Progress in the development of a management strategy evaluation for Pacific halibut

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Abstract

This report describes the evolution of the harvest strategy for Pacific halibut and the ongoing development of a management strategy evaluation.

Introduction

There are different approaches in the provision of scientific advice for fisheries management. One approach is the assessment-based approach that relies on a regular (usually annual) cycle of evaluation of the status of stocks and determination of "best" estimates of biomass and calculation of quotas based on a predetermined target harvest rate. Target harvest rates can be calculated in different ways depending on specific management goals, among others maximizing yield (MSY based), minimizing risk to the stock, coping with fluctuating populations, etc. The early historical emphasis on MSY and optimal target rates has seen a transition into a framework of harvest control rules that includes threshold and limit reference points, and associated target harvest rates (Mace and Sissenwine 2002). This change has being motivated by a transition towards a precautionary approach to fisheries management (FAO 1996) and the realization of the uncertainty associated with assessment model errors, uncertainty around reference points as well as implementation errors and their combined impact on the ability to conduct successful fisheries management. An alternative approach takes into account a greater spectrum of relevant uncertainties using "feedback control policies" (Mace and Sissenwine 2002). They have been referred as "fisheries control system" (Hilborn 1979), "revised management procedure" (IWC 1994), a "system for evaluating management strategies" (ICES 1994), a "management procedures simulation" (ICCAT 2000), "management procedure approach" (Butterworth 2007) and "management strategy evaluation" or MSE (Smith 1994, Smith et al. 1996, Polacheck et al. 1999, De Oliveira et al. 2008, Butterworth et al. 2010). Although sometimes used interchangeably, MSE is a framework used to evaluate management procedures. A management procedure (Butterworth et al. 1997) is a set of pre-agreed decision rules that specify what data are to be collected and how the data are to be used to set a total allowable catch (TAC). This set of rules is to be pre-agreed upon by fishery managers, resource users and scientist (Butterworth and Punt, 1999; Parma 2002). The evaluation of alternative management procedures is typically done by comparing performance statistics reflecting management objectives and interest of managers, resource users and scientists (Butterworth and Punt, 1999; Parma 2002). Rather than focusing on optimality and best estimates (such as in the assessment based approach), the overall objectives of MSE are to determine robust management alternatives under different biological scenarios and to deal explicitly with the associated uncertainty.

Evolution of the Pacific halibut harvest policy

Pacific halibut in the NE Pacific was fished by Native Americans long before it started to be commercially exploited in 1888. The combination of rapid stock declines and expansion of fishing capacity, capabilities and spatial range of the commercial fleet (Thompson 1916) motivated the signing of the halibut convention of 1923, along with the formation of what was to become the IPHC and the start of a series of fishery regulations for the management of the halibut fishery. In the ensuing years, management of Pacific halibut has relied on different methods for assessing stock trends and status as well as different harvest policy approaches.

The first simulation-based evaluation of alternative management strategies for Pacific halibut was reported by Southward (1968). The simulation approach included biological, fishery and management model components with the goal of comparing the relative performance of three alternative strategies for managing the fishery. The first strategy was an empirical rule based on trends in commercial CPUE and juvenile abundance, the second was a rule based on potential yield curves (fitting the Schaefer model) and the third one was a rule based on yield per recruit analysis. Although not called an MSE and limited to the computing capabilities available at the time, the work included all the major elements of modern day MSE work. The main result was that the three rules performed similarly, although the Schaefer model was the most unstable and the empirical CPUE based rule was the cheaper to implement (Southward 1968).

Up to the 1980s the stock status was based on analyses of annual catch and catch-per-unit of effort (CPUE) (Sullivan and McCaughran 1991, Clark 2003). During the early 1980s, annual catch recommendations were calculated as a fraction of estimated annual surplus production in a period of historically low biomass estimates in an effort to rebuild stocks (Deriso and Quinn 1985). The stocks were considered rebuilt by 1984 and a constant harvest rate policy has been in place since 1985. The performance of the constant harvest rate strategy was evaluated using Monte Carlo simulations of future stock trajectories (Parma 1991) and retrospective simulation analysis of past stock trajectories (Parma 1993). Alternatives to the assessment-based constant harvest rate strategy were evaluated using a simulated management procedure approach (Parma 2002). Simulations suggested that a management procedure based on a simple delay-difference model could provide stable and adequate yields and perform similarly to a constant harvest rate and constant spawning-biomass-per-recruit (Parma 2002). The constant target harvest rate strategy has continued to this day and is applied to annual estimates of exploitable biomass as defined by the estimated commercial selectivity from a statistical age structured stock assessment. The target harvest rate has changed over time from a high of 0.35 in 1985 to 0.215 since 2011, except for areas of special concern (due to trends and status of indices) whose target harvest rate is 0.161 (Hare 2011).

Current target harvest rates have been determined by simulation modeling that incorporated uncertainty in density-dependent growth responses, future levels and distribution of recruitment among areas, stock and environmental relationships, and selectivity curves (Clark and Hare 2006). Uncertainty in the annual stock assessment (other than random observation error on biomass estimates) was not incorporated in the original simulations, nor was management uncertainty such as potential differences between recommended and established catch levels (Clark and Hare 2006). A recent external review of the IPHC stock assessment and harvest policy (Francis 2008) pointed out that assuming that the realized harvest is the same as the target harvest could be potential weakness of the current harvest policy. In response to the external review, auto correlated errors in the assessment were included in the simulations and it was reported that the effect was relatively minor and that it was expected to result in a more frequent triggering of target harvest rate reduction (Hare and Clark 2008). An example of realized harvest rate departures from the target harvest rates is the result of the misspecification of closed-area assessments. In summary, area specific closed-area assessments were biased high because the main assumption, that of a closed population, was violated due to ongoing migration of halibut between areas. Misspecification in the closed-area stock assessments resulted in realized harvest rates, estimated by recent coastwide stock assessments with survey-partitioned biomass, as much as three times higher than the target in areas 2B and 2C and as low as half the target harvest rate for Area 4 during part of the last decade (Valero 2012a). Estimated coastwide realized harvest rates have increased from a low of 0.14 in 1997, the earliest year estimated by the current stock assessment, to a high of 0.32 in 2007. Following the implementation of the coastwide assessment with survey-partitioned biomass, coastwide realized harvest rates declined to 0.23, as estimated by the assessment at the end of 2010.

Another source of differences between target and realized harvest rates is due to an ongoing retrospective pattern dating back at least to 2004. The retrospective pattern has resulted in stock assessment estimates of exploitable biomass (EBio) that show downwards revisions of biomass during successive years of up to 39% of the initial estimate (Valero 2012a). Coastwide realized harvest rates have been up to 62% higher than target harvest rates for some recent years, due in part to the retrospective pattern, and to a lesser degree to implementation errors (actual catches departing from recommendations) or adjustments such as the Slow Up Fast down (SUFD). The performance of the harvest policy relative to reference points is also affected by the retrospective pattern. The revised female spawning biomass time trajectory is estimated to have dropped below the 30% (relative to unfished) threshold for five consecutive years (2005 to 2009). Had the female spawning biomass been estimated below 30% at the time, a reduction in the target harvest rate to up to 0.14 would have been triggered following the current harvest control rule (Valero 2012a). The pattern of consistent downward revisions of biomass and upward revision of realized harvest rates are still ongoing and the extent to which the current harvest policy is robust to the processes described above is still unknown.

Other ongoing processes could affect the performance of the current harvest policy. One of them are the long-term and large-scale (both geographic and in the actual magnitude) changes in size-at-age. Observed size-at-age was low in the 1920s, high in the 1970s and 1980s and has been decreasing for most areas since the mid-1980s. Pacific halibut size-at-age changes have been generally attributed to changes in growth rate (Clark and Hare 2002), although a definite process behind the observed pattern there has not been found to date. Alternative processes could be responsible for the observed pattern, including methodological changes in age determination and the effect of size selective fishing. Assumptions regarding the process or processes behind the observed changes in size-at-age can have profound implications on the performance of the stock assessment (e.g. in the effect on selectivities) and harvest policy (e.g. in the potential for density-dependent growth and status relative to reference points).

An additional aspect that can affect the performance of the current harvest policy is the spatial scale at which it is applied. The current policy was developed using simulation based on dynamics of what often referred as “core” areas, IPHC regulatory areas 2B, 2C and 3A. During the last decade reference points from the harvest policy have changed from a minimum biomass to a threshold ($B_{30\%}$) and limit ($B_{20\%}$) relative to unfished conditions (Clark and Hare 2006) and changed from being applied at the regulatory area level to a coastwide level (Hare and Clark 2008).

Current assessment-based approach to derive annual catch limits

Pacific halibut stock assessments have been conducted using a coastwide model since 2006, replacing individual regulatory area closed-area assessments conducted between 1989 (Sullivan et al. 1990) and 2006 (Clark and Hare 2007). The coastwide model produces a coastwide estimate of exploitable biomass. Since quotas are established for each regulatory area, a method is required for dividing the coastwide biomass estimate. The IPHC staff proposed and current method has been to apportion the coastwide exploitable biomass estimate in proportion to the survey index, adjusted for hook competition and survey timing (Webster and Hare 2010). This method assumes that the survey index is proportional to abundance and that there are no differences in survey catchability between IPHC regulatory areas (other than the aforementioned adjustments), assumptions that are consistent with the method used to build the coastwide dataset from individual regulatory area datasets (see Clark and Hare 2007). The main steps involved in the annual process to derive catch limits are outlined in Figure 1. Since the change to coastwide assessment and survey apportionment of biomass, two IPHC sponsored Biomass Apportionment Workshops were held (IPHC 2009a, 2010, Hare et al. 2009, Valero and Hare 2010a) in order to provide a forum to discuss pros and cons of this apportionment method and evaluate potential alternatives. The coastwide stock assessment and survey-based partition of biomass has been accepted by the IPHC as whole and this approach has been used for each management cycle since 2007. In spite of this, there is ongoing discussion among its constituency regarding the validity of its assumptions and merits relative to alternative approaches.

Development of a management strategy evaluation for Pacific Halibut

A management strategy evaluation (MSE) framework can provide a formal way to evaluate the performance of the current harvest strategy to different types and levels of uncertainty. It can also be used to evaluate different management procedures that could be considered as alternatives to the current management approach. Decisions regarding the selection and evaluation of alternative strategies are informed by testing of alternative candidates against a series of pre-agreed performance indicators that reflect management goals. One of most important components of the MSE process is the construction of simulation models, called operating models, that describe potential past and future scenarios for the dynamics of the stock and the fishery and that includes key uncertainties. Other components of the MSE approach are a conditioning module, a projection module and an evaluation module as illustrated in Figure 2 and described below.

Operating models

The goal of the operating models is to describe population and fishery dynamics under alternative hypothesis and model formulations to capture the real (statistical and structural) uncertainty. One of the operating models in development is an expansion of the first two versions of IPHC widgets (Valero and Hare 2009, 2010a). The expanded versions incorporate alternative migration patterns for juveniles and adults such as structuring migration by age, sex, maturity and site fidelity. Expanded models also allow for alternative spatial structure in growth and spawning stock / recruitment relationships as well as different selectivity and catchability types. Other operating models explicitly incorporate alternative size at age dynamics. The first version of operating models using alternative size at age dynamics was a one-area model that has been expanded to a multiple area model with migration. Another set of operating models are based on incorporating historical data in stock assessment analysis using the Stock Synthesis framework (see next section). Operating models are currently being conditioned to different time spans of available data: recent (1996 to present time span used in the coastwide stock assessment) and historical data (different time spans as far back as 1888 depending on data availability for processes of interest), see Figures 3 and 4.

Conditioning

The goal of the conditioning component is to condition the operating models on available historic data to be consistent with the historic dynamics of the stock. It is important to note that the conditioning of operating models is not the same as conducting a full stock assessment. The focus of the conditioning component is not in finding the best assessment of the stock, but rather in making sure that the operating models are consistent with historical data. This is an important distinction since operating models often include processes for which we may not have relevant data to fit. For example, we may have operating models that focus on potential climate impacts on individual growth. Even if we may not have relevant data to provide a definitive description and fit to the process we still want to have operating models that incorporate such an effect in a way that is consistent with historic data on the dynamics of the stock. In other MSE projects underway in the fisheries community, the conditioning of operating models has been done using different approaches. Three alternative approaches are recent stock assessments, all available data and expert opinion. The choice of type of conditioning depends on the hypothesis and focus of the operating model and the data that is going to be conditioned on.

