BSAI Alaska skate – model revision 2014

NPFMC BSAI Groundfish Plan Team, September 2014

Olav Ormseth
NMFS Alaska Fisheries Science Center, Seattle, WA

Executive Summary

This document contains a description of and results from a revised population model for the Alaska skate *Bathyraja parmifera*, the most abundant skate species in the Bering Sea and Aleutian Islands management area (BSAI). The model was first created in 2007 and was substantially revised in 2012. The model was reviewed during the non-target species assessment review conducted by the Center for Independent Experts (CIE) in May 2013. While the reviewers declined to conduct a complete review of the model (citing insufficient time), they did note some major concerns and made some key recommendations. The most important of the recommendations was to include the full eastern Bering Sea (EBS) shelf bottom trawl survey time series, which shows a dramatic increase in skate biomass during the 1980s. Because this increase had not been explained, the model used only a recent portion of the time series (1992-present) when skate biomass estimates have been fairly consistent. The reviewers felt that inclusion of the entire time series was necessary for proper modeling of skate population dynamics and might resolve some of the long-standing problems with the model (e.g. fits to unusual patterns in the length compositions).

In response to the CIE comments, and as part of an ongoing process to improve skate assessments, the BSAI Alaska skate model has been completely reworked for 2014. The most fundamental change is a lengthening of the model time period: the model's start year is 1950, all of the EBS shelf survey data from 1982-present are included, and a reconstruction of historical catches extends the catch time series back to 1954. Ten alternative models were considered, but all of them incorporated this extended time period. The model was also simplified, especially in relation to the 2012 model revision. Four of the models were selected for review by the Plan Team and are presented in this document with results sufficient for comparisons; full model results are included only for the author's preferred model.

Summary of Major Changes

Changes in the input data:

- The entire time series (1982-present) of EBS shelf bottom trawl biomass estimates for skates was included in the model.
- Reconstructed historical catch data beginning in 1954 were included in the model.
- Four length-at-age (LAA) datasets from the EBS shelf survey were included in the model (2003, 2007-2009); a LAA dataset from the longline fishery in 2005 was determined to be inadequate and was not included in the models.
- Enhanced weight-at-length data were obtained from a dataset generated during Alaska skate tagging activities on the EBS shelf survey during 2008-2010.

Changes in assessment methodology:

- For all models, growth parameters are estimated within the model.

This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the National Marine Fisheries Service and should not be construed to represent any agency determination or policy.

- The "embryonic stage" (ages 0-3 in previous models) was eliminated from the model, so that in the model age-0 skates are free-swimming individuals in their first year outside of the eggcase.
- The recruitment function was returned to the original formulation, a Beverton-Holt curve with steepness fixed at 1.0; this effectively defines an average level of recruitment at all stock sizes.
- The maximum age was returned to its original value of 25 (from 30 in the 2012 model).
- Age selectivity was not included in the model.

Summary of results

1) The exploration of the alternative models suggests a discrepancy between the length composition data (survey and fisheries) and the LAA datasets. The largest sizes of skates observed in the LAA datasets are encountered in only very small numbers in the length composition data.

2) As a result of the phenomenon described in (1), there appear to be essentially two modeling "states": one approach ("low biomass") that slightly underestimates LAA at the oldest ages, but provides excellent fits to the length composition data and reasonable estimates of selectivity; and an approach ("high biomass") that more closely fits the LAA data but provides unreasonable selectivity curves and poor fits to the length compositions. Biomass estimates for the "low biomass" state are approximately ½ that of the "high biomass" state.

3) All of the models suggest a depletion of skate biomass during the period 1950-1980, followed by a large recruitment event in the early 1980s and a return to the higher biomass levels that exist today. The recruitment event is consistent with the limited data available regarding average skate size and abundance during the time period.

4) The preferred model is of the "low biomass" type described in (2) above. Two of the alternative models are also "low biomass" approaches, while the fourth is a "high biomass" model.

5) The preferred model produces the following estimates, with estimates from the previous models for comparison:

	2014 preferred model	2012 model	2011 model
unfished total biomass (t)	612,629	808,063	705,216
unfished female spawning biomass ($B_{100\%}$; t)	182,570	261,455	95,511
2013 total biomass (t)	532,109	650,483	513,028
2013 female spawning biomass (B; t)	140,172	194,072	57,150
$B/B_{100\%}$	0.77	0.74	0.60

Overview

The BSAI Alaska skate population model has been used since 2008 for making harvest recommendations. The model was substantially revised in 2012; the main benefit of the revised model was a closer fit to the length-at-age (LAA) data. However aspects of the model, e.g. fits to some of the length composition data, remained problematic. The model was reviewed by the Center for Independent Experts (CIE) in May 2013 as part of their review of non-target assessments conducted by the Alaska Fisheries Science Center (AFSC). The reviewers concluded that they had insufficient time to properly review the Alaska skate model, but did offer some comments. The reviewers noted some problems such as fits to the length composition data, and were unanimous in stating that the model should include the entire eastern Bering Sea (EB) shelf bottom trawl survey time series. That suggestion formed the basis of the modeling approach described in this report.

The 2014 model revision was guided by a conceptual approach with the following aspects:

1) *Determinate growth*: Several features of the data suggest that Alaska skate growth either slows dramatically or stops altogether at older ages. A strong size mode is observed in many of the Alaska skate length compositions at approximately 100 cm, and the proportion of skates at larger sizes decreases abruptly. Skates larger than 100-104 cm appear to be rare in the population. These data suggest that there is an accumulation of large skates in the population that occurs as skates get older but do not grow appreciably in size. All of the growth parameters were estimated within the model, but starting values were chosen and model development was guided assuming determinate growth.

2) *Large recruitment event*: Earlier versions of the model avoided using the full EBS shelf survey time series because a dramatic increase in skate biomass during the 1980s (Figure 1) was difficult to explain and seemed counter to the equilibrium life history strategy assumed for skates. In preparation for the model revision, the available data were explored. Although length data for skates do not exist prior to 1999, it was possible to estimate mean weight of captured skates and mean numerical CPUE for survey hauls using the same net configuration from 1975 to 2013..These data (not included in this document but available) suggest that the increase in skate biomass during the 1980s resulted from both an increase in the number of skates AND the mean size of skates, both of which increased dramatically. This is consistent with a major recruitment event occurring over a small number of years. The data are still being explored, but this apparent recruitment event occurred at approximately the same time as a major ecological regime shift in the late 1970s and may be related to it. Alaska skates have a long (approximately 3.5 years) embryonic development time during which they are growing inside eggcases deposited on the ocean floor, and the duration of the embryonic stage appears to be highly dependent on temperature (Hoff 2007). It may be that fluctuations in development time during this time of environmental change caused the emergence of multiple year classes from their eggcases at the same time. An alternative or additional explanation is that survival of young skates was enhanced by environmental conditions. The development of the model was guided by the assumption that the model should demonstrate a large recruitment event in the late 1970s and/or early 1980s

3) *Simplification*: The model was also developed with an aim towards simplifying it where appropriate. One aspect of this was to use a simpler approach to the stock-recruit function, which is described below. Another aspect was to eliminate the embryonic development period from the model. All previous versions of the model included the embryonic period, and used knife-edged age selectivity to define those ages (0-3.5) where skates were in eggcases and unavailable to either the survey or fisheries. The embryonic period was included because it seemed important

for linking year classes to spawning stocks. However there is essentially no relationship between spawning stock size and recruitment (and in earlier versions of the model, very little contrast in spawning stock size). In addition, the inclusion of knife-edged age selectivity seemed to create problems inside the model. Therefore, all versions of the 2014 modeling process assumed that age-0 skates are those that have recently emerged from eggcases and are free-swimming individuals. Age selectivity was effectively removed from the model by specifying an age-selectivity function where all ages were fully selected, and selectivity was only a function of length.

Data

Survey biomass

Three bottom trawl surveys are conducted in the BSAI region: EBS shelf, EBS slope, and the Aleutian Islands. Because the Alaska skate population is concentrated on the EBS shelf, and the EBS shelf survey provides yearly estimates of biomass, biomass estimates from only the EBS shelf survey are used in this model. Survey efforts on the EBS shelf began in the 1970s, but survey methodology was only standardized in 1982; as a result, the survey time series is considered to begin in 1982. Biomass estimates from 1982-2013 were included in the model. Reliable skate species identification in the survey is only available starting in 1999. For each survey prior to 1999, total skate biomass estimates were partitioned into Alaska skate and "other" skates based on the average proportion (0.95) of Alaska skate in the 1999-2013 surveys (Table 1). The modeling software employs the coefficient of variation (CV) as the standard deviation (*s*) associated with each estimate. For the estimates prior to 1999, a value of *s* was chosen that was intermediate to recent values and a high *s* observed in 1999 (Table 1).

Survey length compositions

Length composition data from the EBS shelf survey were available from 2000-2013 (Table 2). The survey takes length measurements for every skate in each haul. The haul-specific data are then weighted by the number of skates in each haul to produce an estimate of numbers at length for the entire EBS population. The length data were aggregated into 4-cm bins and converted to proportions for inclusion in the model. Sample size is discussed below.

