these values are applied to so few fish they are virtually irrelevant in subsequent calculations. In general, there also seems to have been less flattening of the declines in size-at-age in the commercial data between 2011 and 2012 than in the survey observations.

Auxiliary information

There is a variety of auxiliary information that is analyzed external to the assessment model and contributes to the analysis either as fixed parameter values or as structural assumptions built into the model framework. This includes both biological relationships, as well as information about the methods used to collect the raw data.

Although the stock assessment compares predictions of age frequency to the sampled proportions-at-age, age itself is observed imprecisely and sometimes with some degree of bias. Current ageing is conducted using the Break-and-Bake (BB) method, which has been shown to be unbiased (Piner and Wischnioski 2004). Even unbiased ageing methods are still subject to observation error (imprecision), and this has been thoroughly quantified for the BB method (Clark 2004, Clark and Hare 2006a). The degree of BB ageing imprecision previously estimated and used in all recent stock assessments has not been altered for this analysis. Prior to 2002, ages were read using surface reading, a method that is known to be biased for older fish across many species. Further, the method is much less precise than BB ageing, resulting in lower quality information available to the stock assessment. Although the bias and imprecision have both been quantified for surface-read halibut ages (Clark and Hare 2006a), there has been some concern regarding the quality of these estimates (J. Valero, unpublished analyses) and an effort to re-analyze historical ages is currently underway at the IPHC. Observations-at-age prior to 2002 are corrected to account for the perceived degree of bias and imprecision; however discontinuities are still discernible in the time-series' of length- and weight-at-age for both the survey and fishery (Figs. 11, 12, 23 and 24). This issue was identified during the Scientific Review Meeting (Stewart et al. 2013), and will be the subject of further analysis as re-ageing data become available.

The maturity schedule for Pacific halibut has also been investigated historically and the relative maturity-at-age found to be very stable despite long-term changes in size-at-age (Clark and Hare 2006). Estimates of the age at which 50% of female halibut are sexually mature average 11.6 years, with very few fish mature at ages less than five and nearly all fish mature by about age-17 (Fig. 25).

Natural morality is a notoriously difficult quantity to collect to information on for any fish species, and halibut is no exception to this. Tagging studies can, when correctly accounting for tag loss, tagging morality, reporting rates, and fishing intensity, provide some information on the magnitude of natural mortality. Estimates produced as priors for the IPHC's PIT tagging analyses included a range of values from roughly 0.1 to 0.2. Although there was little statistical difference between an estimated value vs. a fixed value of 0.15, the point estimate produced from the PIT tag analysis was 0.124 (Webster 2010). The asymmetric implications of over- vs. underestimating the true value for natural mortality in a stock assessment (Clark 1999) and a reevaluation of life-history information led to the adoption of the current value of 0.15/year for female halibut in the 1998 stock assessment (Clark and Parma 1998), revised downward from the 1997 assessment, which used a value of 0.2/year (Sullivan and Parma 1997). Uncertainty in this value is discussed in more detail below, and directly included in the results of this assessment via the decision-making table.

Assessment

The evolution of the stock assessment for Pacific halibut has closely tracked that of fisheries science in general (Clark 2003), moving from simple equilibrium-based models to current age-structured approaches (Table 4). Key transitions in this evolution relevant to the changes made for 2012 occurred with the change in natural mortality in 1998 and with the shift to a coastwide stock assessment in 2006. Both of these changes were logical and substantially improved the performance of the models at the time.

Changes to the 2011 assessment

In 2012, the model input data, specific model equations, and the general approach used to assess the halibut stock in recent years was fully reviewed by IPHC staff, and an external review panel. The primary focus of this effort consisted of three parts: 1) investigate and address the cause of the retrospective pattern observed in recent assessments, 2) improve the way uncertainty is propagated through data processing, model estimation and into the results used for management, and 3) identify additional work needed to create a more stable and easily reviewed stock assessment for in the future. This work culminated in a successful Scientific Review Meeting (24-26 October, 2012), from which a detailed summary report is available (Stewart et al. 2013).

The most pressing issue to resolve for 2012 was the pronounced retrospective pattern (Fig. 26) observed among recent Pacific halibut stock assessments (Clark and Hare 2006b, 2007, Hare and Clark 2008, Hare 2009, 2010, 2011). This retrospective pattern resulted in each stock assessment estimating a lower absolute stock level than the previous assessment, which can have strong potential implications for harvest policy (Valero 2011). However, it is difficult to correct adequately for such a bias when the cause is unknown.

The retrospective pattern was clearly evident within the 2011 model (the wobblesq configuration, on which most of the 2011 results were focused) when evaluated by sequentially removing the terminal year of data and re-estimating the time-series of spawning biomass (Fig. 27). As was documented in the 2011 assessment, the retrospective bias in stock size was a direct result of transient overestimation of incoming year-class strengths during the period for which they were relatively poorly informed by the data but contributing significantly to the spawning biomass (i.e., the 1998-2000 cohorts in 2011; Fig. 28).

In order to resolve the retrospective pattern, a detailed investigation of the stock assessment model code and structural assumptions was performed during August and September, 2012. No significant coding errors or inconsistencies in data preparation that appeared to be contributing to the retrospective bias were discovered. Treatment of bycatch mortality (selectivity and magnitude), commercial and survey catchability (identified as a potential factor during the 2011 process; Valero, unpublished analyses), the translation of length- to age-based selectivity, smoothing of recruitment estimates as well as many other potential mechanisms were tested, but none showed any strong correlation with retrospective performance. The most informative tests conducted consisted of: 1) directly penalizing large recruitments, 2) substantially increasing the relative weight placed on the survey trend during model fitting, and 3) evaluating the potential for time-varying availability (Fig. 29). The first of these tests merely provided a means to determine how the fit to all data sources in the model changed as ‘brute force’ was applied to directly remove the retrospective pattern, without any understanding of its underlying cause. This analysis indicated that the age data were clearly linked to the retrospective behavior, as the fit to these data was consistently degraded as the retrospective bias was removed. The second test provided insight into the relative weighting of the various data sets, particularly the consistency of the survey trend with retrospective patterns. It was discovered that the retrospective bias was removed if the survey WPUE trend was substantially up-weighted (thereby decreasing the relative weight on the age data). Although informative, neither of these tests provided an explanation for the retrospective patterns, only a highlighting of which data (the age information) were most closely implicated.

Availability (also called ‘selectivity’) provides the link between the underlying estimated population age-structure and the observed age data in a stock assessment model. When modeled at a small spatial scale the dominant component of this process is represented by vulnerability: which demographic components (i.e., small vs. large fish, old vs. young fish) are most likely to be captured when the gear is deployed. At a coastwide scale, availability includes not only the capture efficiency of the fishing gear, but also the interaction between the spatial distribution of the stock and the differences in population characteristics (i.e., age, length, weight- or length-at-age) among areas. Historical closed area assessment models had maintained a rigid assumption that availability could not vary over time, and this assumption had been carried forward to the current coastwide model, despite the difference in effective application of the relationship at over a much broader spatial scale. Further, the large amount of weight carried by the age-composition data in the assessment model relative to the survey index of abundance was both found to have contributed the observed retrospective bias and the difficulty in identifying it. The age data were largely responsible for stock estimates. As has been the case twice before in the history of the halibut stock assessment (1994 and 2002), a change in the parameterization of availability was required to improve model performance, and remove the retrospective bias. Several different approaches to implementation of time-varying availability were investigated, and all produced results that much more closely matched the observed time-series of survey catch rates than did the 2011 model.

The approach that was selected utilized the same smoother implemented to create continuity between availability of adjacent size bins (Clark and Hare 2006; page 29). This is merely a second differencing equation with a standard error input via the data file. In recent assessments, the standard deviation for the smoothing function over size has been set to 0.05. Values ranging from 0.001 to 0.1 for the standard deviation for the smoother applied to inter-annual changes in availability for each size bin were explored. Values approaching zero produced identical results to a model with no variability over time permitted and larger values quickly converged to relatively stable model estimates of stock size. A working value of 0.025, implying somewhat less change over time than among sizes, produced stable availability estimates and model behavior. This approach also successfully removed the retrospective bias (Fig. 30) in recent status estimates and is consistent with observed geographic and demographic trends.

This change to the assessment model resulted in a much more pronounced decline in the estimated stock trend in recent years (Fig. 31), as a result of much lower estimates of recent recruitments (Fig. 32). These revised estimates also correspond to a large reduction in the average level of productivity, and therefore the absolute value of the spawning biomass reference points (Fig. 33). In tandem, these results suggest only a modest decrease in stock status relative to the harvest policy target. Using only data updated through 2011, the 2011 model estimate of 2012 spawning biomass was 40.9% of the reference level, which was reduced to 31.8% in the revised model, despite a 40% reduction in the absolute estimates. The largest change can be observed in the estimated time-series of age-8+ biomass, which no longer shows a rapid increase in the most recent years (Fig. 34).

Summary of the 2012 model

Little change was made to the 2011 model framework other than the addition of time varying availability, and making aggregate catchability a single estimated quantity. The annual curves remained quite similar for the commercial fishery over time; however the setline survey is estimated to have experienced increasing availability of smaller halibut and decreasing availability of larger fish (Fig. 35). These estimates are consistent with observed increases in abundance in Area 2 and decreases in Areas 3-4, and the biological characteristics generally observed in those areas.

As has been the case in recent assessments, the sport and personal use/subsistence fleets are assigned the same selectivity pattern as the survey. Bycatch morality is assumed to follow a fixed selectivity pattern with a dome-shape, selecting more 40-50 cm halibut than 60+ cm (Fig. 36). Commercial fishery catchability is allowed to vary over time, with the estimated trend for both males and females similar to that seen in previous assessments (Fig. 37). Natural mortality is fixed at a value of 0.15/year for females and estimated to be 0.143 for males. Likelihood equations and model dynamics were also unchanged from previously documented equations (Clark and Hare 2006a).

An effort to fully document all steps involved with data preparation, and the stock assessment model itself, was begun during 2012; however, it was deemed inefficient to proceed with this process until clear guidance on future improvements could be identified. This was achieved during the Scientific Review Meeting (Stewart et al. 2013), and will be completed for the 2013 process. This effort will also focus on developing models with implicit treatment of spatial patterns, better use of data collected prior to 1996, and other improvements identified during the Scientific Review Meeting.

Goodness of fit

The 2012 stock assessment model is able to fit the primary indices of abundance (WPUE and NPUE) from both the setline survey and commercial fishery reasonably well, similar to those fits reported for previous models (Fig. 38). Because the age data are included in the stock assessment in several different forms (e.g., setline survey proportions-at-age and NPUE-at-age) there is a great deal of redundancy in the fitting. For this reason, only one set of fits to age data from the setline survey and commercial fishery are presented graphically. Redundant sources produced very similar patterns. The fit to the total setline survey proportions-at-age captures the general modal structure of the observed data (Fig. 39), and is similar for both females (Fig. 40) and males (Fig. 41). The fit to the commercial fishery total catch-at-age (Fig. 42), as well as the females (Fig. 43) and males (Fig. 44) separately is similar to that of the setline survey.

As is often the case patterns in goodness-of-fit can be much more readily identified through examination of residual plots than through direct examination of fits to the data. Residual patterns for survey proportions-at-age indicate some lack-of-fit associated with the above average 1987 year-class (Fig. 45). This lack of fit shows a transition from positive to negative values occurring at age-16 in 2003, right after the change from surface to break-and-bake ageing methods. A similar pattern can be seen in the female residuals (Fig. 46), which also show positive values for the oldest fish. Male survey residuals tend to show more negative residuals across the youngest and oldest ages (Fig. 47), but a similar transition after 2002. Fishery residuals also display these patterns for fit to total numbers-at-age (Fig. 48), as well as females (Fig. 49) and males (Fig. 50) separately.

Biomass, recruitment and reference point results

The results of the 2012 stock assessment indicate that the Pacific halibut stock has been declining continuously over much of the last decade (Fig. 51, Table 5). This decline has been a result of decreasing size-at-age, as well as relatively poor recruitment strengths (Fig. 52, Table 5). In the last few years, both the exploitable and spawning stock biomass appear to have stabilized, and the predicted numbers-at-age have remained relatively consistent for older ages (e.g., 15-25 years; Table 6). Based on the reductions in recent harvest levels and evidence from the survey index of abundance as well as the age-composition data, the stock assessment estimates that the current stock trajectory is relatively flat. Spawning biomass is estimated to have increased from 197 to 201 million lb from 2012 to 2013 and exploitable biomass from 179 to 186 million lb over the same period.

The current harvest policy for Pacific halibut utilizes a ramp from target harvest rates to no fishing between 30% relative spawning biomass and 20% relative spawning biomass (Fig. 53). At the beginning of 2013, the stock is estimated to be at 35% of the reference level, just above the harvest policy threshold (Fig. 54, Table 5). The details of the calculation of relative spawning biomass have not changed from recent assessments. Briefly, this calculation relies on a historical estimate of spawning-biomass-per-recruit (118.5 lb/age-6 recruit), using size-at-age from the 1960s to 1970s (Hare 2012). Average estimated age-6 recruitment is calculated from the assessment, corrected for environmental regime (Clark and Hare 2006), and then multiplied by the historical spawning-biomass-per-recruit to produce and estimate of the average spawning biomass in the absence of fishery removals.

The current harvest policy assigns a harvest rate of 21.5% to Areas 2A, 2B, 2C and 3A, and a harvest rate of 16.125% to Areas 3B, 4A, 4B, and 4CDE. Because the harvest policy is defined at the Area-specific level, the results of apportionment calculations must be used (Webster and Stewart 2013), to evaluate the relative fishing intensity, even though the assessment is conducted at a coastwide scale. Specifically, in order to compare the effective coastwide harvest rate (ECHR) estimated in the stock assessment to a target level, exploitable biomass must be apportioned to area, with area-specific catch limits aggregated back to the coastwide level (Fig. 55). Using this method, harvest rates are estimated to have been well above targets for the last decade (Fig. 56). This calculation is made in hindsight, and does not correspond to the estimates and targets as historical management decisions were being made, but to the realized harvest rates now estimated in the 2012 stock assessment. Reductions in harvest levels in 2011 and 2012 have brought realized harvest rates much of the way back toward the coastwide target, and declines in spawning biomass appears to have moderated and reversed slightly in 2012 (Fig. 57).

To provide a direct link, or bridge, with the 2011 stock assessment results, those values are reported along with revised results from that model using the final data sets available through 2011 and through 2012 (Table 7). The estimated trend and absolute level of spawning biomass are both very similar between the two models, with the primary divergence visible in the most recent five years (Fig. 58). The very sharp increase estimated by the 2011 model (and previous models) was an artifact of the retrospective pattern, and such increases had been predicted for several sequential assessments, but had never been subsequently observed in the data. The trend in the estimate of spawning biomass for the 2011 stock assessment model updated through 2012 indicated a continued retrospective pattern, further reinforcing the improvements made in the 2012 stock assessment model.

Major sources of uncertainty

Estimation uncertainty, or the portion of uncertainty associated with estimating the most likely values for the parameters of the stock assessment from the available data, is relatively small. Although this is common for many fisheries stock assessments, the degree of pre-model processing and redundancy in the halibut data sets likely result in a substantial underestimation of this source of uncertainty. Nonetheless, it is included in the decision-making framework described below. Additional sources of uncertainty include choices made in structuring the assessment model (e.g., explicit inclusion or exclusion of spatial processes), steps taken during data processing, and many other sources that are not included in the results. The Scientific Review Meeting identified a number of data and model related aspects of uncertainty that could be included in future stock assessments, but for which there was insufficient time during the 2012 process to adequately pursue.

During the 2012 stock assessment process there was substantial discussion regarding estimates of total removals used in the halibut stock assessment. Some of these removals are observed directly through landings, but many others, such as discard mortality and some sources of bycatch in non-target fisheries are inferred from sparse or incomplete data. Using methods consistent with previous years' analyses, this stock assessment includes estimates of removals including all sizes of halibut from all sources for which an estimate is available. To the extent that these estimates are incorrect or incomplete, the results of the assessment will be biased. It is difficult to predict how changes in estimated removals might influence model results, and potential effects are likely to depend on the trends and absolute scale of such changes. This is the case for nearly all stock assessment analyses, and is an important source of uncertainty if the differences among current estimates and actual removals are large. If improved estimates are made available, these can be directly incorporated into the 2013 stock assessment. If uncertainty estimates can be generated for currently used values, or even if plausible ranges removals can be identified, this is a source of uncertainty that could be directly incorporated into the decision-making framework outlined below.

Recent trends of below average recruitment and decreasing size-at-age have been important contributing factors in the overall stock decline. Unfortunately, although the stock assessment can track these trends quite precisely, it does not provide information on the mechanisms causing these trends. The effects of recent poor recruitment are likely to influence spawning biomass trends in the near-term, as these weak cohorts mature. Regardless of harvest levels, potential increases in stock biomass will also be very sensitive to future trends in size-at-age and recruitment. Until these processes are better understood they represent a substantial source of uncertainty that is difficult to include in the forecast projections. Extending the time-series of data included in the stock assessment may help to better identify covariates (e.g., Clark and Hare 2002) which will improve understanding of these population mechanisms. Extending the time-series may also help to reduce the effects of the current 'one-way-trip' of decreasing indices of abundance. Such trends are known to create problems for stock assessment models in delineating between productivity and absolute population size (e.g., Hilborn and Walters 1992).

Sensitivity analyses using the 2011 model

Because survey catchability was a major source of discussion during the 2011 stock assessment process, and was suggested to be a potential factor contributing to the retrospective bias (Valero, unpublished analyses), a sensitivity to the treatment of this parameter is presented for the wobblesq model. Using data updated through 2012, a single value for catchability was (constant over time), was estimated and compared with the time-varying implementation in the wobblesq model. This analysis revealed a similar pattern as in 2011: the absolute stock estimate decreased slightly, but over a relatively small range compared to the full application of time-varying availability (Fig. 59). This is likely due to time-varying catchability capturing a small amount of the demographic shift in availability, but not enough to remove the retrospective pattern.

Sensitivity analyses

During preliminary model investigation conducted during 2012, a wide range of sensitivity analyses were conducted in order to better understand the general modeling approach, identify important aspects of the data and weighting of these data during model fitting, and determine which components in the entire analysis had the most direct effect on absolute estimates of stock size. A discussion of a number of these analyses is included in the Scientific Review Meeting document (Stewart et al. 2013), and several were identified as high-priority for a full investigation during the 2013 stock assessment process. For 2012, natural mortality was identified as the most influential fixed parameter or assumption in the Pacific halibut stock assessment.

Natural mortality is a dominant source of uncertainty in many fisheries stock assessments. A value of 0.15/year for female halibut has been used for all recent halibut assessments (the value for males has been estimated, the relative difference between the sexes being well-informed by the observed sex-ratios in the age data), based on a downward revision made for the 1998 assessment. That well-justified revision resulted in a significant change to the estimates of stock size at the time. In order to avoid abrupt changes in future estimates uncertainty in the natural mortality rate is explicitly included in this assessment. The approach is based on selecting two alternate values of natural mortality, each approximately half as likely as the current best estimate (0.15). These values were 0.10 and 0.2, which produced estimates of spawning biomass that differed by more than 80 million lb (Fig. 60). The method of including and reporting this uncertainty in the decision-making table is described below, as part of the forecasting approach.

An extensive bait-comparison experiment was conducted during the 2012 setline survey (Webster et al. 2013), which included setting somewhat fewer skates baited with the standard bait of chum salmon. Although the number of skates deployed was still within historical survey protocols, there is some information to suggest slightly higher catch-rates for skates at the ends of the gear (Webster and Hare 2011), and this was factored in to the bait experiment analysis. Since number of skates deployed is not a direct component in the standard survey analysis, a stock assessment sensitivity run was conducted by decreasing the 2012 survey catch rate to by 3%. This value represents the maximum difference estimated for any area-specific comparison of end- vs. middle-skates that had a substantial quantity of data available (the values actually range below zero as well). This analysis confirmed that current assessment results were not sensitive to small changes in survey catch rates (Fig. 61).

Retrospective analyses

A retrospective analysis of the 2012 model revealed little pattern in recent spawning biomass estimates as data are sequentially removed from the model (Fig. 62). This is important information for the decision-making process, as previous estimates have been known to include bias, which indicated that reduced catches might be warranted (Valero 2012). Although the improvement in model performance in 2012 is no guarantee that future retrospective patterns may not arise from other aspects of the model (or data sources), the lack of a retrospective pattern means that the results of the 2012 stock assessment are likely to be more reliable than those reported in recent years.

Forecasts and decision-making table

For the 2012 assessment, significant improvements to the methods used to forecast future stock size and to calculate the uncertainty associated with these predictions were made. Changes from previous assessments included integrating the forecasting step into the stock assessment model (rather than treating it as a subsequent independent calculation), which enabled direct inclusion of estimation uncertainty. In addition, given the pronounced declining trends in recent size-at-age, alternative projections were run using observed size-at-age from 2012, as well as fitting a linear trend to the most recent three years of data.

Stock projections rely on the results from the stock assessment, summaries of the removals in 2012, as well as the results of apportionment calculations. The steps included: 1) analyzing the survey catch rates consistent with recent approaches (Webster and Stewart 2013), 2) using the estimated survey biomass distribution to apportion the coastwide exploitable biomass estimates from the stock assessment, 3) applying the area-specific harvest rates to generate the TCEY for each area, 4) subtracting the other removals (O26), assuming that the values for 2013 remain constant at 2012 levels (with the exception of commercial wastage, and sport and personal use in Area 2A and sport in 2B, which are scaled proportional to the TCEY), and 5) calculating the total coastwide mortality (including U26). This calculation results in the application of the current harvest policy, completely consistent with the approach used in recent stock assessments.

The projected removals consistent with the current harvest policy are identified as the Blue Line in the decision-making table and forecast results. For alternative levels of coastwide harvest, the TCEY values were scaled according to the calculations above, and a range of levels from no removals (useful as a comparison to potential management actions; this represents the predicted stock dynamics in the absence of future harvest) to a total mortality of 60 million lb was considered. Increments among alternatives were initially set to roughly 10 million lb of total mortality, with additional rows for a zero FCEY, as well as a row corresponding to the current harvest policy applied to the updated results of the 2011 stock assessment (for bridging comparison). At the request of the Commissioners during the Interim Meeting, two additional rows adjacent to the Blue Line, but differing by only 5 million lb total mortality were added to the decision making table.

Models using all three values of natural mortality were projected three years into the future assuming constant catches at the value identified for each row of the table. Each of these results includes a distribution for forecast quantities, representing estimation uncertainty. These distributions were then weighted and combined, assigning 50% of the probability to the best estimate of natural mortality (0.15) and 25% to the higher and lower alternatives, in order to generate a single probability distribution for a suite of risk metrics. Risk metrics included harvest intensity, stock status relative to harvest policy reference points, stock trend relative to 2013 estimates, as well as catch trend relative to the catch associated with each row.

Initial projections were found to be sensitive to the treatment of future size-at-age. Therefore, based on the advice of the Scientific Review Meeting, forecasts were conducted using recent trend, which indicated a reduced level of future biomass relative to simply assuming the 2012 size-at-age would persist (Fig. 63).

Although the stock is projected to remain stable or increase slightly in the absence of mortality during 2013, all levels of harvest evaluated resulted in declines in the current stock size by 2014 (Fig. 64). There is a 25% probability that the stock will be below the harvest policy threshold of 30% of the reference level of spawning biomass, regardless of the removals in 2013 (column b, Table 8); however there is less than a 1% probability that the stock is below the harvest policy limit of 20% relative spawning biomass (column c). There is a 23% probability that the stock will be smaller in 2014 than it is estimated to be in 2013 in the absence of any removals. Because the stock trajectory is estimated to be very flat, any removals in 2013 yield a much larger probability of a smaller stock in 2014 than 2013, ranging from 76% to 86% over the range of alternatives evaluated (column d). Despite the high probability of a one-year decline in the stock abundance, there is a very low probability that this decline will be large. Probabilities of a greater than 5% stock decline are all 4% or less (column e).

Given recent poor recruitment, declines in spawning biomass are projected to be very likely over a three-year projection, with a probability of 41% in the absence of harvest, increasing rapidly to 95-99% over the alternatives considered (Fig. 65; Table 8, column f). However, the probabilities of dropping below management reference points by 2016 do not change appreciably from those for 2014 (Table 9). Given the current harvest policy, if a fishery CEY of 22.7 million pounds (the Blue line) is removed in 2013, there is an almost even chance (48%) that the exploitable biomass in

2014 could produce a catch at least as large (column g). For smaller removals, there is a very high probability that the harvest policy catch would be larger in 2014, but there is a very low probability of the same or larger FCEY for catches above 22.7 million pounds. Similarly, all harvests smaller than 17.7 million pounds result in a very low probability (1% or less) of exceeding the coastwide target, but those above 22.7 have very high probabilities (75% to > 99%; Table 8, column a).

Future research

Historically, there has been significant investigation into the performance of both area-specific and coastwide models for conducting the halibut stock assessment. Recently, new fisheries approaches have been developed and tested for dealing with spatial processes. These improvements represent an opportunity to revisit the problem in the near-term. Building upon the work completed for 2012, and following the guidance of the Scientific Review Meeting (Stewart et al. 2013), future efforts will focus on several key aspects of the stock assessment:

1) Improved accounting for additional sources of uncertainty through reduced data processing, use of more flexible model structures capable of directly including alternate structural hypotheses, Bayesian methods for fully integrating parameter uncertainty and model averaging.
2) Development of implicitly and explicitly spatial models to better incorporate the spatial variability observed for halibut.
3) Further investigation of the factors contributing to recruitment strength and observed size-at-age in order to better forecast trends in these quantities.
4) Simulation testing the stock assessment model based on data generated from a research model.

Additional work during 2013 will address the specific items relating to data processing and model details listed in the report from the Scientific Review (Stewart et al. 2013).

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We thank all of the IPHC staff for their contributions to data collection, analysis and preparation for the stock assessment. Ian Stewart particularly wishes to thank everyone involved in the assessment process for helping me to better understand 100 years of scientific research in less than three months. The improvements made for 2012 were made possible by extensive analysis and investigation by previous assessment authors and IPHC staff including: Steven Hare, Bill Clark, Juan Valero, as well as many others. The Scientific Review Meeting held 24-26 October, 2012 provided a great deal of insight and creative ideas for best presenting the 2012 assessment results, particularly the format and contents of the decision-making table. Contributions from Jim Ianelli and Robyn Forrest substantially improved the content and clarity of this analysis.

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Table 1. Time-series of removals (by source; million lb, net wt.) used in the stock assessment.

Year	Commercial fishery	Commercial wastage	Bycatch	Sport	Personal use	Total
1996	47.69	0.73	14.46	8.08	0.54	71.51
1997	65.49	1.05	13.51	9.03	0.54	89.61
1998	70.12	1.20	13.43	8.59	0.74	94.07
1999	74.70	1.34	13.84	7.38	0.75	98.00
2000	68.55	1.29	13.29	9.01	0.76	92.89
2001	70.97	1.44	13.16	8.10	0.77	94.45
2002	74.95	1.66	12.61	8.01	0.76	97.99
2003	73.36	1.77	12.58	9.35	1.38	98.44
2004	73.31	1.93	12.58	10.70	1.53	100.05
2005	72.11	2.03	13.26	10.86	1.54	99.80
2006	68.12	2.05	13.08	10.19	1.48	94.92
2007	63.03	2.29	12.27	11.46	1.49	90.53
2008	58.70	2.34	11.89	10.67	1.34	84.93
2009	52.18	2.62	11.38	8.75	1.31	76.24
2010	49.83	3.04	10.63	7.80	1.24	72.54
2011	39.61	2.21	9.90	7.08	1.24	60.04
2012	31.87	1.54	9.87	6.85	1.24	51.36

Table 2. List of data sources included in the assessment.

Years	Range	Resolution	Data
Setline survey data			
1997-2001, 2002-2011	Ages: 6-20+, 6-25+	Males, Females, Total	Proportions-at-age, Standard Error (SE) proportions-at-age, Numbers-per-unit-effort (NPUE)-at-age, SE of NPUE-at-age, Mean length-at-age, Ageing bias-corrected mean length-at-age, Mean weight-at-age, Ageing bias-corrected mean weight-at-age, Proportion legal (over 32”), Legal weight-at-age
1996-2011	Aggregated	Aggregated	NPUE, SE of NPUE, Weight-per-unit-effort (WPUE), SE of WPUE
Commercial fishery data			
1996-2001, 2002-2011	Ages: 6-20+, 6-25+	Males, Females, Total	Numbers-at-age, SE of Numbers-at-age, NPUE-at-age, SE of NPUE-at-age, Mean weight-at-age, Ageing bias-corrected mean weight-at-age
1996-2011	Aggregated	Aggregated	NPUE, SE of NPUE, WPUE, SE of WPUE
Bycatch data			
1996-2011	Lengths: 0-120 cm, 10-cm bins	Aggregated	Numbers, SE of numbers
1996-2011	Ages: 6-30	Males, Females, Total	Ageing bias-corrected mean length-at-age, SE of ageing bias-corrected mean length-at-age, Ageing bias-corrected mean weight-at-age
Removals data			
1996-2011	Aggregated	Aggregated	Total weight of removals for: commercial, discard, bycatch, sport, personal use
Ageing imprecision data			
Aggregated	Ages: 1-20, 1-30	Aggregated	Transition matrix from observed: surface to canonical age, break-and-bake to canonical age
Maturity data			
Aggregated	Ages:6-30+	Females	Maturity-at-age

Table 3. Indices of O32 abundance used in the stock assessment (WPUE in lb/skate, NPUE in number/skate).

Year	Setline survey WPUE	Setline survey WPUE SE	Setline survey NPUE	Setline survey NPUE SE	Fishery WPUE	Fishery WPUE SE	Fishery NPUE	Fishery NPUE SE
1996	NA	NA	NA	NA	415	9	14.4	0.32
1997	138.2	4.0	8.0	0.2	423	9	14.4	0.31
1998	133.9	3.7	7.6	0.2	429	9	15.3	0.33
1999	126.1	3.7	6.9	0.2	398	9	15.1	0.34
2000	120.6	3.3	6.8	0.2	417	9	15.2	0.34
2001	112.3	3.3	6.6	0.2	382	9	14.0	0.32
2002	108.8	3.2	6.6	0.2	379	9	13.8	0.33
2003	91.6	2.7	6.0	0.2	346	8	12.8	0.31
2004	88.4	2.6	6.6	0.2	338	8	13.1	0.31
2005	82.1	2.4	6.1	0.2	314	7	12.5	0.30
2006	71.1	2.2	5.6	0.1	283	7	11.5	0.28
2007	65.8	1.9	5.8	0.1	268	6	11.3	0.28
2008	60.2	1.7	5.7	0.1	249	6	10.6	0.26
2009	55.4	1.6	5.5	0.1	236	5	10.3	0.24
2010	47.0	1.5	5.2	0.1	210	5	9.5	0.23
2011	44.7	1.3	5.1	0.1	209	5	9.6	0.24
2012	49.9	1.5	5.5	0.1	209	5	9.5	0.23

Table 4. Summary of historical stock assessment models.