The conditioning of operating models for Pacific halibut described in the previous section is done using SS3 (Stock Synthesis version 3). Stock Synthesis (Methot 2000, 2011) is a state of the art generalized framework for modeling fish stocks. Stock Synthesis has been extensively reviewed and widely used in the US and international fisheries community for stock assessments including tunas (Maunder and Silva 2011), flatfishes (Stewart 2008, Hicks and Wetzel 2011), Pacific hake (Stewart et al. 2011) and a variety of other groundfish (see Lee et al. 2011). It has the flexibility to model different types and levels of complexity of population dynamics in relationship to the quantity and quality of available data and hypotheses about the dynamics of the resource and the fishery. At this stage, the Pacific halibut population is assumed to be a single coastwide stock along the Pacific coast of the United States and Canada. The model dynamics is two-sex and uses either sex specific (survey) or sex combined (commercial fishery) age compositions depending on data availability. The modeled period includes the years 1888-2010 (last year of available data). Data type and years available are summarized in Figure 4. The model uses all removals from 1888 structured in four fisheries (Commercial, Sport and Subsistence, Bycatch, and Wastage) and the IPHC survey (Figs. 3 and 4). In its current version, growth is estimated internally in the model and selectivities are modeled as a function of age, allowing for changes over time to take into account changes in hook type and changes in minimum size limit in the commercial fishery. Changes in ageing methods from surface age to break and burn (Forsberg 2001) are incorporated in the model following methods described in Clark, 2004 (Fig. 5). Commercial catchability is allowed to have a non-linear relationship with abundance but survey catchability is assumed constant and proportional to abundance. A Beverton-Holt stock recruitment relationship is used, with a fixed relatively high steepness value (0.85) and a relatively large variability allowed to recruitment deviations (sigmaR = 0.6).

The model produced good fits to historical and recent available data under the specifications described above. Fits to commercial weight per unit of effort (WPUE) and survey WPUE are shown in Figures 6 and 7. Model fits to commercial age composition for both sexes combined from 1935 to 2010 are shown in Figure 8 and fits to sex-specific survey age composition from 1997 to 2010 are shown in Figure 9. Time series of recruitment estimates and 95% confidence intervals are shown in Figure 10, the largest estimated recruitment year corresponds to 1987, followed by 1983 and 1977. The Beverton-Holt stock recruitment fit is shown in Figure 11, additional stock/recruitment relationships are under analysis including other functional forms such as Ricker, environmental covariates and different recruitment eras.

Estimated time series of female spawning biomass with 95% confidence intervals are shown in Figure 12. The estimated unfished level and its confidence interval are in the range of recent values used as part of the current harvest policy, although the later have been based on estimates of recent recruitment (from 1996 onwards, excluding the most recent estimated years) and a spawning biomass per recruit ratio from an unproductive regime (see Hare 2012). The time series of female spawning biomass estimated here is similar in its trajectory to that estimated by Parma (2002) for years 1974 to 2000. The different timing of the estimated SBio increase by both models could be attributed to the treatment of changes from J to C hook in the early 1980s and its effect on assumed selectivity and catchability of commercial fishing gear. Parma (2002) also conducted 10-year projections, which are consistent in trajectory and biomass levels to the estimates of the conditioning model (Figure 13). Time series of SBio estimates from the conditioning model and recent stock assessments conducted between 2006 and 2011 have similar declining trajectories for the earliest estimated years of recent assessments. However, the last estimated years of each recent assessment indicate a reversing SBio trend and a rapid estimated increase, which contrast with the consistent declining trend estimated by the conditioning model (Fig. 14). The five-year projections following recent assessment years also contrast with downward revisions and continuation of declining SBio trend in subsequent recent stock assessments as described in Valero (2012), the downwards revised trend for earlier estimated years is close to that estimated by the conditioning model fits and those projected by Parma (2002) (Fig. 14). Similar patterns of differences emerge when comparing times series of total biomass of halibut ages 8 and older (8+) as estimated by the conditioning model and recent stock assessments (Fig. 15). Although estimated 8+ time series are similar in trajectory and biomass levels for the early part of recent assessments, the conditioning model estimates a continuing decline while recent assessments estimate a change in trend followed by a rapid increase that is revised downwards in subsequent assessments.

Projection

The goal of the projection component is to re-create all steps involved in the annual management cycle (Fig. 2). This includes how catches are taken from the conditioned operating models (as described in previous sections), what data to collect, how to use the data to determine stock status and trends and how to determine next year catches and any other relevant management actions. For evaluation purposes this process is not only repeated over several years during a pre-specified projection time, but it is also repeated many times to incorporate different types of uncertainty in the process. The approach used takes advantage of the parametric bootstrapping component of the Stock Synthesis model. This component allows to simulated data sets that are generated based on characteristics of the real data and the likelihood functions used in the model. This approach has been used recently to explore the ability of different stock assessment models to estimate natural mortality (Lee et al. 2011). An example of simulated spawning biomass trajectories using the bootstrap component is illustrated in Figure 17.

Evaluation

The evaluation component summarizes results of simulations based on performance indicators of alternative management strategies. Performance indicators reflect management goals and will be instrumental in the evaluation, comparison and eventual selection of alternative management strategies. Common indicators include measures of yield, conservation risk, stability and others. Additional specific performance indicators could be identified via consultation of stakeholders involved in the process.

Summary and future steps

The development of an MSE is a time-involved enterprise that requires involvement, consultation and agreement among all interested parties, from scientist, managers and resource users. The development and implementation of MSE is an active area of work worldwide that typically involves the following steps (modified from Kolody and Anganuzzi 2010), although not necessarily always in the following order, and steps are frequently revised iteratively:

1) *Define objectives and performance metrics*.
   Where we are now: only from *status quo* harvest strategy, we still need to define what level and type of stakeholder participation we are to use to define objectives and metrics.
2) *Develop candidate harvest strategies and harvest control rules*.
   Where we are now: current candidates need to be discussed and expanded.
3) *Develop operating models and condition them to historic data.*
   Where we are now: Set of operating models under development and conditioning.
4) *Simulation test of candidate harvest strategies.*
   Where we are now: Awaiting previous steps.
5) *Select harvest strategy*.
   Where we are now: Awaiting previous steps.
6) *Implement harvest strategy.*
   Where we are now: Awaiting previous steps.

References

Breen, P.A., Kim, S.W., Bentley, N. and P. Starr. 2003. Preliminary evaluation of maintenance management procedures for New Zealand rock lobster (*Jasus edwardsii*) fisheries. New Zealand Fisheries Assessment Report 2003/20: 65pp.

Butterworth, D. S. 2007. Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science, 64: 613–617.

Butterworth, D. S., Cochrane, K. L. and De Oliveira, J. A. A. 1997. Management procedures: a better way to manage fisheries? The South African experience. In Pikitch, E. K., Huppert, D. D. and Sissenwine, M. P., eds. Global Trends: Fisheries Management (Proceedings of the Symposium held at Seattle, Washington, 14 - 16 June, 1994). Am. Fish. Soc. Symp. 20, 83-90.

Butterworth, D. S. and Punt, A.E. 1999. Experiences in the evaluation and implementation of management procedures. ICES J. Mar. Sc. 56:985-998.

Butterworth, D. S., Bentley, N., De Oliveira, J. A. A., Donovan, G. P., Kell, L. T., Parma, A. M., Punt, A. E., Sainsbury, K, Smith, A. D. M. and Stokes, T. K. 2010. Purported flaws in management strategy evaluation: basic problems or misinterpretation? ICES Journal of Marine Science, 67: 567–574.

Clark, W. G. 2003. A Model for the World: 80 Years of Model Development and Application at the International Pacific Halibut Commission, Nat. Res. Model. 16, 491–503.

Clark, W. G. 2004. Statistical distribution of IPHC age readings. Int. Pac. Halibut comm. Report of Assessment and Research Activities 2003: 99-100.

Clark, W. G. and Hare, S. R. 2002. Effects of climate and stock size on recruitment and growth of Pacific halibut. North American Journal of Fisheries Management. 22: 852-862.

Clark, W. G., Hare, S. R and Leaman, B. 2004. Sources of uncertainty in annual CEY estimates. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2003: 163-170.

Clark, W. G. and Hare, S. R. 2006. Assessment and management of Pacific halibut: data, methods and policy. Int. Pac. Halibut Comm. Sci. Rep. 83.

Clark, W. G. and Hare, S. R. 2007. Motivation and plan for a coastwide assessment. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2006: 83-96.

De Oliveira, J. A. A., Kell, L. T., Punt, A. E., Roel, B. A., and Butterworth, D. S. 2008. Managing without best predictions: the management strategy evaluation framework. In Advances in Fisheries Science. 50 Years on from Beverton and Holt, pp. 104–134. Ed. by A. Payne, J. Cotter, and T. Potter. Blackwell Publishing, Oxford. xxi + 546 p.

Deriso, R. B. and Quinn II, T. J. 1985. Methods of population assessment of Pacific halibut. Int. Pacific Halibut Comm. Sci. Rep. No. 72.

FAO. 1996. Precautionary approach to capture fisheries and species introductions. Elaborated by the Technical Consultation on the Precautionary Approach to Capture Fisheries (Including Species Introductions). Lysekil, Sweden, 6-13 June 1995. Published as FAO Technical Guidelines for Responsible Fisheries No. 2. Food and Agriculture Organization of the United Nations , Rome, Italy.

Forsberg, J. E. 2001. Aging manual for Pacific halibut: procedures and methods used at the International Pacific halibut Commission (IPHC). Int. Pac. Halibut Comm. Sci. Rep. 46.

Hare, S. R. 2011. Potential modifications to the IPHC harvest policy. Int. Pac. Halibut Comm. Report of Assesment and Research Activities 2010: 177-199.

Hare, S. R. 2010. Assessment of the Pacific halibut stock at the end of 2009. Int. Pac. Halibut Comm. Report of Research and Assessment Activities 2010: 91-10.

Hare, S. R. 2011. Assessment of the Pacific halibut stock at the end of 2010. Int. Pac. Halibut Comm. Report of Research and Assessment Activities 2010: 85-176.

Hare, S. R. 2012. Assessment of the Pacific halibut stock at the end of 2011. Int. Pac. Halibut Comm. Report of Research and Assessment Activities 2011: 91-194.

Hare, S. R. and Clark, W. C. 2008. 2007 IPHC harvest policy analysis: past, present and future considerations. Int. Pac. Halibut Comm. Report of Research and Assessment Activities 2007: 275-296.

Hare, S. R., Webster, R. A., Valero, J. L. and Leaman, B. 2009. Question and significannt comments arising at the Apportionment Workshop. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008: 107-136.

Hicks, A. C. and Wetzel, C. 2011. The Status of Dover Sole (*Microstomus pacificus*) along the U.S. West Coast in 2011. www.pcouncil.org/wp-content/uploads/G4a_ATT11_STATUS_DOVER_SEPT2011BB.pdf

Hilborn, R. 1979. Comparison of fisheries control systems that utilize catch and effort data. Journal of the Fisheries Research Board of Canada 36:1477-1489.

ICCAT. 2000. Report of the meeting of the ICCAT ad hoc working group on the precautionary approach (Dublin, Ireland, 17-21 May.) 1999. ICC AT Collective Volume of Scientific Papers 51 : 1941 -2057.

ICES. 1994. Report of the working group on long term management measures. ICES CM 1994/ Assess: II.

IPHC. 2009a. IPHC Biomass Apportionment Workshop summary. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008: 95-106.

IPHC. 2009b. Biomass Apportionment Workshop. Presentation during the 2nd Biomass Apportionment Workshop, Seattle, April 29-30, 2009. Available at http://www.iphc.int/presentations/baw2009/Wkshp_Slides_BML_0409_v6.pdf

IPHC. 2010. IPHC 2009 Biomass Apportionment Workshop summary and responses to significant questions arising at the workshop. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009: 241-292.

IWC. 1994. The revised management procedure (RMP) for baleen whales. Report of the International Whaling Commission 44: 142- 152.

Kolody, D. and Angannuzzi, A. 2010. Management Strategy Evaluation as a tool to assist the IOTC in meeting its management objectives. Indian Ocean Tuna Commission Working Party on Billfish Working Paper.

Lee, H. H., Maunder, M. N., Piner, K. R. and Methot, R. D. 2011. Estimating natural mortality within a fisheries stock assessment model: An evaluation using simulation analysis based on twelve stock assessments. Fisheries Research 109: 89-94.