Catch

Incidental catches of skates in the BSAI occur in several target fisheries but can be broken down into catches by two gear types: longline and trawl (Table 3 and Figure 2). These fisheries have different selectivities and the majority of catches occur in the longline fisheries. Retention of skates is high and discard mortality is assumed to be 100%; therefore all captured skates are assumed to be dead.

All of the models considered for the 2014 revision used catch data from 1954-2013. All data regarding Alaska skate catches rely to some degree on assumptions regarding the proportion of Alaska skates in the total skate catch. The earlier data also rely on assumptions regarding removals by gear type.

- *1954-1996*: Reconstruction of skate catches relied heavily on two assumptions: 1) that the proportion of trawl vs. longline effort was represented by the proportion of yellowfin sole catch vs. Pacific cod catch, and 2) that the total catch of Alaska skates could be estimated by subdividing the catch of an "Other Species" group (skates, sculpins, sharks, and octopus) based on the proportion of skates in Other Species catches in the modern era (2003-2013) and the proportion of Alaska skates in recent trawl surveys (1999-2013).
- *1997-2013*: Skate-specific catches are available during the modern era from two sources: the Blend database (1992-2002) and the Catch Accounting System (CAS) maintained by the Alaska Regional Office (AKRO). Specific catch data for Alaska skate either do not exist or are

unreliable, due to the difficulty of identifying *Bathyraja* species skates in longline fisheries. Therefore, the catches were partitioned based on survey species composition during 1999-2013 and the distribution of effort among the EBS shelf and slope and the Aleutian Islands (AI). The methodology is described in complete detail in Ormseth and Matta (2007).

The reconstructed catch data were heavily influenced by the assumptions regarding the proportion of skates in the "Other Species" catch. To explore this assumption and how different catch histories influenced the model, two catch datasets were created. One dataset ("high catch") used the assumption described above, that the proportion of skates during the entire catch history was the same as it was 2003-2013. An alternative dataset ("low catch") modified the proportion of skates using the ratio of estimated skate biomass in 1982 to the estimated skate biomass during 2003-2013. The base model was run using these datasets. Results were similar between the runs, and the "high catch" model provided slightly better fits to the data. Therefore, only the "high catch" dataset was used in developing the alternative models presented here.

Fishery length compositions

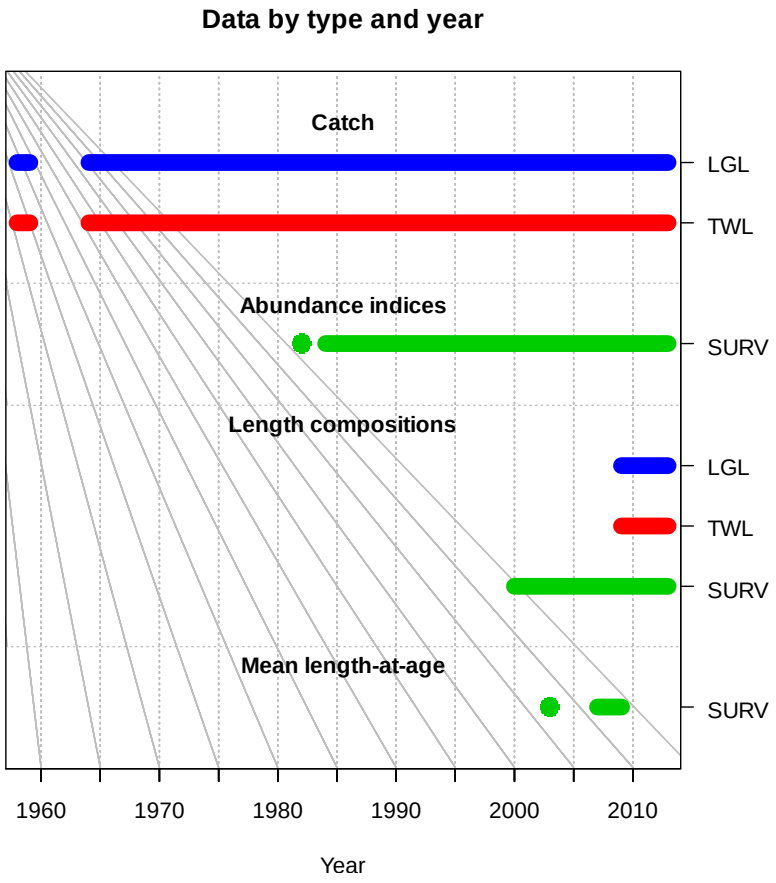
Fishery length compositions from 2009-2013 were included for both gear types. Length data for the Alaska skate were collected during 2007 & 2008 as a special project by fishery observers, but the datasets are incomplete. In 2008 the observer manual was changed to require collection of skate lengths on every haul where they were present in the target fisheries for Pacific cod and flatfishes, and this change was fully implemented for 2009. Therefore, 2009 is considered the first year of reliable fishery length composition data for Alaska skate. Length data were aggregated into 4-cm bins and converted to proportions as for the survey data (Table 4). Sample size is discussed below.

Length at age

Four LAA datasets from the years 2003 (N=182), 2007 (N=237), 2008 (N=165), and 2009 (N=330) were included in the model. Age was determined through examination of annual growth rings in vertebral thin sections following hatching from the eggcase. All four datasets used vertebrae collected during the EBS shelf survey. The 2003 dataset was generated during a graduate student project (Matta 2006); the remaining datasets resulted from production ageing at the AFSC. A dataset generated from vertebrae collected during the 2005 longline fishery and included in earlier model versions was considered to be flawed (due to a poor sampling design) and was eliminated from the model.

Sample size

Appropriate sample size (N) for the length compositions and LAA data can be difficult to determine. Previous versions of the model used N=100 for all length compositions. After exploring the literature, including other SAFE reports conducted by the AFSC, and through discussions with other assessment authors, the following approach was taken regarding sample size. In general, hauls are considered to be the sampling unit rather than individual length measurements. The total number of hauls each year varies little for the survey, so N=200 was used for all survey length compositions. In the fisheries, a large number of hauls is sampled, so the square root of the number of hauls was used for input N to avoid overemphasis on fishery length compositions. For the LAA data, the actual number of individuals was used as input N. Some exploration of the effect of changing input Ns was performed: for example, fishery length composition N was set equal to the survey N. Unless very large changes were made, these changes had only minor influence on the model.



Summary of data sources included in all 4 model alternatives.

Analytic Approach

Model structure

The 2014 model revisions were conducted using Stock Synthesis 3 (SS3) assessment software[1] (Methot 2005, 2007). Stock Synthesis allows the flexibility to incorporate both age- and size-structured information in an age-structured model. In the models described here, natural mortality is the only parameter that is explicitly age-based; selectivity, maturity, and mean body weight are length-based parameters. Length-at-age data and estimates of ageing error are used by SS3 to convert the size-based information into age-specific values that can be used to model the population through time. In SS3 it is possible to differentially weight the likelihood components by specifying weighting factors (lambdas) in the control file. With one exception, the model alternatives presented here weight all components equally.

Ten different models were explored during the 2014 revision process. Four of these models were chosen for presentation to the Plan Team: a base model (also the author's preferred model) and 3 alternatives. All four models used the same data described above. They differed in the following ways:

- Model 1: Base model with features described below. Author's preferred model.
- Model 2: Base model with σ_R fixed at 0.5. This alternative allowed greater variability in annual recruitment, testing assumptions regarding the degree of annual recruitment variability in Alaska skates.
- Model 3: Base model with selectivity parameter # 6 fixed for both fisheries and the survey, creating asymptotic selectivity curves. This model offered a contrast to the dome-shaped selectivity curves generated in the base model.
- Model 4: Base model with high emphasis (lambda=5) placed on the LAA data. This model is included to represent the "high biomass" approach described above.

All of the models continued a number of assumptions used since the model was first created. The entire BSAI was treated as one homogenous area. Because growth and maturity patterns are similar for males and females, only one sex was specified. Spawning was assumed to occur at the midpoint of the year. No informative priors were used. It was assumed that parameters did not vary with season or year and were not influenced by environmental conditions. All parameters are listed in Table 5 and described in more detail below.

Parameters estimated independently:

Natural mortality (M)

In 2007, a value of 0.13 was chosen from a set of *M* values estimated using different life history parameters (Matta 2006): growth parameters (Alverson and Carney 1975, Pauly 1980, Charnov 1993), longevity (Hoenig 1983), reproductive potential (Rikhter and Efanov 1976, Roff 1986), von Bertalanffy k (Jensen 1996, Gunderson 2003), and age at maturity (Jensen 1996). Previous runs of the model have demonstrated that this value of *M* provides the best model fit, so *M* in the model continues to be fixed at 0.13.