Years	Model	Issues
Pre-1977	Yield, yield-per-recruit, simple stock-production models	No growth or recruitment variability
1978-1981	Cohort analysis, coastwide, natural mortality (M)=0.2	Unstable estimates
1982-1983	Catch-AGE-ANalysis (CAGEAN; age-based availability), coastwide, M=0.2	Migratory dynamics not accounted for
1984-1988	CAGEAN, area-specific, migratory and coastwide, M=0.2	Trends differ by area
1989-1994	CAGEAN, area-specific, M=0.2, age-based selectivity	Retrospective pattern
1995-1997	Statistical Catch-Age (SCA), area-specific, length-based selectivity, M=0.2	M estimate imprecise
1998-1999	SCA, area-specific, length-based selectivity, M=0.15	Poor fit to data
2000-2002	New SCA, area-specific, constant age-based selectivity, M=0.15	Retrospective pattern
2003-2006	SCA, area-specific, constant length-based selectivity, M=0.15	Migratory dynamics created bias
2006-2011	SCA, coastwide, constant length-based availability, M=0.15	Retrospective pattern

Table 5. Time-series of population estimates (million lb, numbers in millions). Age-6 recruits in 2013 reflect the mean, rather than an estimate updated by the data.

Year	Total biomass	Exploitable biomass	Spawning biomass	Relative spawning biomass	Age-6 recruits
1996	1,225.51	518.76	351.35	61%	12.96
1997	1,270.41	569.70	383.30	67%	11.47
1998	1,243.76	575.37	401.01	70%	9.91
1999	1,174.19	555.38	397.35	69%	9.01
2000	1,062.68	503.88	368.05	64%	17.61
2001	941.56	445.44	327.82	57%	18.88
2002	927.20	418.53	318.63	56%	13.56
2003	893.57	380.42	288.05	50%	12.59
2004	837.31	339.08	259.68	45%	20.13
2005	781.80	300.62	233.87	41%	27.20
2006	772.50	268.46	214.80	37%	21.04
2007	795.46	236.33	201.97	35%	14.86
2008	788.50	210.10	192.90	34%	14.49
2009	750.72	191.32	186.97	33%	9.32
2010	716.08	180.56	187.94	33%	7.83
2011	667.25	173.91	190.11	33%	7.20
2012	632.77	178.84	196.91	34%	3.78
2013	598.03	186.49	200.68	35%	*14.13*

Table 6. Estimated numbers-at-age (millions). Age-6 in 2013 reflects the mean, rather than an estimate updated by the data.

	Age (yr)														
Year	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20+
1996	12.96	13.32	19.76	25.77	10.12	5.74	5.75	5.92	3.12	1.75	2.07	1.78	0.94	1.92	0.62
1997	11.47	11.01	11.29	16.68	21.61	8.43	4.74	4.70	4.81	2.52	1.40	1.65	1.41	0.74	2.00
1998	9.91	9.75	9.33	9.53	13.95	17.90	6.90	3.84	3.77	3.84	2.00	1.10	1.29	1.10	2.11
1999	9.01	8.42	8.27	7.87	7.96	11.54	14.61	5.57	3.07	2.99	3.03	1.56	0.86	1.00	2.45
2000	17.61	7.66	7.14	6.96	6.56	6.57	9.38	11.71	4.42	2.42	2.34	2.35	1.21	0.66	2.61
2001	18.88	14.97	6.49	6.01	5.81	5.43	5.36	7.55	9.33	3.50	1.90	1.83	1.83	0.93	2.49
2002	13.56	16.04	12.67	5.47	5.01	4.79	4.41	4.30	5.98	7.32	2.72	1.47	1.41	1.40	2.57
2003	12.59	11.53	13.56	10.61	4.53	4.11	3.87	3.52	3.39	4.67	5.67	2.10	1.13	1.08	2.96
2004	20.13	10.69	9.72	11.33	8.75	3.69	3.30	3.07	2.76	2.64	3.60	4.35	1.61	0.86	3.00
2005	27.20	17.08	9.01	8.11	9.31	7.08	2.94	2.59	2.38	2.11	2.01	2.72	3.28	1.21	2.84
2006	21.04	23.06	14.40	7.50	6.64	7.50	5.59	2.29	1.99	1.80	1.59	1.50	2.04	2.45	2.99
2007	14.86	17.84	19.47	12.02	6.16	5.36	5.94	4.34	1.75	1.50	1.35	1.19	1.12	1.52	4.00
2008	14.49	12.59	15.09	16.29	9.90	4.98	4.25	4.60	3.30	1.31	1.12	1.00	0.88	0.83	4.02
2009	9.32	12.26	10.67	12.65	13.47	8.02	3.95	3.30	3.51	2.48	0.98	0.83	0.74	0.65	3.53
2010	7.83	7.87	10.36	8.92	10.44	10.94	6.41	3.11	2.56	2.69	1.88	0.74	0.63	0.56	3.11
2011	7.20	6.61	6.65	8.67	7.35	8.47	8.74	5.05	2.41	1.96	2.06	1.42	0.56	0.47	2.74
2012	3.78	6.08	5.58	5.57	7.16	6.00	6.83	6.97	3.98	1.89	1.53	1.60	1.10	0.43	2.47
2013	*14.13*	3.19	5.12	4.67	4.60	5.87	4.88	5.51	5.58	3.17	1.50	1.21	1.27	0.87	2.27

Table 7. Results of the bridging analysis, comparing the 2011 (wobblesq) model with data through 2011, data through 2011 but updated in 2012, data through 2012 and the current assessment model results (right-hand column).

Model	2011 (wobblesq)			2012
End year	2011	2011	2012	2012
Data finalized in:	November 2011	November 2012	November 2012	November 2012
Quantity				
2012 Spawning biomass	319	309	272	197
2012 Relative spawning biomass	42%	41%	38%	34%
2013 Spawning biomass	--	--	324	201
2013 Relative spawning biomass	--	--	46%	35%
2012 Exploitable biomass	260	252	219	179
2013 Exploitable biomass	--	--	258	186
2012 Coastwide harvest rate	19.4%	18.9%	21.8%	26.7%

Table 8. Decision-making table. Values indicate the probability of the outcome in each column given the level of removals for that row.

Coastwide Fishery CEY (total removals) millions lb	Fishing intensity	Stock status		Stock trend			Catch trend
	Effective coastwide HR	Spawning biomass					Fishery CEY
	2013	2014				2016	2014
	is greater than target	is less than 30%	is less than 20%	is less than 2013	is 5% less than 2013	is less than 2013	is less than 2013
0.0 (0.0)	0%	25%	<1%	23%	<1%	41%	0%
0.0 (16.5)	<1%	25%	<1%	76%	2%	95%	0%
3.4 (20.0)	<1%	25%	<1%	77%	2%	96%	<1%
12.9 (30.0)	1%	25%	<1%	79%	2%	97%	1%
17.7 (35.0)	23%	25%	<1%	80%	2%	97%	19%
22.7 (40.2)	50%	25%	<1%	82%	3%	97%	48%
27.3 (45.0)	75%	25%	<1%	83%	3%	98%	75%
32.1 (50.0)	84%	25%	<1%	84%	3%	98%	85%
36.2 (54.3)	97%	25%	<1%	85%	4%	98%	97%
41.6 (60.0)	>99%	25%	<1%	86%	4%	99%	>99%
	a	b	c	d	e	f	g

Table 9. Extended decision-making table columns for 3-year projections.

Coastwide Fishery CEY (total removals) millions lb	Stock trend		
	Spawning biomass		
	2016	2016	2016
	is less than 2013	is less than 30%	is less than 20%
0.0 (0.0)	41%	24%	<1%
0.0 (16.5)	95%	27%	<1%
3.4 (20.0)	96%	27%	<1%
12.9 (30.0)	97%	27%	<1%
17.7 (35.0)	97%	27%	<1%
22.7 (40.2)	97%	28%	<1%
27.3 (45.0)	98%	28%	<1%
32.1 (50.0)	98%	28%	<1%
36.2 (54.3)	98%	28%	<1%
41.6 (60.0)	99%	29%	<1%

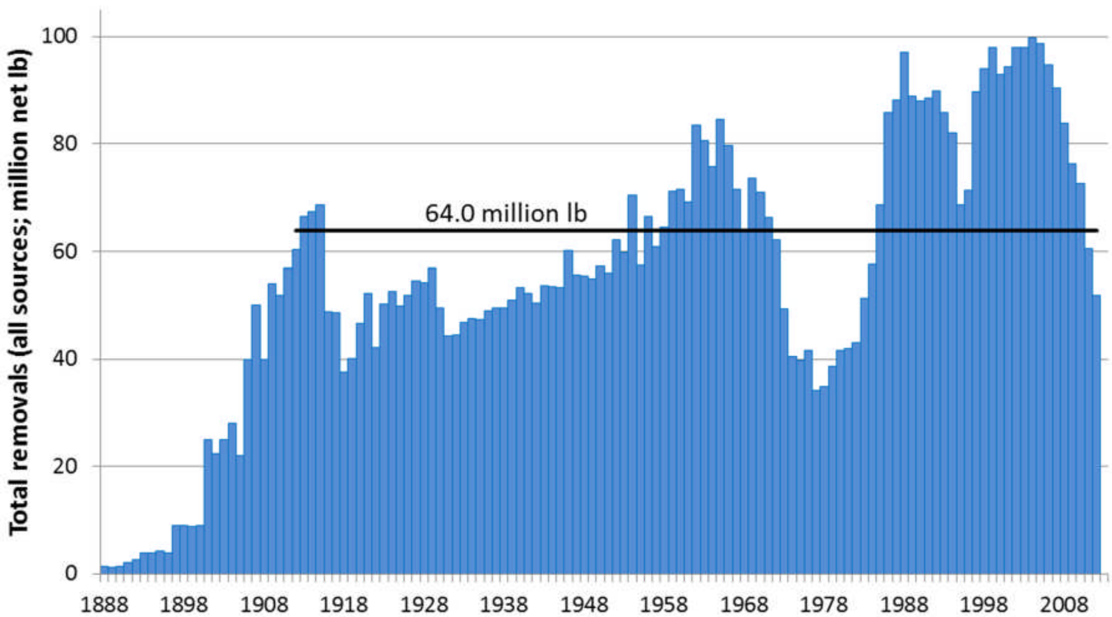

Figure 1. Time series of total removals (million lb) from all sources, 1888-2012. Horizontal line indicates the most recent 100-year average.

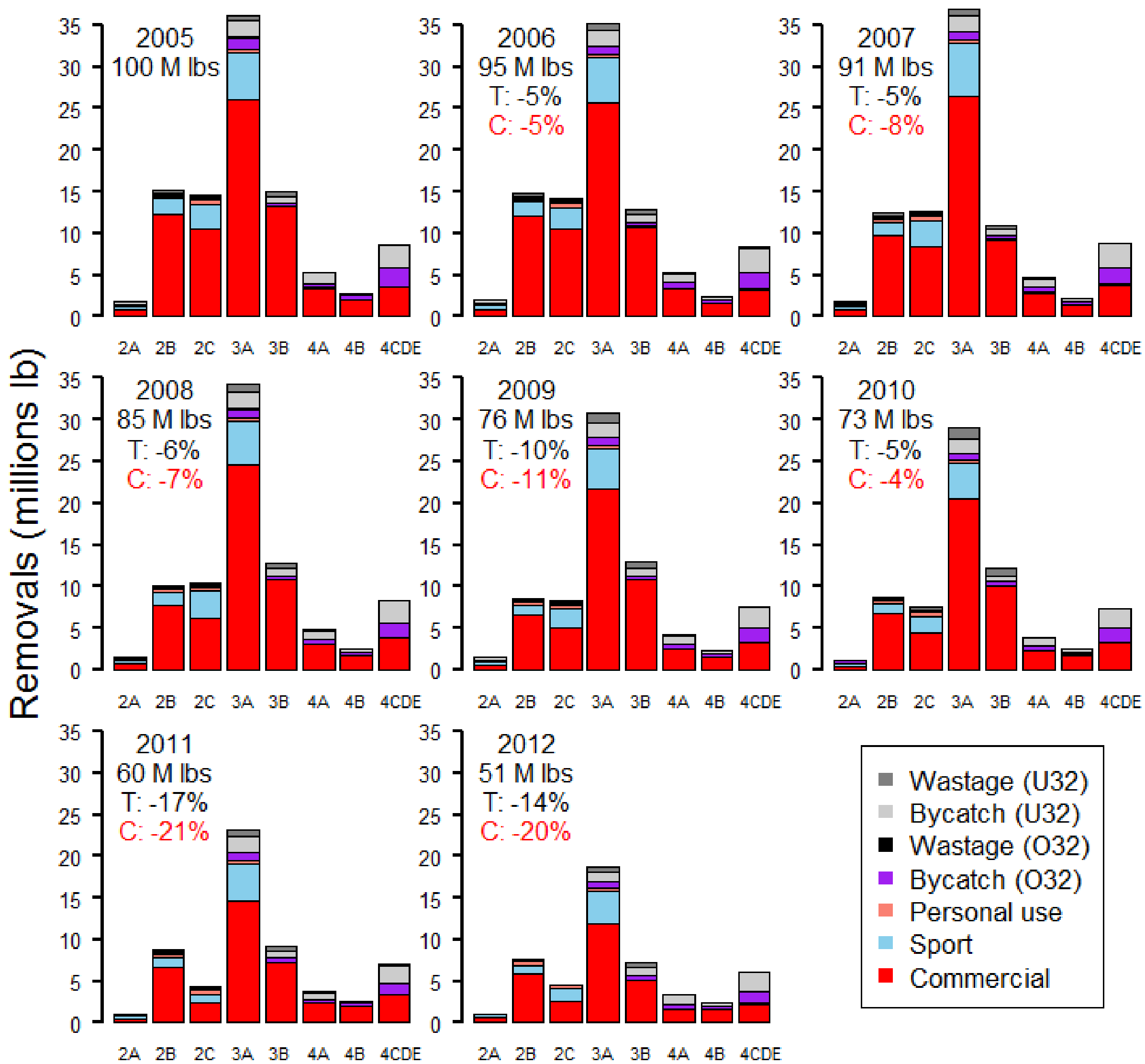

Figure 2. Recent removals by regulatory area and source, 2005-2012. Values below the year labels indicate the total removals from all sources, the percent change in the total from the previous year and the percent change from the directed fishery removals in the previous year.

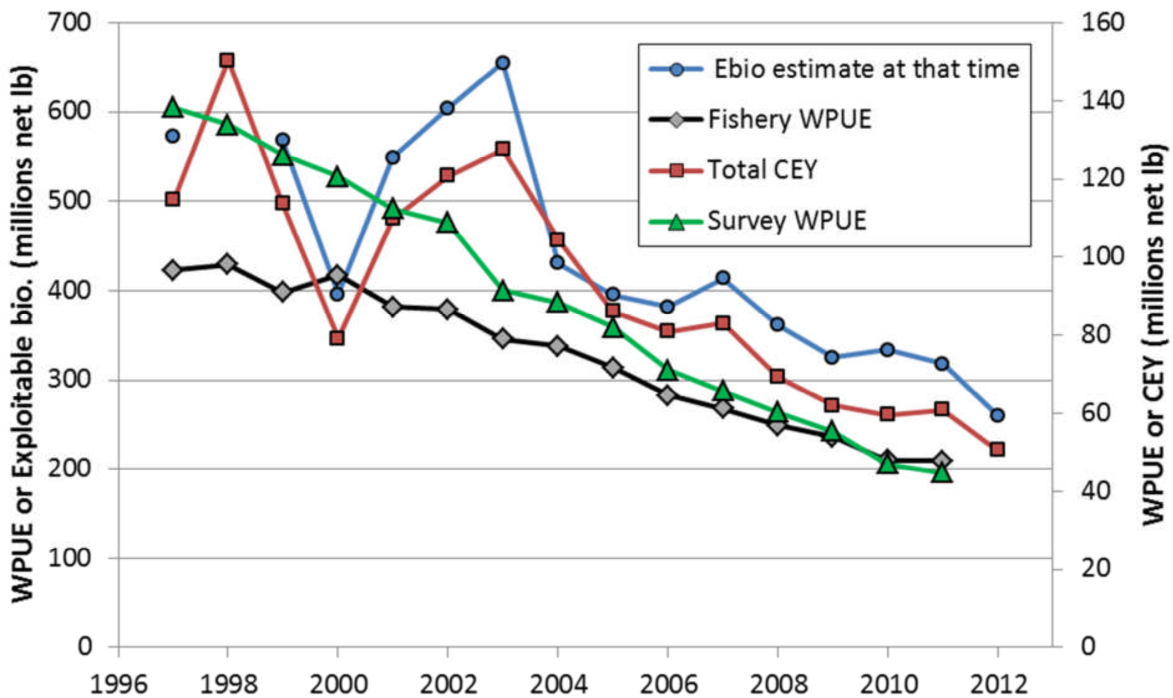

Figure 3. Time series management decisions (Total CEY), and available information at the time the decision was made from the stock assessment (exploitable biomass; million lb), the setline survey (WPUE; lb/skate) and the commercial fishery (WPUE; lb/skate).

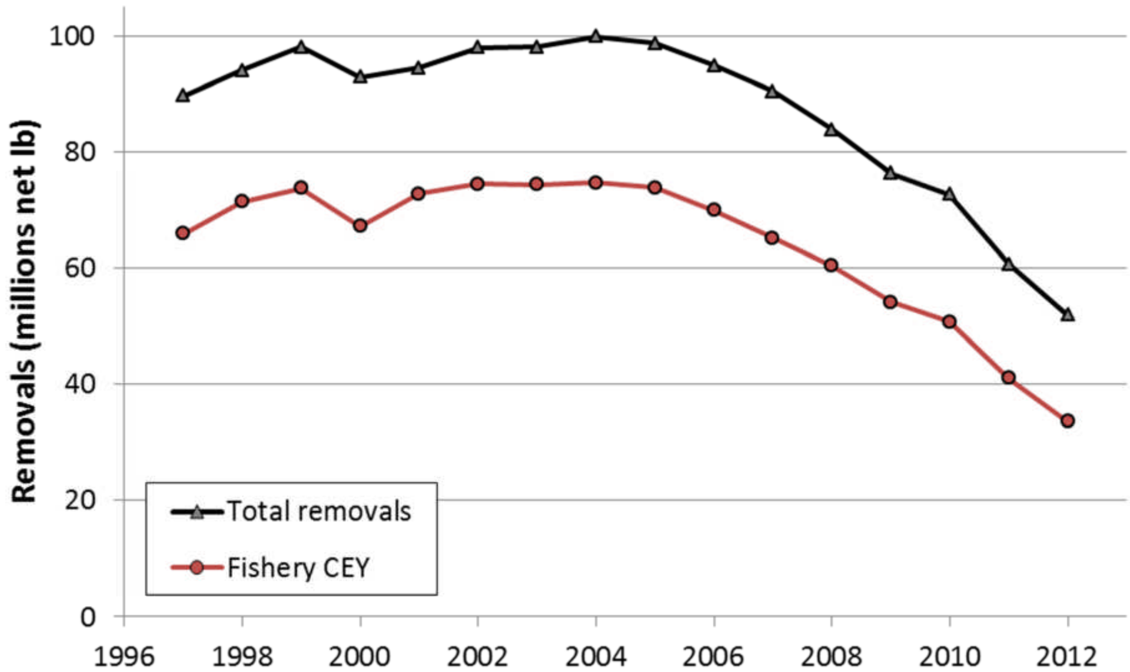

Figure 4. Time series fishery targets harvests (Fishery CEY), and total removals from all sources (million lb).

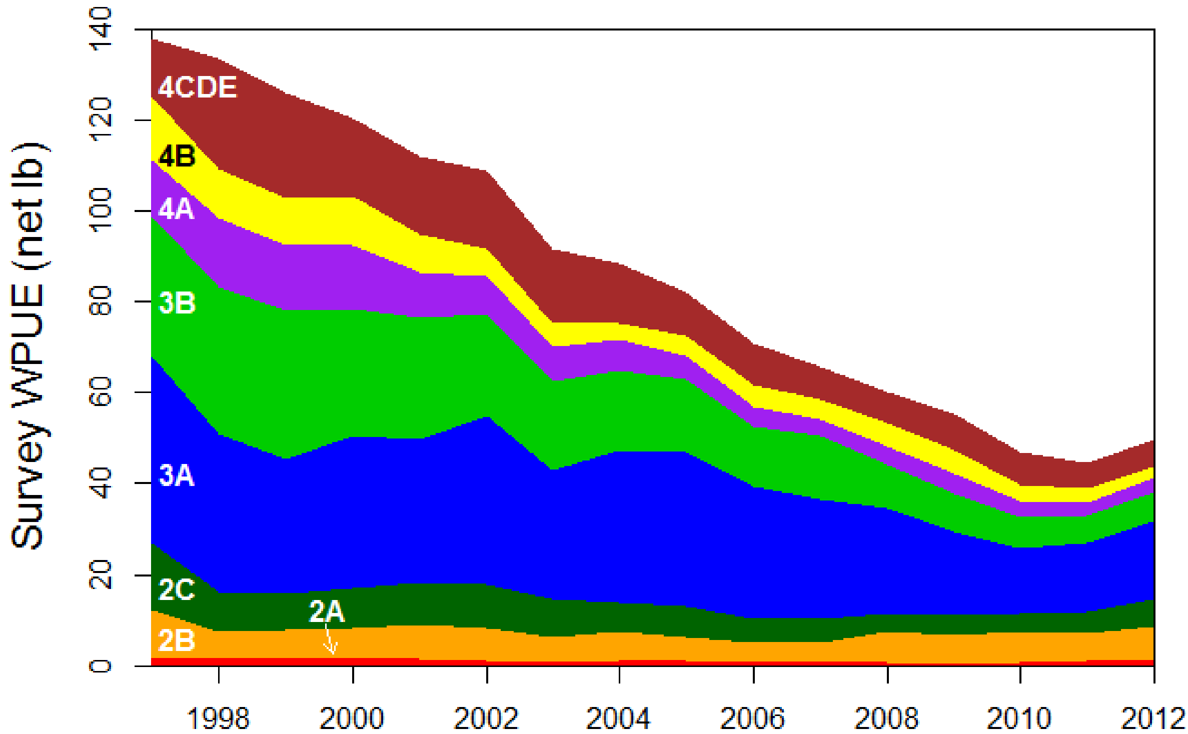

Figure 5. Trend in setline survey WPUE, 1997-2012, colors indicate the contributions from each regulatory area to the geographically-weighted total.

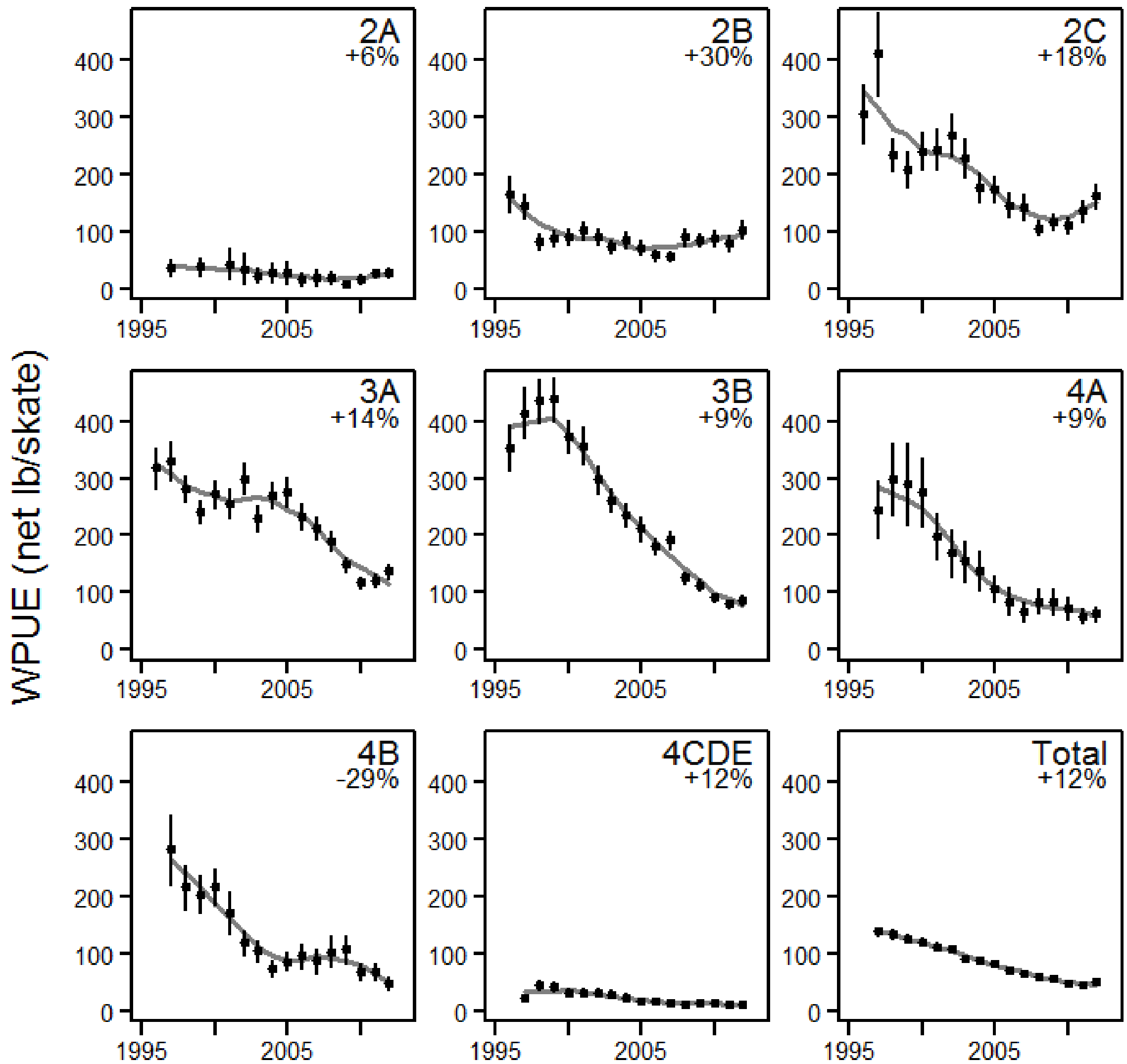

Figure 6. Trends in setline survey WPUE by regulatory area, percentages below the area labels indicate the percent change from 2011 to 2012 observations.

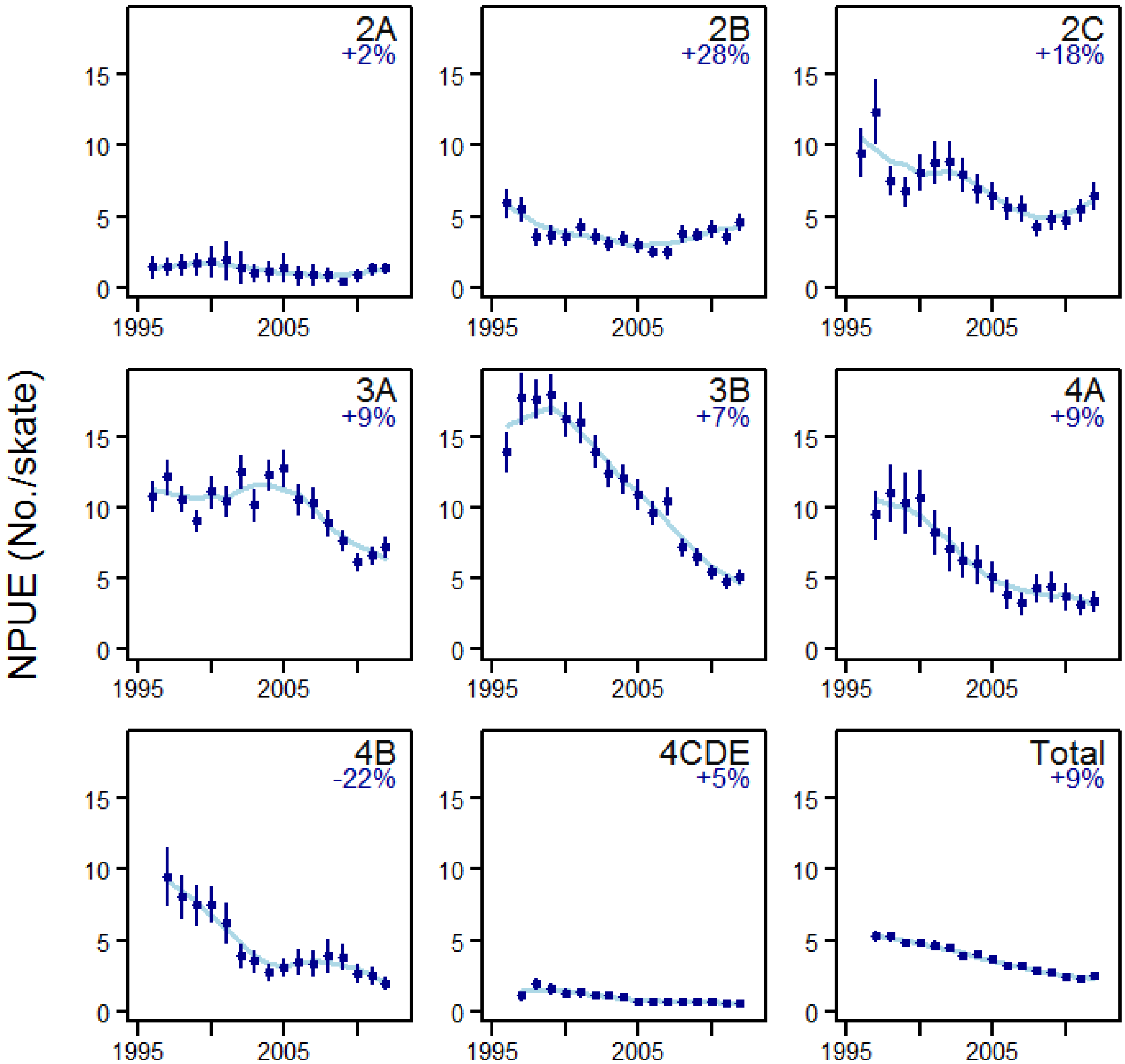

Figure 7. Trends in setline survey NPUE by regulatory area, percentages below the area labels indicate the percent change from 2011 to 2012 observations.