Mace, P. M., and Sissenwine, M. P. 2002. Coping with uncertainty: evolution of the relationship between science and management. In: Incorporating Uncertainty into Fisheries Models. American Fisheries Society Symposium, 27, pp. 9-28. Ed. by J. M. Berkson, L. L. Kline, and D. J. Orth. American Fisheries Society, Bethesda, Maryland.

Maunder, M. N. and Aires-da-Silva, A. 2011. Status of yellowfin tuna in the eastern Pacific Ocean in 2009 and outlook for the future. Inter-Amer. Trop. Tuna Comm., Stock Assessment Report, 11: 3-16

Methot, R. D. 2000. Technical description of the Stock Synthesis assessment program. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-43.

Methot, R. D. 2011. User Manual for Stock Synthesis. Model Version 3.21. Northwest Fisheries Science Center.

Parma, A. M. 1991 Performance of alternative harvest rates Int. Pac. Halibut Comm. Report of Commission Activities 1990.

Parma, A. M. 1993. Retrospective catch-at-age analysis of Pacific halibut: implications on assessment of harvesting policies. Pages 247–265 in G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke and T. J. Quinn II, eds. Proc. Int'l. Symp. Management Strategies for Exploited Fish Populations. Alaska Sea Grant College Program Report No. AK-SG-93-02. Alaska Sea Grant College Program, Univ. Alaska, Fairbanks, Alaska.

Parma, A. M. 2002. In search of robust harvest rules for Pacific halibut in the face of uncertain assessments and decadal changes in productivity. Bulletin of Marine Science 70: 423-453.

Polacheck, T., Klaer, N. L., Millar. C. and Preece, A. L. 1999. An initial evaluation of management strategies for the southern bluefin tuna fishery. ICES Journal of Marine Science 56:81 1- 826.

Smith, A. D. M. 1994. Management strategy evaluation: The light on the hill. In: D.A. Hancock (ed.), Population dynamics for fisheries management. Australian Society for Fish Biology, Perth, Western Australia, pp. 249-253.

Smith, A. D. M., Punt, A. E., Wayte, S. E. and Klaer, N. L. 1996. Evaluation of harvest strategies for eastern gemfish (*Rexea solandri*) using Monte Carlo simulation. Pages 120--164 in A. D.M. Smith, editor. Evaluation of harvesting strategies for Australian fisheries at different levels of risk from economic collapse. Fisheries Research and Development Corporation Report T93/238, Australia.

Southward, G. M. 1968. A Simulation of Management Strategies in the Pacific Halibut Fishery, Int. Pac. Halibut Comm. Report 47.

Stewart, I. J. 2008. Updated U.S. English sole stock assessment: Status of the resource in 2007. In: Status of the Pacific Coast Groundfish Fishery through 2008, Stock Assessment and Fishery Evaluation: Stock Assessments, STAR Panel Reports, and Rebuilding Analyses. Pacific Fishery Managment Council, Portland, OR, 213 p.

Stewart, I. J., Forrest, R. E., Grandin, C., Hamel, O. S., Hicks, A. C., Martell, S. J. D and Taylor, I. G. 2011. Status of the Pacific hake (whiting) stock in U.S. and Canadian Waters in 2011. In: Status of the Pacific Coast Groundfish Fishery through 2011, Stock Assessment and Fishery Evaluation: Stock Assessments, STAR Panel Reports, and Rebuilding Analyses. Pacific Fishery Management Council, Portland, Oregon. 217 p.

Sullivan, P. J, Neal, P. R. and Vienneau, B. 1990. Population Assessment, 1989. Int. Pac. Halibut Comm. Stock Assessment Document IV.

Sullivan, P. J. and McCaughran, D. A. 1993. The Pacific halibut: stock assessment strategies and management implications. Proceedings of the 1992 World Fisheries Congress, Athens. Theme 5, Assessment Methodologies and Management.

Thompson, W. F. 1916. Statistics of the halibut fishery in the Pacific: Their bearing on the biology of the species and the condition of the banks. British Columbia Fisheries Department, 1915: 65-126.

Thompson,W. F. and Van Cleve, R. 1936. Life history of the Pacific halibut - Distribution and early life history. Int. Fisheries Comm. Rep. 9.

Valero, J. L. 2011. 87th International Pacific Halibut Commission Annual Meeting. Projections of exploitable biomass using alternative methods and assumptions. Public Session presentation. January 25, 2011. Victoria, Canada. http://www.iphc.int/meetings/2011am/AltProjections_Juan_v4_web.pdf

Valero, J. L. 2012a. Harvest policy considerations on retrospective bias and biomass projections. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2011:311-330.

Valero, J. L. 2012b. Projections of Pacific halibut coastwide exploitable biomass using alternative methods and assumptions. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2011:267-280.

Valero, J. L. and Hare S. R. 2009. Exploring effects of fishing and migration on the distribution of Pacific halibut. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2008:265-298.

Valero, J. L. and Hare S. R. 2010a. Exploring effects of fishing and migration on Pacific halibut dynamics with Widget 2. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009:209-240.

Valero, J. L. and Hare S. R. 2010b. Report cards summarizing results from alternative widget runs during and after IPHC Biomass Apportionment Workshop II. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009:293-306.

Valero, J. L and Webster, R. A. 2012. Current understanding of Pacific halibut migration patterns. Int. Pac. Halibut Comm. Report of Assessmnent and Research Activities 2011: 341-380.

Webster, R. A. 2010. Analysis of PIT tag recoveries through 2009. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009: 177-186.

Webster, R. A. and Hare, S. R. 2010. Adjusting IPHC setline survey WPUE for survey timing, hook competition and station depth. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2009: 187-208.

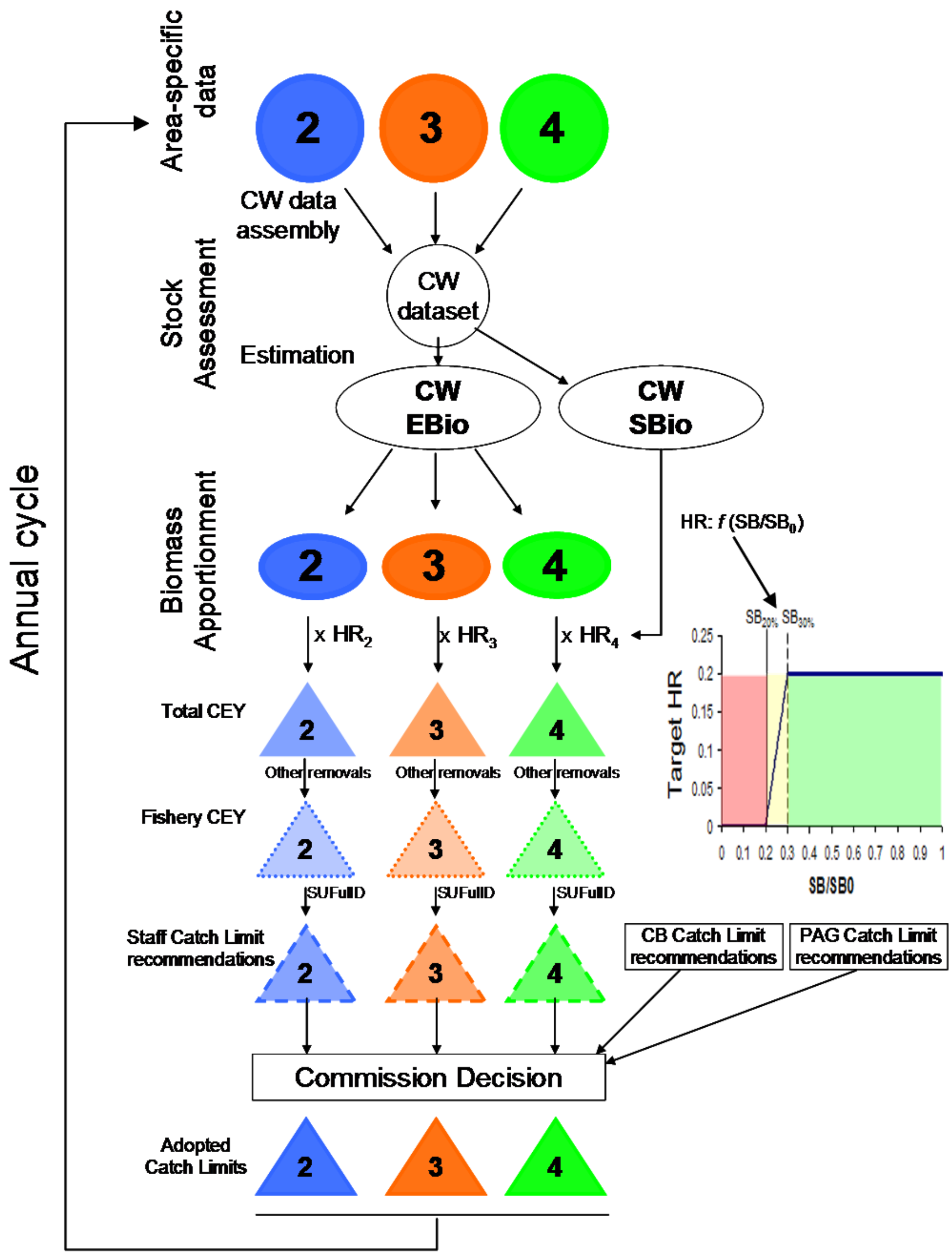

Figure 1. Schematic representation of current annual cycle to derive CEY recommendations based on a coastwide assessment (CW) and a survey-based apportionment of exploitable biomass (EBio). "SB": female spawning biomass, "SB0": estimated unfished SBio, "CB": Conference Board, "PAG": Processor Advisory Group, "SUFullD": Slow Up, Full Down adjustment. Ovals represent biomass estimates, other area-specific data are used to assembly the CW dataset, such as length and age compositions, etc; triangles represent CEY estimates. The scheme is simplified to three hypothetical areas.

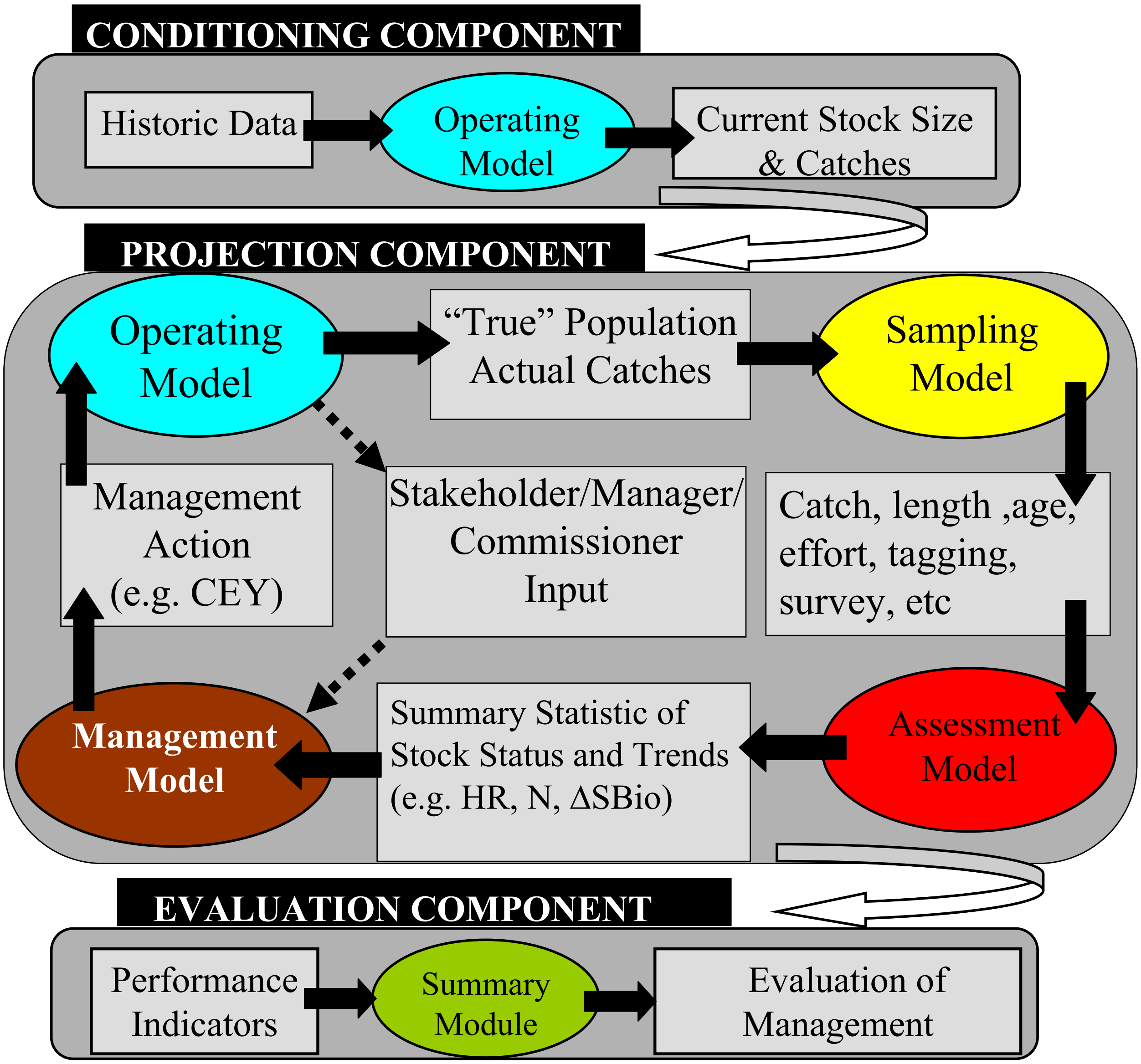

Figure 2. Schematic of the main components of a Management Strategy Evaluation (MSE).