Length at maturity

SS3 incorporates female maturity parameters into the model using the following equation:

[1] NOAA Fisheries Toolbox Version 3.23b, 2011. Stock Synthesis 3, Richard Methot, Northwest Fisheries Science Center, Seattle, WA. [Internet address: http://nft/nefsc.noaa.gov]

$$\text{proportionmature} = \frac{1}{1+e^{b(L-L_{50})}},$$

where L_{50} is the length at 50% maturity and b is a slope parameter. Maturity parameters were obtained from Matta (2006), where b = -0.548 and L_{50} = 93.28 cm TL. Maturity was estimated directly from paired length and maturity stage data; maturity stage was easily assessed through macroscopic examination of the reproductive organs.

Ageing error
Each vertebra was aged three independent times by a primary age reader without knowledge of the specimen's biological information. For each true age, the standard deviation of the estimated age was calculated from the three reads of each vertebra and incorporated into the model to account for variability in age determination.

Survey catchability
The approach to survey catchability remains unchanged from previous models. Survey catchability was fixed at 1. The EBS shelf survey appears to sample Alaska skates very reliably, with CVs of approximately 0.05. In addition, we did not adjust catchability for the segments of the Alaska skate population (AI and EBS slope) that are not observed by the EBS shelf survey. Over 96% of the Alaska skate population is on the shelf and surveys from the other areas are infrequent.

Age selectivity
In contrast to earlier versions of the model, selectivity at age was not included in the model, i.e. all ages were fully selected and selectivity was solely a function of length.

Weight at length
Parameters from the allometric length-weight relationship ($W = aTL^b$, where W is weight in kg and TL is total length in cm) were obtained through analysis of a new dataset generated during an Alaska skate tagging project conducted aboard EBS shelf surveys 2008-2010 (O. Ormseth, unpublished data). Parameters were not significantly different between sexes, so data were combined. For sexes combined, a was estimated as 9.0×10^{-6} and b was estimated as 2.9617 (Figure 3; r^2 = 0.93, N = 1,515).

Spawner-recruit parameters
The 2013 version of the model used a survivorship function developed for low-fecundity species rather than a traditional stock-recruit function. Upon further review, it was decided that insufficient data were available to parameterize the more complex survivorship function. All of the 2014 models returned to the approach used in the original model, where a Beverton-Holt function is specified and steepness fixed at 1.0 to create a mean level of recruitment. Models 1, 3, & 4 used a fixed σ_R value of 0.4; in model 2 σ_R was fixed at 0.5.

<u>Parameters estimated conditionally:</u>

Growth parameters
An analysis by Matta (2006) suggested that a Gompertz growth model best fit the length-at-age data for Alaska skate. As in the 2012 model, the Gompertz growth function was approximated in SS3 by choosing the Schnute 4-parameter growth model option (Schnute 1981). The Schnute model takes the form:

$$Y(t) = \left\{ y_1^{\gamma} + \left(y_2^{\gamma} - y_1^{\gamma}\right) \frac{1 - exp[-\kappa(t-\tau_1)]}{1 - exp[-\kappa(\tau_2 - \tau_1)]} \right\}^{1/\gamma}$$

where $Y(t)$ is length at age t; y_1 and y_2 are the length at ages $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$, respectively; and κ and γ are parameters that control the shape of the growth curve. In SS3, κ is referred to as the von Bertalanffy *k* parameter and γ is referred to as the Richards coefficient. All growth parameters were estimated within the model, as were the two uncertainty parameters (CV of LAA at ages $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$).

Length selectivity
For models 1, 2, & 4 all length selectivity parameters were estimated within the model. All models used a double-normal selectivity function recommended in the documentation for SS3 (Methot 2012). The double-normal is defined by six parameters for each fishery or survey, where p1 is the peak or ascending inflection size, p2 is the width of the plateau, p3 is the ascending width, p4 is the descending width, p5 is the selectivity at the first length bin, and p6 is the selectivity at the last length bin. In model 3, p6 was fixed so that the selectivity function was asymptotic. Selectivity parameters are summarized in Table 5. All bounds were the default values specified in the SS3 documentation.

Spawner-recruit parameters
The natural log of unfished recruitment (R_0) was estimated within the model. In addition, recruitment deviations were estimated for 1950-2013; in SS3 each deviation is considered a separate parameter.

Initial fishing mortality
Initial fishing mortality was estimated within the model for each of the two fisheries.

Results

Model Evaluation

Model evaluation criteria

A summary of model fit comparisons is located in Table 6. The models were evaluated using the following criteria:

1) Where possible, negative log-likelihood values and Akaike information criterion (AIC; determined using the number of active parameters) were used to compare overall model fit. Lower values indicated a better fit.
2) Model fit to the survey data was conducted by comparing root mean squared error (RMSE) and the proportion of survey biomass estimates where the model estimate was within the 95% confidence interval (CI) of the observed value. For RMSE, lower values indicated a better fit, whereas for proportion of model estimates within the CIs, higher values indicated a better fit.
3) Comparison of effective sample sizes (N_{eff}) for length compositions, with higher N_{eff} indicating better fit to the data.
4) Comparison of effective sample sizes (N_{eff}) for LAA datasets, with higher N_{eff} indicating better fit to the data.
5) Visual inspection of model fits to length compositions and LAA data.
6) Reasonable estimates of fishery length selectivity parameters.
7) Reasonable estimates of unfished recruitment and recruitment variability as well as consistency with the conceptual approach described in the overview.
8) The preferred model was also tested for sensitivity to jittering of initial values.

Evaluation of model criteria

1) Comparison of likelihoods and/or AIC values was only valid for comparing models 1-3, because model 4 changed the way likelihood was computed. Model 3 estimated 3 fewer parameters than

the other models, so the AIC value is the most appropriate for comparison. Model 1 had the lowest AIC value, followed by models 2 and 3.

2) All of the models showed good fits to the survey data. Model 2 had the lowest RMSE, while Model 4 had the highest proportion of model biomass estimates within the CI of the observed value.
3) Effective Ns for the length compositions were much greater than unity for all the models. The highest effective Ns were observed in Models 1 & 2, which had very similar values. In Model 4, length composition effective Ns were much lower than the other 3 models.
4) For the LAA data, Model 4 had the highest effective N, while Model 3 had the lowest.
5) Visually, Models 1 & 2 had the best fits to the length composition data (Figure 4). The fit was slightly less good for Model 3. Model 4 had noticeably worse fits to the length composition data; Model 4 did not fit at all to the mode at large sizes in the longline and survey length compositions. All of the models fit the LAA data well (Figures 5 & 6). As described above, Models 1-3 slightly underestimated LAA at larger ages. Model 4 provided a closer fit to the LAA data. However all four models underestimated LAA in the 2003 dataset.
6) There was a substantial difference in the selectivity curves produced by the models (Figure 7). Models 1 & 2 produced descending limbs for both fisheries and the survey. The decrease in selectivity at larger sizes varied by fleet, with final selectivity ranging from 0.5 to 0.8. In contrast, Model 4 produced dramatic dome-shaped selectivity, with selectivity rapidly descending to zero above 100 cm. Model 3 was parameterized so that selectivity was asymptotic.
7) Models 1-3 provided different estimates of recruitment (Figure 8), but all of the estimates were consistent with a large recruitment event in the early 1980s. In contrast, while Model 4 estimated a spike in recruitment in the early 1980s, this was followed by even greater spikes during the 1990s. The recruitment event in Models 1 & 3 occurred over several years, while in Model 2 there was a single year of very high recruitment.

<u>Discussion of model evaluation and designation of preferred model</u>

The base model (Model 1) provided the best overall fits when the data are considered as a whole (Figures 9-15), produced results that are consistent with the conceptual approach, and is the author's preferred model. There are two potential issues with Model 1. First, as is the case for the other "low biomass" models, LAA was slightly underestimated which may lead to an underestimate of spawning biomass (Figure 16). However, particularly for the 2008 and 2009 datasets, the underestimate was small. In addition, as described earlier, closer fits are only possible if the selectivity function is allowed to drop to zero. Essentially, the model can only fit the larger sizes in the LAA dataset by reducing the selectivity to an unrealistic level.

An additional issue is the estimation of descending limbs for the selectivity functions. Examination of the distribution of Alaska skate by size in the BSAI (Figure 17) suggests that the fisheries and survey may indeed have limited access to larger skates. Alaska skates display a marked ontogenetic movement from nursery areas on the slope in towards the inner domain of the EBS shelf. They reach the innermost shelf at approximately the age of maturity, at which time they appear to either disperse or return to the slope for spawning. Thus, the largest skates are generally encountered either along the slope or in the innermost domain. The variation in the descending limbs is consistent with this pattern. The trawl fishery, which is conducted mainly in the middle domain where few large skates are found, has the biggest decrease. The longline fishery, which occurs mainly in the outer domain and along the slope, has only a small decrease in selectivity at large sizes. The survey is intermediate to the two fisheries.

Time series results

Results presented below are for the preferred model, Model 1.

Definitions

Biomass is shown as total (age 0+) biomass (metric tons; t) of all Alaska skates in the population, and as female spawning biomass (t). Recruitment is reported as the number (in thousands) of Alaska skates at age 0.

Biomass time series

Time series of total biomass and spawning biomass estimates from 1950-2013 are reported in Table 7. Spawning biomass is also shown in Figure 16. The model suggests that the skate population declined beginning in the 1950s, with the steepest decline during the 1970s. The population then rebounded dramatically during the 1980s and has been relatively stable since 1990.