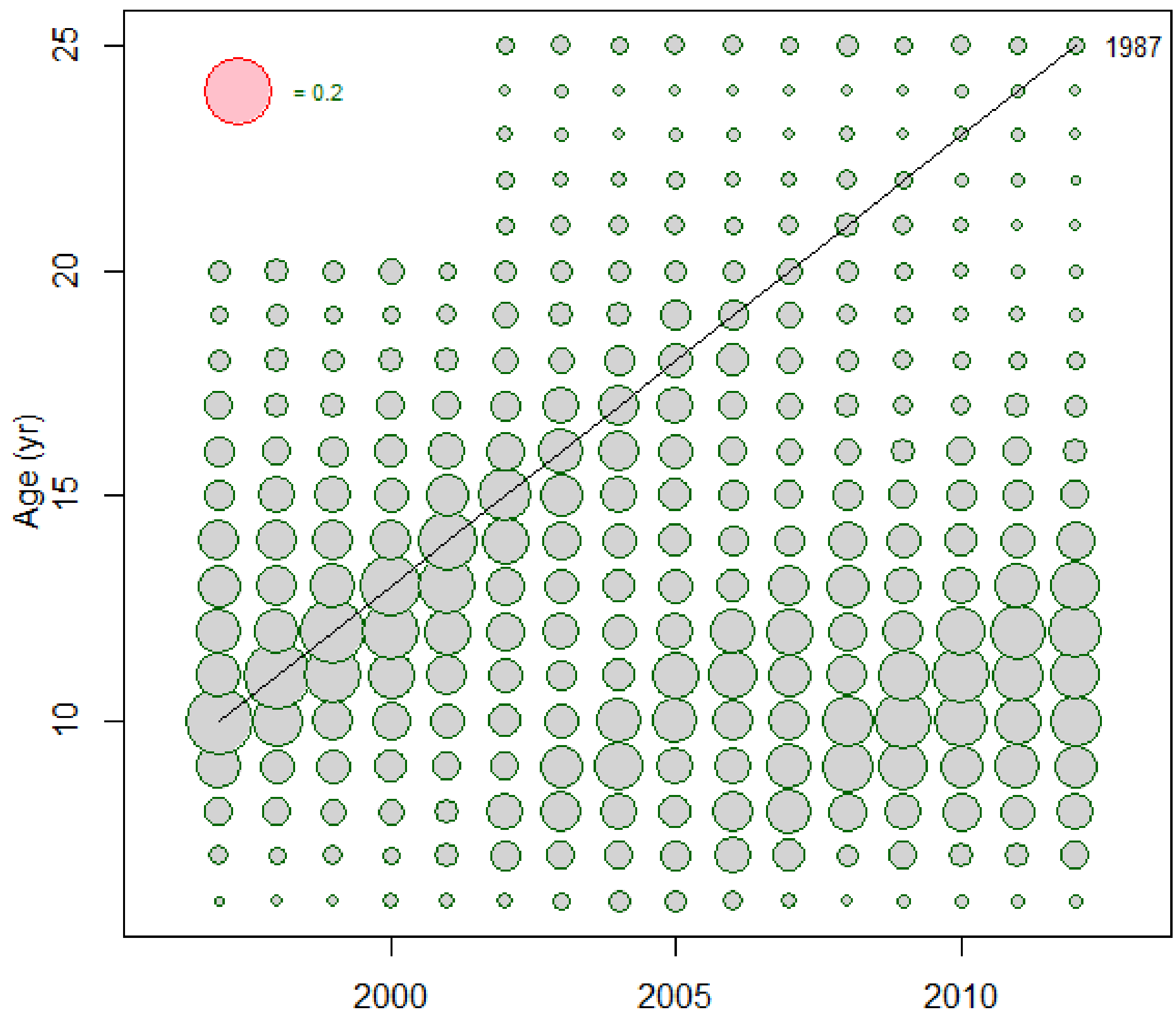

Figure 8. Observed proportions-at-age from the setline survey, 1997-2012. The area of each circle is scaled relative to the legend value in the upper left. Age-20 (prior to 2002) and age-25 (thereafter) represent plus-groups containing that age and all older ages. The 1987 year-class is identified by the diagonal line for visual reference.

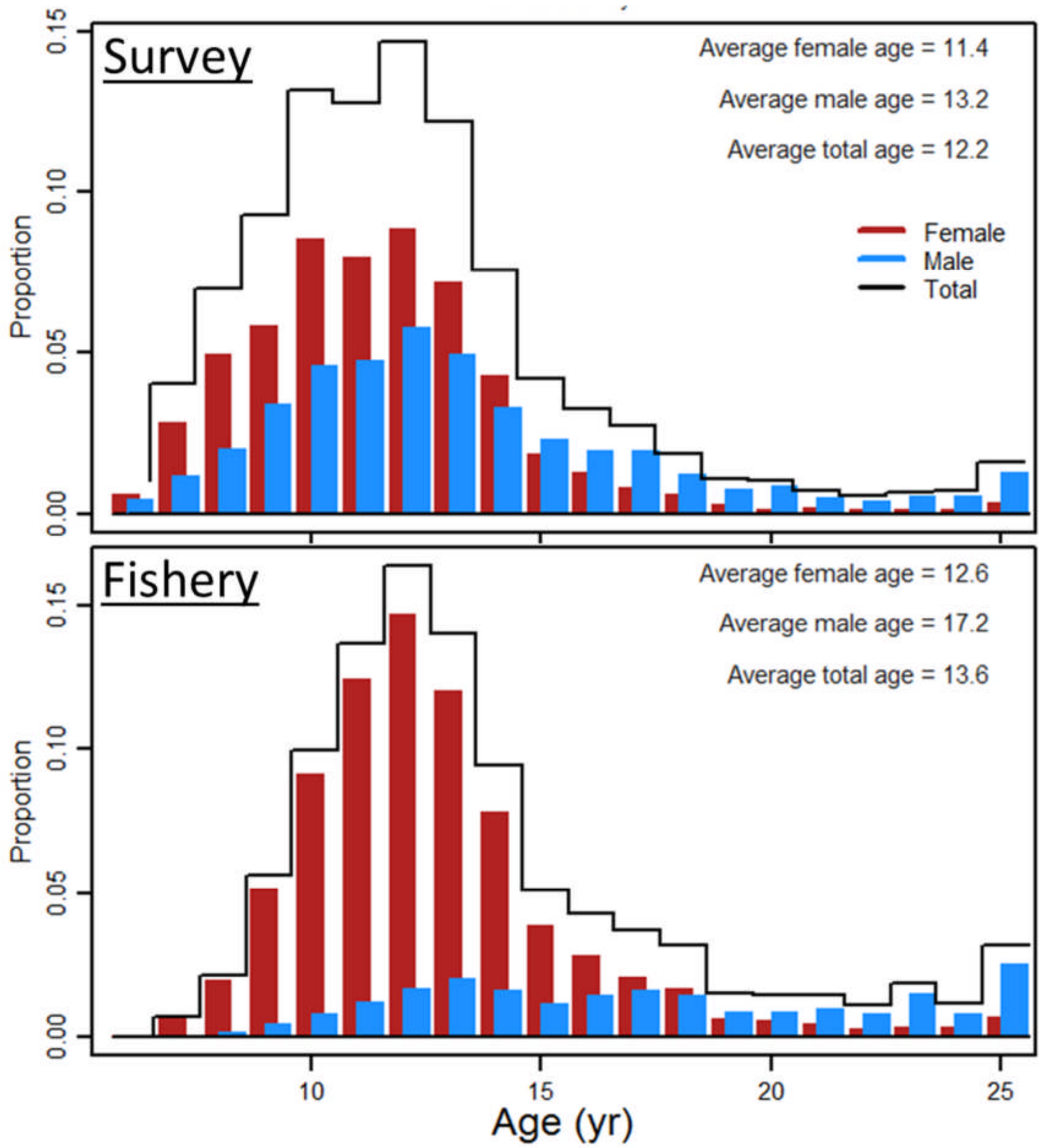

Figure 9. Coastwide aggregate age distributions from the 2012 setline survey (upper panel) and commercial fishery (lower panel).

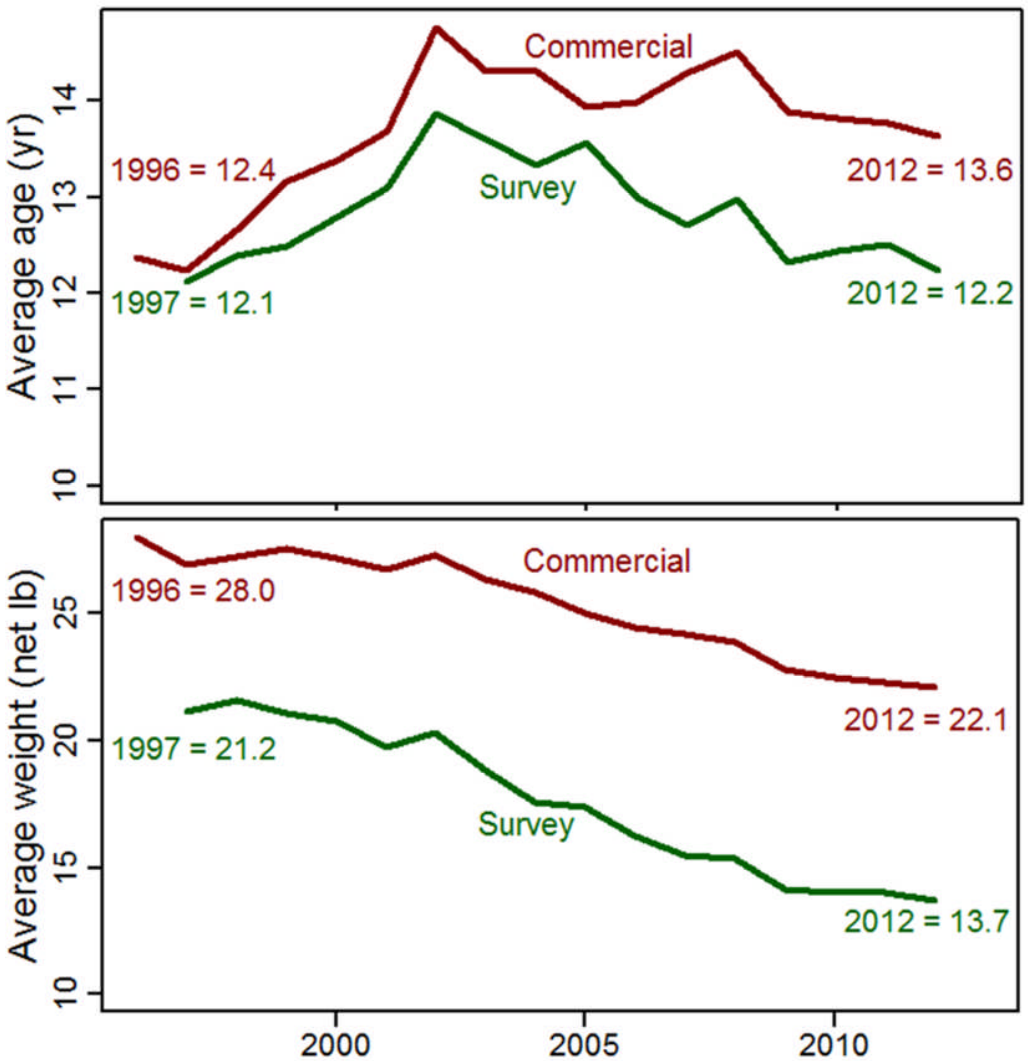

Figure 10. Trends in average age (upper panel) and average fish weight (lower panel) observed in the setline survey and commercial fishery. Values represent coastwide weighted averages across all regulatory areas.

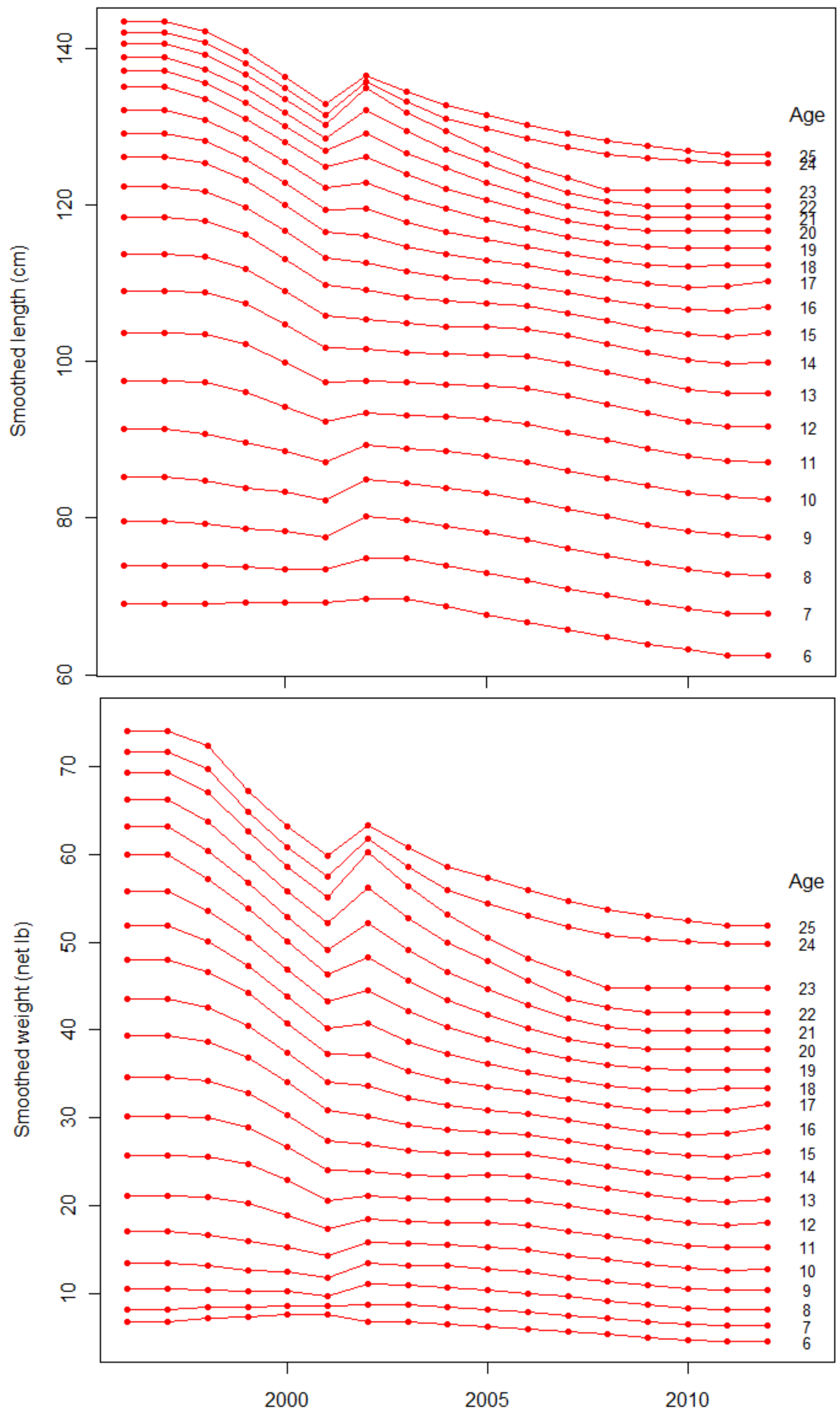

Figure 11. Trends in smoothed female setline survey length-at-age (upper panel) and weight-at-age (lower panel), 1996-2012.

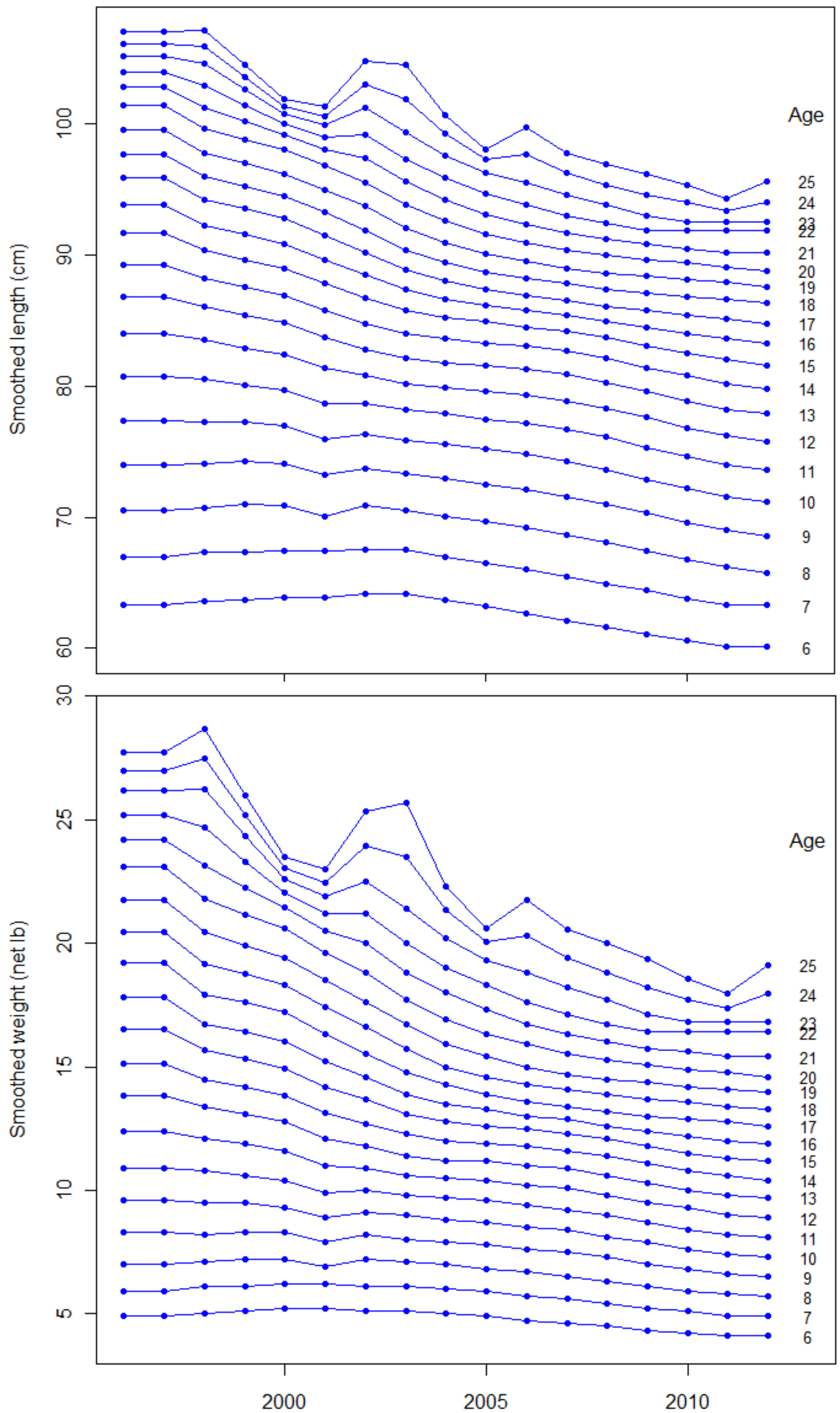

Figure 12. Trends in smoothed male setline survey length-at-age (upper panel) and weight-at-age (lower panel), 1996-2012.

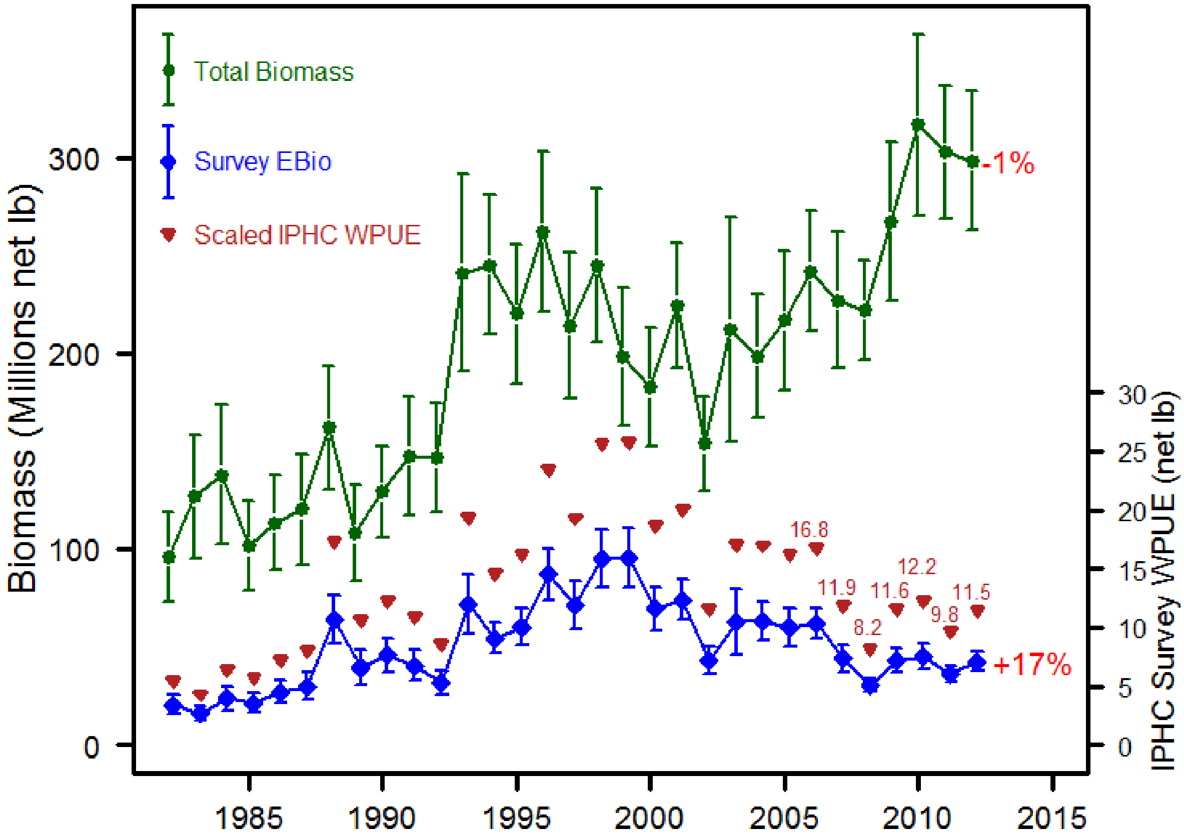

Figure 13. Comparison of area-swept estimated total biomass from the NOAA Bering Sea bottom trawl survey for all sizes of halibut (upper line, with approximate 95% confidence intervals), the portion of that biomass believed to be available to the IPHC setline survey (lower line, with approximate 95% confidence intervals) and the calibrated survey WPUE estimate based on comparison data from 2006 (inverted triangles; numbers above points indicate annual estimates).

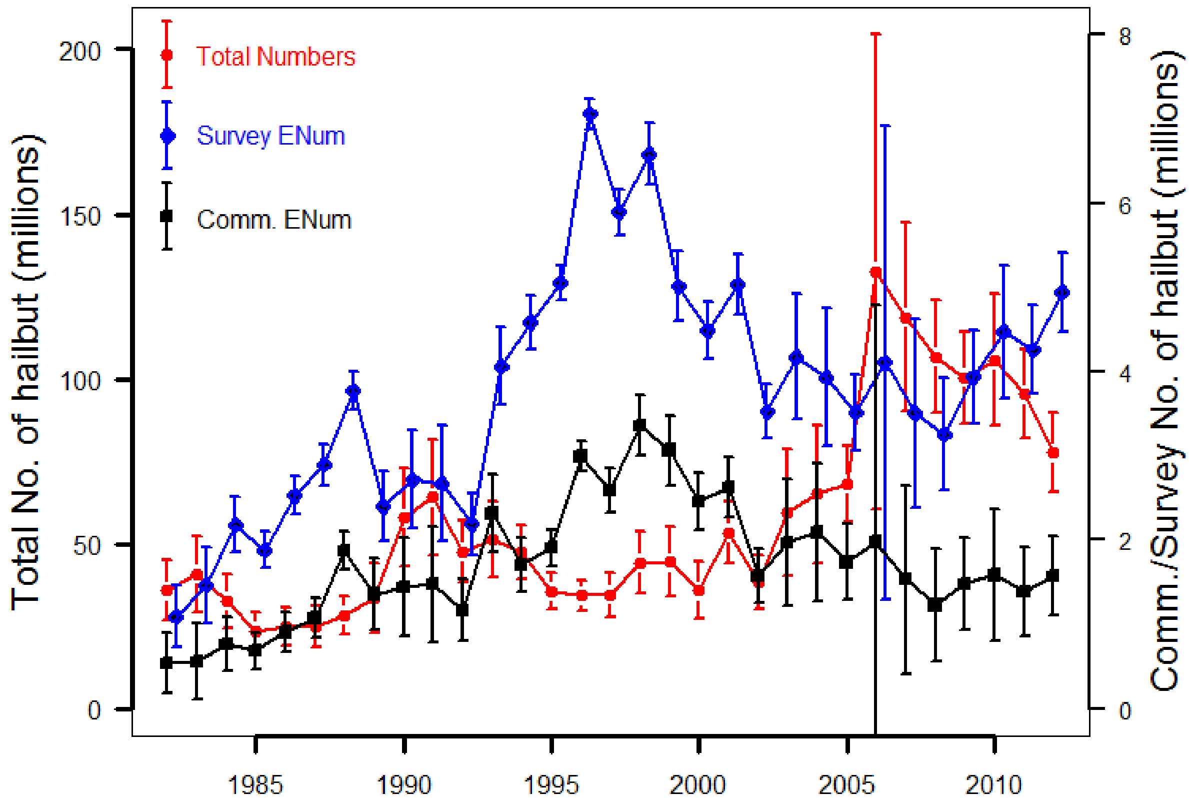

Figure 14. Comparison of area-swept estimated total numbers from the NOAA Bering Sea bottom trawl survey for all sizes of halibut (middle line at the end of the time-series, with approximate 95% confidence intervals), the portion of those numbers believed to be available to the IPHC setline survey (upper line at the end of the time-series, with approximate 95% confidence intervals) and the portion of those numbers estimated to be available to the commercial fishery (lower line at the end of the time-series, with approximate 95% confidence intervals).

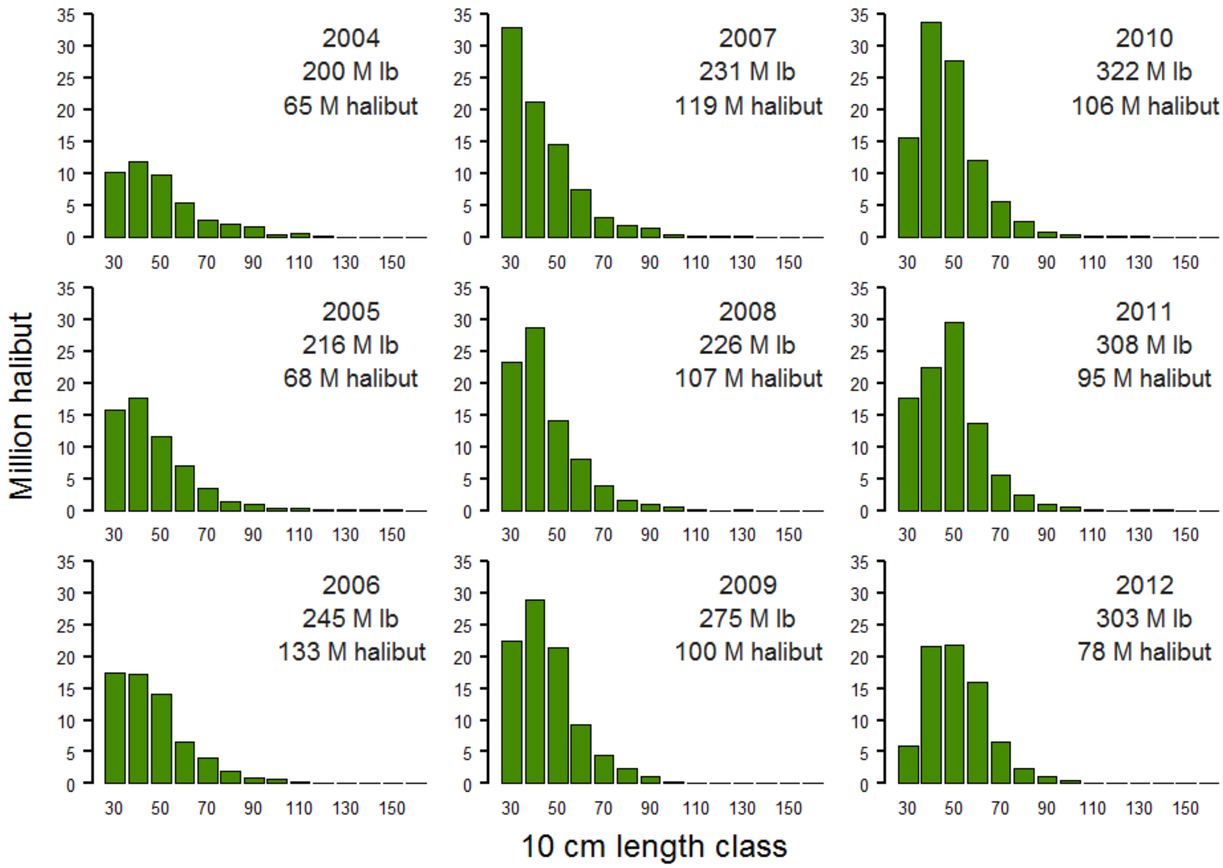

Figure 15. Recent area-swept estimates of total numbers of fish from the NOAA Bering Sea bottom trawl survey by 10-cm size-bin (30-160 cm), 2004-2012. Values reported below the year labels indicate the total biomass and total numbers estimates for that year.

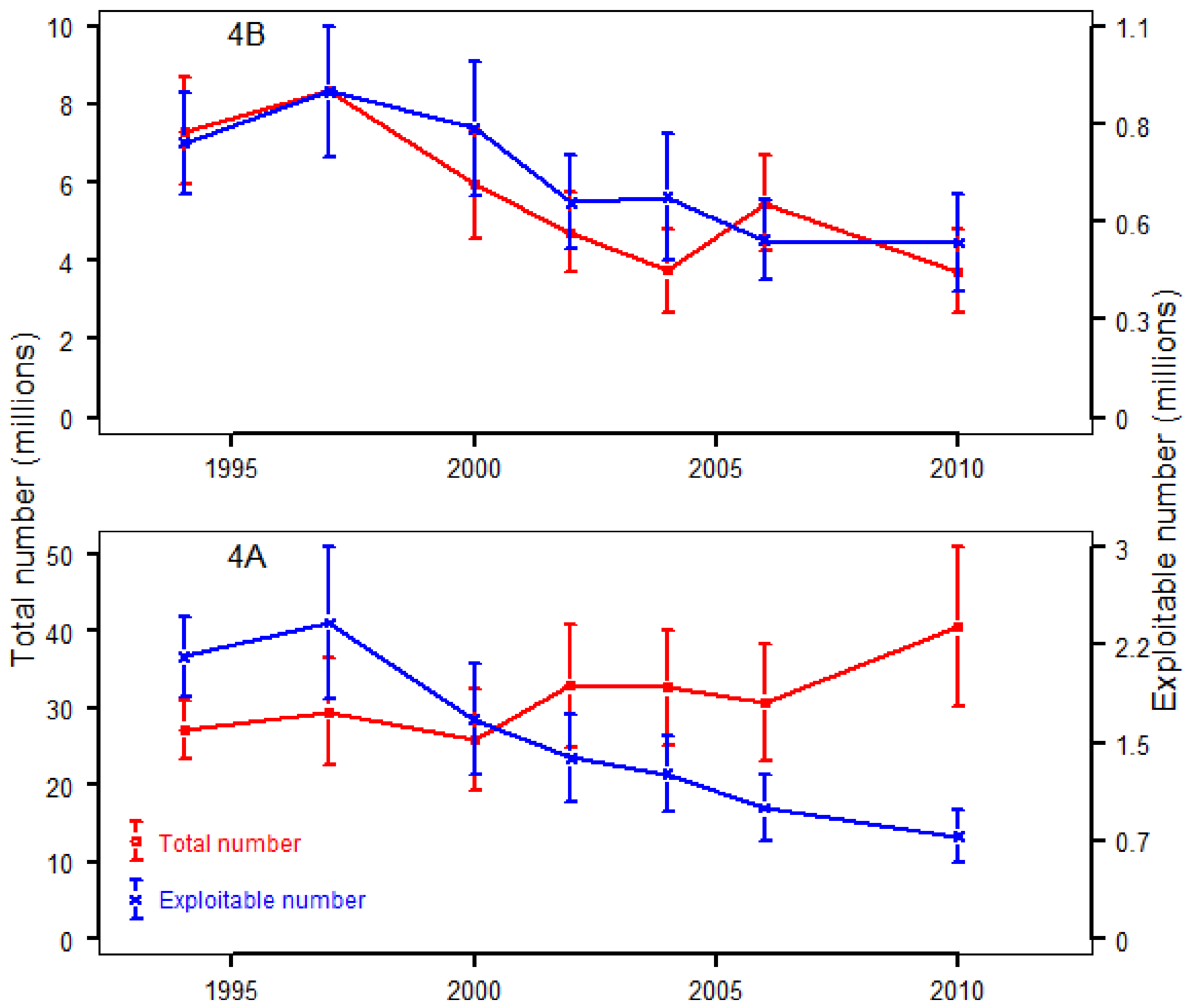

Figure 16. Comparison of area-swept estimated total numbers from the NOAA Aleutian Islands bottom trawl survey for all sizes of halibut (points, with approximate 95% confidence intervals), and the portion of those numbers believed to be available to the IPHC setline survey (crosses, with approximate 95% confidence intervals).