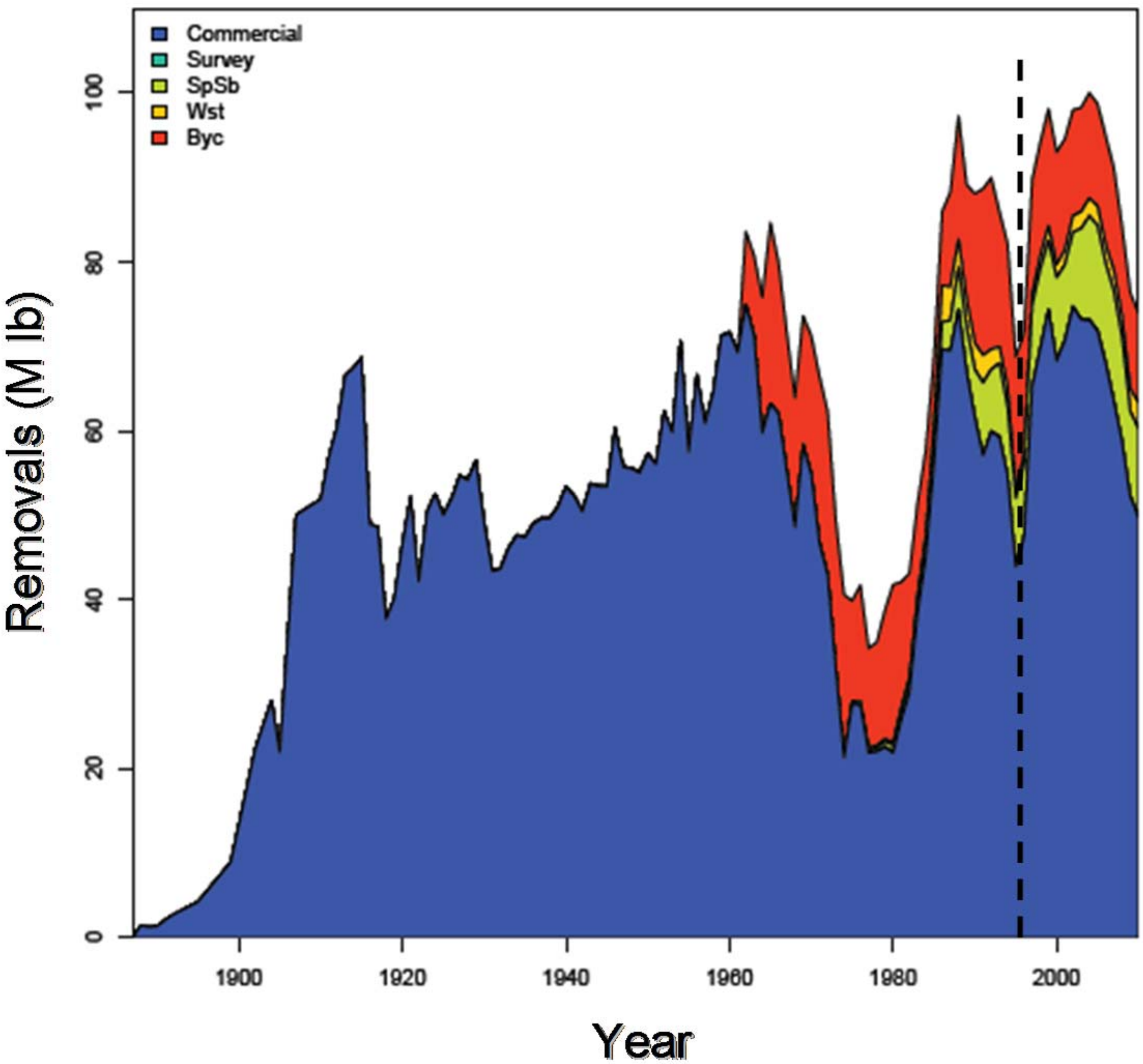

Figure 3. Coastwide total removals from the beginning of the commercial fishery in 1888 to 2010 in millions of pounds (M lb). Removal components are Commercial, Survey, Sport and Personal (SpSb), Wastage (Wst) and Bycatch (Byc). All removals are used for the historical conditioning of the model, the vertical dashed line is year 1996 which is the beginning of the data used for the current stock assessment.

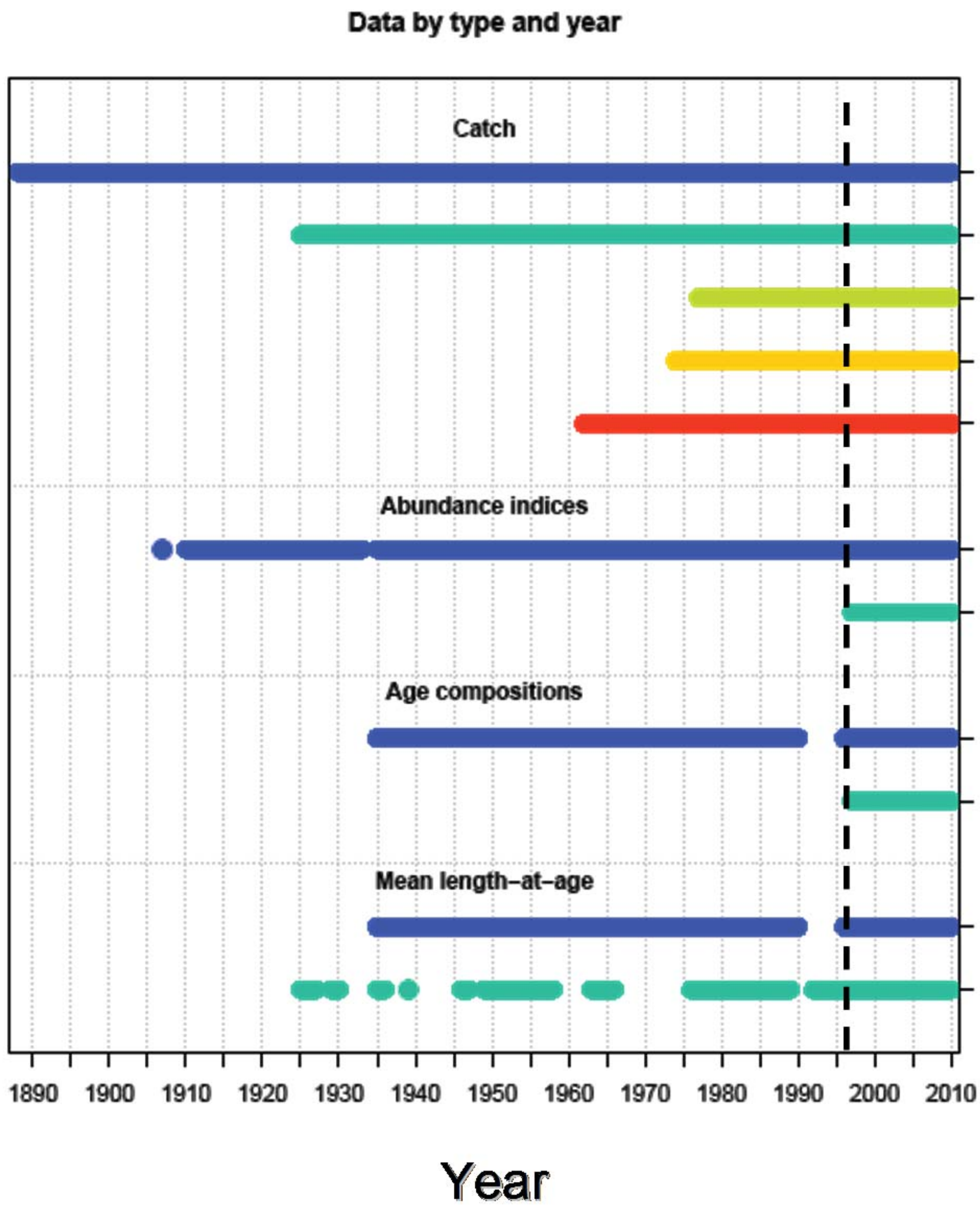

Figure 4. Overview of data sources used in the conditioning model for Pacific halibut, 1888 to 2010. All available data are used for the historical conditioning of the model, the vertical dashed line is year 1996 which is the beginning of the data used for the current stock assessment.

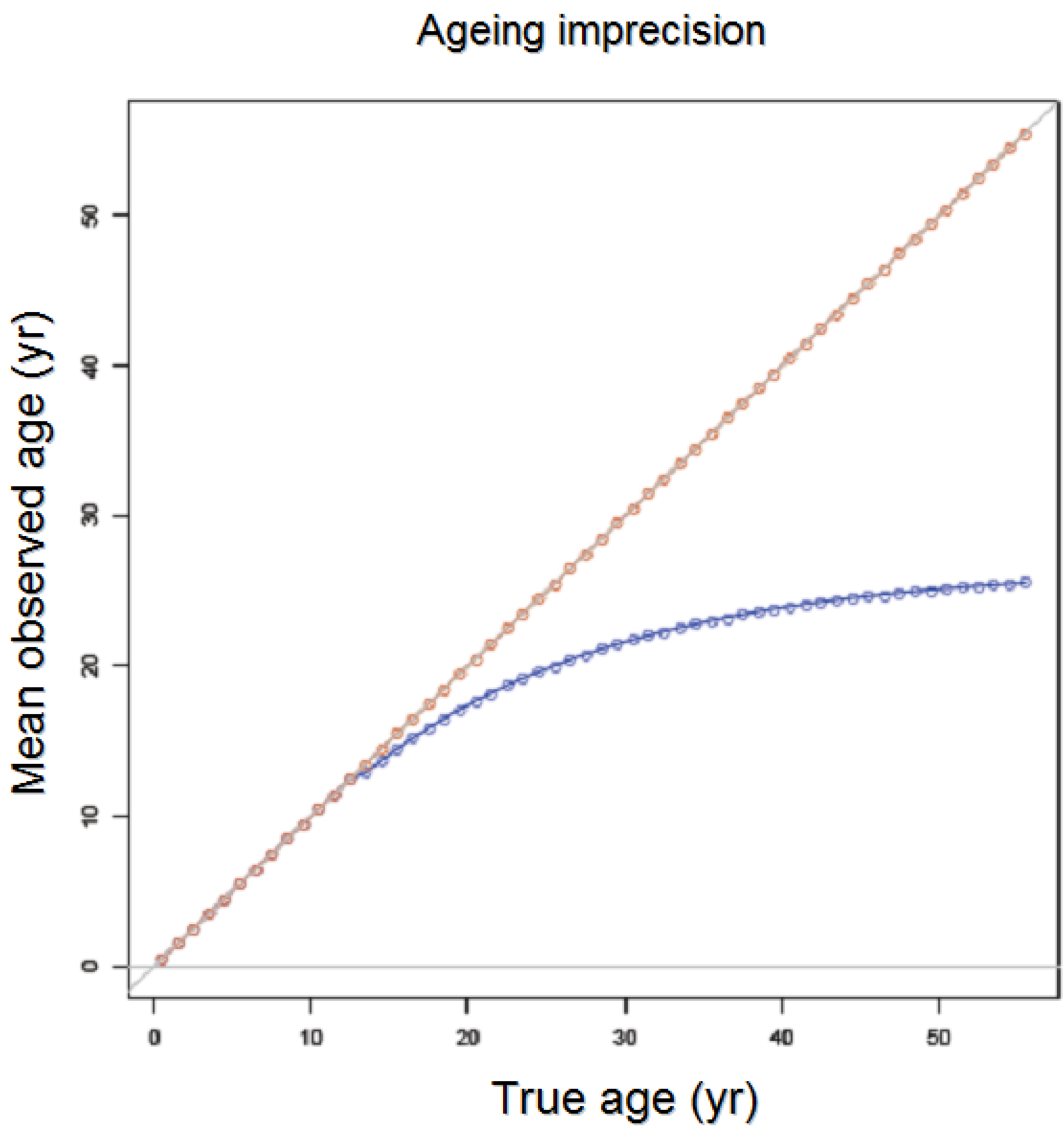

Figure 5. Ageing imprecision used in the conditioning model following Clark (2004).