Recruitment

Time series of age 0 recruitment are reported in Table 7 and Fig. 8. The model suggests that a period of increased recruitment occurred between the years 1980-1984, with the highest level of recruitment in 1982. The model also estimates the recruitment was low during the 2000s but has rebounded since 2010.

Exploitation rate

A time series of exploitation (catch/total biomass) is given in Table 8. These rates suggest that skates experienced the greatest fishing pressure in the 1970s and that most of these removals occurred in the trawl fishery. Exploitation rates have been fairly stable (~0.4-0.5) since the 1990s.

Literature Cited

Alverson, D.L., and M.J. Carney. 1975. A graphic review of the growth and decay of population cohorts. J. Cons. Int. Explor. Mer 36:133-143.

Charnov, E.L. 1993. Life history invariants some explorations of symmetry in evolutionary ecology. Oxford University Press Inc., New York. 167p.

Gertseva, V. and I.G. Taylor. 2012. Status of the spiny dogfish shark resource off the continental U.S. Pacific Coast in 2011. Pacific Fishery Management Council, Portland, OR. Online at: http://www.pcouncil.org/groundfish/stock-assessments/by-species/spiny-dogfish/

Gunderson, D.R., Zimmerman, M., Nichol, D.G., and Pearson, K. 2003. Indirect estimates of natural mortality rate for arrowtooth flounder (*Atheresthes stomias*) and darkblotched rockfish (*Sebastes crameri*). Fishery Bulletin 101: 175 – 182.

Hoenig, J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. 82(1): 898-902.

Hoff, G.R. 2007. Reproduction of the Alaska skate (*Bathyraja parmifera*) with regard to nursery sites, embryo development and predation. PhD dissertation, University of Washington, Seattle.

Jensen, A.L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Can. J. Aquat. Fish. Sci. 53: 820-822.

Matta, M.E. 2006. Aspects of the life history of the Alaska skate, *Bathyraja parmifera*, in the eastern Bering Sea. M.S. thesis, University of Washington, Seattle.

Methot RD. 1990. Synthesis model: an adaptable framework for analysis of diverse stock assessment data. International North Pacific Fisheries Commission Bulletin 50:259-277

Methot RD. 2005. Technical description of the Stock Synthesis II assessment program. NOAA Fisheries, Seattle, WA.

Methot, R. 2012. User manual for the integrated analysis program Stock Synthesis 3(SS3). Model version 3.23. Northwest Fisheries Service, NOAA Fisheries, Seattle, WA.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. Int. Explor. Mer 39(2):175-192.

Rikhter, V.A., and V.N. Efanov. 1976. On one of the approaches to estimation of natural mortality of fish populations. ICNAF Res. Doc. 76/VI/8. Serial N. 3777. 13p.

Roff, D.A. 1986. The evolution of life history parameters in teleosts. Can. J. Fish. Aquat. Sci. 41:989-1000.

Schnute, J. 1981 A versatile growth model with statistically stable parameters. Can. J. Fish. Aquat. Sci. 38: 1128-1140.

Tables

Table 1. Modified estimates of Alaska skate biomass (t) from the EBS shelf bottom trawl survey, 1982-2013. Estimates and CVs in bold (1999-2013) were obtained directly from trawl survey data when species identification was reliable. Estimates and CVs prior to 1999 were partitioned using species composition data from 1999-2013.

year	biomass	CV
1982	188,913	0.10
1983	-	0.10
1984	209,774	0.10
1985	232,937	0.10
1986	263,007	0.10
1987	297,021	0.10
1988	328,893	0.10
1989	355,234	0.10
1990	375,175	0.10
1991	386,636	0.10
1992	388,674	0.10
1993	387,919	0.10
1994	385,716	0.10
1995	383,717	0.10
1996	380,941	0.10
1997	377,194	0.10
1998	376,421	0.10
1999	**377,719**	**0.16**
2000	**379,072**	**0.06**
2001	**380,939**	**0.06**
2002	**384,289**	**0.06**
2003	**388,028**	**0.05**
2004	**390,231**	**0.05**
2005	**392,508**	**0.05**
2006	**396,045**	**0.05**
2007	**399,272**	**0.07**
2008	**401,804**	**0.06**
2009	**404,458**	**0.06**
2010	**403,475**	**0.06**
2011	**396,464**	**0.05**
2012	**384,451**	**0.06**
2013	**188,913**	**0.06**

Table 2. Alaska skate EBS shelf survey length compositions, 2000-2013. Bin number is the lower limit of each 4 cm length bin; data are proportions of each bin. N = sample size used in the model.

	year													
bin	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000
20	0.005	0.010	0.007	0.005	0.003	0.005	0.004	0.007	0.004	0.009	0.003	0.004	0.004	0.003
24	0.034	0.032	0.025	0.027	0.015	0.019	0.025	0.030	0.016	0.021	0.016	0.015	0.009	0.012
28	0.044	0.047	0.037	0.024	0.027	0.024	0.026	0.020	0.019	0.020	0.017	0.021	0.017	0.012
32	0.038	0.048	0.048	0.042	0.029	0.030	0.031	0.027	0.026	0.032	0.017	0.025	0.017	0.020
36	0.049	0.043	0.049	0.041	0.032	0.039	0.033	0.037	0.036	0.042	0.027	0.027	0.020	0.028
40	0.051	0.047	0.054	0.044	0.049	0.045	0.043	0.052	0.048	0.052	0.036	0.039	0.028	0.031
44	0.047	0.052	0.057	0.048	0.052	0.059	0.048	0.050	0.058	0.055	0.048	0.054	0.042	0.042
48	0.055	0.046	0.054	0.080	0.060	0.055	0.055	0.062	0.059	0.055	0.041	0.064	0.049	0.049
52	0.063	0.052	0.065	0.049	0.067	0.054	0.051	0.052	0.066	0.064	0.049	0.063	0.056	0.066
56	0.059	0.047	0.053	0.041	0.053	0.058	0.055	0.054	0.064	0.067	0.054	0.061	0.059	0.061
60	0.061	0.055	0.047	0.044	0.052	0.061	0.056	0.048	0.060	0.067	0.053	0.065	0.059	0.055
64	0.045	0.046	0.039	0.040	0.044	0.051	0.055	0.059	0.062	0.057	0.060	0.065	0.061	0.056
68	0.036	0.047	0.048	0.052	0.052	0.044	0.050	0.056	0.047	0.050	0.066	0.061	0.059	0.052
72	0.035	0.046	0.042	0.042	0.047	0.046	0.048	0.051	0.051	0.053	0.057	0.061	0.068	0.061
76	0.027	0.038	0.042	0.045	0.050	0.040	0.049	0.044	0.050	0.043	0.055	0.051	0.069	0.064
80	0.039	0.032	0.029	0.047	0.040	0.040	0.038	0.045	0.046	0.047	0.056	0.047	0.063	0.064
84	0.030	0.027	0.026	0.039	0.042	0.040	0.045	0.036	0.042	0.041	0.061	0.047	0.047	0.054
88	0.036	0.036	0.045	0.045	0.045	0.051	0.039	0.042	0.045	0.045	0.057	0.046	0.067	0.061
92	0.052	0.065	0.054	0.054	0.060	0.051	0.061	0.063	0.055	0.049	0.070	0.053	0.064	0.067
96	0.074	0.072	0.070	0.079	0.073	0.063	0.069	0.060	0.057	0.056	0.072	0.058	0.065	0.070
100	0.066	0.069	0.060	0.061	0.068	0.070	0.065	0.059	0.054	0.047	0.048	0.047	0.050	0.043
104	0.040	0.029	0.030	0.037	0.030	0.041	0.039	0.031	0.026	0.021	0.026	0.018	0.020	0.022
108	0.012	0.012	0.012	0.011	0.008	0.012	0.012	0.010	0.009	0.006	0.008	0.006	0.005	0.005
112	0.002	0.002	0.005	0.003	0.003	0.002	0.002	0.004	0.001	0.000	0.001	0.001	0.001	0.001
116	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
120	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
124	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
128	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
132	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
N	200	200	200	200	200	200	200	200	200	200	200	200	200	200

Table 3. Estimated catches (t) of Alaska skates in the BSAI by gear type, 1954-2013. Various methods were employed in the estimation, depending on time period and data availability; see text for details. Source for all data is the NMFS Alaska Regional Office.