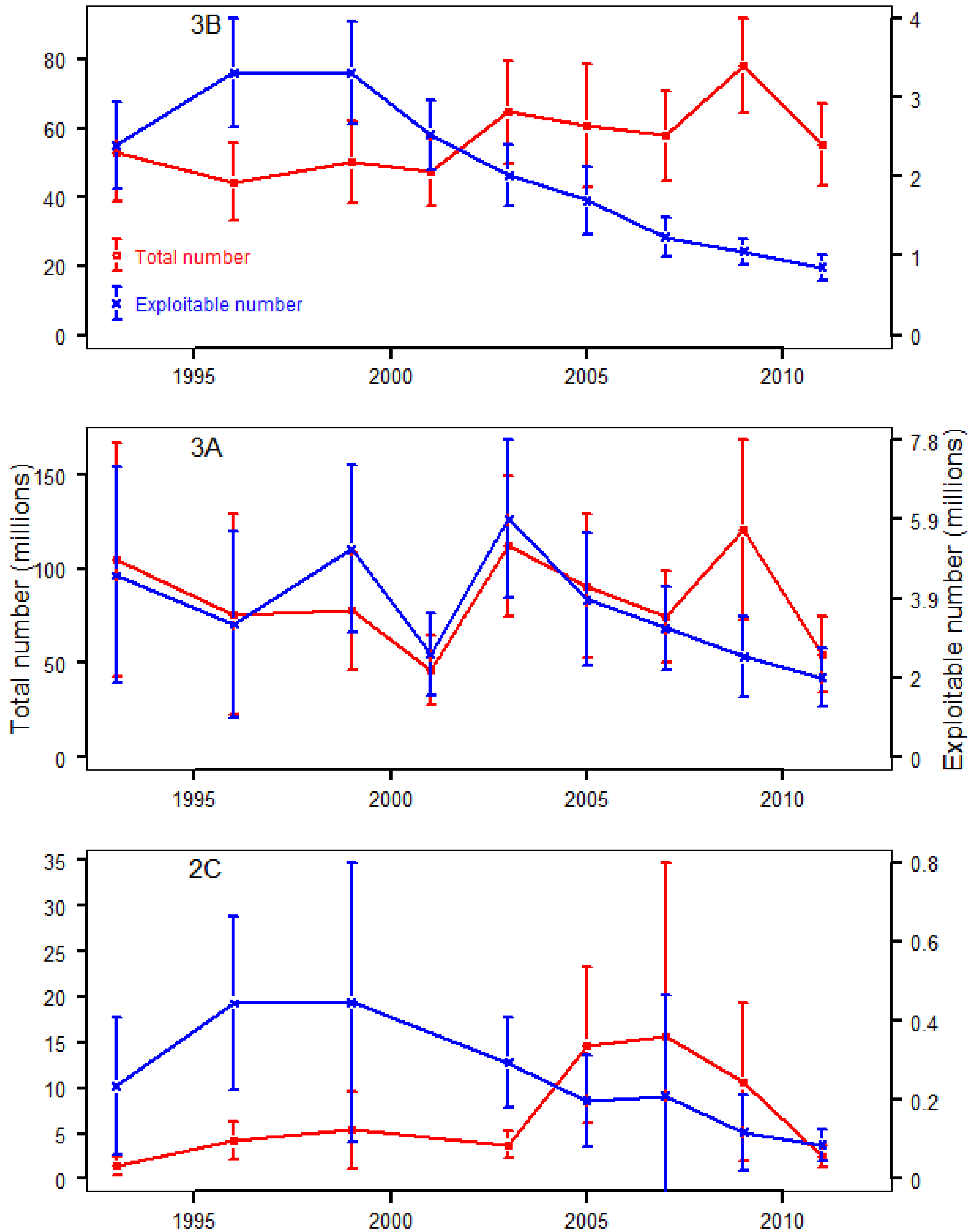

Figure 17. Comparison of area-swept estimated total numbers from the NOAA Gulf of Alaska bottom trawl survey for all sizes of halibut (points, with approximate 95% confidence intervals), and the portion of those numbers believed to be available to the IPHC setline survey (crosses, with approximate 95% confidence intervals).

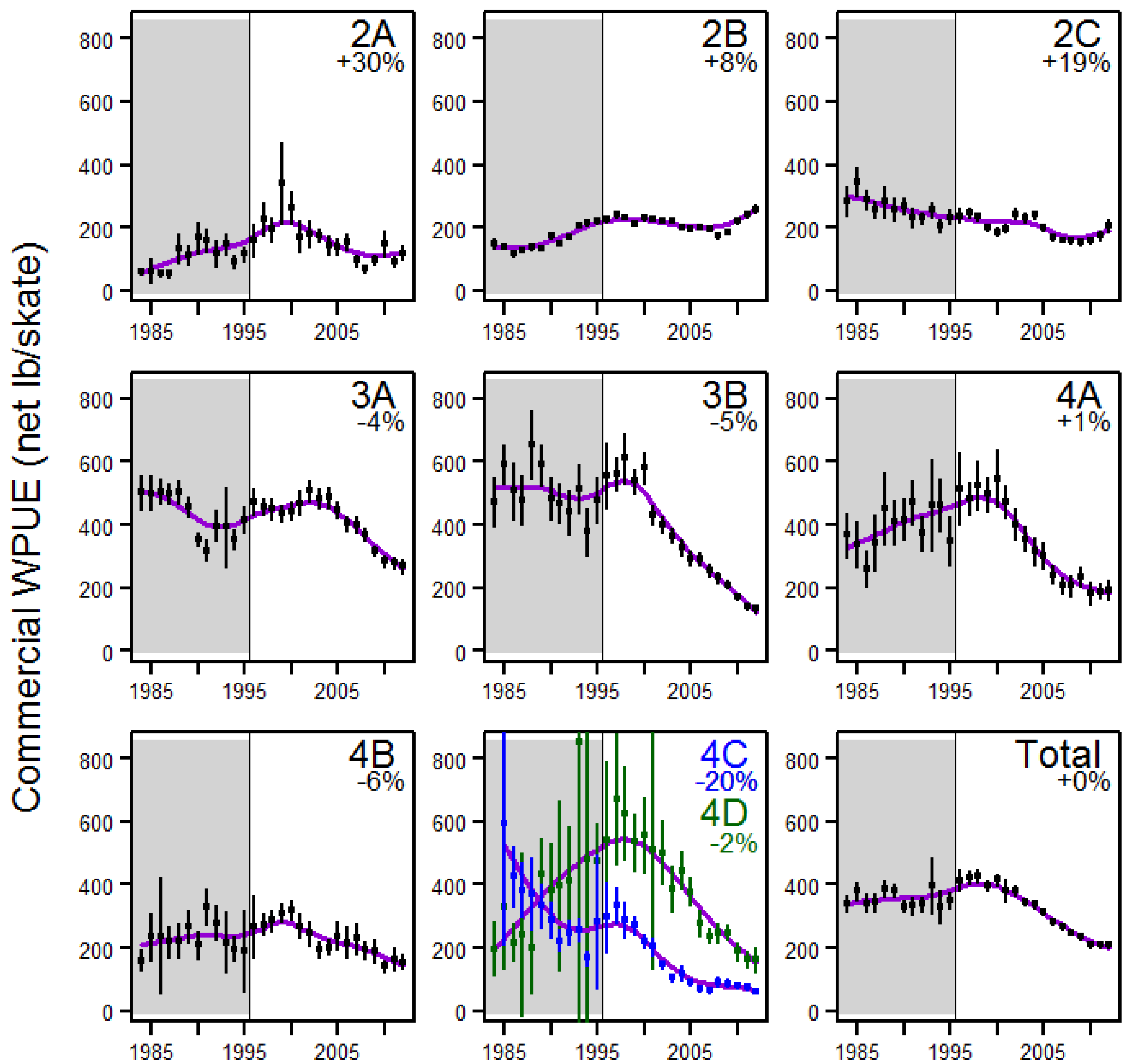

Figure 18. Trends in commercial fishery WPUE by regulatory area, percentages below the area labels indicate the percent change from 2011 to 2012 observations. The shaded portion in each panel indicates historical data not currently included in the stock assessment model.

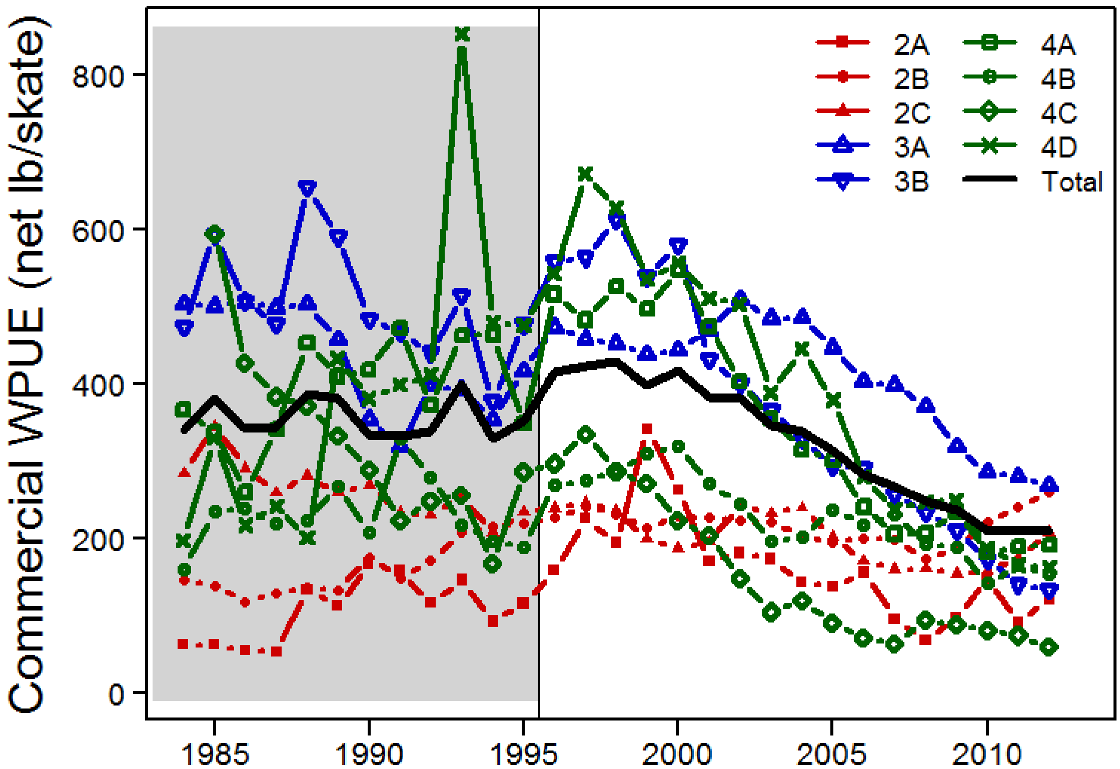

Figure 19. Trends in commercial fishery WPUE by regulatory area. The shaded portion in each panel indicates historical data not currently included in the stock assessment model.

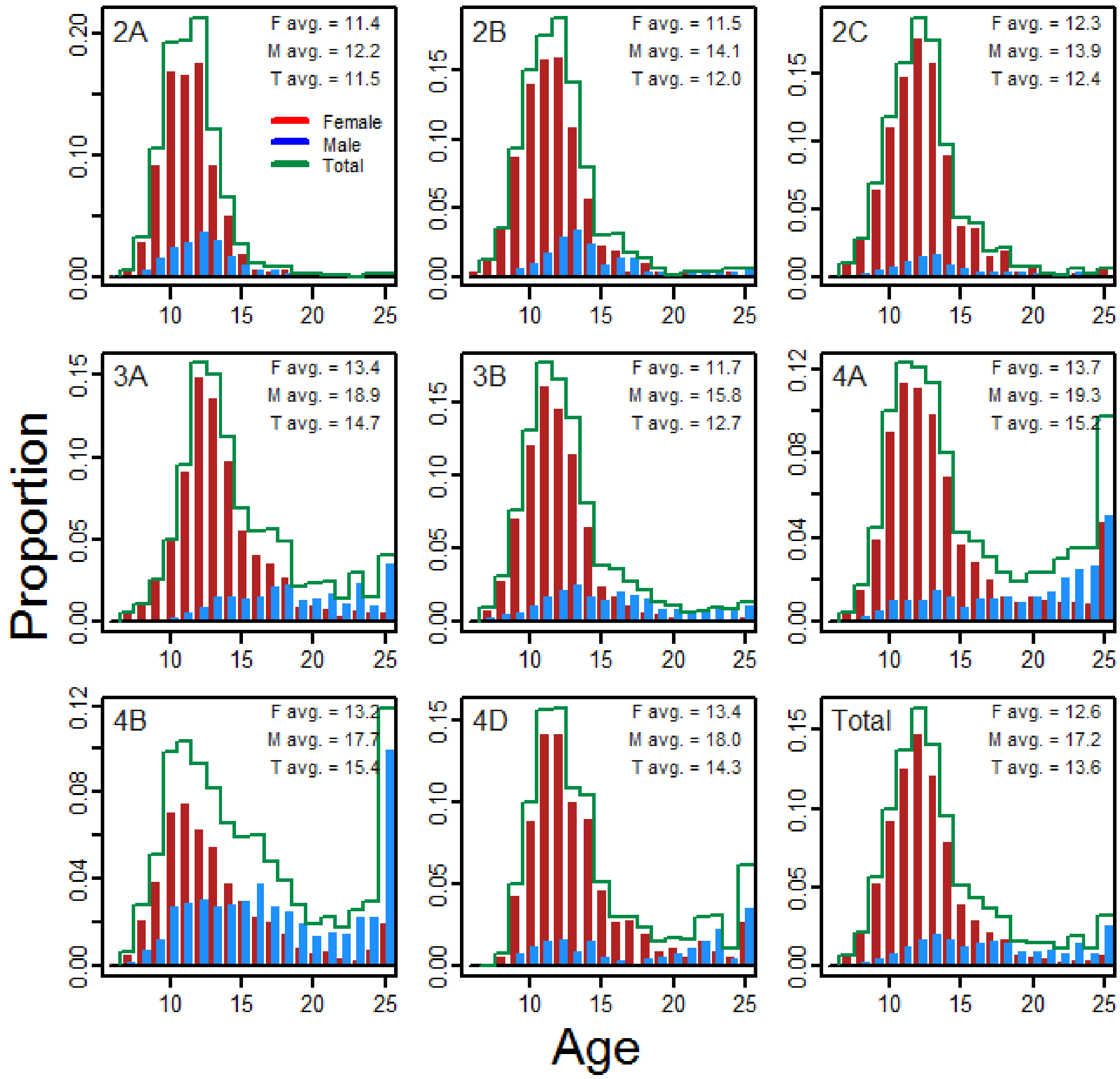

Figure 20. Age distributions from the 2012 commercial fishery by regulatory area.

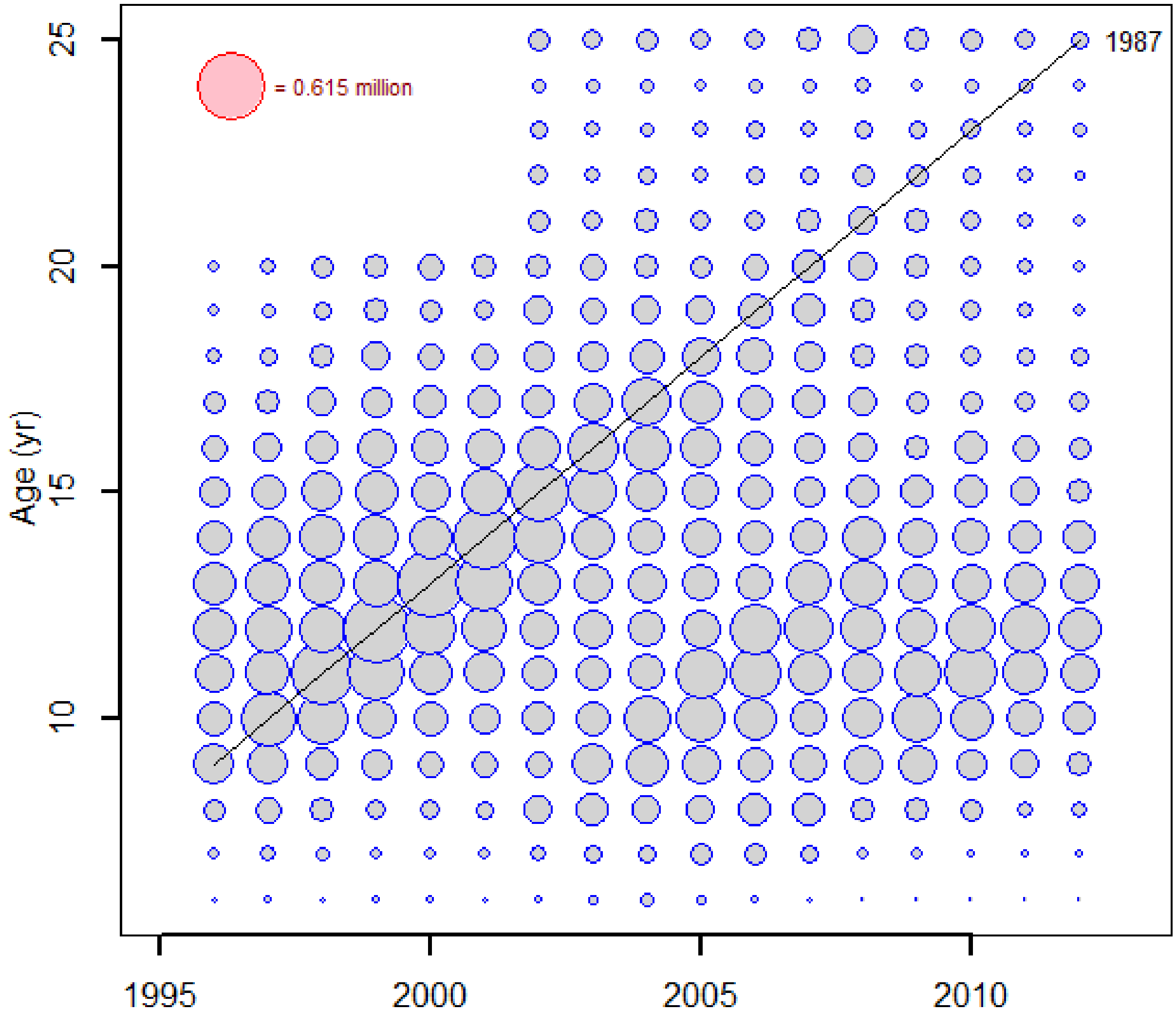

Figure 21. Observed numbers-at-age from the commercial fishery, 1996-2012. The area of each circle is scaled relative to the legend value in the upper left. Age-20 (prior to 2002) and age-25 (thereafter) represent plus-groups containing that age and all older ages. The 1987 year-class is identified by the diagonal line for visual reference.

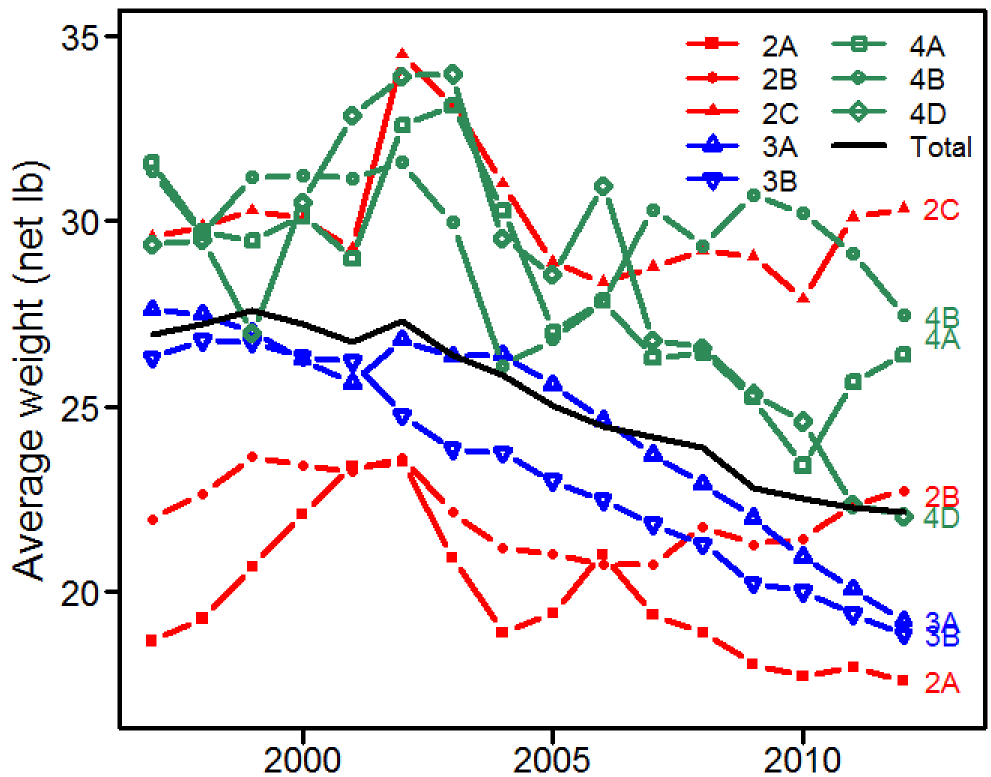

Figure 22. Trends in average fish weight observed in the commercial fishery by regulatory area.

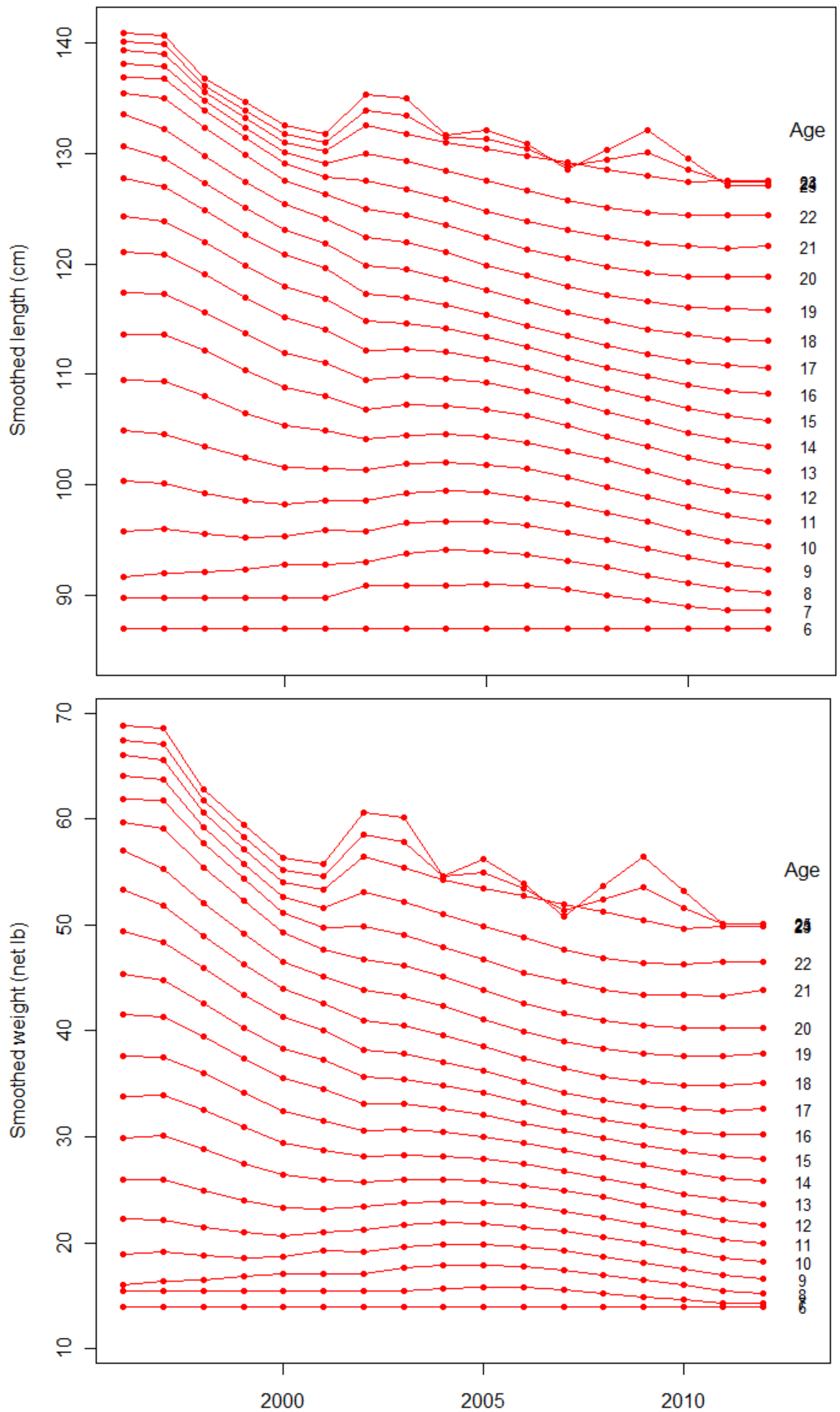

Figure 23. Trends in smoothed female commercial fishery length-at-age (upper panel) and weight-at-age (lower panel), 1996-2012.

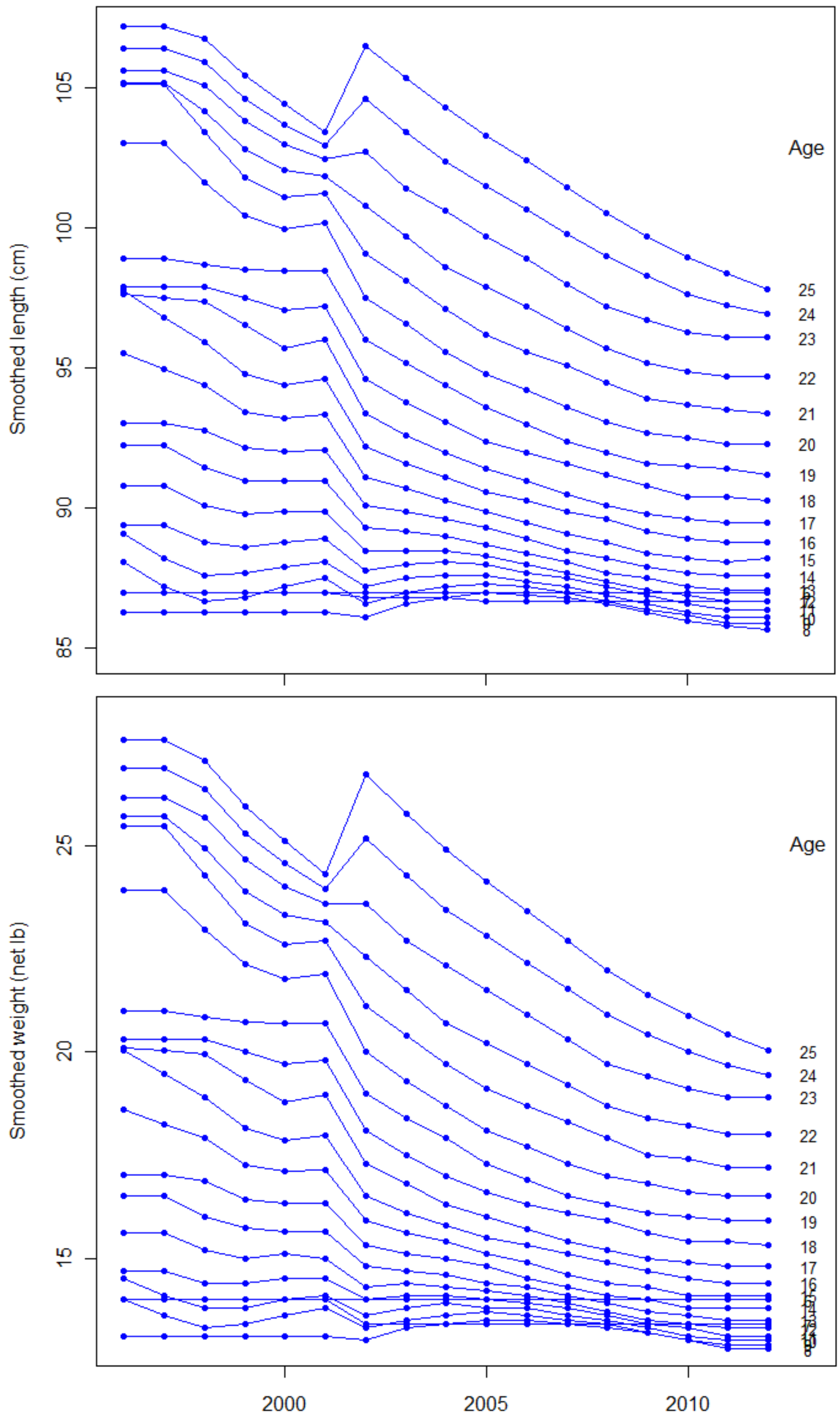

Figure 24. Trends in smoothed male commercial fishery length-at-age (upper panel) and weight-at-age (lower panel), 1996-2012.

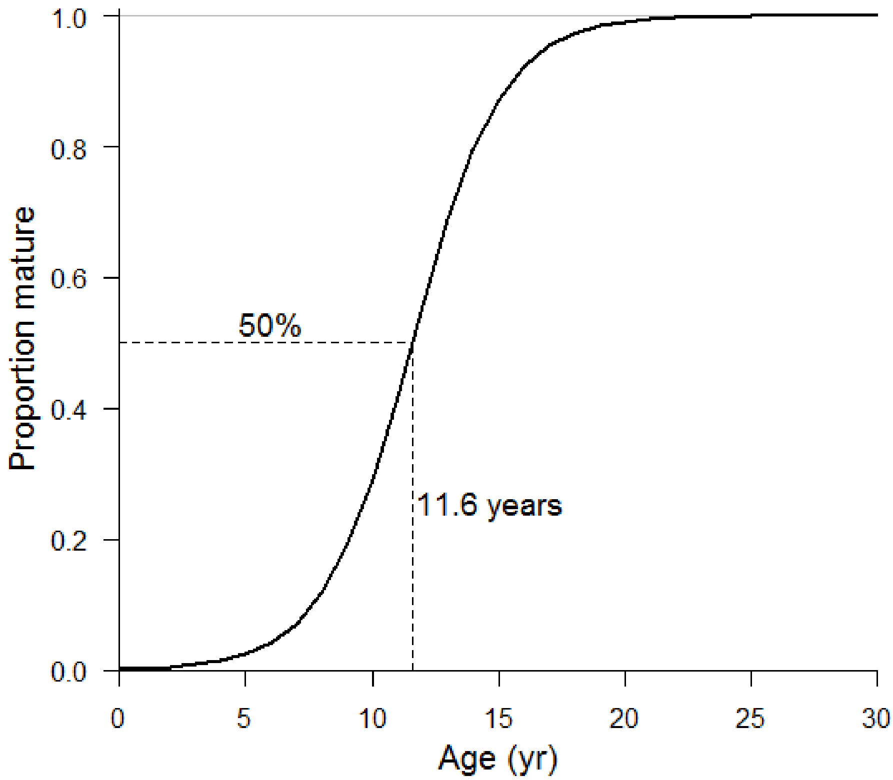

Figure 25. Maturity curve used to calculate the proportion of female stock contributing to the spawning biomass.