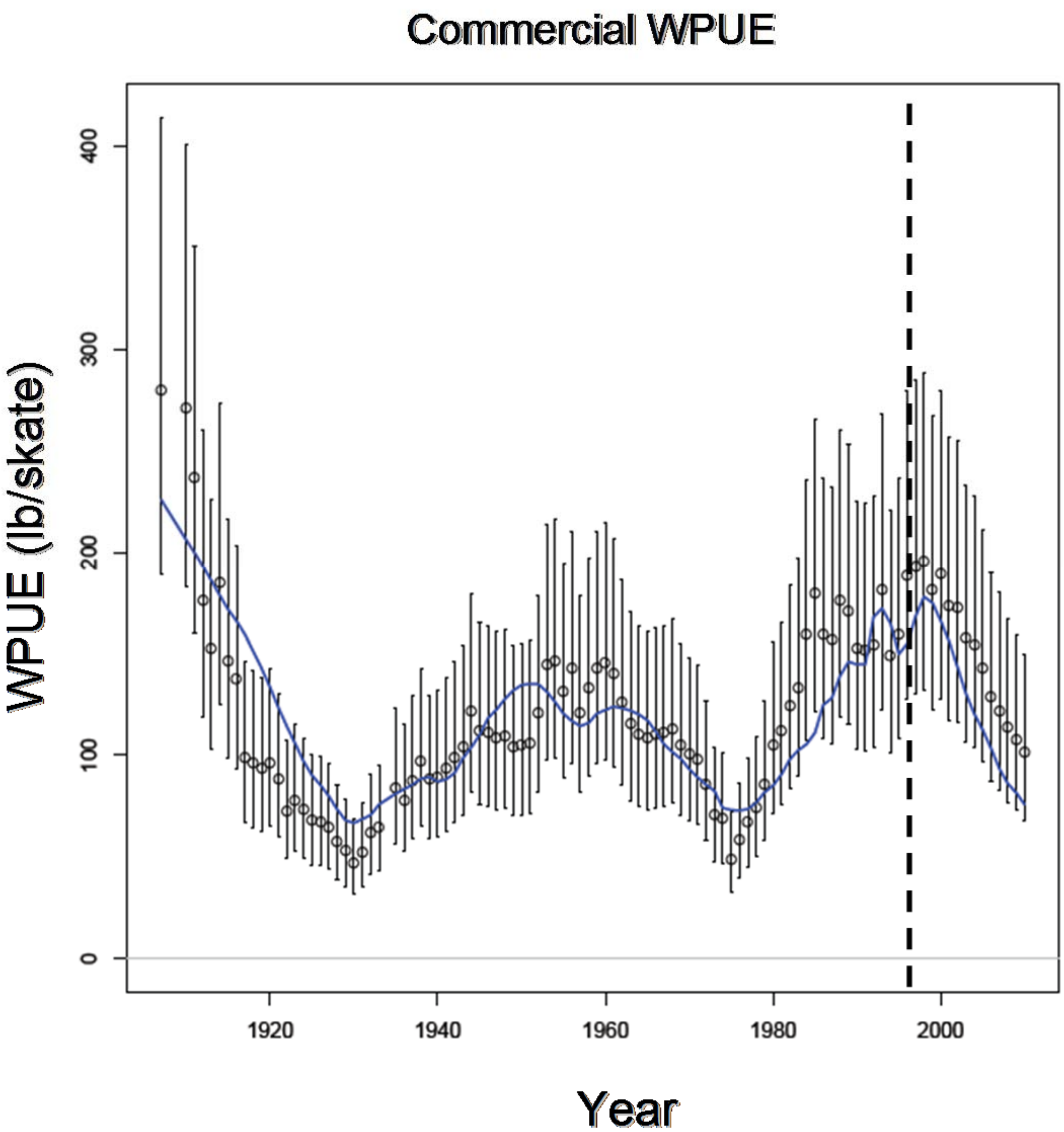

Figure 6. Commercial weight per unit of effort (WPUE) in pounds per skate and conditioning model fit (blue line). All available WPUE data are used for the historical conditioning of the model, the vertical dashed line is year 1996 which is the beginning of the data used for the current stock assessment.

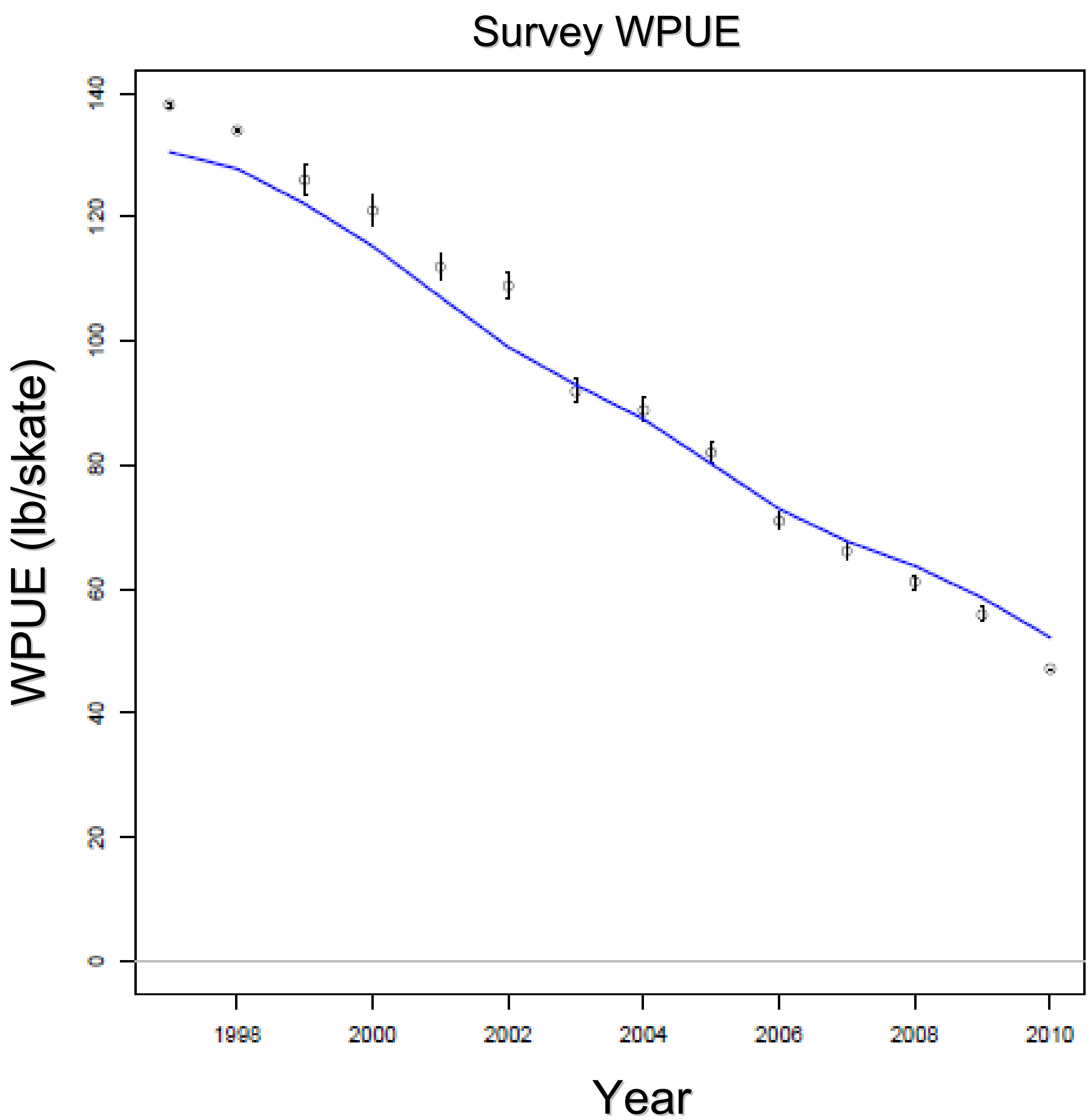

Figure 7. Survey weight per unit of effort (WPUE) in pounds per skate and model fit (blue line).

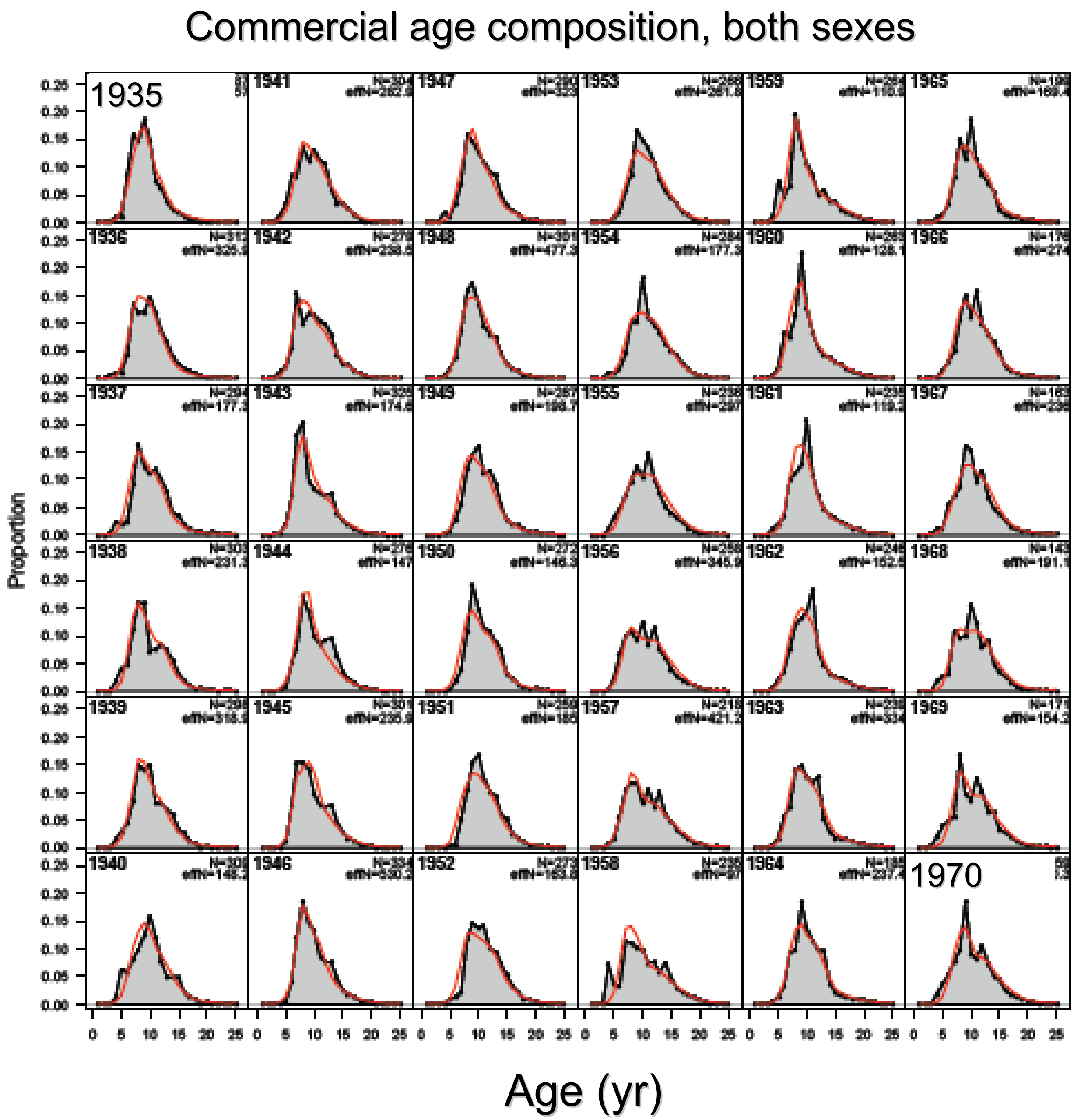

Figure 8. Conditioning model fit (red line) to the observed commercial age composition data from 1935 to 1970, both sexes combined.