year	longline	trawl		year	longline	trawl
1954	0	0		1985	1,443	4,045
1955	0	0		1986	1,301	3,675
1956	0	0		1987	1,062	3,006
1957	0	0		1988	1,443	4,287
1958	8	61		1989	588	1,752
1959	21	156		1990	688	2,009
1960	0	0		1991	6,246	1,372
1961	0	0		1992	12,492	2,804
1962	0	0		1993	9,004	2,021
1963	0	0		1994	10,475	2,351
1964	43	304		1995	10,967	2,462
1965	150	928		1996	9,311	2,090
1966	130	924		1997	13,059	2,932
1967	537	1,967		1998	14,100	3,178
1968	1,539	9,252		1999	10,288	2,318
1969	690	4,365		2000	13,362	3,055
1970	1,220	6,502		2001	14,244	3,291
1971	856	5,613		2002	15,943	3,571
1972	1,377	4,916		2003	14,087	3,342
1973	3,264	23,062		2004	16,286	3,886
1974	3,700	24,994		2005	17,661	3,405
1975	3,348	22,736		2006	14,907	3,346
1976	1,702	10,897		2007	13,638	3,069
1977	2,559	15,090		2008	15,743	3,557
1978	3,864	25,571		2009	15,031	3,388
1979	2,609	16,207		2010	12,761	2,896
1980	4,578	12,310		2011	17,270	3,854
1981	4,503	12,553		2012	18,334	4,110
1982	2,349	6,437		2013	20,042	4,485
1983	1,971	5,456				
1984	1,072	2,995				

Table 4. Alaska skate length compositions from the BSAI longline and trawl fisheries, 2009-2013. Bin number is the lower limit of each 4 cm length interval. N = sample size used in the model (square root of number of sampled hauls).

	longline					trawl				
bin	2009	2010	2011	2012	2013	2009	2010	2011	2012	2013
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.003	0.004	0.002	0.002	0.001
24	0.000	0.000	0.000	0.001	0.000	0.011	0.011	0.012	0.003	0.006
28	0.000	0.000	0.000	0.003	0.000	0.024	0.018	0.020	0.010	0.009
32	0.001	0.001	0.000	0.007	0.000	0.034	0.031	0.026	0.011	0.010
36	0.001	0.001	0.001	0.010	0.001	0.051	0.037	0.034	0.017	0.020
40	0.003	0.002	0.003	0.013	0.002	0.063	0.053	0.049	0.034	0.039
44	0.006	0.006	0.007	0.018	0.003	0.064	0.055	0.059	0.042	0.047
48	0.011	0.014	0.014	0.021	0.008	0.056	0.050	0.052	0.052	0.050
52	0.020	0.024	0.020	0.025	0.013	0.051	0.042	0.047	0.049	0.051
56	0.025	0.032	0.027	0.030	0.022	0.044	0.041	0.040	0.043	0.045
60	0.034	0.046	0.041	0.041	0.031	0.043	0.043	0.038	0.044	0.042
64	0.044	0.056	0.050	0.053	0.038	0.048	0.048	0.039	0.046	0.043
68	0.058	0.069	0.064	0.068	0.056	0.049	0.056	0.053	0.054	0.050
72	0.063	0.070	0.077	0.072	0.069	0.048	0.053	0.060	0.069	0.055
76	0.068	0.062	0.074	0.072	0.079	0.041	0.049	0.059	0.070	0.058
80	0.068	0.071	0.077	0.080	0.093	0.052	0.054	0.059	0.080	0.068
84	0.067	0.067	0.076	0.077	0.097	0.044	0.054	0.053	0.071	0.069
88	0.081	0.071	0.082	0.087	0.105	0.059	0.056	0.060	0.077	0.080
92	0.094	0.090	0.095	0.094	0.115	0.059	0.069	0.069	0.073	0.081
96	0.124	0.103	0.112	0.098	0.117	0.056	0.068	0.068	0.069	0.077
100	0.119	0.104	0.106	0.078	0.089	0.049	0.055	0.058	0.051	0.058
104	0.067	0.057	0.049	0.034	0.040	0.029	0.029	0.025	0.022	0.029
108	0.030	0.028	0.018	0.013	0.013	0.010	0.013	0.010	0.008	0.007
112	0.009	0.013	0.004	0.003	0.003	0.006	0.004	0.002	0.002	0.002
116	0.005	0.006	0.001	0.001	0.002	0.002	0.003	0.002	0.000	0.001
120	0.001	0.004	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001
124	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
128	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
132	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
N	67	65	72	77	85	56	61	56	50	61

Table 5. Input parameter values for the base model (Model 1) of the revised model. Where parameters were estimated freely within the model, minimum and maximum bounds are shown. Superscripts indicate how parameters were changed in the alternative models.

parameter		value	min	max	fix?
growth and natural mortality	natural mortality (*M*)	0.13			X
	length at A1 (L1)	20	-10	30	
	length at A2 (L2)	110	70	150	
	von Bertalanffy coefficient (κ)	0.15	0.05	0.15	
	Richards coefficient (γ)	0.1	-1	2	
	CV of LAA @ L1	0.1	0.05	0.35	
	CV of LAA @ L2	0.1	0.05	0.25	
length-weight relationship	coefficient (a)	2.44×10^{-6}			X
	exponent (b)	3.35			X
length at maturity	length at 50% maturity (a)	93.28			X
	slope (b)	-0.548			X
length-fecundity relationship	intercept	-14.7			X
	slope	0.214			X
stock-recruit function	ln virgin recruitment level (R_0)	10.00	5	15	
	steepness	1			X
	σ_R	0.4[a]			X
EBS shelf survey catchability	ln catchability (q)	0			X
longline length selectivity[b]	peak (p1)	111	7.6	126	
	top (p2)	-0.1	-6	4	
	ascending width (p3)	4.9	-1	9	
	descending width (p4)	4.7	-1	9	
	selectivity at first size bin (p5)	-2.2	-5	9	
	selectivity at last size bin (p6)	9	-5	9	
trawl length selectivity[b]	peak (p1)	49	7.6	126	
	top (p2)	-5	-6	4	
	ascending width (p3)	4.8	-1	9	
	descending width (p4)	4.4	-1	9	
	selectivity at first size bin (p5)	-0.7	-5	9	
	selectivity at last size bin (p6)	9	-5	9	
survey length selectivity[b]	peak (p1)	49	7.6	126	
	top (p2)	-5	-6	4	
	ascending width (p3)	4.8	-1	9	
	descending width (p4)	4.4	-1	9	
	selectivity at first size bin (p5)	-0.7	-5	9	
	selectivity at last size bin (p6)	9	-5	9	
initial fishing mortality	longline fishery F	0.030	0	1	
	trawl fishery F	0.005	0	1	

a: In model 2, σ_R was fixed at 0.5.

b: In model 3, p6 was fixed at the starting value for all fleets.

Table 6. Results from models 1-4 for use in model comparison and evaluation.

model number	**1**	**2**	**3**	**4**
description	base	base w/ sigmaR=0.5	base w/ asymptotic selectivity	base w/ high emphasis on LAA
likelihood components				
survey	-37.28	-40.33	-32.00	-41.86
length comps	79.35	79.04	82.56	109.18
LAA	127.22	127.19	131.82	472.68
recruitment	-41.79	-30.80	-42.81	-43.75
total	**127.52**	**135.11**	**139.59**	**496.29**
parameters estimated	89	89	86	89
AIC	433.0	448.2	451.2	1170.6
L_amin	13.95	13.93	15.84	18.37
L_amax	102.12	102.12	102.72	122.27
k	0.379	0.379	0.349	0.275
Richards	-1	-1	-1	-1
CV young	0.350	0.350	0.290	0.256
CV old	0.050	0.050	0.050	0.050
ln (R_0)	10.02	10.22	10.02	10.43
$B_{100\%}$	182,570	186,685	147,978	372,685
RMSE_survey	0.125	0.117	0.132	0.118
% within survey CI	81%	81%	77%	87%
mean longline input N	73	73	73	73
mean longline eff N	979	984	900	527
mean longline effN/N	13.4	13.4	12.3	7.198
mean trawl input N	57	57	57	57
mean trawl eff N	1,153	1,209	778	526
mean trawl effN/N	20.3	21.3	13.7	9.244
mean survey input N	200	200	200	200
mean survey eff N	803	800	745	550
mean survey effN/N	4.0	4.0	3.7	2.7
mean LAA N	224	224	224	224
mean LAA eff N	7,875	5,468	1,779	11,071
mean LAA eff N/N	35.2	24.4	8.0	49.5

Table 7. Time series of total (age 0+) biomass, spawning biomass and the number of age 0 recruits predicted by the revised model.