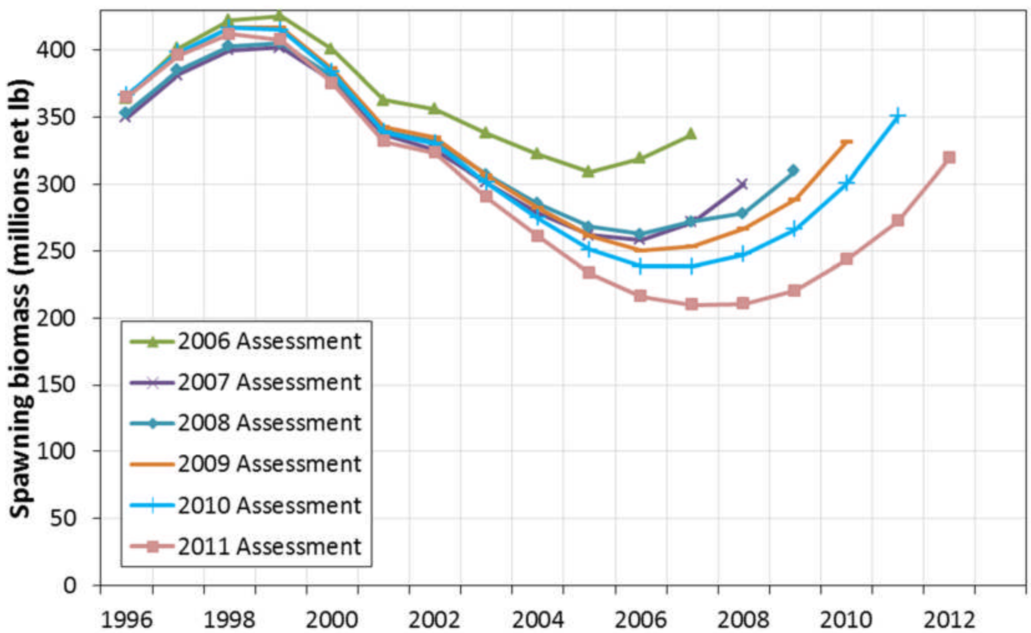

Figure 26. Retrospective analysis among recent stock assessments.

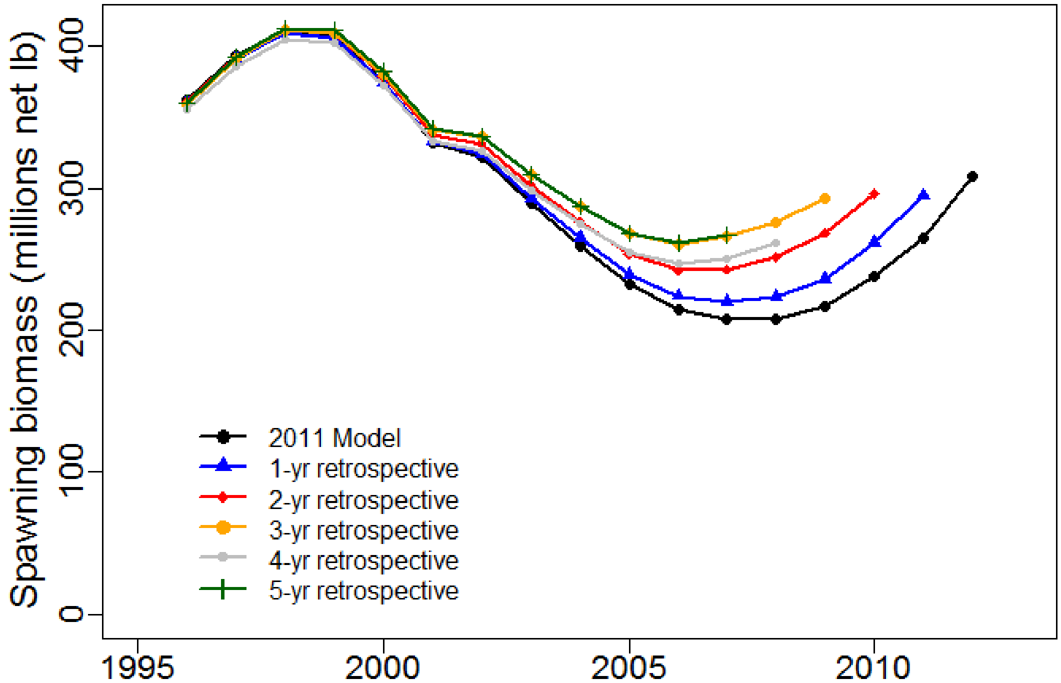

Figure 27. Retrospective analysis for the 2011 "wobblesq" model.

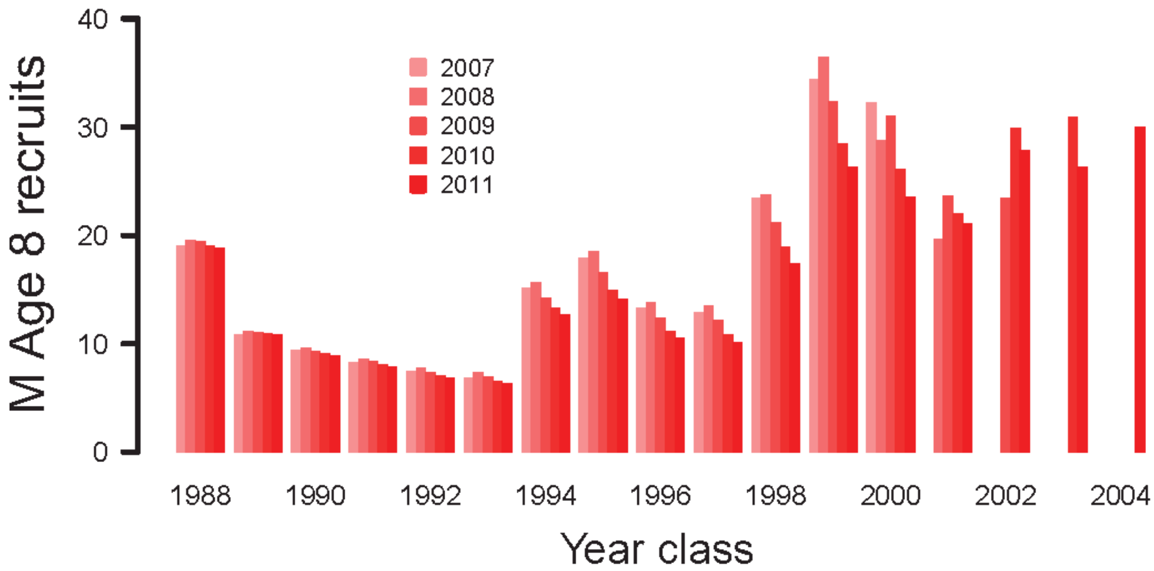

Figure 28. Retrospective analysis of cohort-strength estimates from the 2011 wobblesq model (figure from the 2011 stock assessment document).

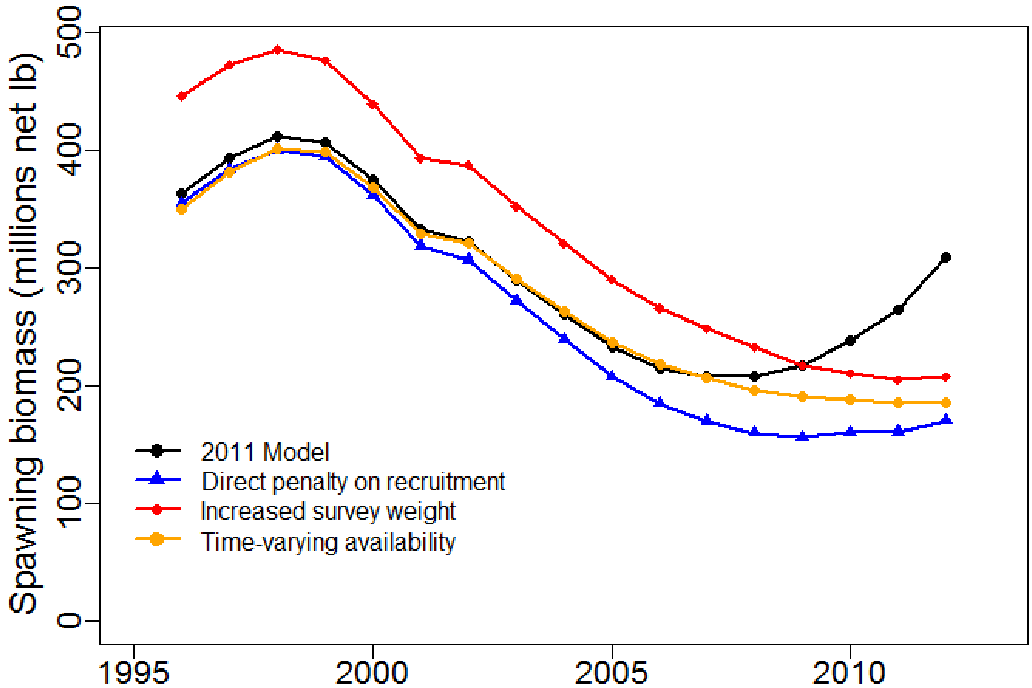

Figure 29. Comparison of three alternative approaches solving the retrospective pattern in the 2011 wobblesq model.

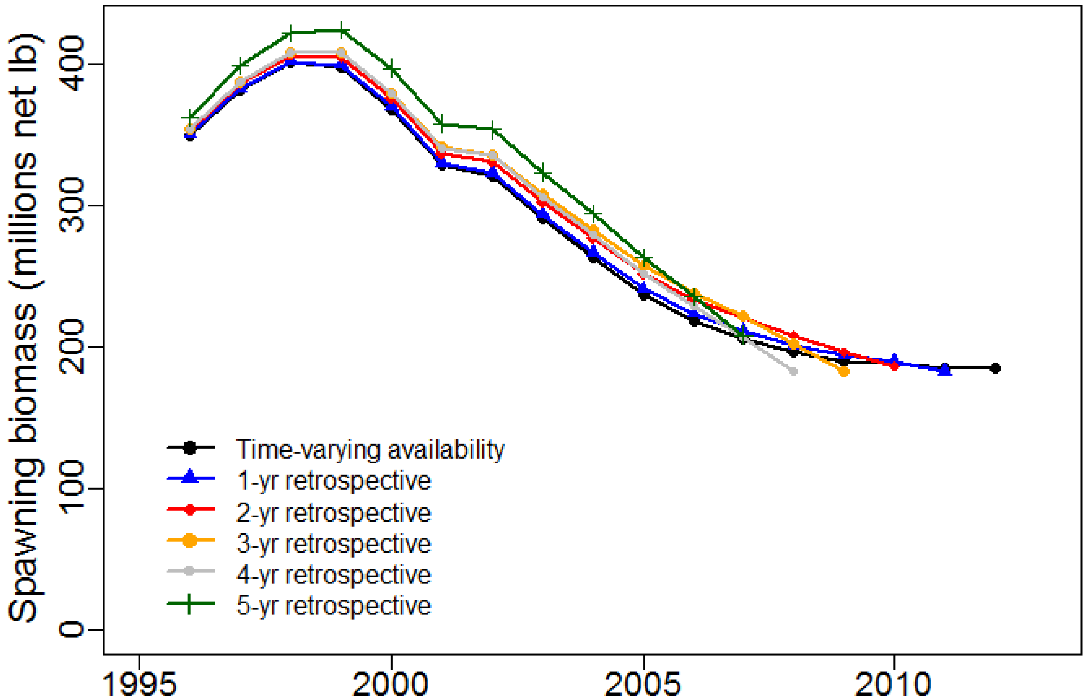

Figure 30. Retrospective analysis for the model allowing time-varying availability, and using data through 2011.

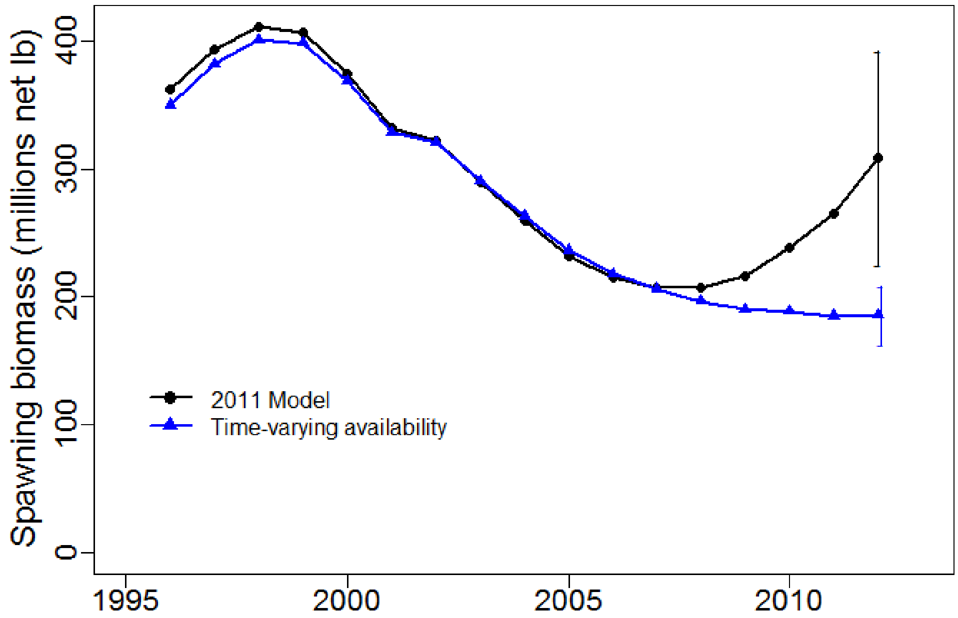

Figure 31. Comparison of the 2011 and revised stock assessment models using data updated through 2011.

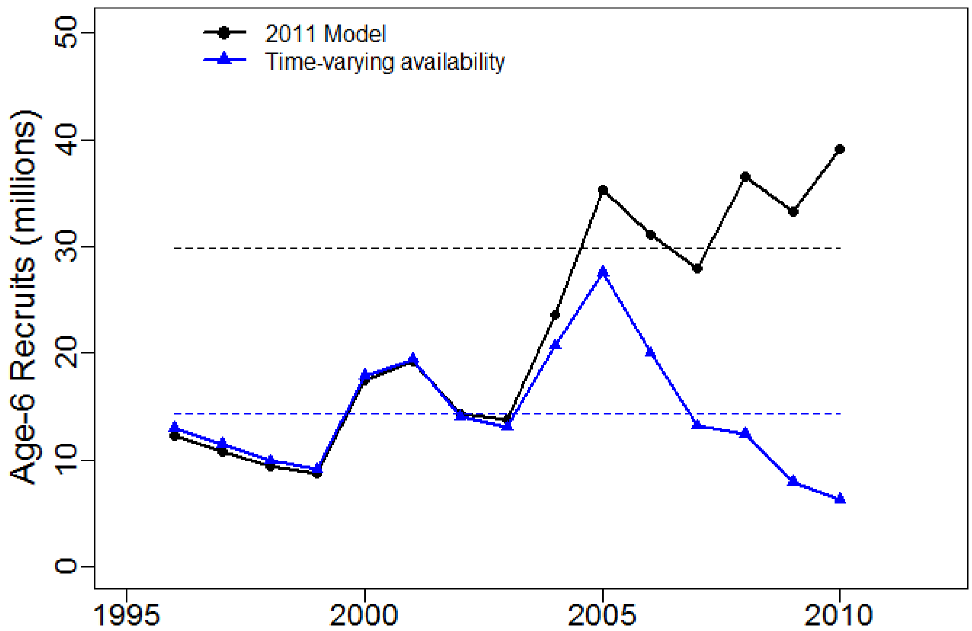

Figure 32. Comparison of the 2011 and revised stock assessment model estimates of recruitment using data updated through 2011.

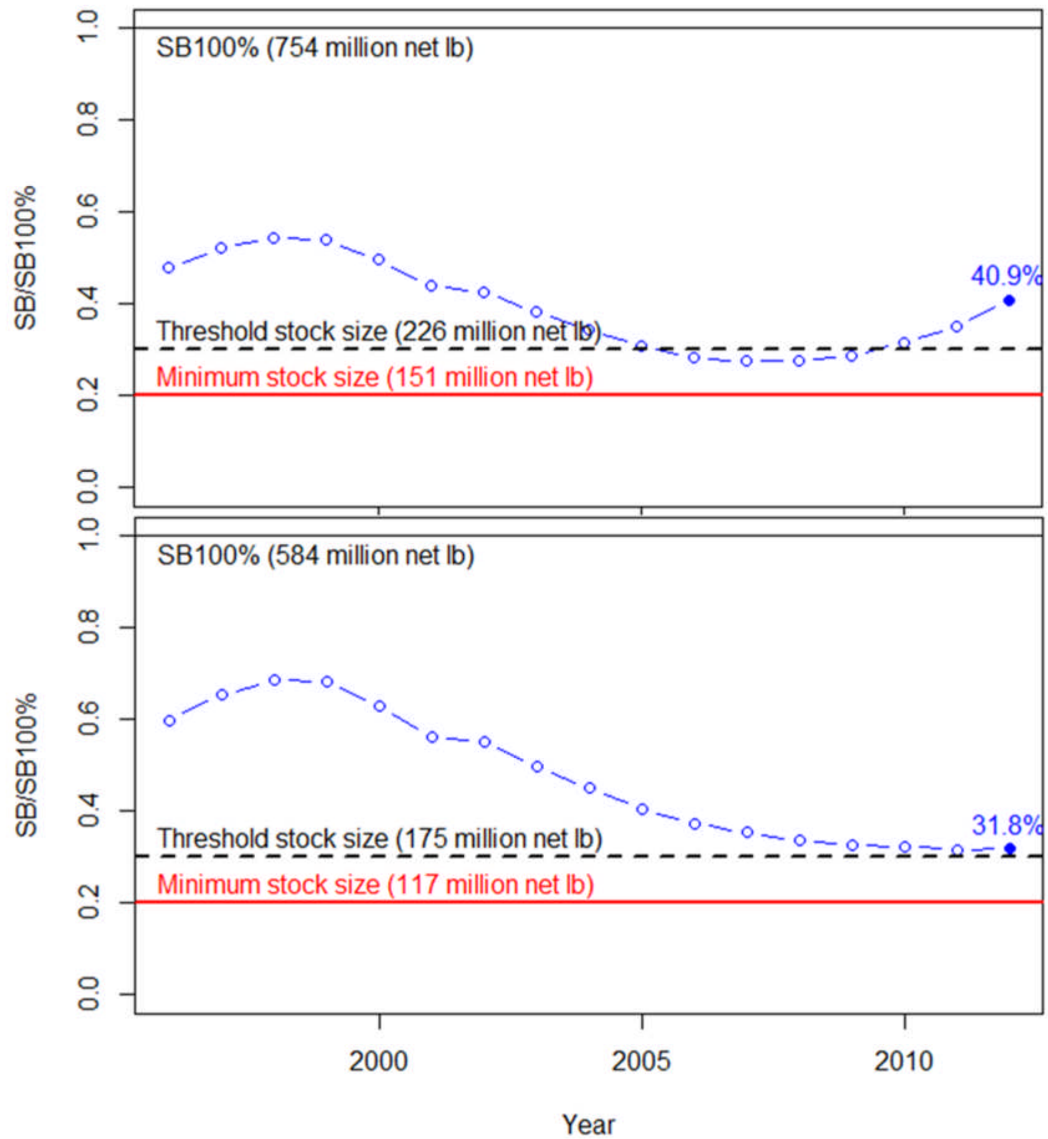

Figure 33. Comparison of the relative spawning biomass estimates from the 2011 (wobblesq) model (upper panel) and the current assessment (lower panel) using data through 2011.

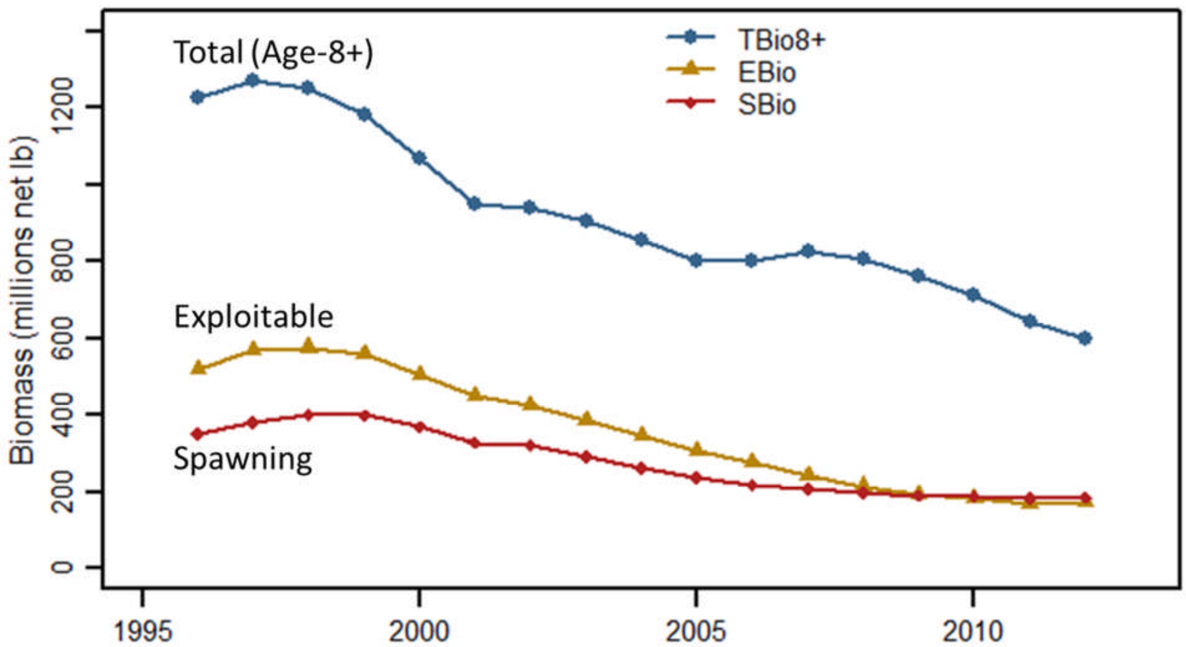

Figure 34. Biomass time-series results from the model allowing time-varying availability, and using data through 2011.

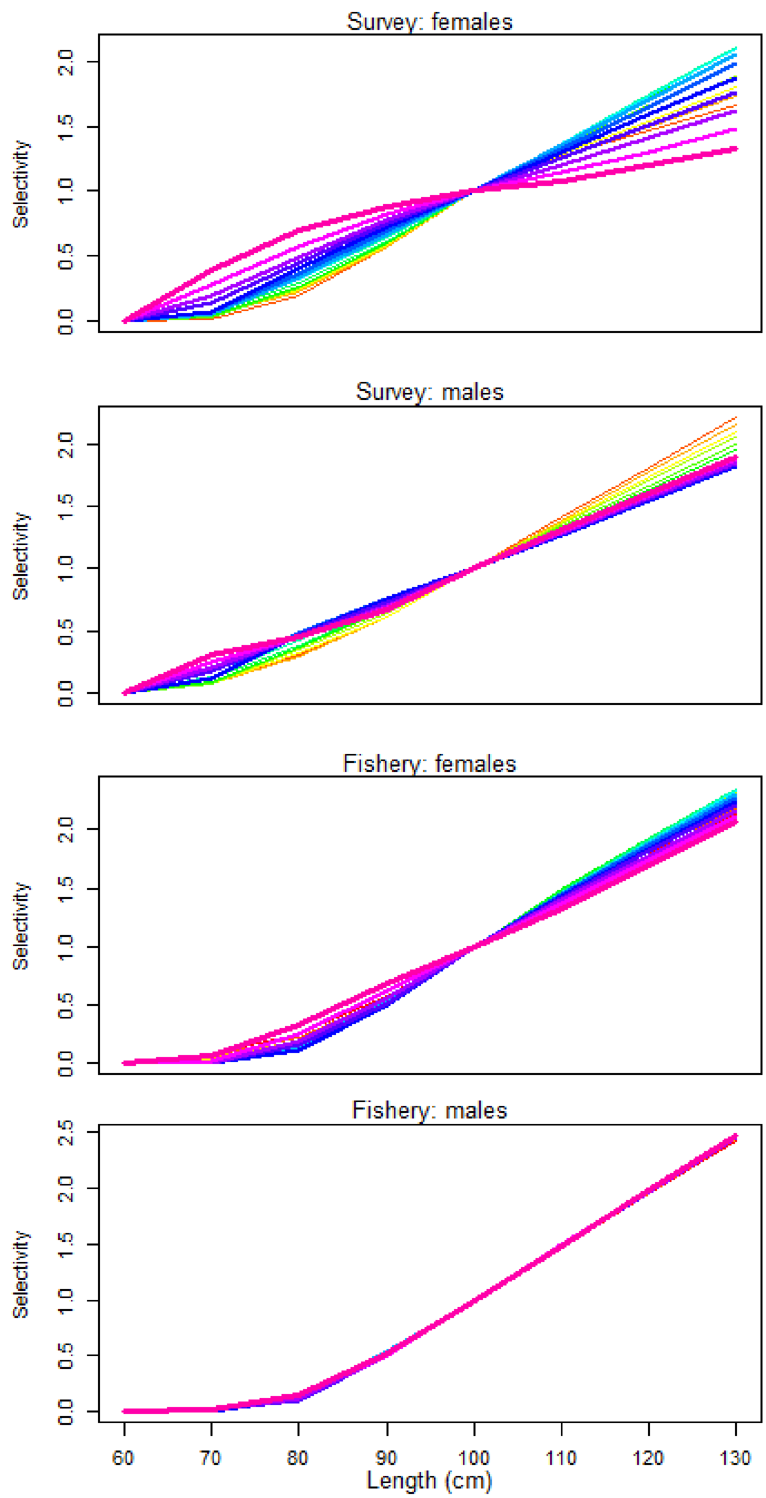

Figure 35. Estimated annual availability curves for the setline survey (upper two panels) and the commercial fishery (lower two panels) by sex. Note that the upper curve for the 60-80 cm range on each panel represents the most recent year, indicating a shift toward smaller fish.

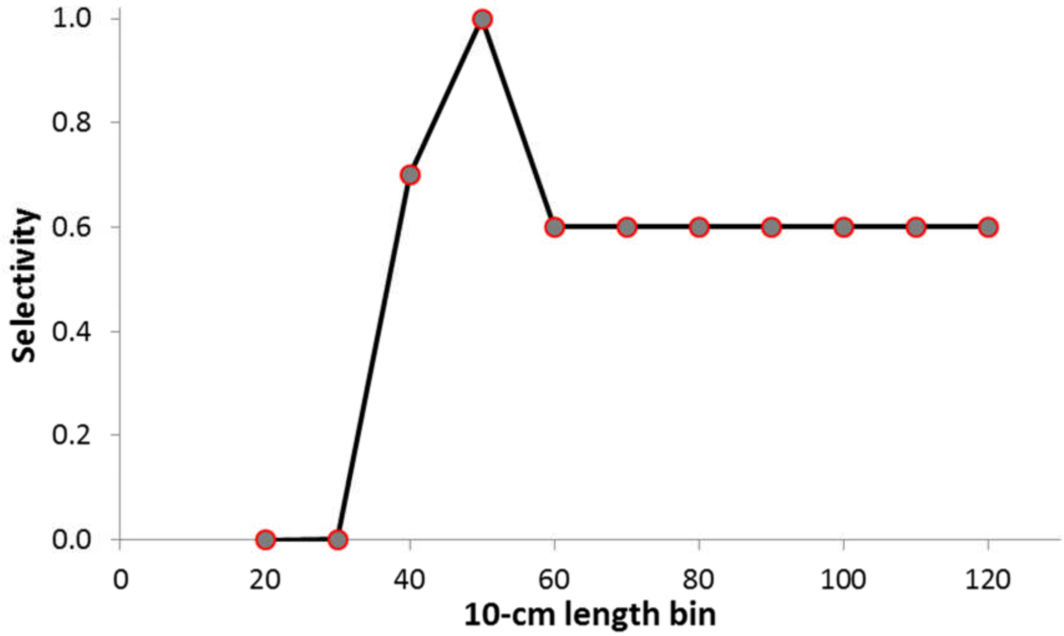

Figure 36. Fixed selectivity curve assigned to bycatch mortality.

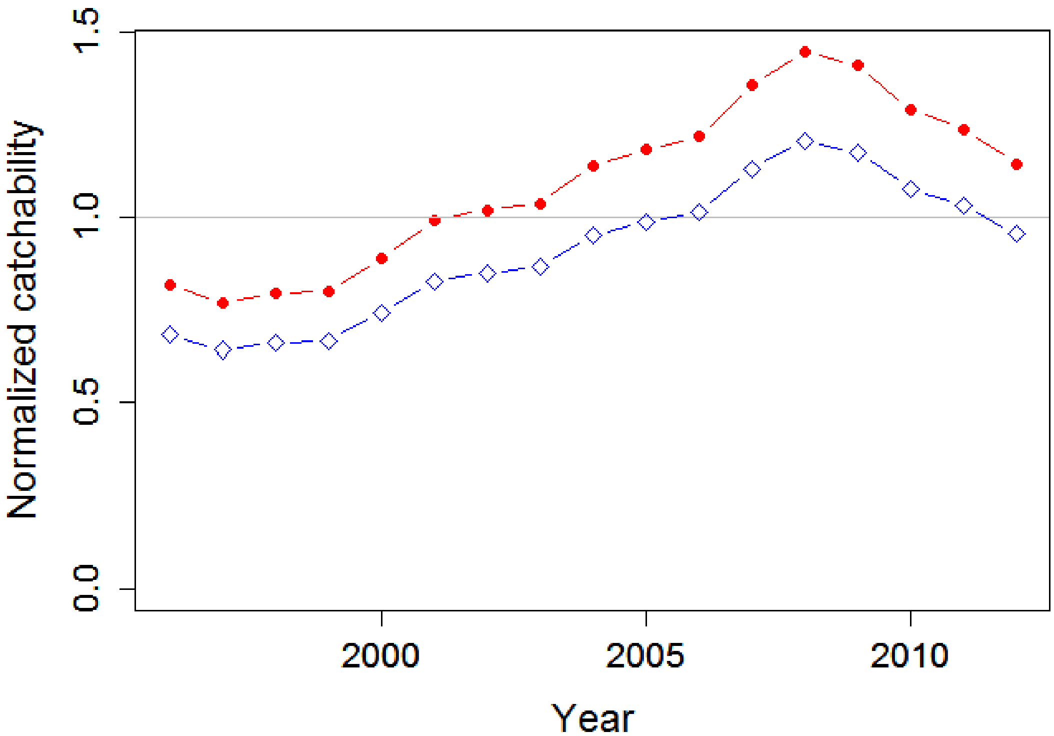

Figure 37. Estimated trends in sex-specific catchability for the commercial fishery (females are represented by the upper line, males the lower line).