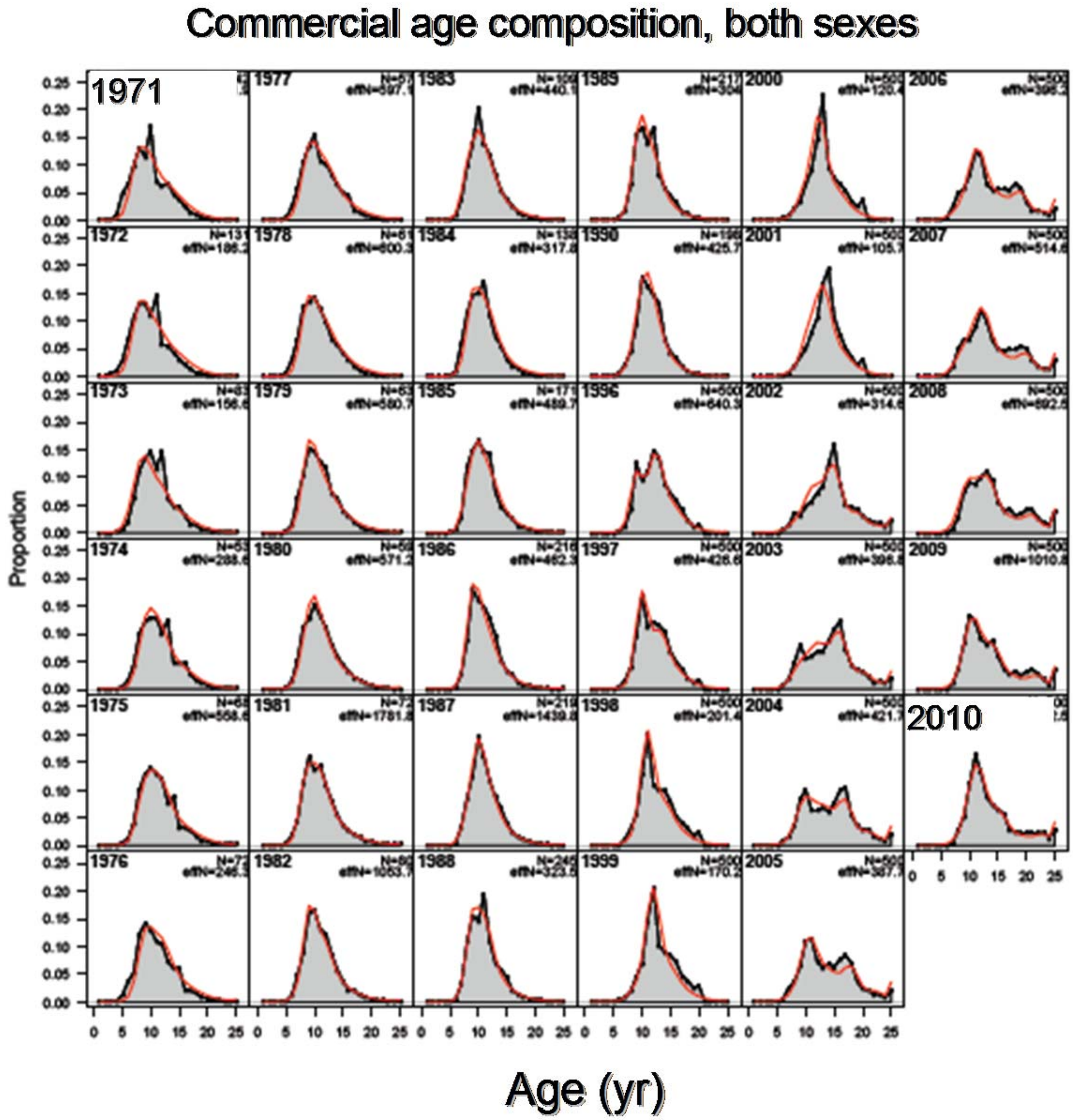

Figure 8 (cont.). Conditioning model fit (red line) to the observed commercial age composition data from 1971 to 2010, both sexes combined.

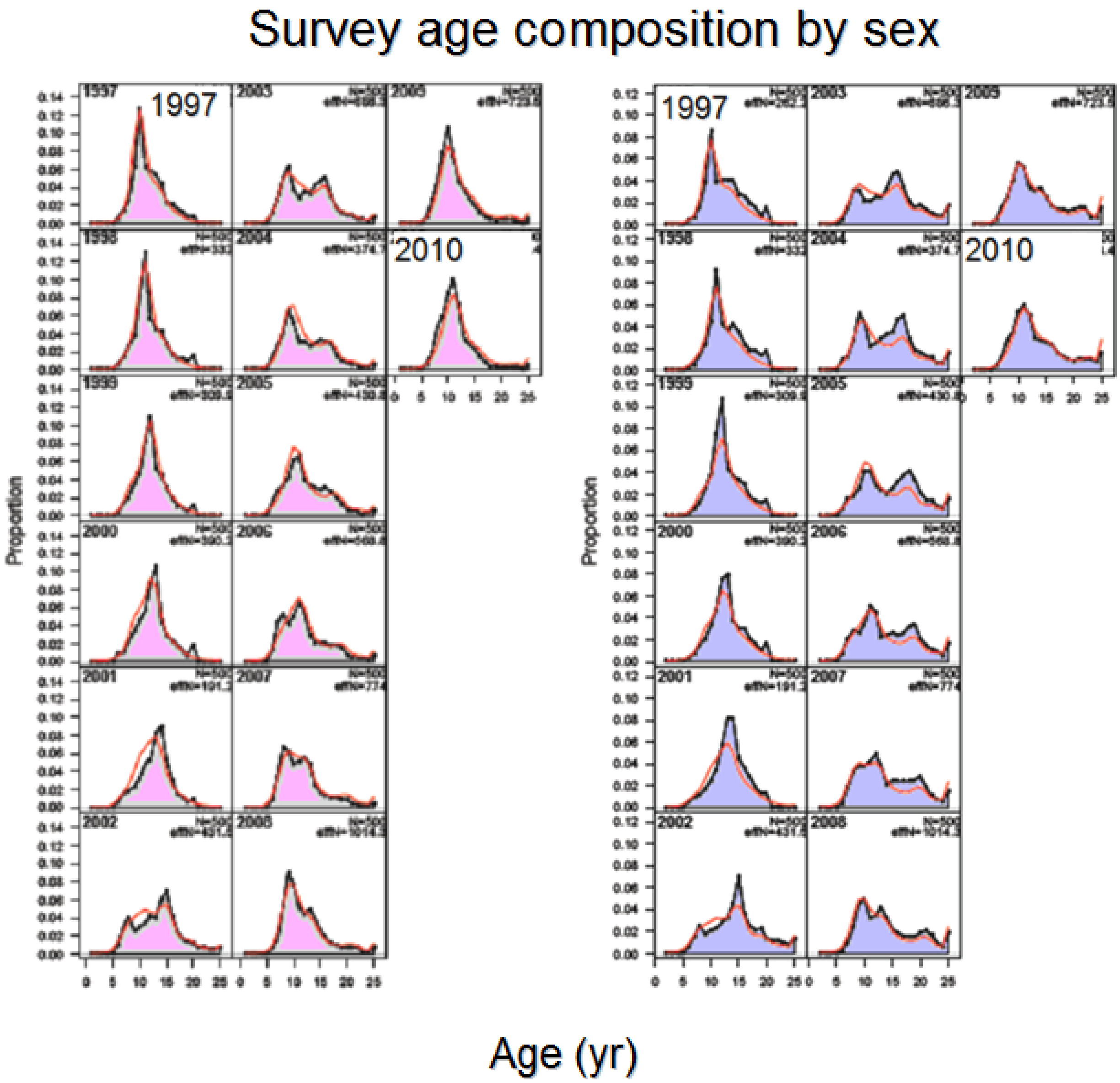

Figure 9. Conditioning model fit (red line) to the observed survey age composition data for females (pink, left panels) and males (blue, right panels) from 1997 to 2010.

Figure 10. Time series of age 0 recruit estimates with 95% confidence intervals (CI).

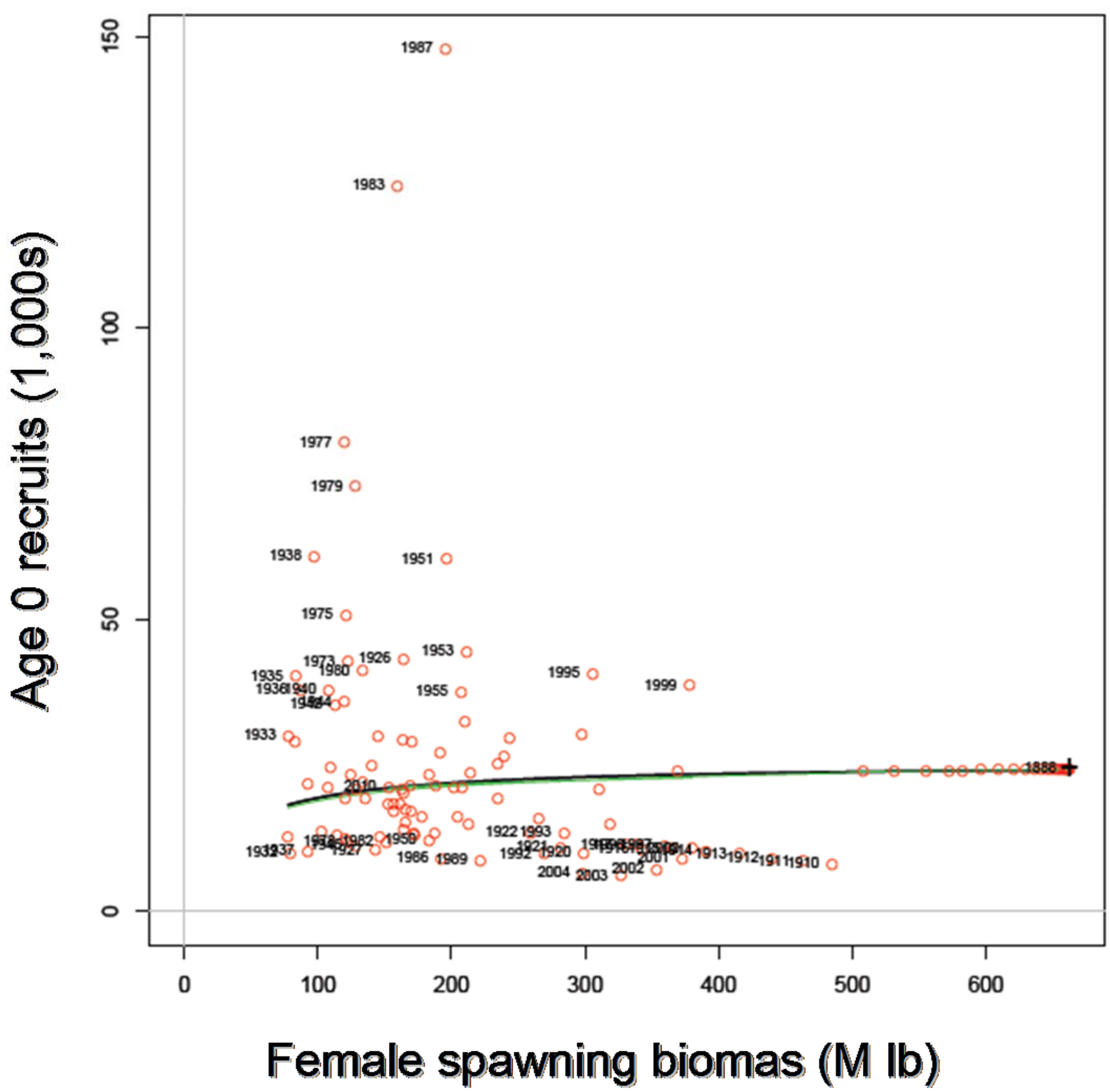

Figure 11. Numbers of age 0 halibut recruits (in thousands) and female spawning biomass in millions of pounds (M lb). The solid line is a Beverton-Holt stock recruitment fit to the data.