year	total biomass (t)	female spawning biomass (t)	recruits (1000s)	year	total biomass (t)	female spawning biomass (t)	recruits (1000s)
unfished	612,629	182,570	26,985	1982	260,511	70,844	64,887
1950	612,522	182,570	23,433	1983	265,706	68,472	52,377
1951	612,283	182,570	23,269	1984	277,719	67,039	36,329
1952	611,790	182,570	23,086	1985	299,752	67,075	29,069
1953	610,854	182,570	22,884	1986	327,575	67,592	25,564
1954	609,241	182,570	22,662	1987	362,138	69,194	24,245
1955	606,725	182,570	22,418	1988	401,394	72,255	24,337
1956	603,163	182,570	22,152	1989	439,173	76,926	25,706
1957	598,550	182,570	21,867	1990	476,861	85,241	28,539
1958	593,016	182,570	21,563	1991	508,128	100,633	29,728
1959	586,702	181,826	21,245	1992	527,197	116,867	25,233
1960	579,801	180,587	20,915	1993	531,712	129,550	25,116
1961	572,797	178,971	20,579	1994	535,259	139,949	31,079
1962	565,651	177,044	20,239	1995	533,806	145,896	35,814
1963	558,450	174,938	19,900	1996	530,040	148,071	29,813
1964	551,237	172,756	19,564	1997	527,981	148,280	33,081
1965	543,675	170,455	19,238	1998	522,105	145,807	36,041
1966	535,385	167,945	18,933	1999	516,458	142,784	36,588
1967	527,137	165,459	18,661	2000	517,548	141,422	40,726
1968	517,466	162,545	18,425	2001	517,061	138,614	32,662
1969	499,522	157,150	18,215	2002	517,673	135,488	29,658
1970	487,612	153,447	18,004	2003	518,436	132,878	33,526
1971	473,315	148,929	17,783	2004	523,019	132,310	40,115
1972	460,687	144,792	17,578	2005	525,941	131,049	36,004
1973	448,742	140,718	17,424	2006	528,406	130,383	33,587
1974	417,156	130,749	17,358	2007	533,408	131,351	29,027
1975	384,101	120,118	17,411	2008	539,448	133,345	28,154
1976	354,847	110,362	17,686	2009	542,080	135,809	21,208
1977	340,544	104,752	18,387	2010	544,327	137,703	18,513
1978	322,618	97,912	19,877	2011	547,315	139,429	17,937
1979	294,445	88,030	22,754	2012	542,107	139,599	20,272
1980	278,886	81,537	28,044	2013	532,109	140,172	24,736
1981	267,875	75,948	37,907				

Table 8. Time series of exploitation rates (catch/total biomass) as estimated by the base model (Model 1).

year	LL	trawl	total	year	LL	trawl	total
1950	0.000	0.000	0.000	1982	0.012	0.033	0.044
1951	0.000	0.000	0.000	1983	0.010	0.027	0.036
1952	0.000	0.000	0.000	1984	0.005	0.014	0.019
1953	0.000	0.000	0.000	1985	0.006	0.016	0.023
1954	0.000	0.000	0.000	1986	0.005	0.013	0.018
1955	0.000	0.000	0.000	1987	0.004	0.009	0.013
1956	0.000	0.000	0.000	1988	0.004	0.012	0.017
1957	0.000	0.000	0.000	1989	0.002	0.005	0.006
1958	0.000	0.000	0.000	1990	0.002	0.005	0.007
1959	0.000	0.000	0.000	1991	0.015	0.003	0.018
1960	0.000	0.000	0.000	1992	0.028	0.007	0.035
1961	0.000	0.000	0.000	1993	0.021	0.005	0.025
1962	0.000	0.000	0.000	1994	0.024	0.006	0.030
1963	0.000	0.000	0.000	1995	0.026	0.006	0.031
1964	0.000	0.001	0.001	1996	0.022	0.005	0.027
1965	0.000	0.002	0.003	1997	0.031	0.007	0.038
1966	0.000	0.002	0.003	1998	0.034	0.008	0.042
1967	0.001	0.005	0.006	1999	0.025	0.006	0.031
1968	0.004	0.024	0.028	2000	0.033	0.008	0.040
1969	0.002	0.012	0.014	2001	0.035	0.008	0.043
1970	0.003	0.018	0.021	2002	0.039	0.009	0.048
1971	0.002	0.016	0.018	2003	0.034	0.008	0.042
1972	0.004	0.015	0.018	2004	0.039	0.009	0.049
1973	0.009	0.072	0.081	2005	0.042	0.008	0.050
1974	0.011	0.084	0.096	2006	0.035	0.008	0.043
1975	0.011	0.083	0.094	2007	0.032	0.007	0.039
1976	0.006	0.042	0.048	2008	0.036	0.008	0.045
1977	0.010	0.061	0.071	2009	0.035	0.008	0.042
1978	0.016	0.111	0.127	2010	0.029	0.007	0.036
1979	0.011	0.076	0.087	2011	0.039	0.009	0.048
1980	0.021	0.060	0.081	2012	0.042	0.010	0.051
1981	0.022	0.063	0.085	2013	0.046	0.011	0.057

Figures

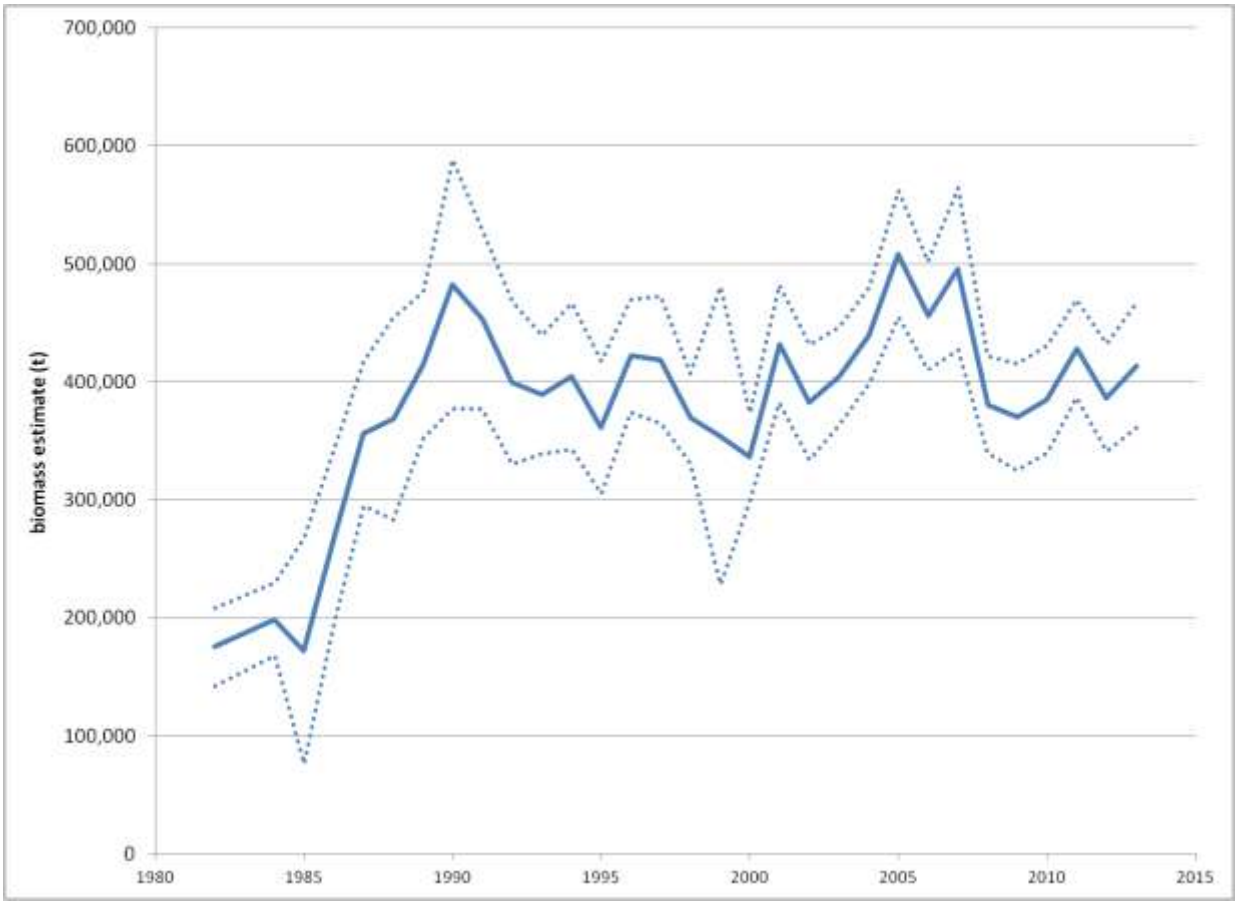


Figure 1. Eastern Bering Sea shelf bottom trawl survey biomass estimates (t) for all skates in the BSAI skate complex, 1982-2013. Dashed lines indicate 95% confidence interval.