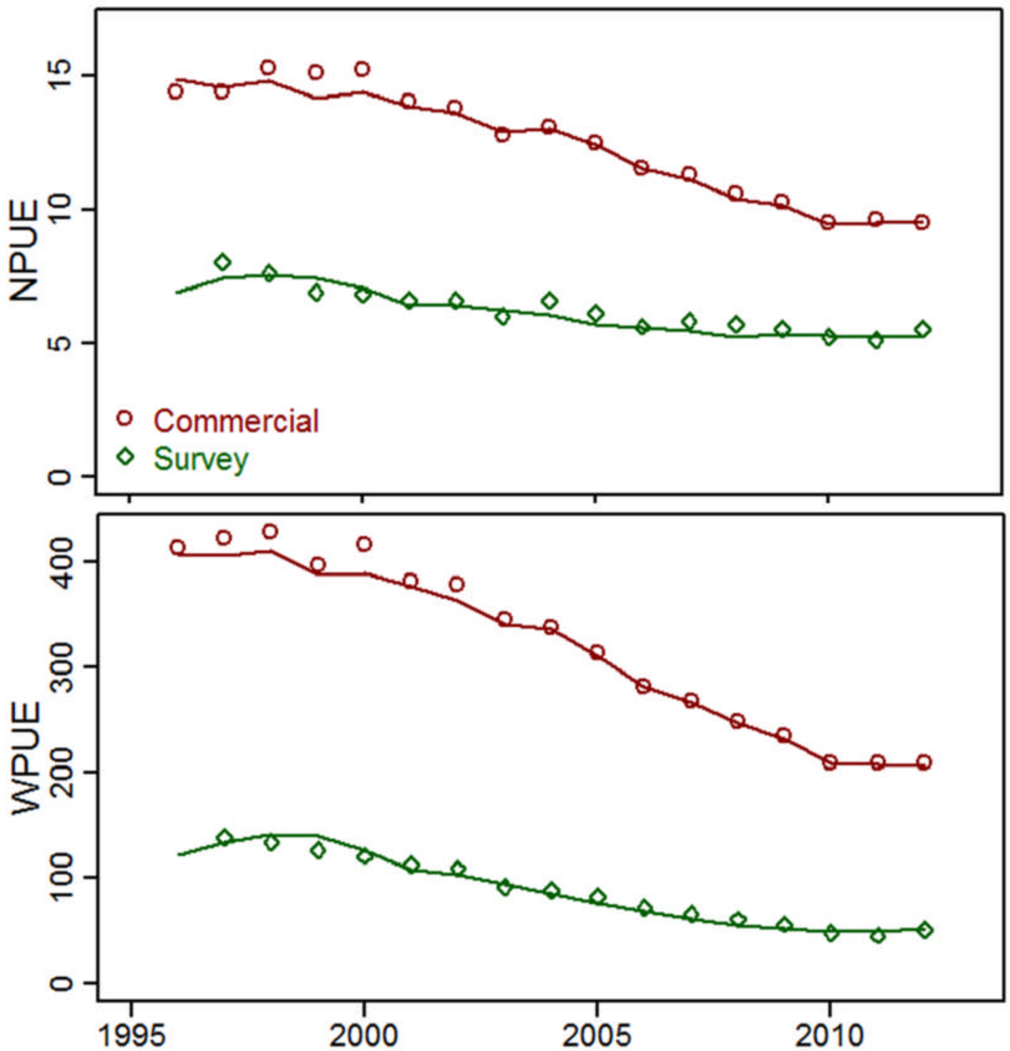

Figure 38. Fit to the commercial fishery and setline survey WPUE and NPUE indices of abundance.

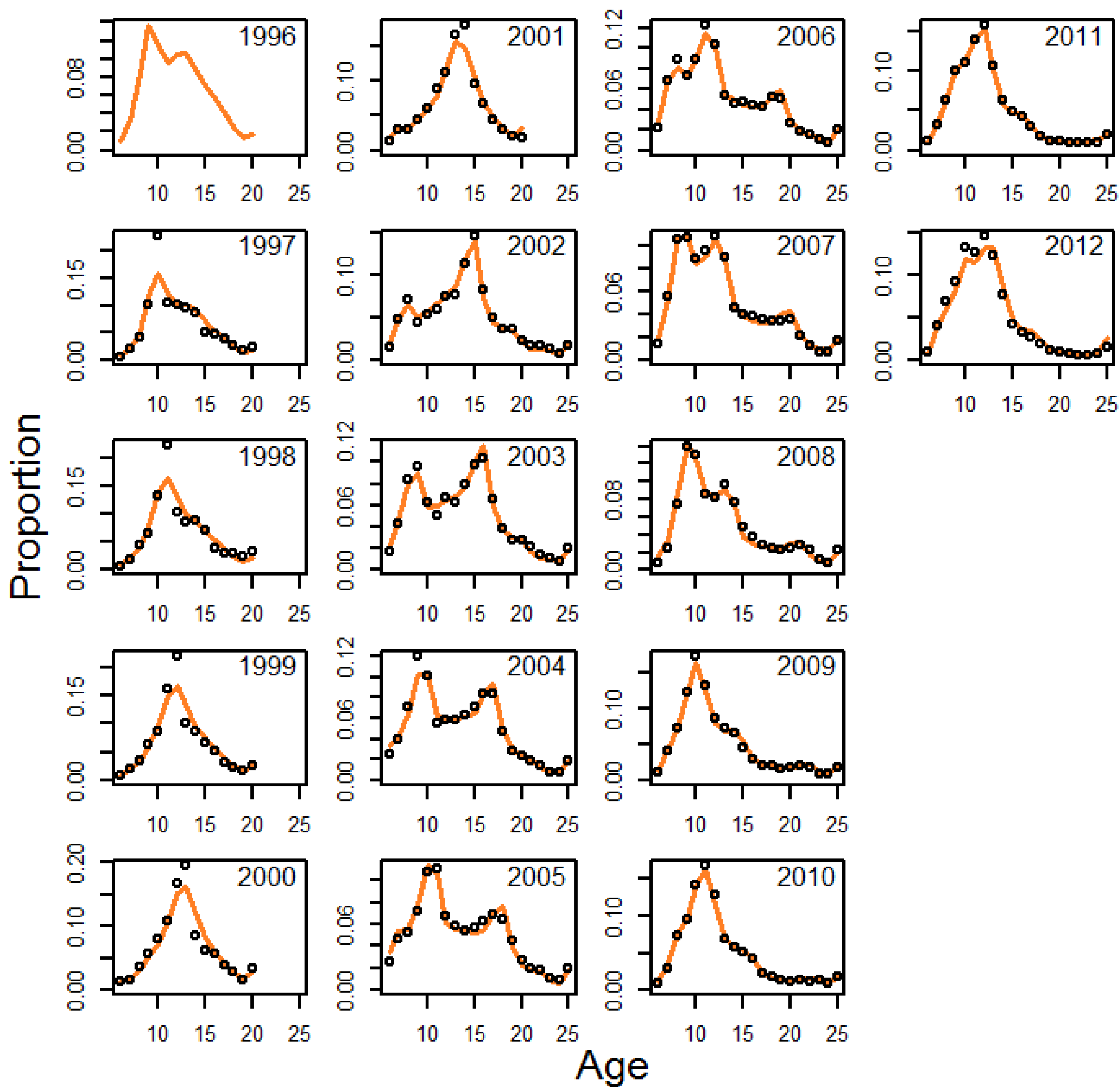

Figure 39. Fit to setline survey total proportions-at-age (points indicate the observed data, lines the model predictions.

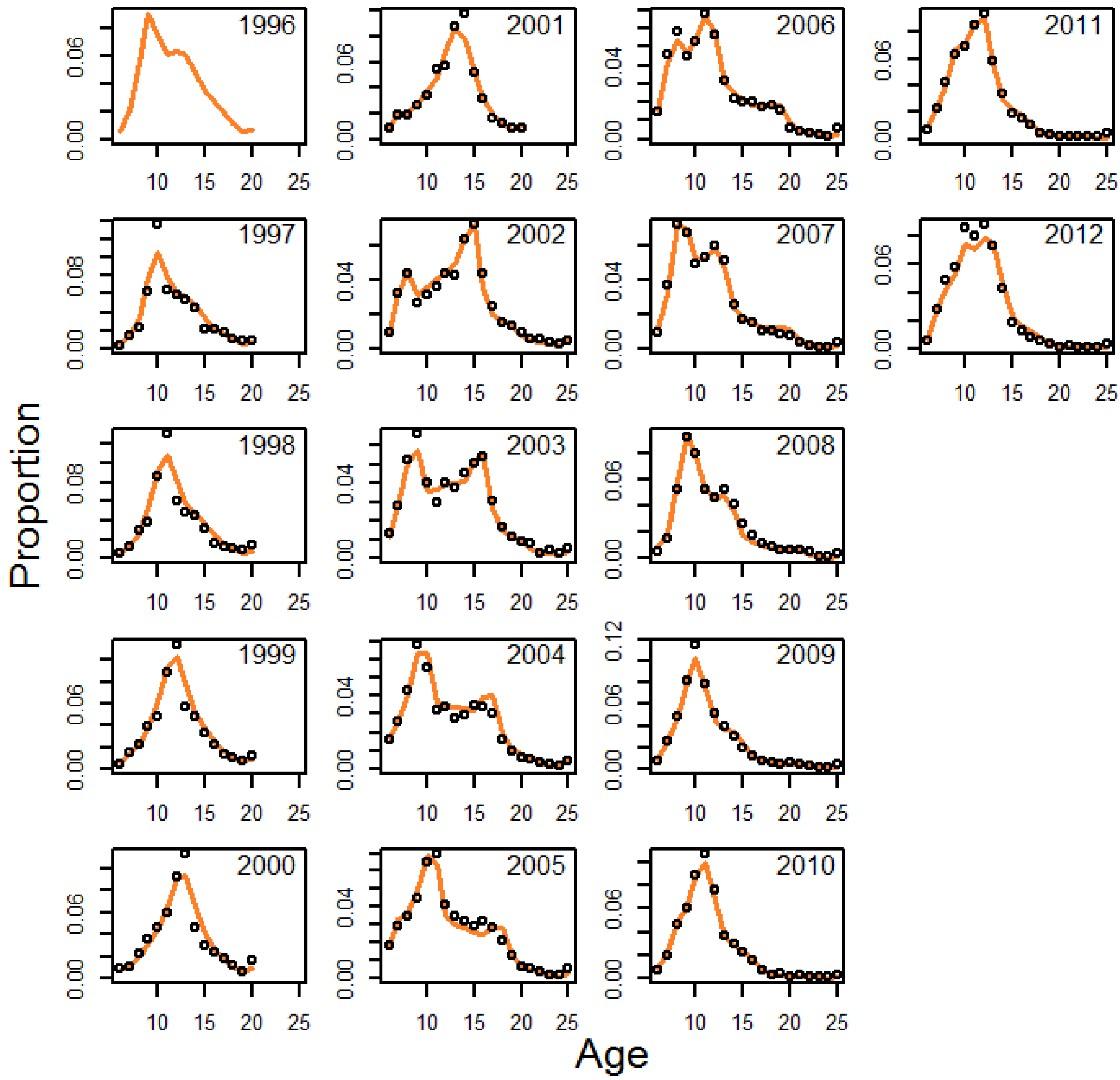

Figure 40. Fit to setline survey female proportions-at-age (points indicate the observed data, lines the model predictions.

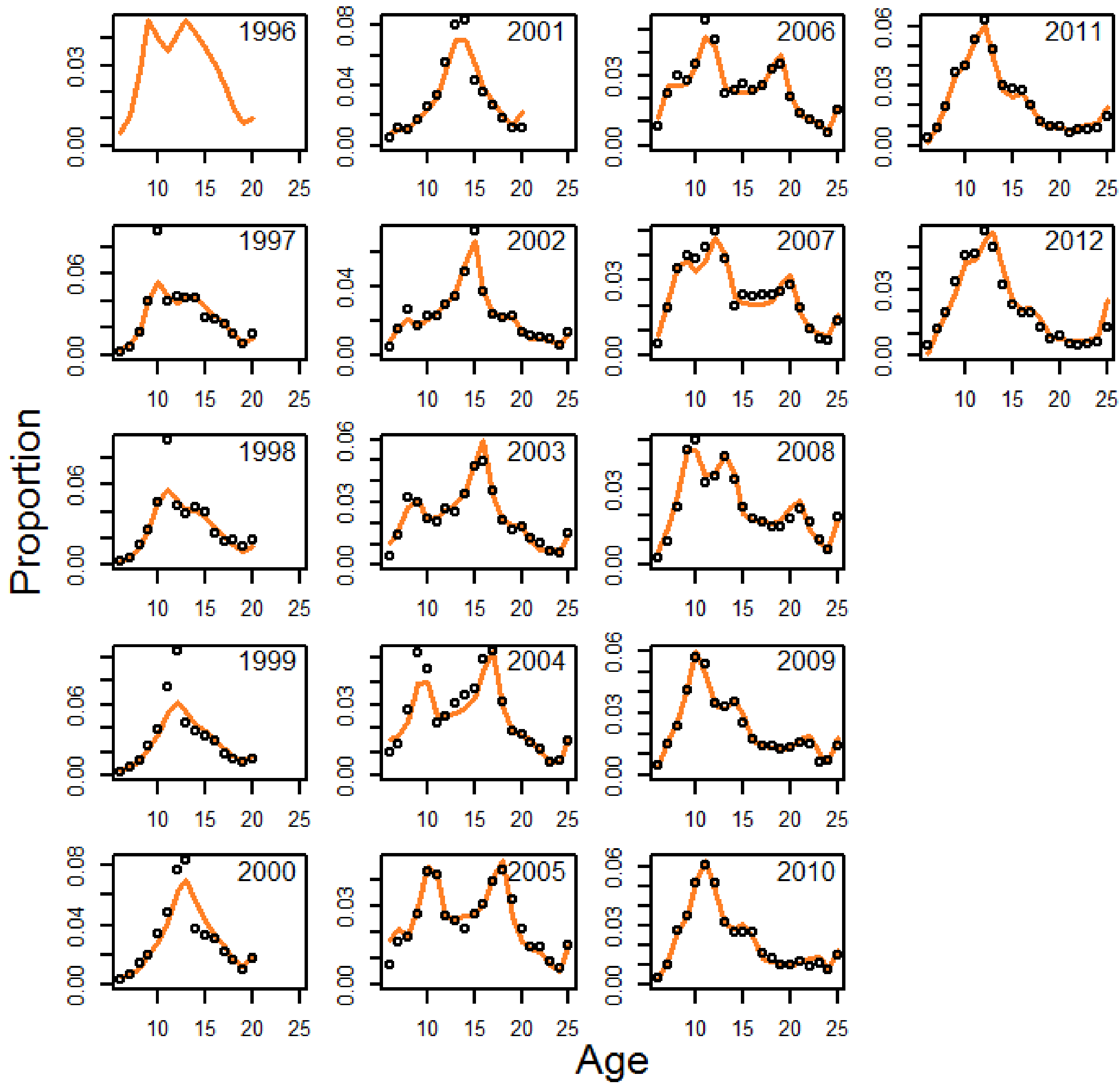

Figure 41. Fit to setline survey male proportions-at-age (points indicate the observed data, lines the model predictions.

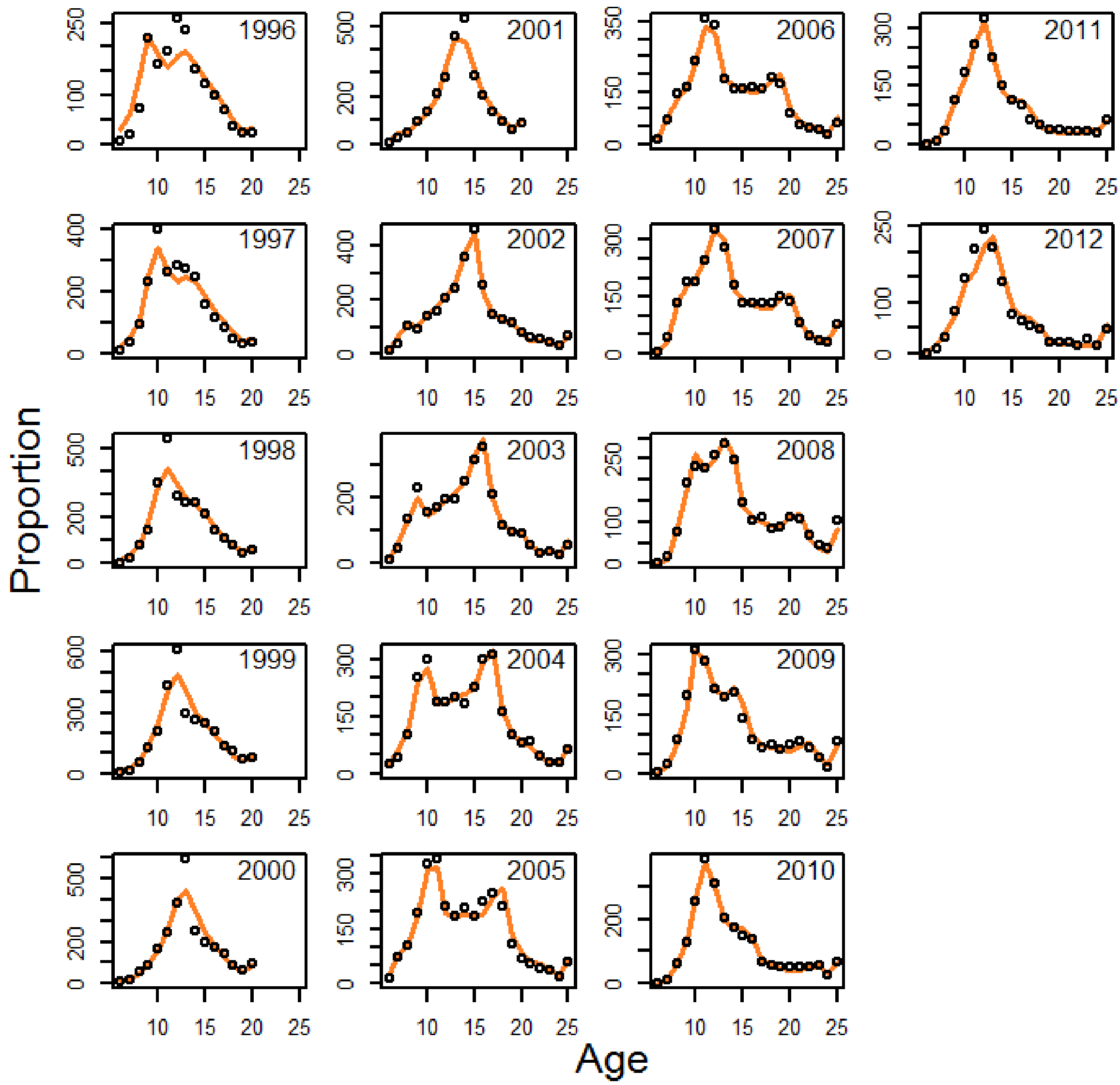

Figure 42. Fit to commercial fishery total catch-at-age (points indicate the observed data, lines the model predictions.

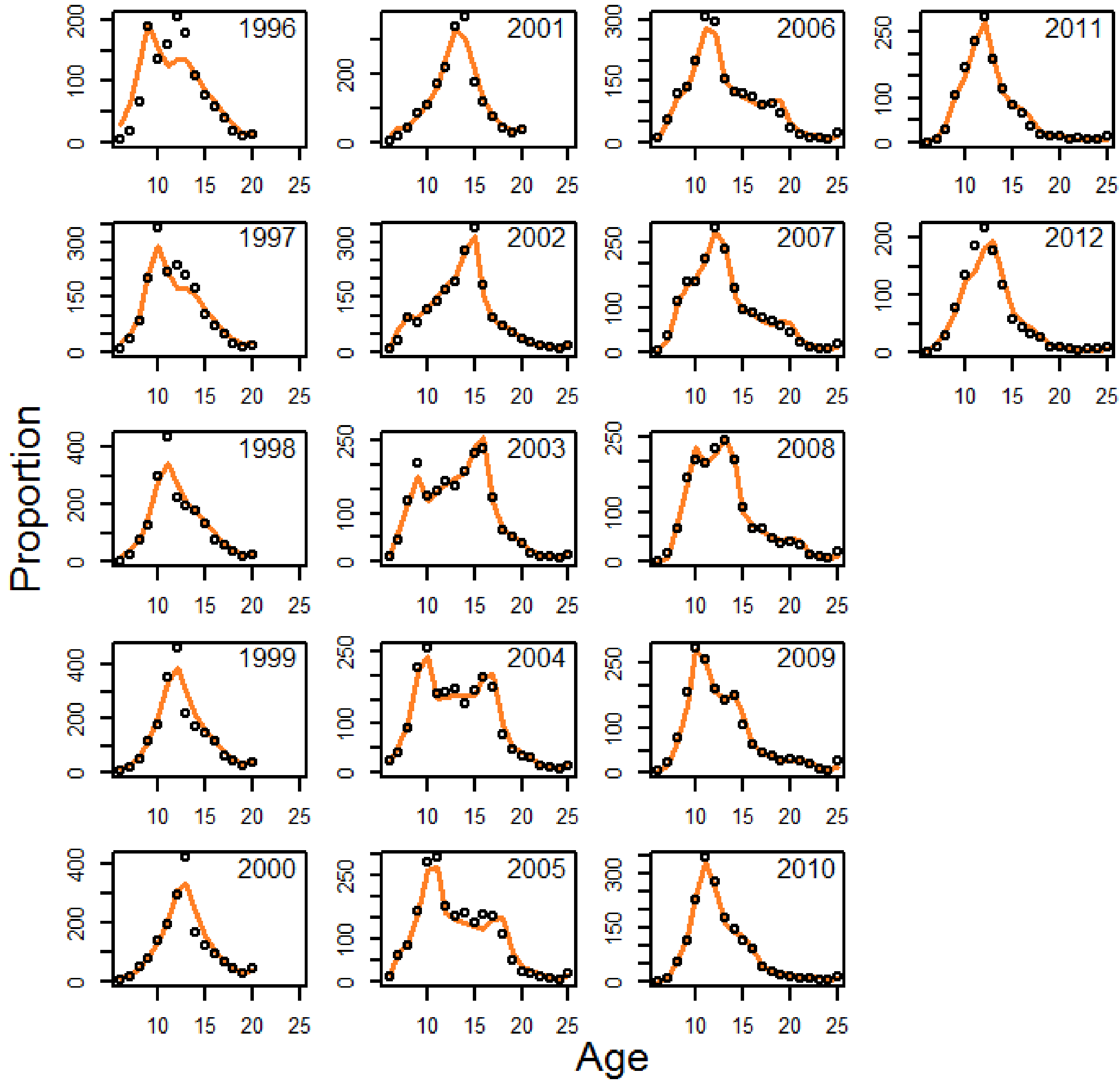

Figure 43. Fit to commercial fishery female catch-at-age (points indicate the observed data, lines the model predictions.

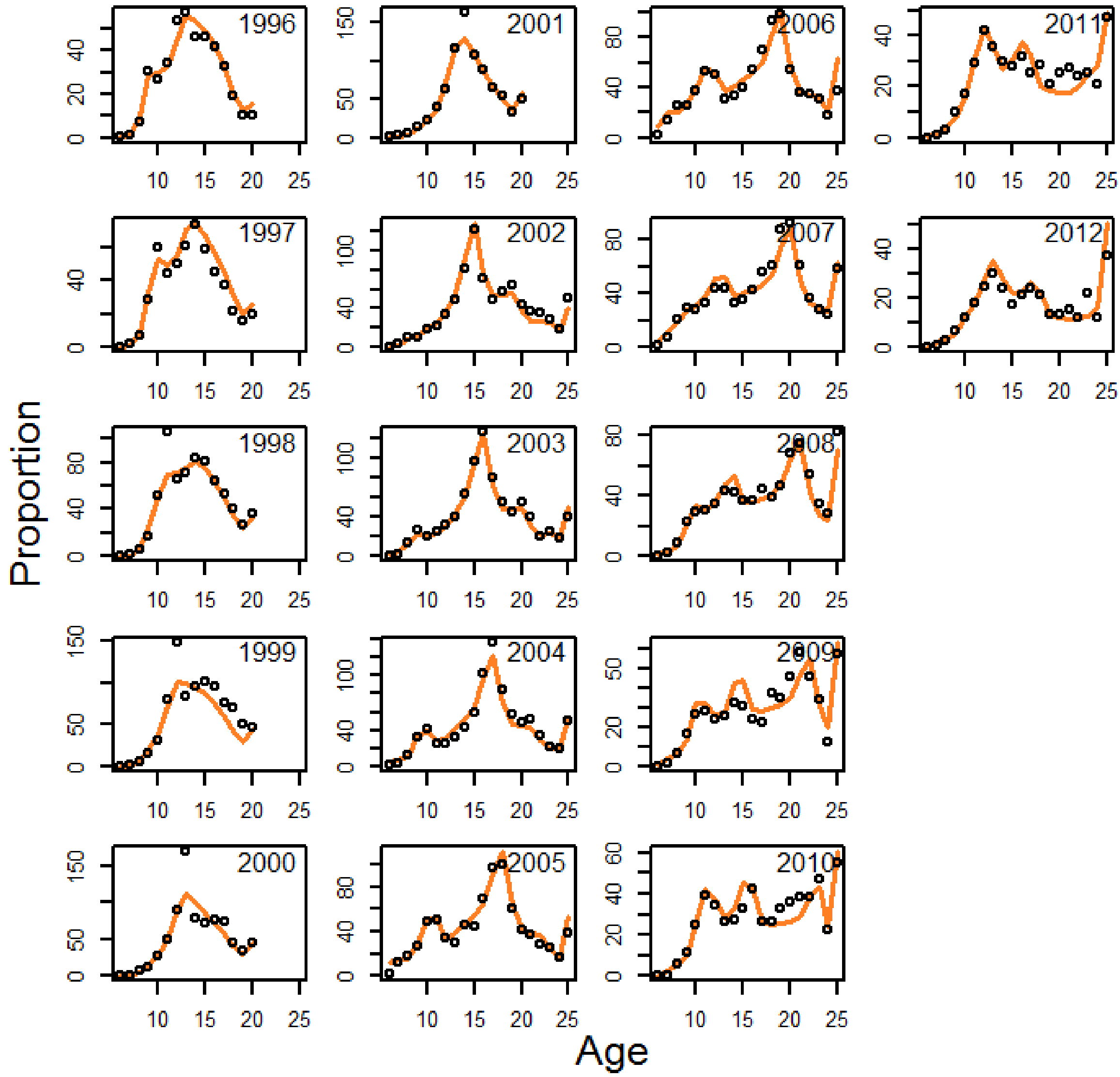

Figure 44. Fit to commercial fishery male catch-at-age (points indicate the observed data, lines the model predictions.

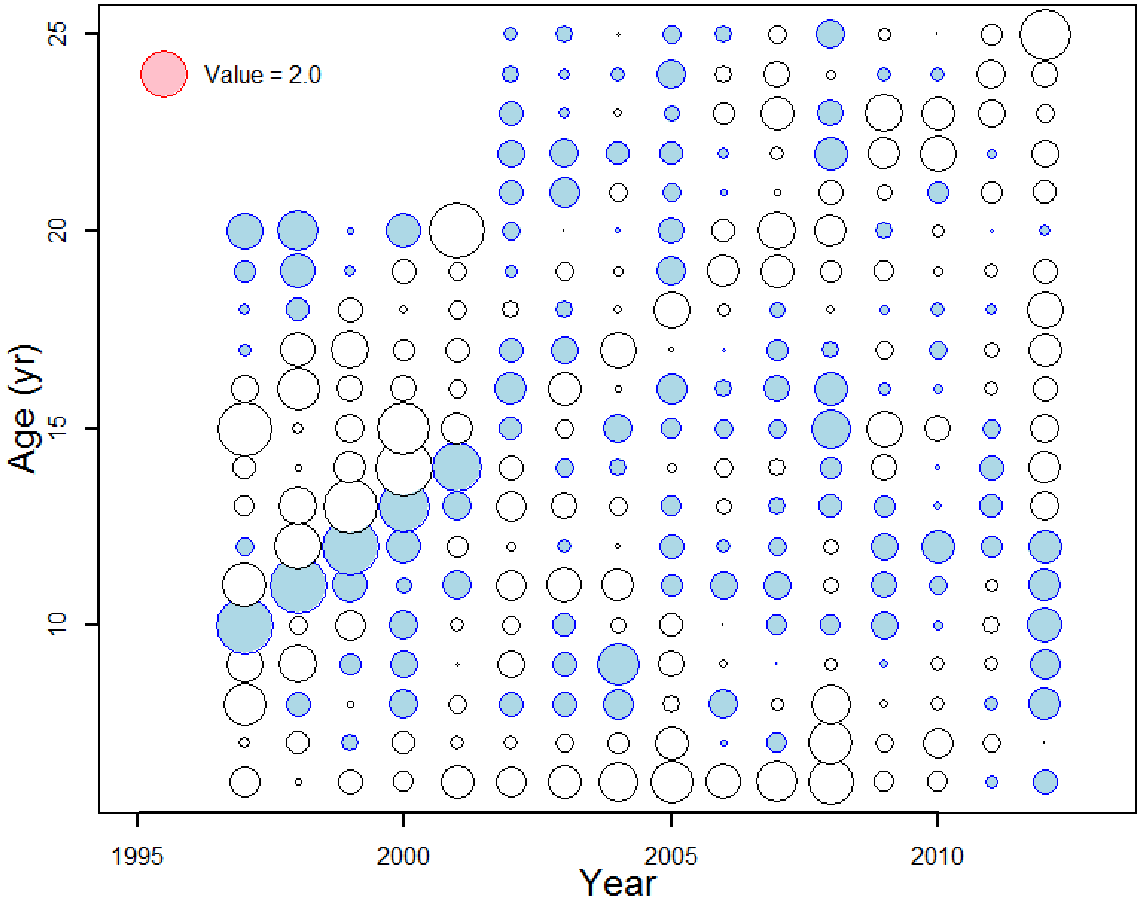

Figure 45. Standardized residuals (observed minus expected values) from the fit to setline survey total catch-at-age. Circle areas are scaled relative to the legend value in the upper left, filled circles indicate positive values.

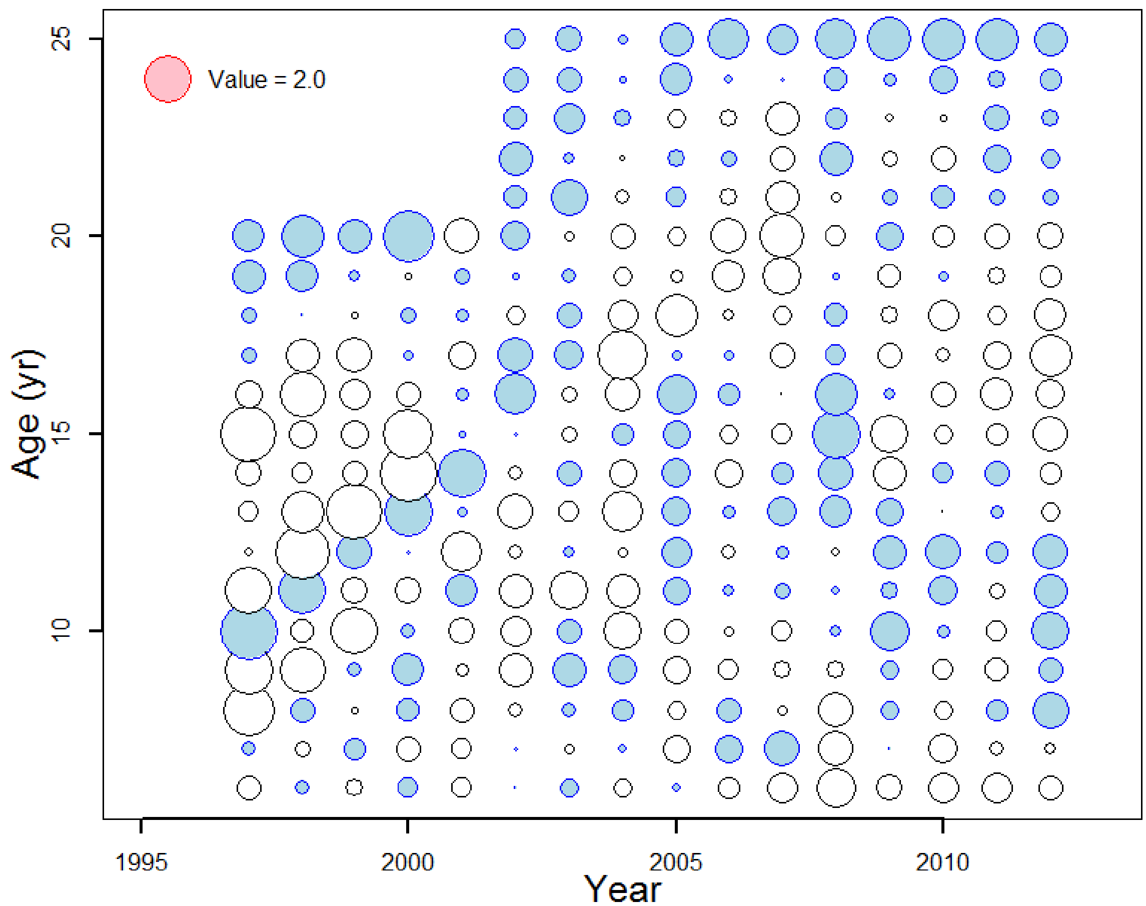

Figure 46. Standardized residuals (observed minus expected values) from the fit to setline survey female catch-at-age. Circle areas are scaled relative to the legend value in the upper left, filled circles indicate positive values.