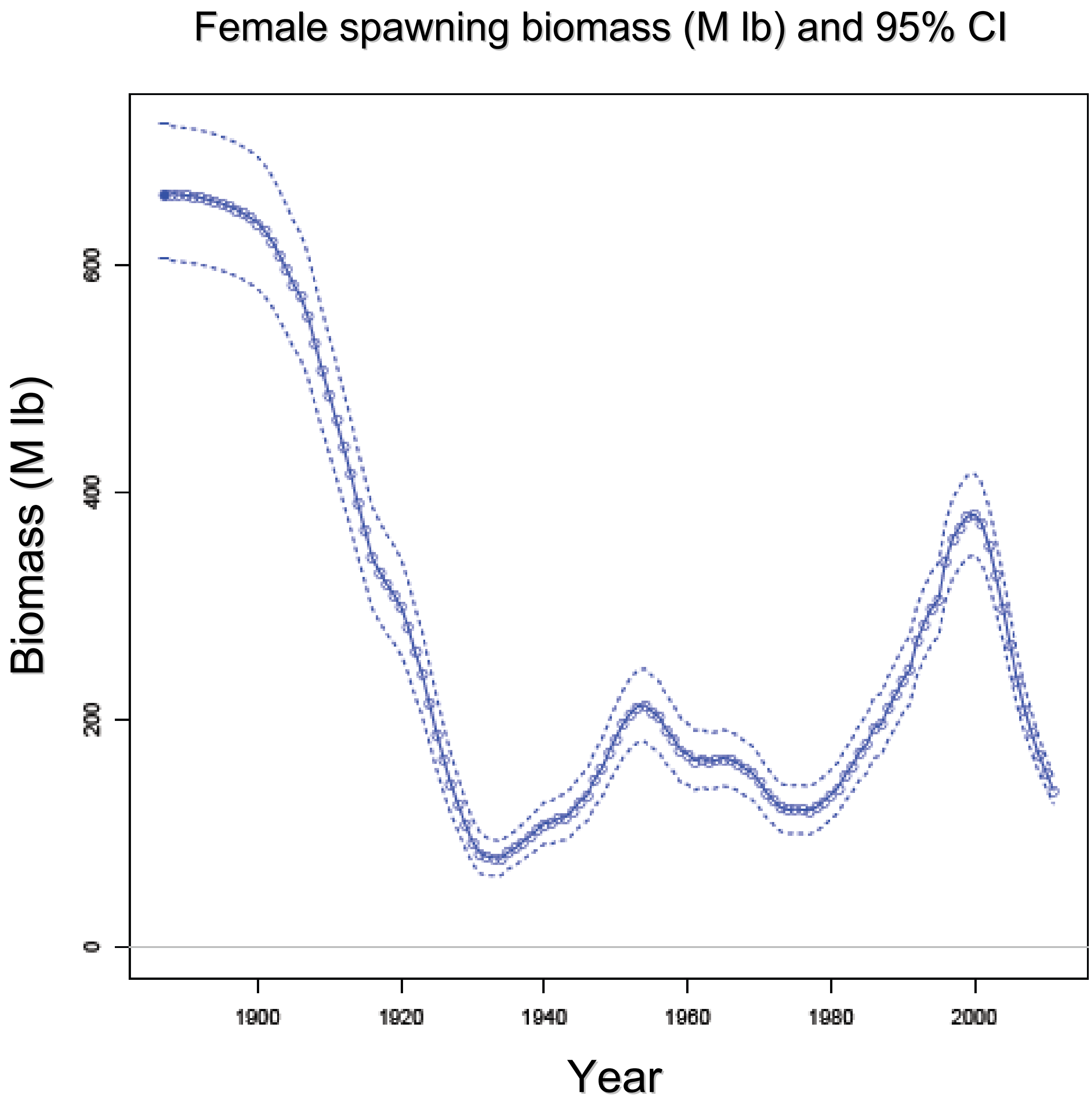

Figure 12. Estimated female spawning biomass in millions of pounds (M lb) with 95% confidence intervals.

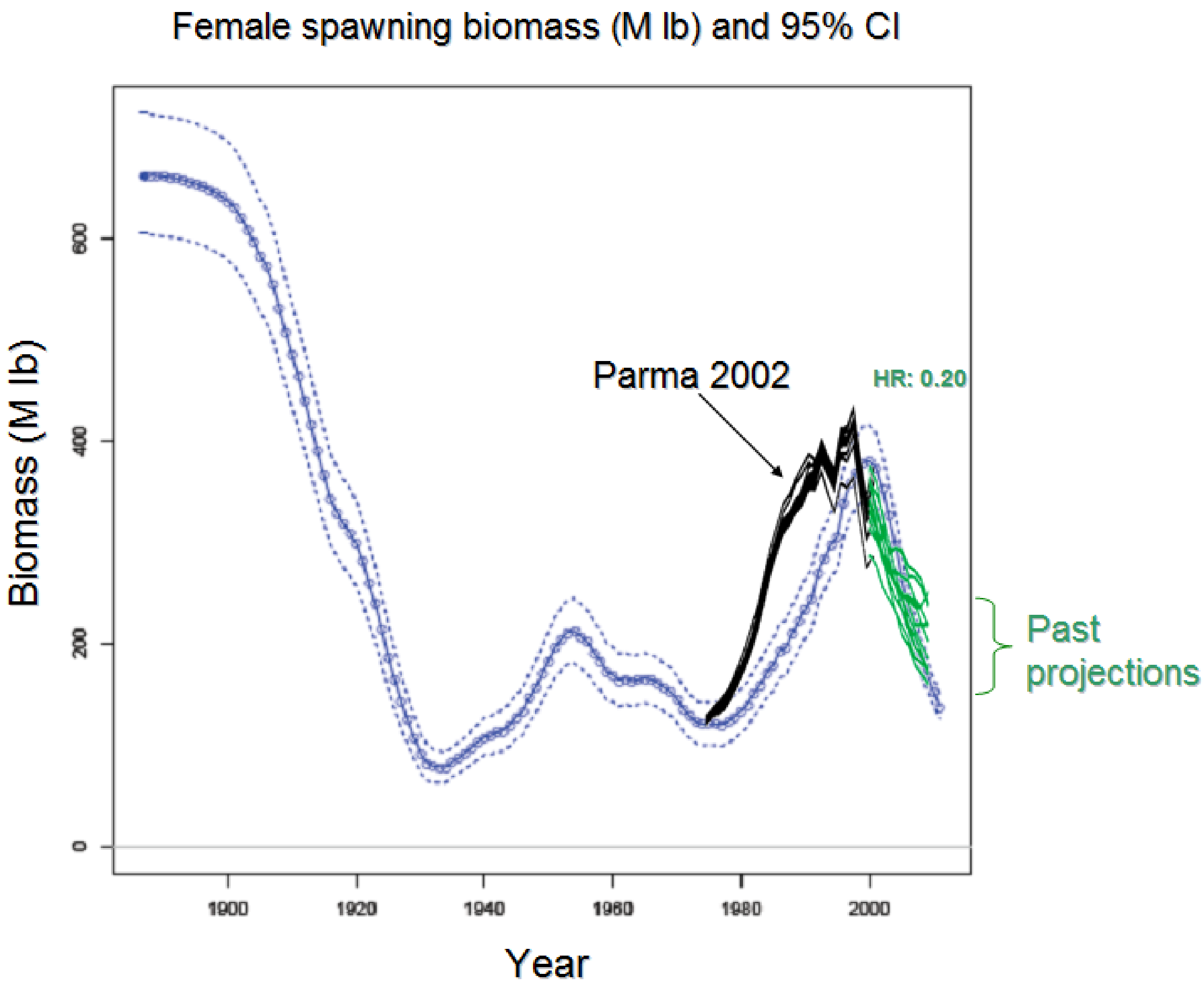

Figure 13. Estimated female spawning biomass (blue line with open circles) in millions of pounds (M lb) with 95% confidence intervals. Black lines are female spawning biomass estimates between 1974 and 2000 and green lines are subsequent 10-year projections conducted by Parma (2002). See electronic version for colors.

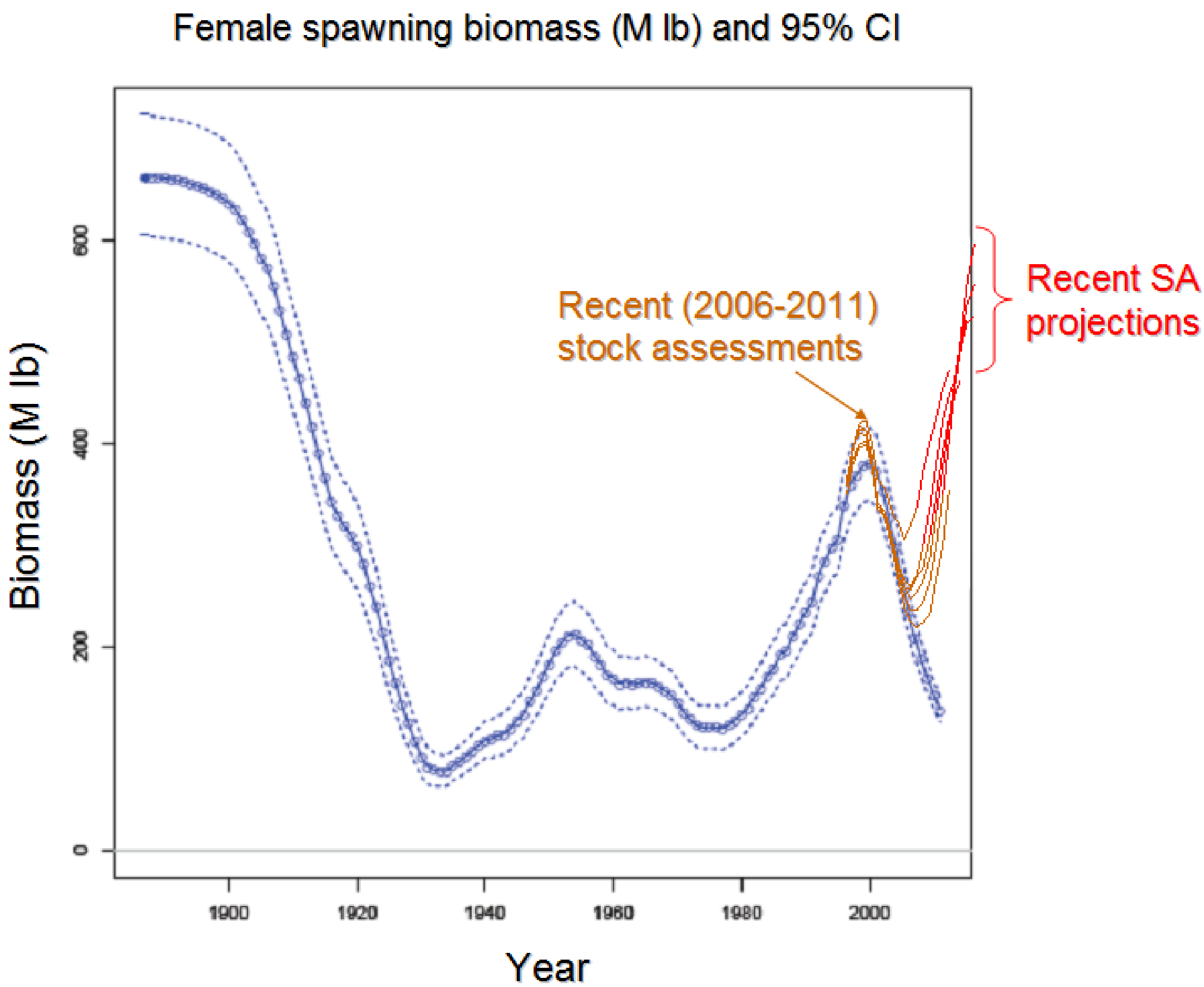

Figure 14. Estimated female spawning biomass (blue line with open circles) in millions of pounds (M lb) with 95% confidence intervals. Brown lines are female spawning biomass estimates between 1996 and 2011 as estimated by the stock assessments at the end of 2006, 2007, 2008, 2009, 2010 and 2011 and the subsequent retrospective downward revisions through the years 2006 to 2010. Red lines are 5-year projections conducted at the end of each assessment year. Time series obtained from Clark and Hare (2006, 2008), Hare and Clark (2008b, 2009), and Hare (2010, 2011, 2012). See electronic version for colors.