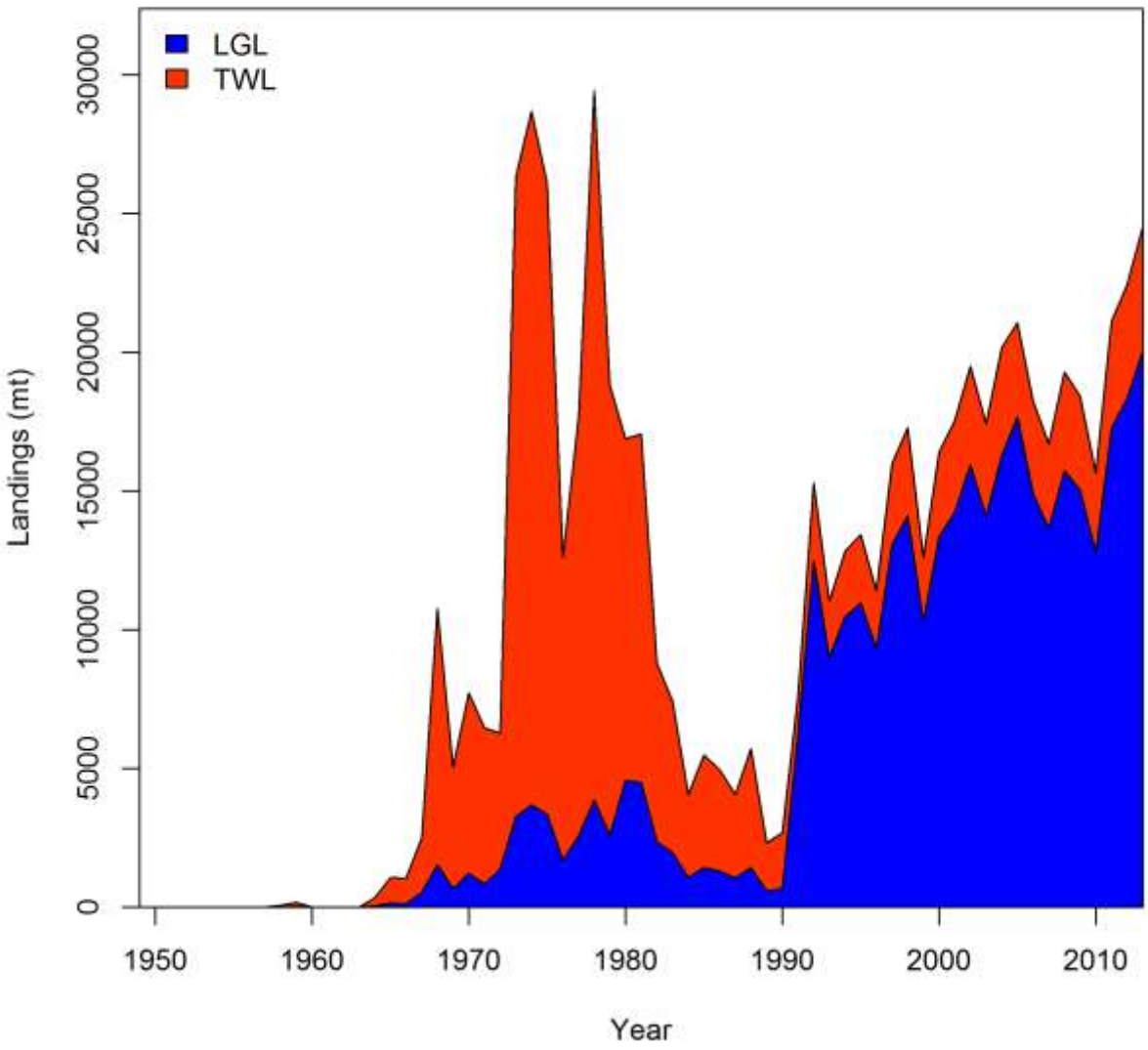


Figure 2. Estimated catch of Alaska skates (t) in the BSAI 1954-2013. LGL = longline fishery, TWL = trawl fishery.

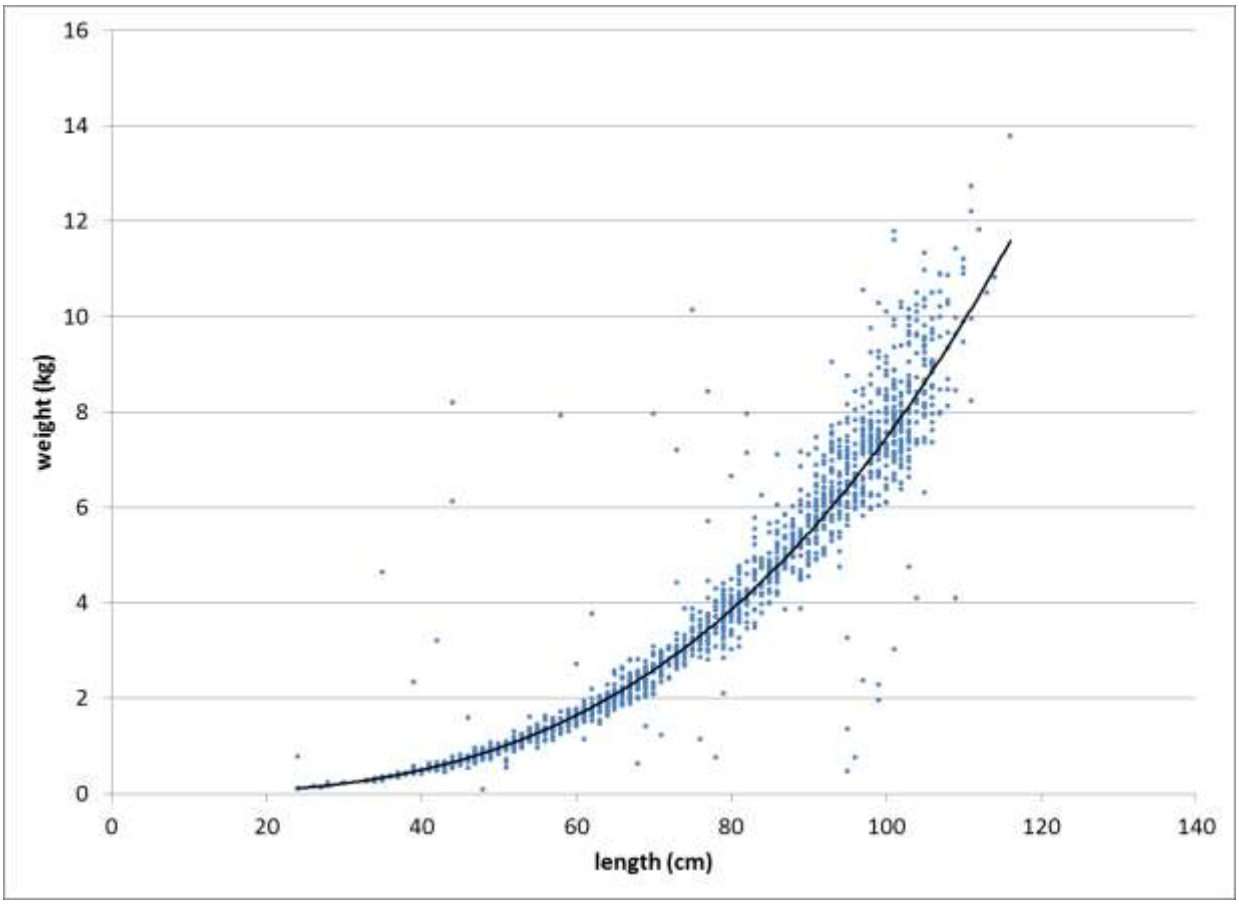


Figure 3. Length-weight relationship for Alaska skates captured in the EBS shelf trawl survey, 2008-2010. Black line indicates line of best fit to the data, $r^2 = 0.93$, N = 1,515.