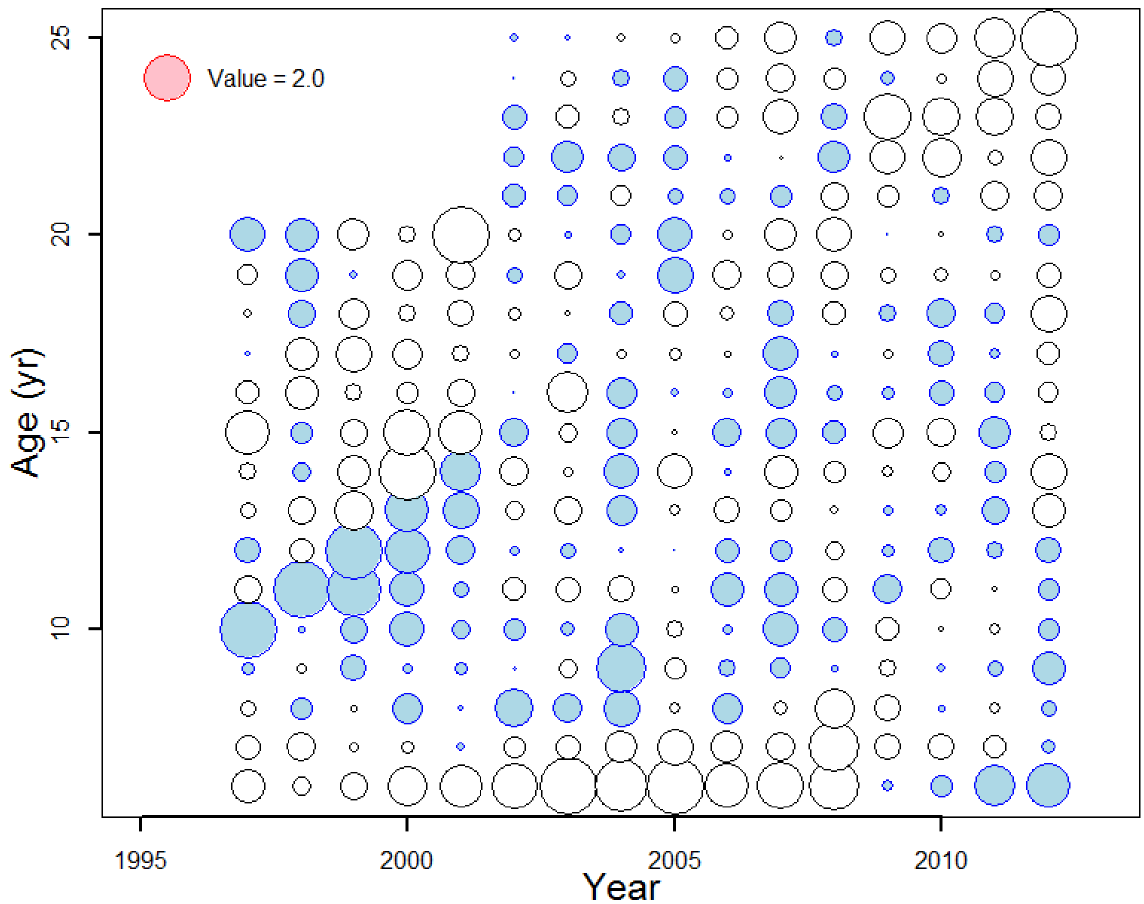

Figure 47. Standardized residuals (observed minus expected values) from the fit to setline survey male catch-at-age. Circle areas are scaled relative to the legend value in the upper left, filled circles indicate positive values.

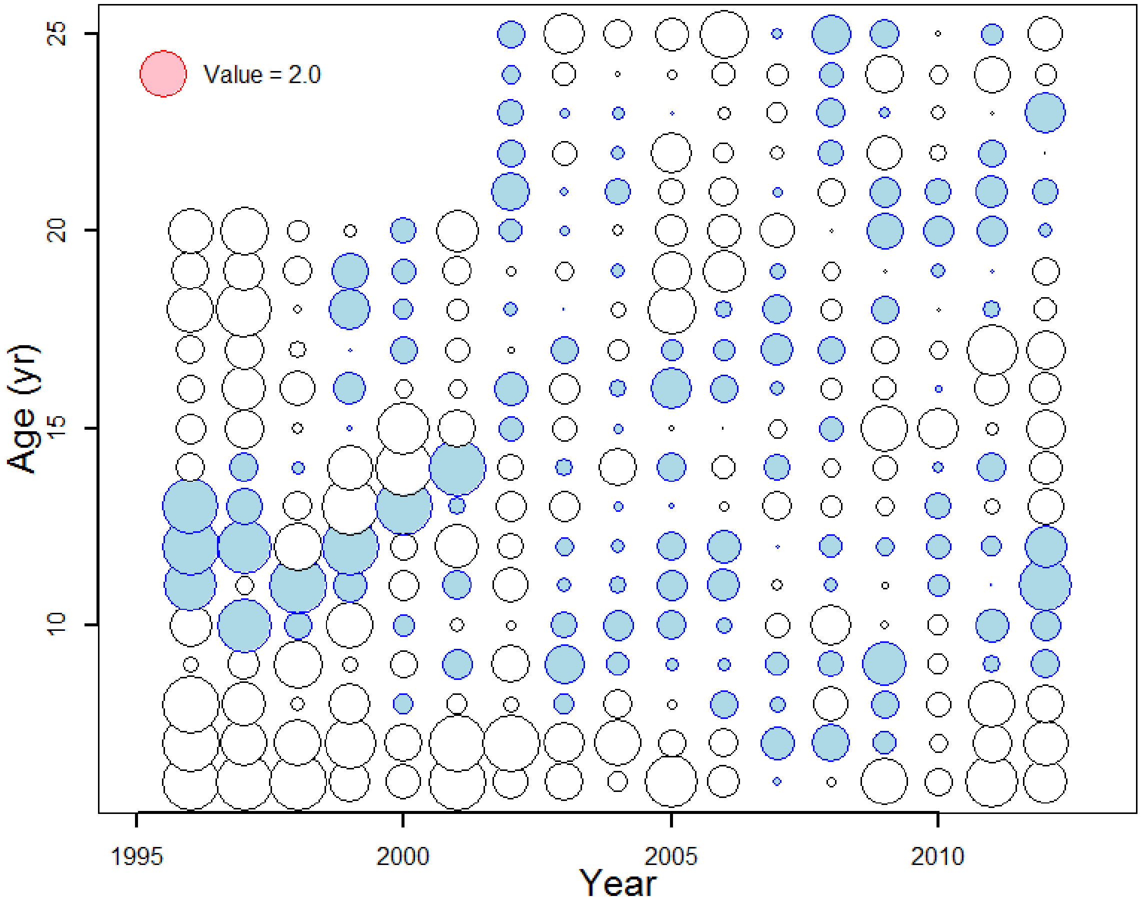

Figure 48. Standardized residuals (observed minus expected values) from the fit to commercial fishery total catch-at-age. Circle areas are scaled relative to the legend value in the upper left, filled circles indicate positive values.

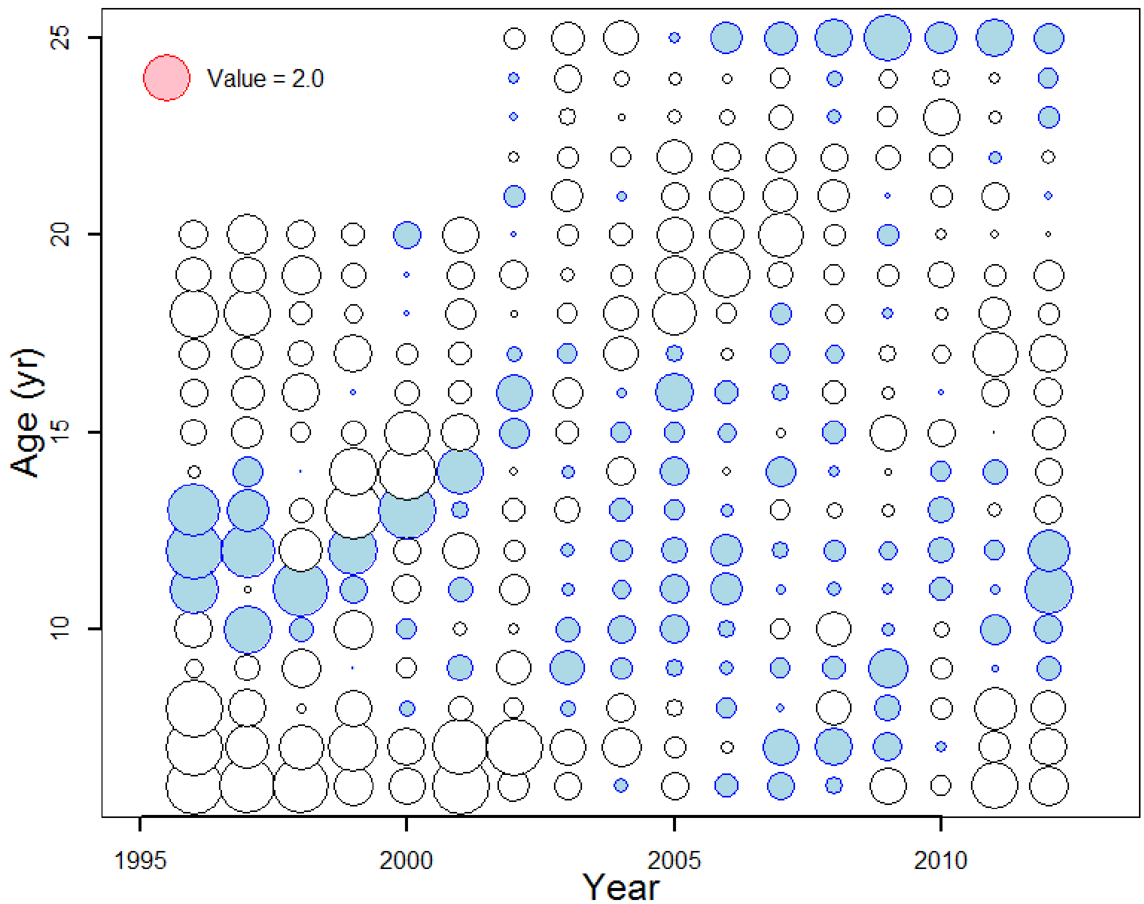

Figure 49. Standardized residuals (observed minus expected values) from the fit to commercial fishery female catch-at-age. Circle areas are scaled relative to the legend value in the upper left, filled circles indicate positive values.

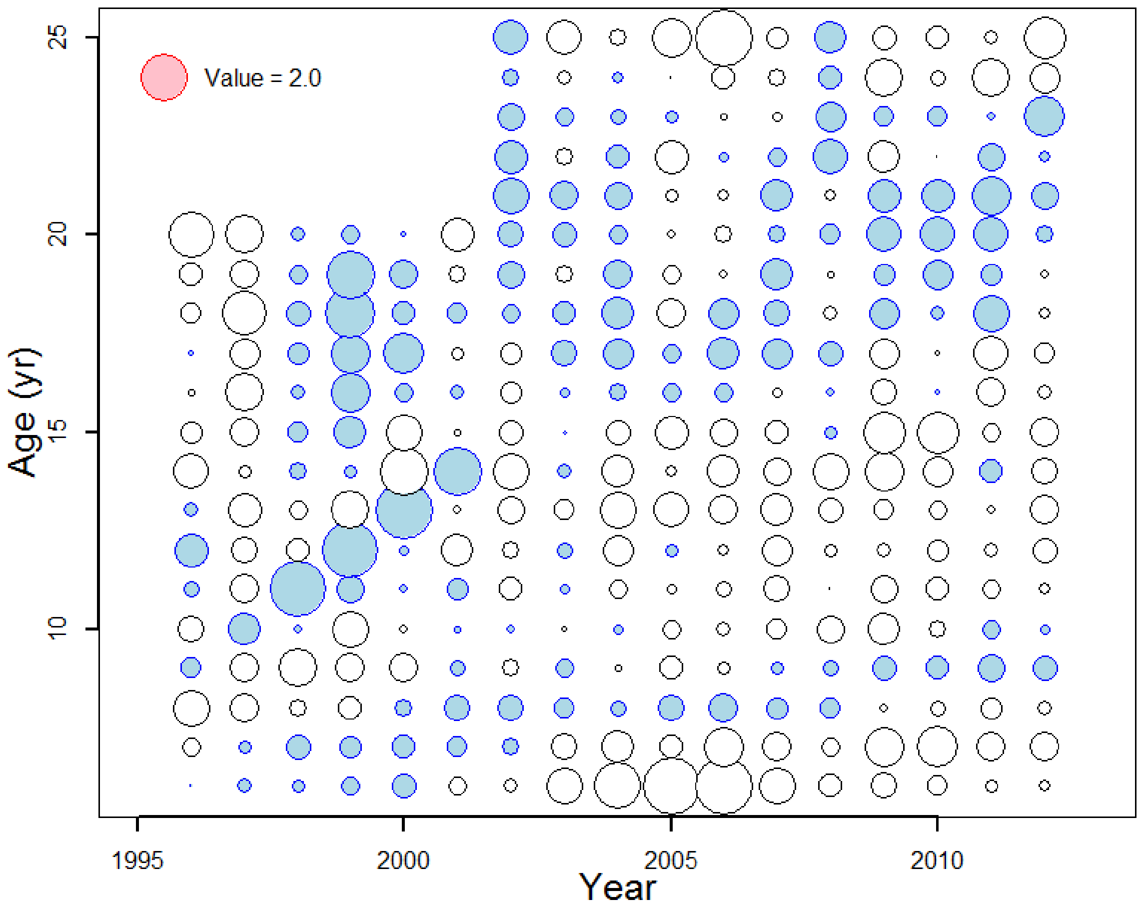

Figure 50. Standardized residuals (observed minus expected values) from the fit to commercial fishery male catch-at-age. Circle areas are scaled relative to the legend value in the upper left, filled circles indicate positive values.

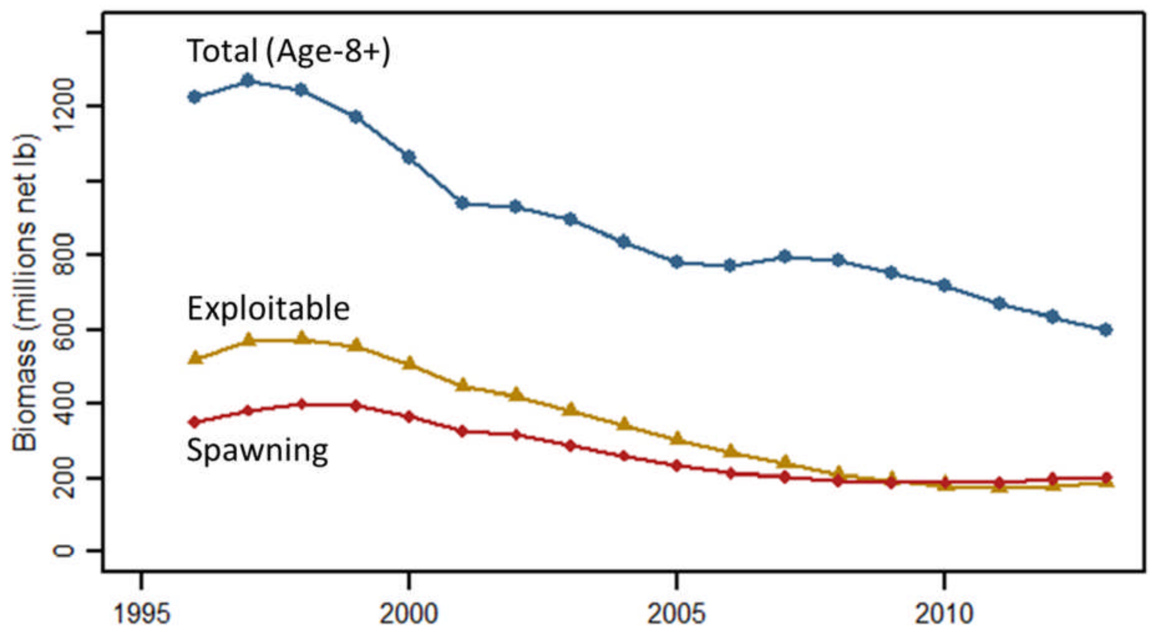

Figure 51. Time series of biomass results.

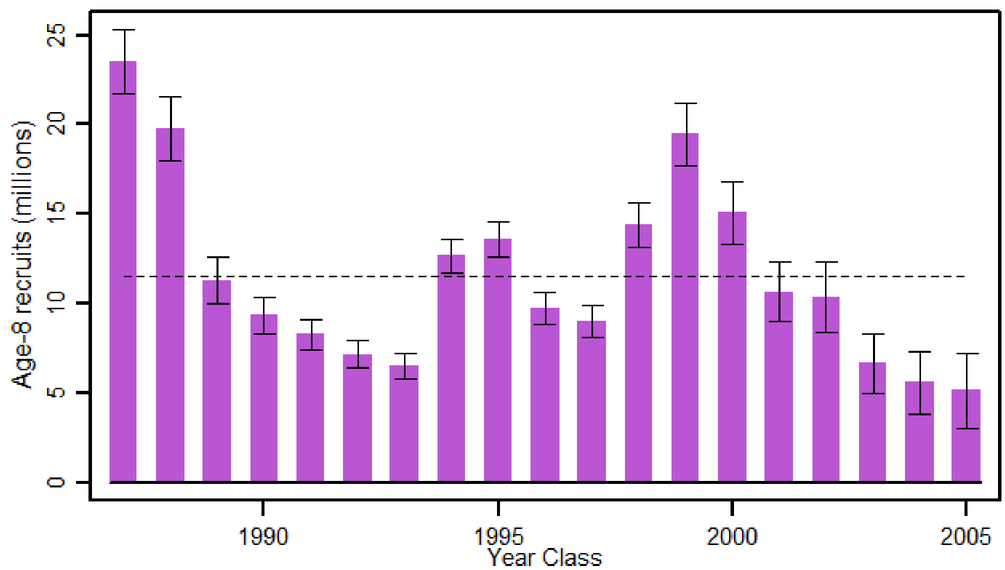

Figure 52. Time series of age-8 recruitments with estimation uncertainty.

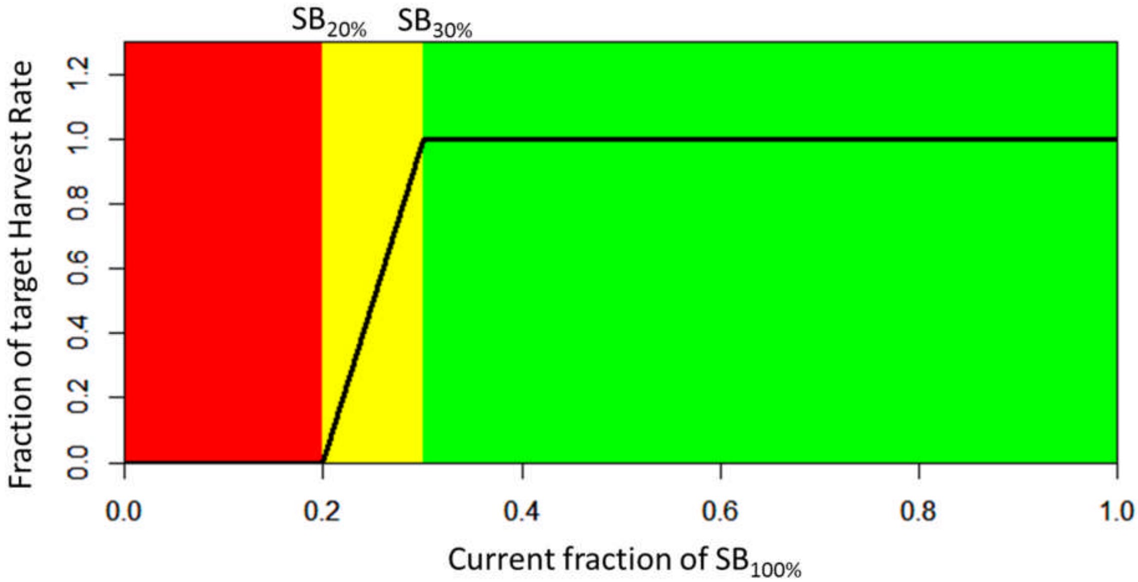

Figure 53. Illustration of the current IPHC harvest control rule for determining the relative target harvest rate as a function of relative spawning biomass, consistent with the IPHC's overall harvest policy.

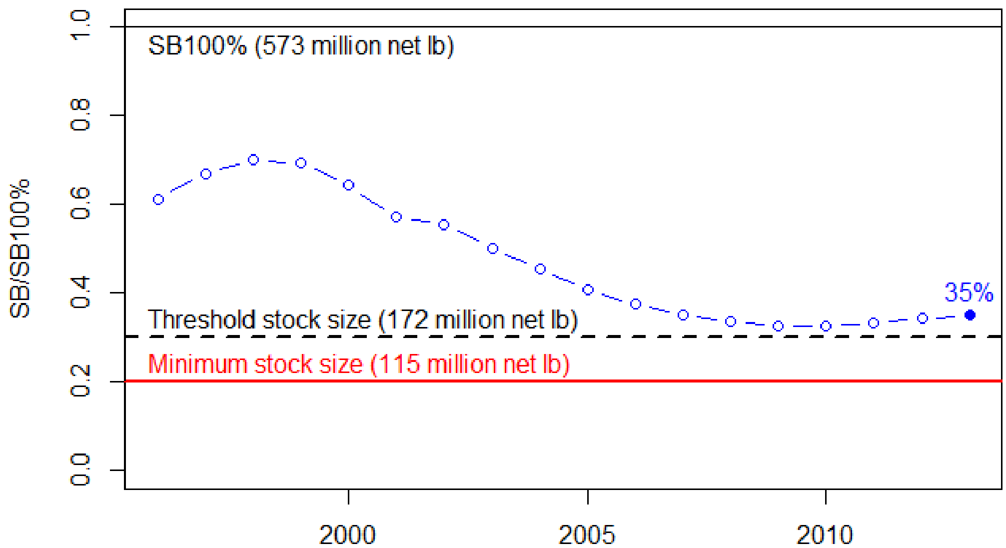

Figure 54. Time-series of spawning biomass relative to harvest policy reference points.

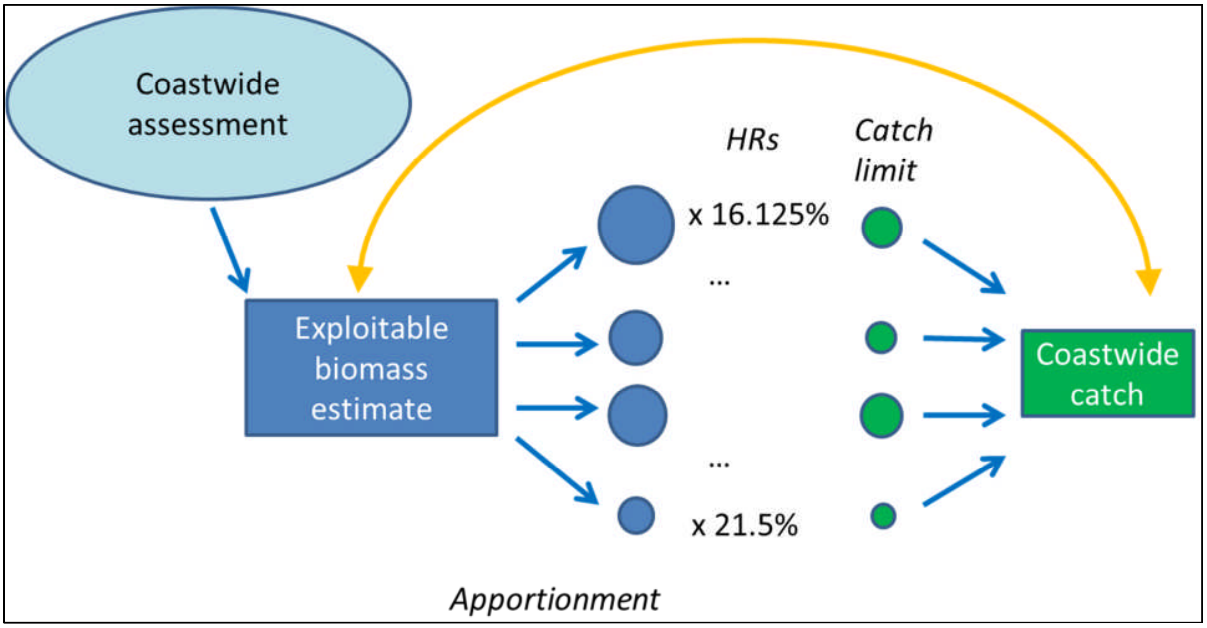

Figure 55. Illustration of the method for calculating the Effective Coastwide Harvest Rate (ECHR), consistent with the IPHC's overall harvest policy.

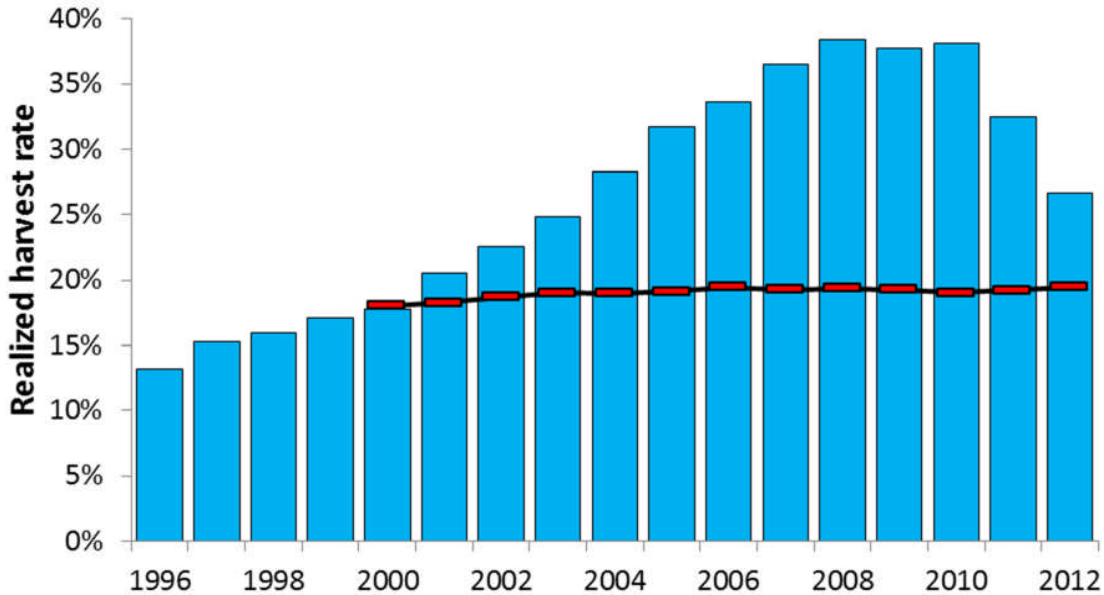

Figure 56. Time series of realized coastwide harvest rates (bars) and hindcast harvest rate targets (horizontal dashes). Note that hindcast harvest rate targets represent the current perception of exploitable biomass, not the perception in that year.

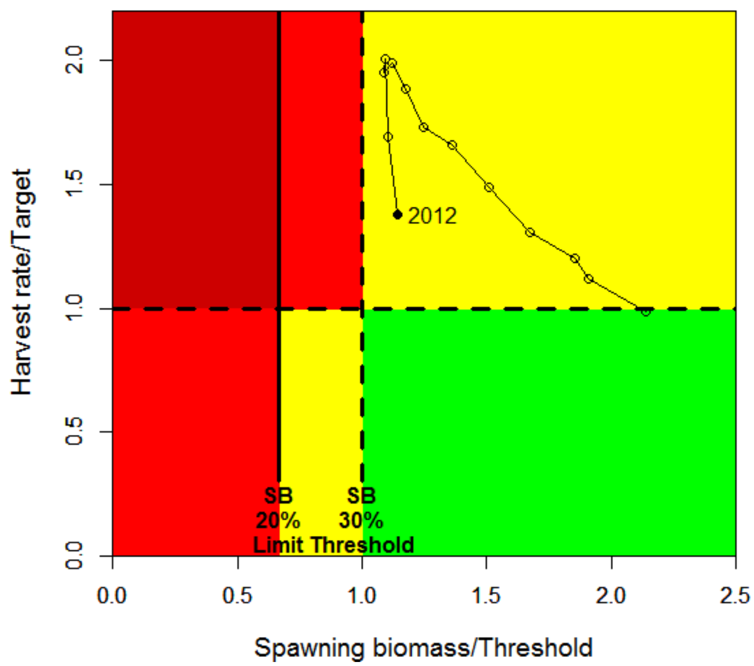

Figure 57. Phase plot of relative stock size and fishing intensity.

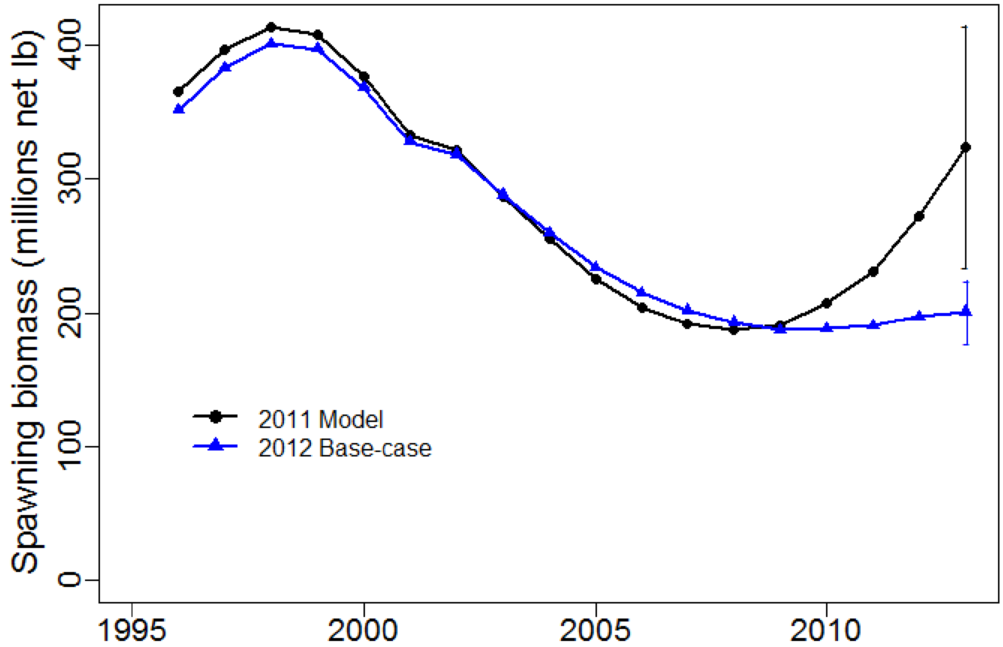

Figure 58. Results of bridging analysis indicating the spawning biomass estimated by the 2011 (wobblesq) model updated with data through 2012 and the current assessment model (2012 Base-case).