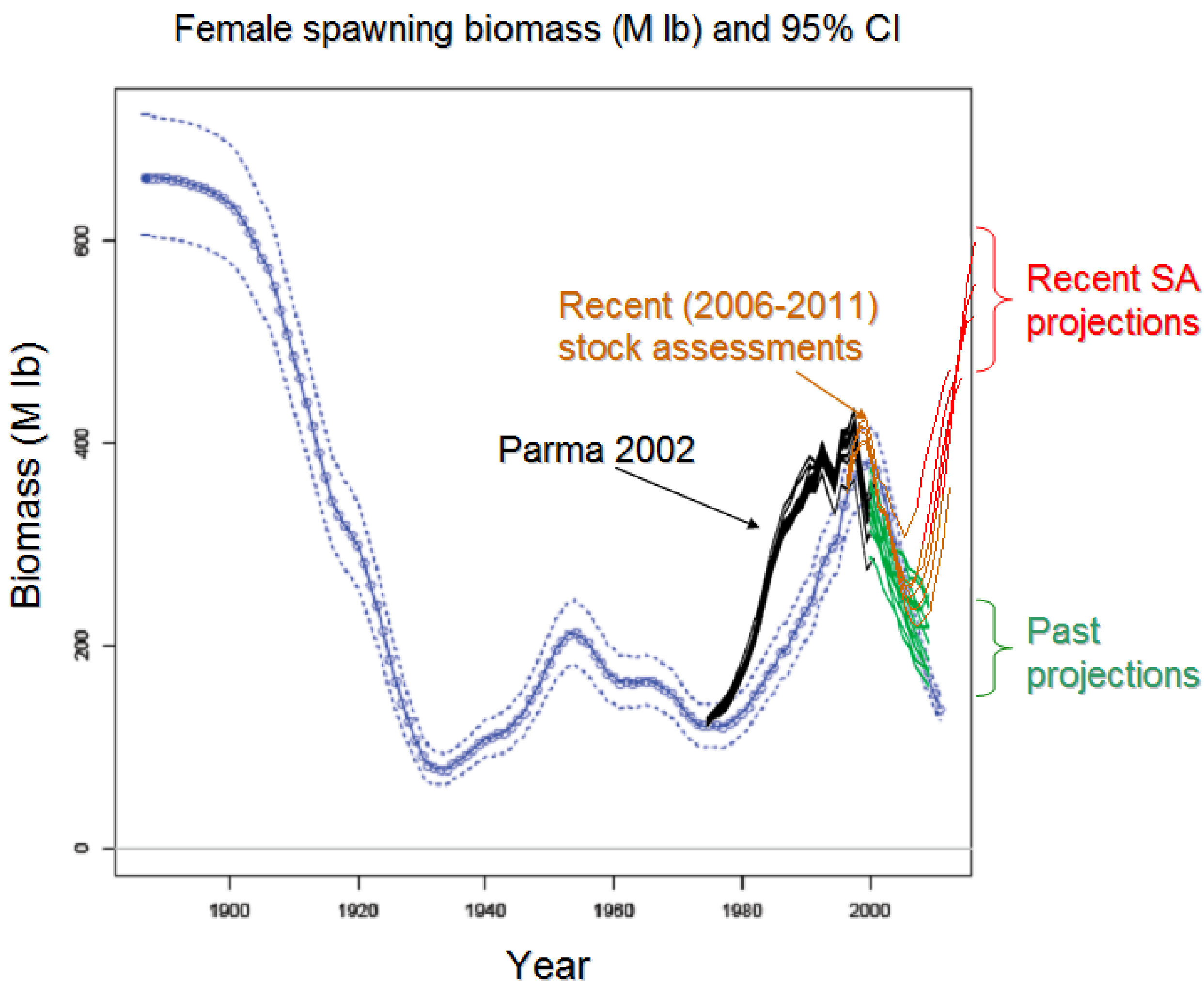

Figure 15. Estimated female spawning biomass (blue line with open circles) in millions of pounds (M lb) with 95% confidence intervals. Black lines are female spawning biomass estimates between 1974 and 2000 and green lines are subsequent 10-year projections conducted by Parma (2002). Brown lines are female spawning biomass estimates between 1996 and 2011 as estimated by the stock assessments at the end of 2006, 2007, 2008, 2009, 2010 and 2011 and the subsequent retrospective downward revisions through the years 2006 to 2010. Red lines are 5-year projections conducted at the end of each assessment year. Time series obtained from Clark and Hare (2006, 2008), Hare and Clark (2008b, 2009), and Hare (2010, 2011, 2012). See electronic version for colors.

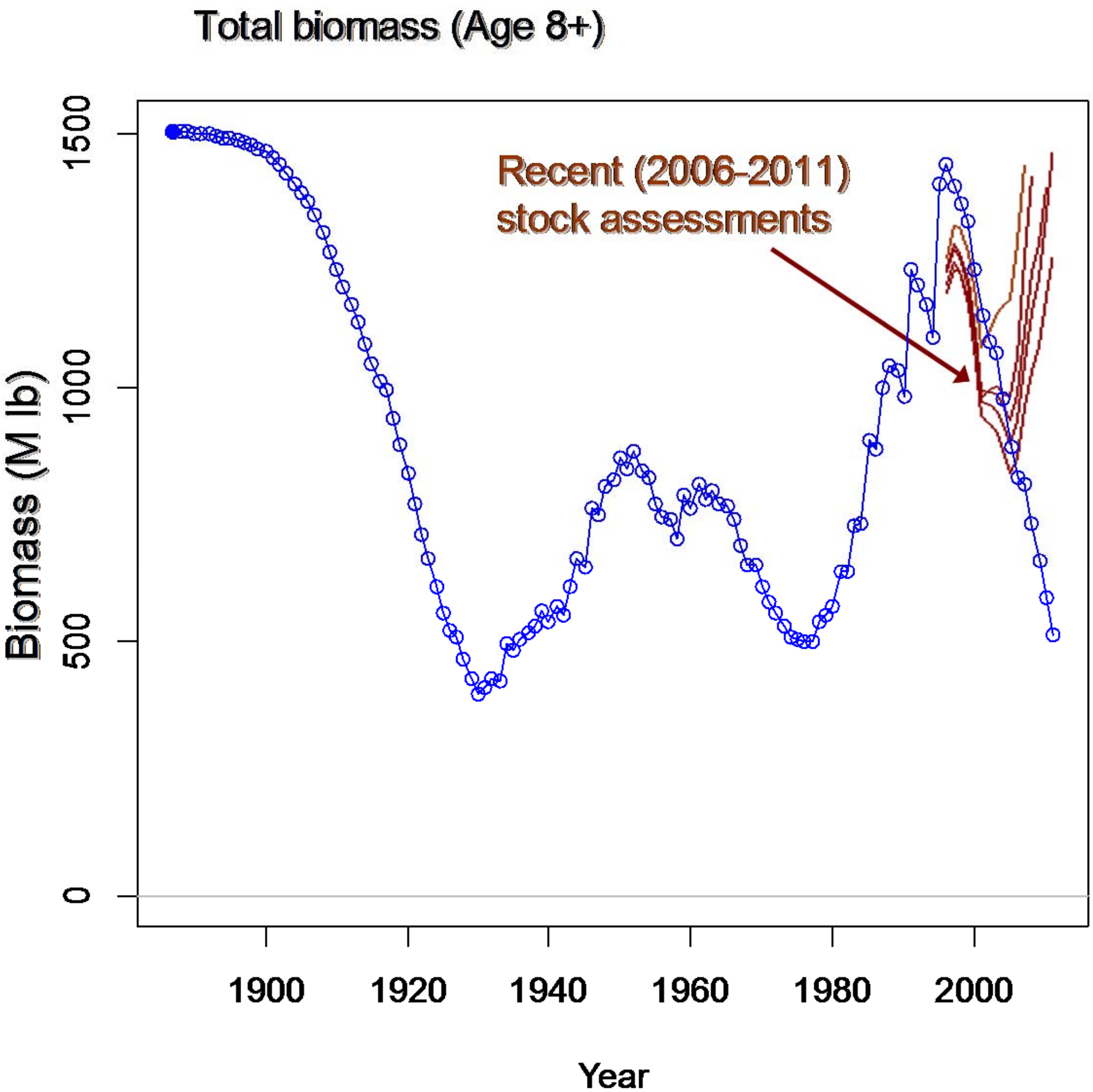

Figure 16. Estimated total biomass of halibut age 8 and older (8+, blue line with open circles) in millions of pounds (M lb). Brown lines are age 8+ biomass estimates between 1996 and 2011 as estimated by the stock assessments at the end of 2006, 2007, 2008, 2009, 2010 and 2011 and the subsequent retrospective downward revisions through the years 2006 to 2010. Time series for recent assessments obtained from Clark and Hare (2006, 2008), Hare and Clark (2008b, 2009), and Hare (2010, 2011, 2012). See electronic version for colors.

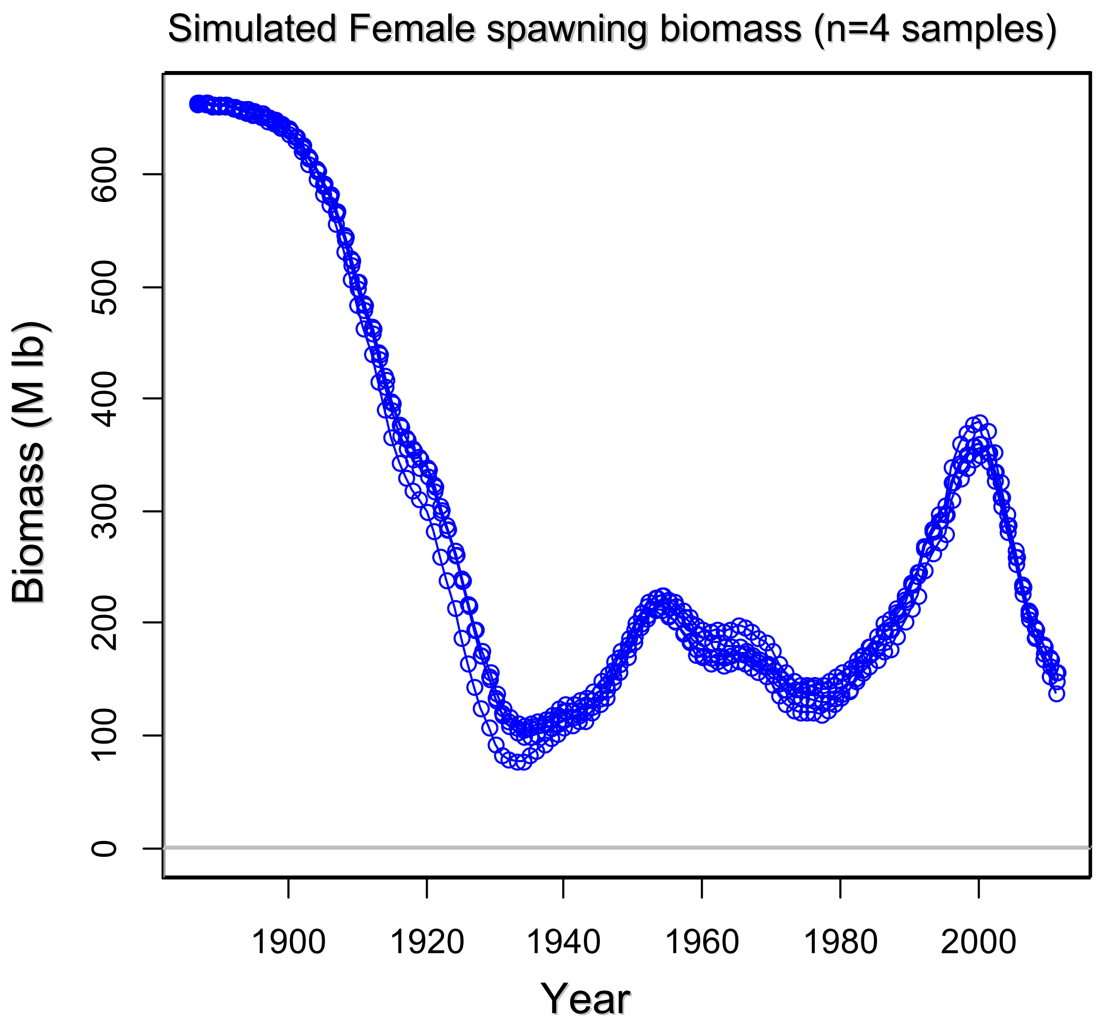

Figure 17. Sample (n=4) of historical female spawning biomass bootstrapped from conditioning model fits.