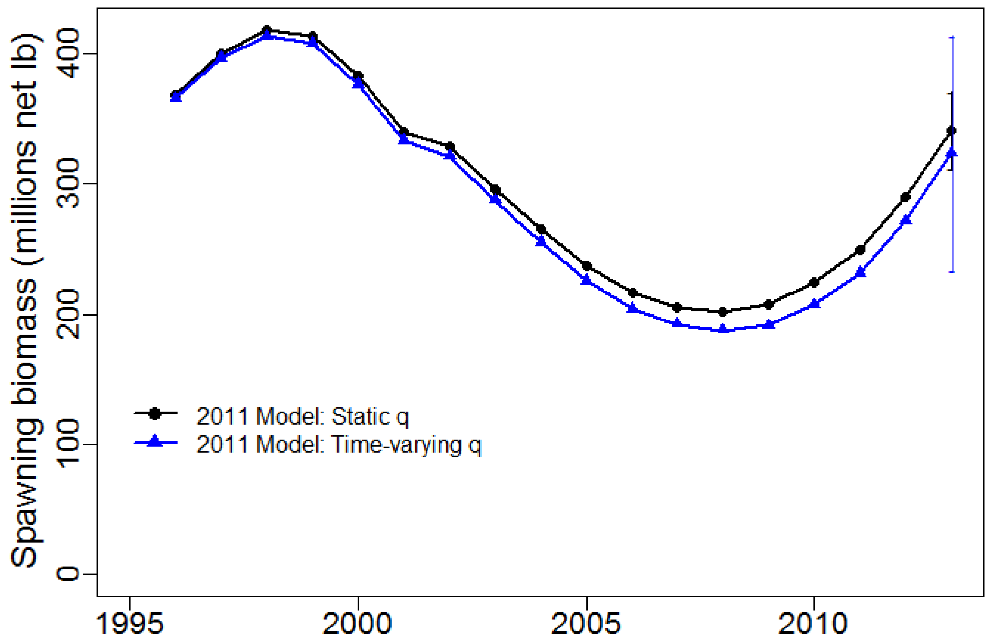

Figure 59. Sensitivity analysis for the 2011 (wobblesq) model illustrating the effect of time-varying vs. time-invariant setline survey catchability.

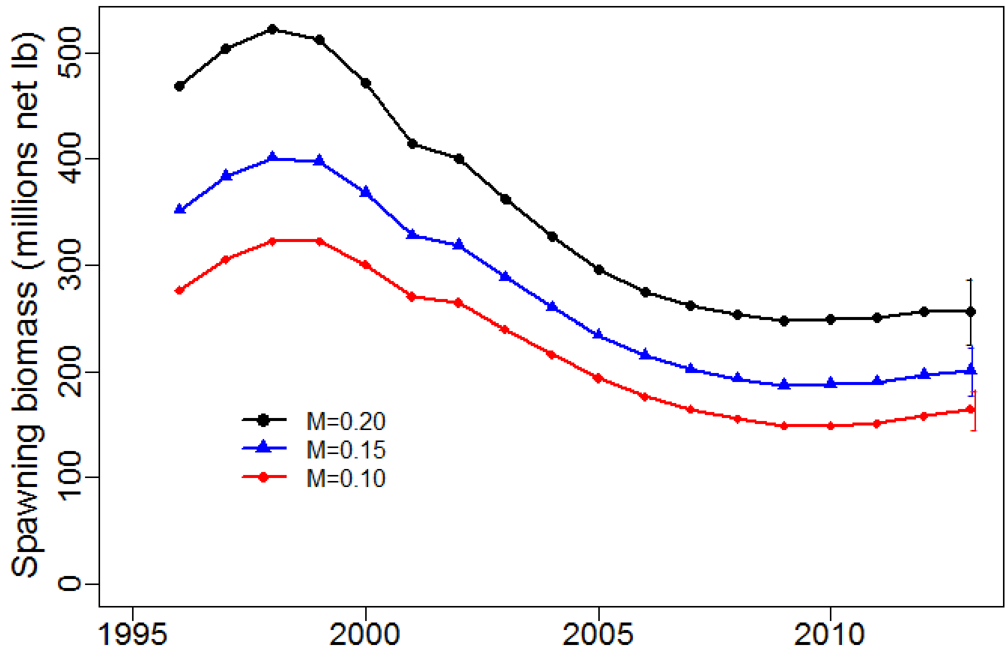

Figure 60. Sensitivity analysis to the value used for female natural mortality; the results from the best-estimate (0.15/year) are represented by the middle line.

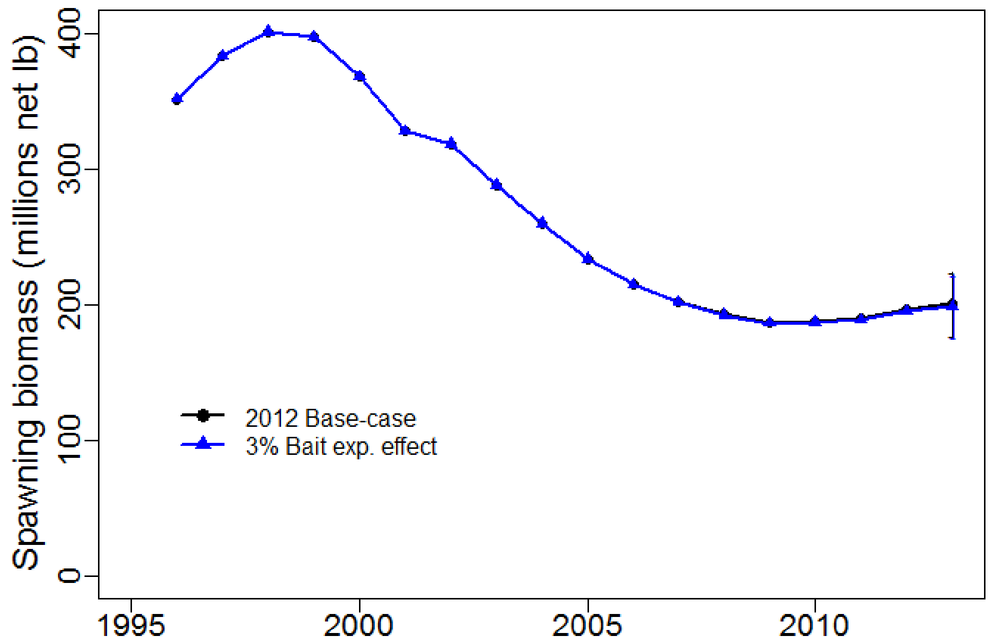

Figure 61. Sensitivity analysis to hypothetical very strong effects of the bait experiment on standard survey skates deployed.

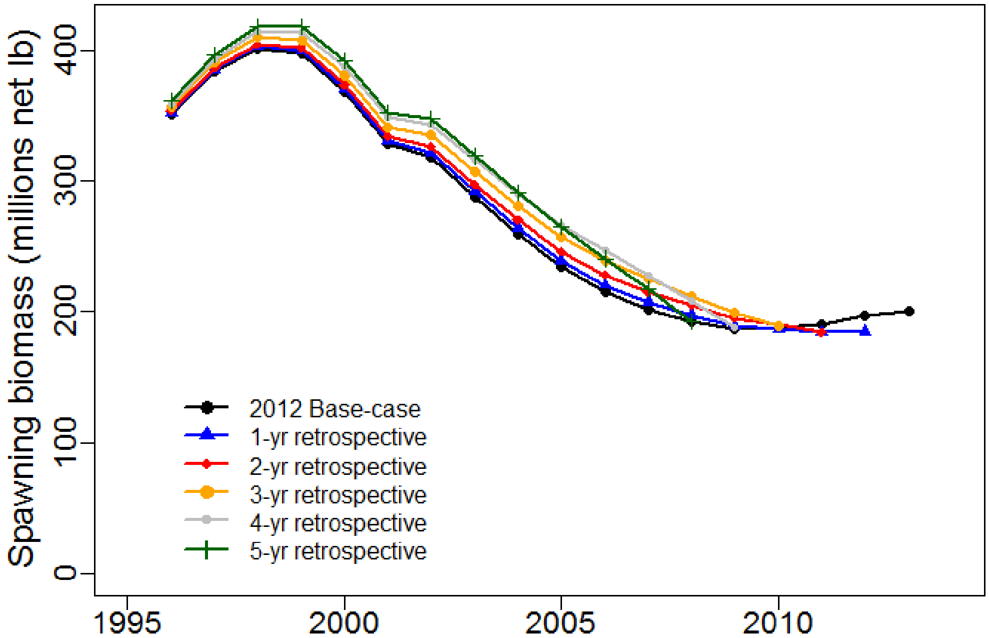

Figure 62. Results of the retrospective analysis on spawning biomass estimates.

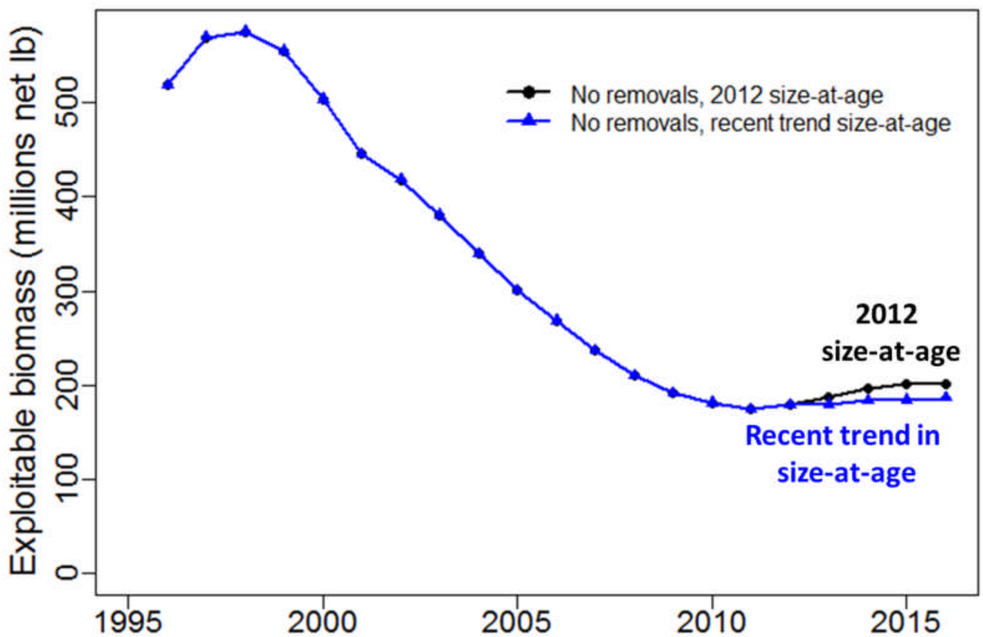

Figure 63. Comparison of exploitable biomass for three-year forecasts assuming size-at-age remains constant at 2012 observed values (upper line) or follows recent (and generally declining) trends by age (lower line).

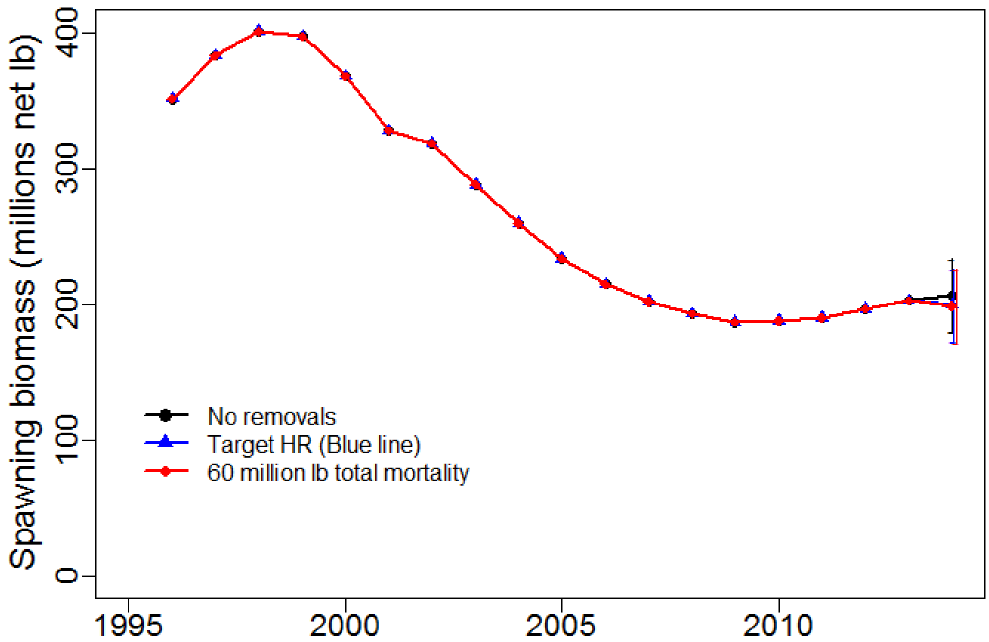

Figure 64. One-year forecasts under alternative removal scenarios.

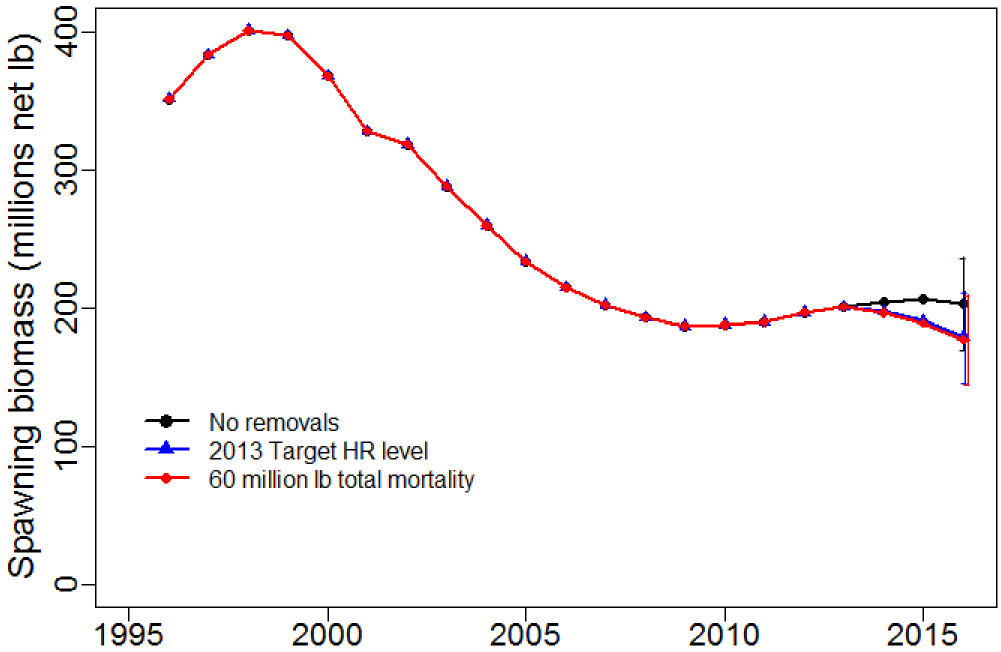

Figure 65. Three-year forecasts under alternative removal scenarios and assuming recent trends in size-at-age continue.

Appendix A: Data summaries by regulatory area.

Table A1. Time-series of total removals by regulatory Area (million lb, net wt.).

Year	2A	2B	2C	3A	3B	4	4A	4B	4CDE	Total
1974	1.00	6.43	6.17	13.50	5.10	8.33	NA	NA	NA	40.54
1975	0.94	9.18	6.93	13.85	4.65	4.28	NA	NA	NA	39.84
1976	0.72	9.51	6.28	14.64	5.20	5.29	NA	NA	NA	41.63
1977	0.70	7.39	3.87	13.02	5.12	4.14	NA	NA	NA	34.24
1978	0.59	6.20	4.82	13.75	3.17	6.38	NA	NA	NA	34.90
1979	0.54	6.84	5.56	17.62	1.33	6.79	NA	NA	NA	38.68
1980	0.52	7.16	4.12	18.44	1.53	9.95	NA	NA	NA	41.72
1981	0.70	7.01	4.87	19.85	2.02	7.62	NA	NA	NA	42.06
1982	0.74	6.60	4.33	18.16	7.04	6.21	NA	NA	NA	43.08
1983	0.81	6.63	7.30	18.15	9.80	8.72	NA	NA	NA	51.41
1984	1.03	10.55	6.86	23.10	8.30	7.89	NA	NA	NA	57.73
1985	1.17	12.32	10.51	24.17	11.85	8.69	NA	NA	NA	68.71
1986	1.40	13.25	12.21	37.74	9.78	11.54	NA	NA	NA	85.92
1987	1.52	14.83	12.28	37.49	9.11	12.98	NA	NA	NA	88.21
1988	1.22	15.27	13.11	46.55	7.39	13.70	NA	NA	NA	97.23
1989	1.29	12.69	11.73	41.97	9.01	12.42	NA	NA	NA	89.10
1990	0.95	11.06	12.39	38.19	11.13	--	4.67	2.34	7.33	88.06
1991	0.94	9.76	12.28	34.44	14.44	--	4.87	2.69	9.11	88.53
1992	1.15	9.98	12.81	37.05	11.10	--	5.35	3.56	8.85	89.86
1993	1.22	13.23	14.35	33.44	9.24	--	4.52	2.87	6.99	85.86
1994	1.01	12.02	13.44	34.97	5.46	--	4.12	3.12	7.92	82.07
1995	1.17	12.56	10.02	26.32	5.00	--	3.74	2.66	7.28	68.73
1996	1.16	11.25	11.50	27.77	5.76	--	3.81	3.05	7.22	71.51
1997	1.41	14.11	12.66	33.71	10.79	--	4.88	4.24	7.82	89.61
1998	1.94	14.90	13.42	33.76	12.86	--	5.39	3.79	8.01	94.07
1999	1.80	14.37	12.74	33.11	15.98	--	6.36	4.48	9.17	98.00
2000	1.68	12.63	11.43	28.00	17.39	--	7.08	5.57	9.11	92.89
2001	1.99	12.06	11.02	29.82	18.52	--	6.84	5.32	8.88	94.45
2002	1.92	14.20	11.38	30.26	19.83	--	6.97	4.93	8.51	97.99
2003	1.52	13.89	11.83	32.24	19.62	--	6.78	4.66	7.90	98.44
2004	1.69	14.71	14.47	35.54	17.39	--	5.31	3.49	7.48	100.05
2005	1.88	15.24	14.65	36.17	14.94	--	5.38	2.84	8.70	99.80
2006	1.98	14.80	14.24	35.13	12.78	--	5.25	2.43	8.33	94.92
2007	1.73	12.52	12.69	36.96	10.88	--	4.71	2.24	8.81	90.53
2008	1.63	10.12	10.50	34.23	12.85	--	4.74	2.51	8.35	84.93
2009	1.50	8.60	8.41	30.73	12.92	--	4.20	2.30	7.57	76.24
2010	1.18	8.71	7.48	29.07	12.22	--	3.91	2.54	7.45	72.54
2011	1.07	8.75	4.32	23.20	9.30	--	3.71	2.66	7.03	60.04
2012	1.15	7.74	4.61	18.73	7.21	--	3.45	2.37	6.11	51.36

Table A2. Time-series of fishery removals by regulatory Area (million lb, net wt.).

Year	2A	2B	2C	3A	3B	4	4A	4B	4C	4D	4E	Total
1974	0.52	4.62	5.60	8.19	1.67	0.71	NA	NA	NA	NA	NA	21.31
1975	0.46	7.13	6.24	10.60	2.56	0.63	NA	NA	NA	NA	NA	27.62
1976	0.24	7.28	5.53	11.04	2.73	0.72	NA	NA	NA	NA	NA	27.54
1977	0.21	5.43	3.19	8.64	3.19	1.22	NA	NA	NA	NA	NA	21.88
1978	0.10	4.61	4.32	10.30	1.32	1.35	NA	NA	NA	NA	NA	22.00
1979	0.05	4.86	4.53	11.34	0.39	1.37	NA	NA	NA	NA	NA	22.54
1980	0.02	5.65	3.24	11.97	0.28	0.71	NA	NA	NA	NA	NA	21.87
1981	0.20	5.66	4.01	14.23	0.45	NA	0.49	0.39	0.30	0.01	0.00	25.74
1982	0.21	5.54	3.50	13.52	4.80	NA	1.17	0.01	0.24	0.00	0.01	29.01
1983	0.27	5.44	6.38	14.13	7.76	NA	2.50	1.34	0.42	0.15	0.01	38.39
1984	0.43	9.05	5.87	19.77	6.69	NA	1.05	1.10	0.58	0.39	0.04	44.97
1985	0.50	10.49	9.42	21.77	11.09	NA	1.78	1.28	0.64	0.70	0.04	57.70
1986	0.59	11.43	11.04	34.66	9.22	NA	3.56	0.28	0.72	1.29	0.05	72.83
1987	0.60	12.42	11.05	32.89	8.10	NA	3.83	1.56	0.91	0.73	0.12	72.20
1988	0.49	12.91	11.57	39.41	7.20	NA	1.96	1.62	0.72	0.46	0.01	76.34
1989	0.48	10.48	9.73	35.19	8.04	NA	1.05	2.72	0.59	0.69	0.01	68.98
1990	0.34	8.69	10.06	29.96	8.91	NA	2.61	1.39	0.55	1.05	0.06	63.62
1991	0.36	7.26	9.03	24.07	12.35	NA	2.35	1.58	0.71	1.50	0.11	59.31
1992	0.44	7.68	10.06	27.43	8.80	NA	2.75	2.36	0.81	0.74	0.07	61.15
1993	0.51	10.72	11.48	23.08	7.92	NA	2.61	2.00	0.85	0.85	0.07	60.08
1994	0.37	9.98	10.61	25.69	3.90	NA	1.84	2.06	0.73	0.73	0.12	56.02
1995	0.30	9.66	7.82	18.46	3.13	NA	1.63	1.69	0.67	0.65	0.13	44.14
1996	0.30	9.58	8.92	19.87	3.69	NA	1.72	2.10	0.69	0.72	0.12	47.69
1997	0.42	12.46	9.96	24.71	9.12	NA	2.93	3.35	1.13	1.16	0.25	65.49
1998	0.46	13.23	10.24	25.85	11.22	NA	3.44	2.92	1.26	1.32	0.19	70.12
1999	0.46	12.75	10.21	25.43	13.91	NA	4.40	3.60	1.77	1.91	0.27	74.70
2000	0.49	10.84	8.48	19.33	15.47	NA	5.18	4.72	1.75	1.94	0.35	68.55
2001	0.68	10.33	8.44	21.60	16.37	NA	5.05	4.50	1.66	1.86	0.48	70.97
2002	0.86	12.11	8.63	23.27	17.35	NA	5.11	4.10	1.22	1.76	0.56	74.95
2003	0.82	11.82	8.44	22.82	17.26	NA	5.04	3.88	0.89	1.96	0.42	73.36
2004	0.88	12.20	10.27	25.24	15.48	NA	3.58	2.73	0.96	1.66	0.32	73.31
2005	0.81	12.37	10.66	26.19	13.20	NA	3.42	1.98	0.54	2.59	0.37	72.11
2006	0.83	12.04	10.51	25.77	10.80	NA	3.34	1.59	0.49	2.37	0.37	68.12
2007	0.79	9.80	8.50	26.55	9.27	NA	2.84	1.42	0.55	2.73	0.58	63.03
2008	0.68	7.78	6.22	24.58	10.75	NA	3.03	1.77	0.73	2.56	0.60	58.70
2009	0.49	6.66	4.97	21.80	10.80	NA	2.54	1.60	0.65	2.22	0.46	52.18
2010	0.42	6.76	4.50	20.52	10.13	NA	2.33	1.84	0.79	2.12	0.41	49.83
2011	0.55	6.72	2.46	14.70	7.33	NA	2.36	2.06	0.79	2.19	0.46	39.61
2012	0.59	5.93	2.70	11.96	5.08	NA	1.58	1.71	0.58	1.42	0.32	31.87

Table A2. Time-series of setline survey WPUE by regulatory Area (O32; net lb/skate).

Year	2A	2B	2C	3A	3B	4A	4B	4D	4IC	4ID	4S	4N	4CDE	Total
1974	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1975	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1976	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1977	NA	13.7	NA	58.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1978	NA	19.1	NA	26.9	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1979	NA	NA	NA	41.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1980	NA	25.5	NA	76.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1981	NA	16.5	NA	131.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1982	NA	20.6	113.7	130.3	NA	NA	NA	NA	NA	NA	5.5	0.0	NA	NA
1983	NA	18.0	142.2	119.0	NA	NA	NA	NA	NA	NA	4.3	0.2	NA	NA
1984	NA	57.4	259.6	361.2	NA	NA	NA	NA	NA	NA	6.4	0.5	NA	NA
1985	NA	41.7	260.5	377.5	NA	NA	NA	NA	NA	NA	5.8	0.7	NA	NA
1986	NA	37.8	282.6	305.1	NA	NA	NA	NA	NA	NA	7.3	0.2	NA	NA
1987	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.1	0.3	NA	NA
1988	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	17.3	0.2	NA	NA
1989	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	10.6	0.2	NA	NA
1990	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	12.3	0.7	NA	NA
1991	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	11.0	2.0	NA	NA
1992	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.6	0.8	NA	NA
1993	NA	95.7	NA	261.1	NA	NA	NA	NA	NA	NA	19.4	4.8	NA	NA
1994	NA	NA	NA	253.9	NA	NA	NA	NA	NA	NA	14.7	3.7	NA	NA
1995	31.0	159.1	NA	300.1	NA	NA	NA	NA	NA	NA	16.3	3.5	NA	NA
1996	33.7	165.9	306.2	317.3	352.2	NA	NA	NA	NA	NA	23.5	18.1	NA	NA
1997	36.4	144.1	410.6	330.6	413.9	245.4	281.6	111.2	111.2	111.2	19.3	4.0	23.2	138.2
1998	37.3	83.3	234.8	281.2	434.9	299.0	215.6	299.0	299.0	299.0	25.6	6.5	44.5	133.9
1999	38.3	88.1	208.9	240.7	437.9	290.3	203.1	290.3	290.3	290.3	25.8	0.0	42.1	126.1
2000	40.6	91.2	240.1	271.7	373.1	275.8	216.3	212.9	212.9	212.9	18.7	2.9	31.5	120.6
2001	43.0	101.1	244.1	256.1	357.1	198.8	171.3	196.8	196.8	196.8	20.0	4.5	31.3	112.3
2002	34.5	91.8	267.8	299.4	297.2	168.4	119.1	262.5	262.5	262.5	11.6	2.1	31.1	108.8
2003	22.8	72.7	228.3	229.3	261.6	154.1	104.1	194.8	194.8	194.8	17.0	3.5	29.0	91.6
2004	27.9	85.8	176.0	269.7	236.3	137.4	73.3	131.9	131.9	131.9	17.0	3.1	23.3	88.4
2005	29.0	71.9	174.7	275.9	211.2	106.8	86.2	69.2	69.2	69.2	16.2	3.4	17.4	82.1
2006	16.8	58.7	146.7	232.5	181.2	84.9	95.5	54.4	60.5	111.2	16.8	3.3	17.0	71.1
2007	19.4	57.2	142.6	211.6	191.3	66.5	87.2	58.6	46.1	50.9	11.9	2.7	13.3	65.8
2008	19.1	89.8	106.4	189.1	126.0	84.1	103.3	77.5	69.7	15.4	8.2	2.5	12.1	60.2
2009	8.3	86.3	115.6	148.8	113.0	84.1	106.8	78.4	53.1	20.4	11.6	3.3	14.5	55.4
2010	17.3	88.8	110.3	117.1	91.4	73.0	68.4	48.0	55.3	57.8	12.2	3.2	13.1	47.0
2011	27.0	79.8	136.3	120.5	79.8	58.4	67.9	33.5	51.5	14.3	9.7	3.2	10.1	44.7
2012	28.5	103.4	161.4	137.0	86.8	63.6	48.3	36.2	37.0	1.4	11.5	3.7	11.2	49.9

Table A2. Time-series of fishery WPUE by regulatory Area (net lb/skate).

Year	2A	2B	2C	3A	3B	4A	4B	4C	4D	4E	Total
1974	59	64	57	65	57	NA	NA	NA	NA	NA	NA
1975	59	68	53	66	68	NA	NA	NA	NA	NA	NA
1976	33	53	42	60	65	NA	NA	NA	NA	NA	NA
1977	83	61	45	61	73	NA	NA	NA	NA	NA	NA
1978	39	63	56	78	53	NA	NA	NA	NA	NA	NA
1979	50	48	80	86	37	NA	NA	NA	NA	NA	NA
1980	37	65	79	118	113	NA	NA	NA	NA	NA	NA
1981	33	67	144	142	160	158	99	110	NA	NA	NA
1982	22	69	146	168	203	103	NA	91	NA	NA	NA
1983	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1984	63	147	284	502	474	366	161	NA	197	NA	341
1985	62	139	345	500	592	337	234	594	330	NA	380
1986	55	118	290	506	506	260	238	427	218	NA	342
1987	53	130	260	498	478	342	220	384	241	NA	344
1988	134	137	281	503	654	453	224	371	201	NA	387
1989	113	133	258	457	590	409	268	333	432	NA	381
1990	168	176	270	354	484	418	209	288	381	NA	332
1991	158	149	233	319	466	471	329	223	399	NA	333
1992	117	171	230	397	440	372	280	249	412	NA	339
1993	147	208	256	393	514	463	218	257	851	NA	399
1994	93	215	207	354	377	463	197	167	480	NA	328
1995	116	219	234	417	476	349	189	286	475	NA	351
1996	159	227	239	473	557	515	269	297	543	NA	415
1997	226	241	246	458	563	483	275	335	671	NA	423
1998	194	232	236	452	611	525	287	287	627	NA	429
1999	342	213	199	437	538	497	310	271	535	NA	398
2000	263	229	187	443	579	548	320	223	556	NA	417
2001	171	227	196	469	431	474	270	203	511	NA	382
2002	181	223	244	508	399	402	245	148	503	NA	380
2003	173	221	233	485	365	355	196	105	388	NA	346
2004	143	203	240	486	328	315	202	120	445	NA	338
2005	137	195	203	446	293	301	238	91	379	NA	314
2006	156	201	170	403	292	241	218	72	280	NA	283
2007	96	198	160	398	257	206	230	65	237	NA	268
2008	69	174	161	370	234	206	193	94	247	NA	249
2009	98	188	155	318	211	234	189	88	249	NA	236
2010	149	222	158	285	173	182	142	82	188	NA	210
2011	92	240	175	280	140	189	165	75	166	NA	209
2012	120	259	208	269	134	191	154	60	162	NA	209