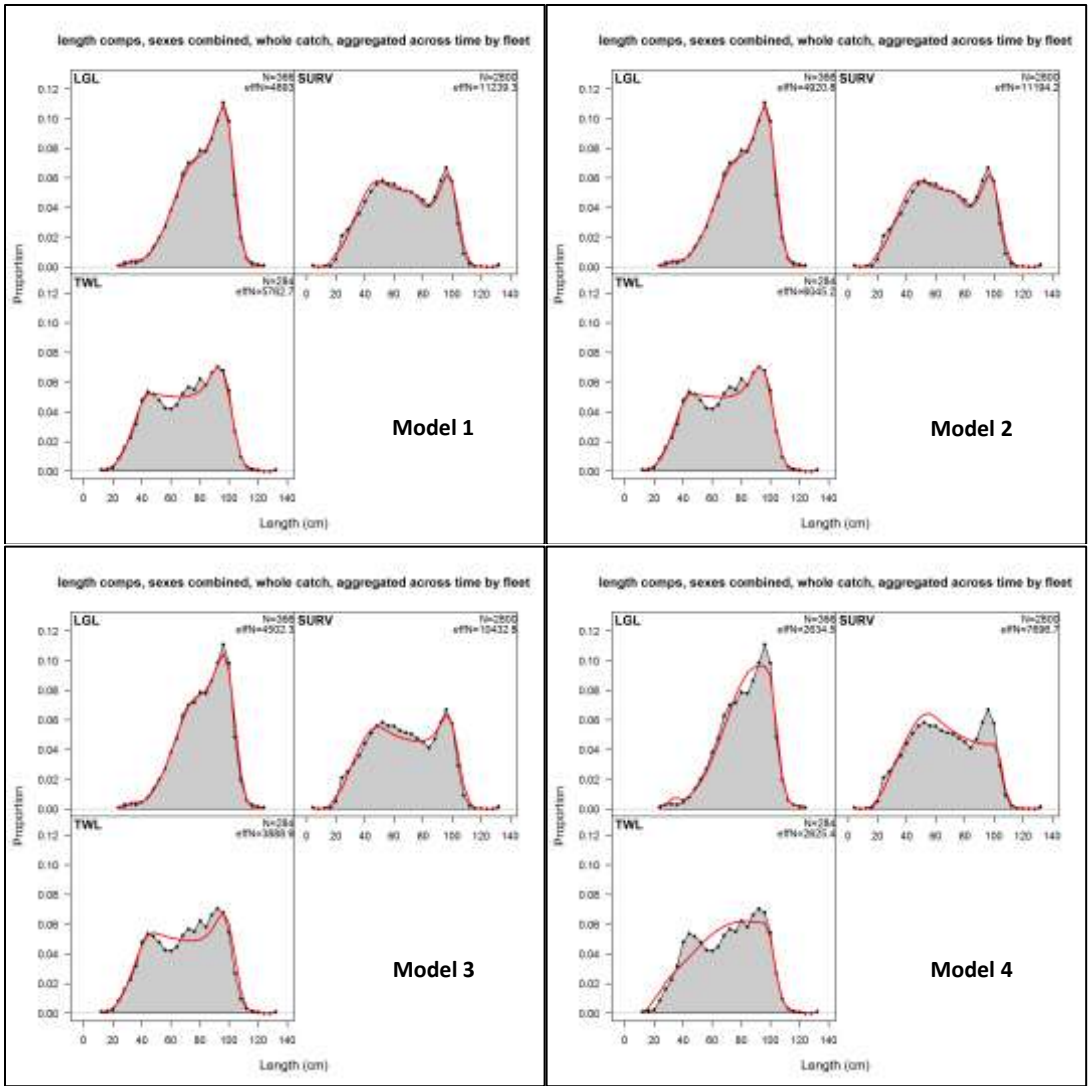


Figure 4. Fits to length composition data for the 4 alternative models. For each fleet, observed data (grey) and model fit (red line) are aggregated across years. LGL = longline fishery, TWL = trawl fishery, SURV = trawl survey.

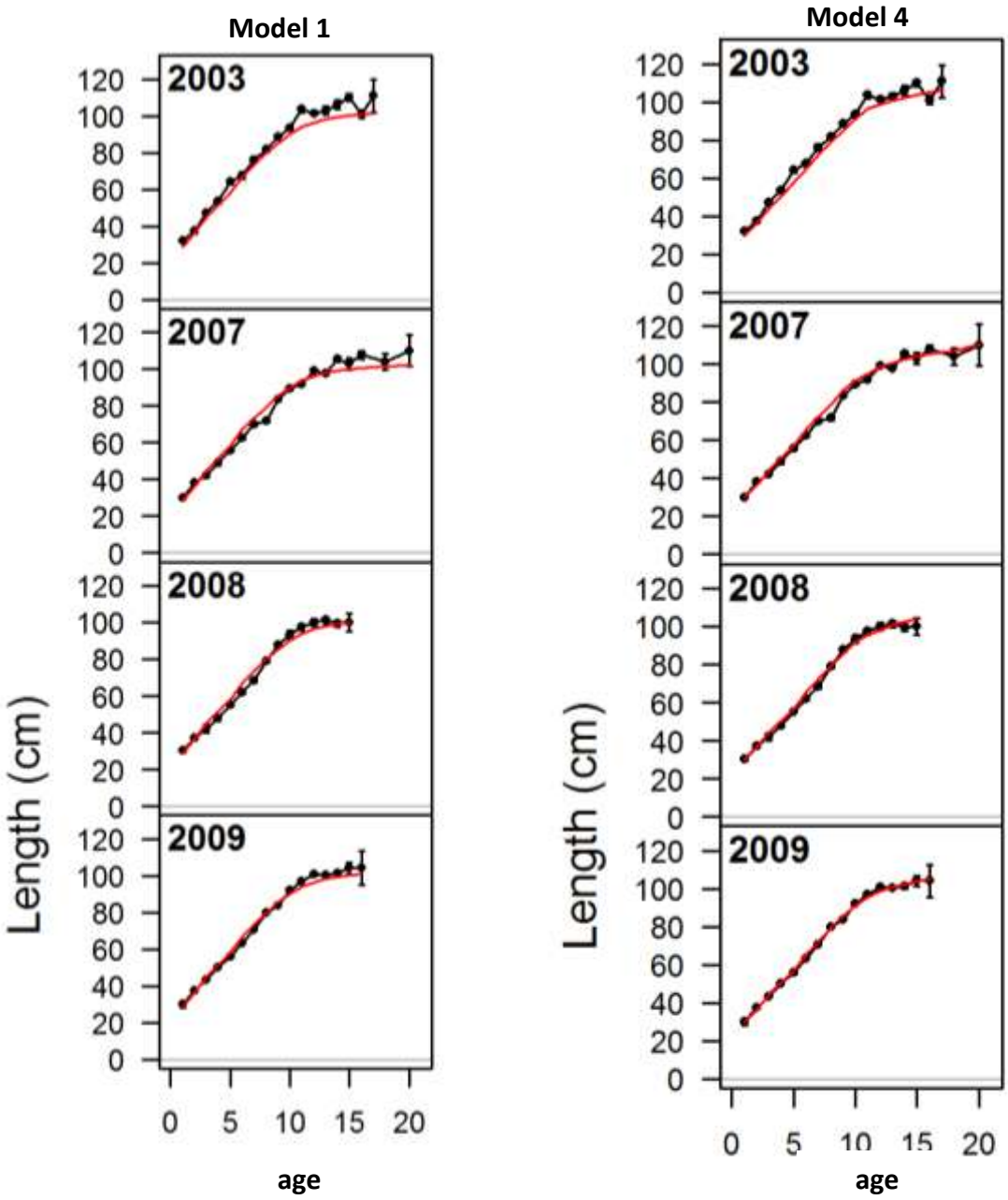
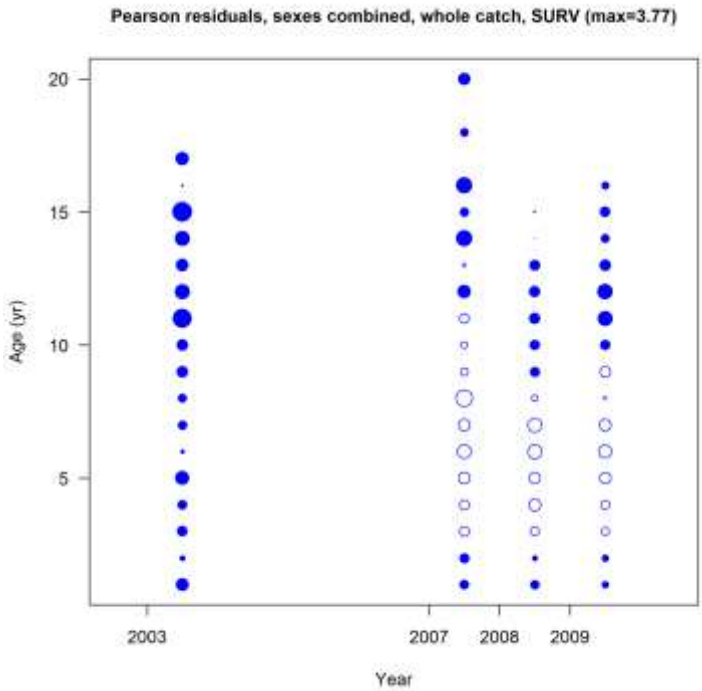


Figure 5. Observed (black circles) and model-predicted (red line) length-at-age for the four datasets included in the models. Left panel is Model 1, right panel is Model 4.



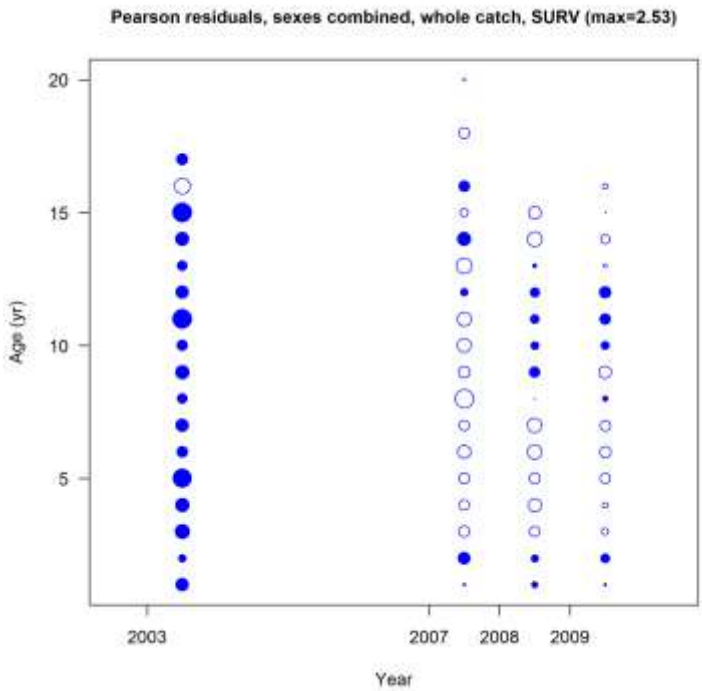


Figure 6. Pearson residuals for the length-at-age-datasets for Model 1 (top panel) and Model 4 (bottom panel).

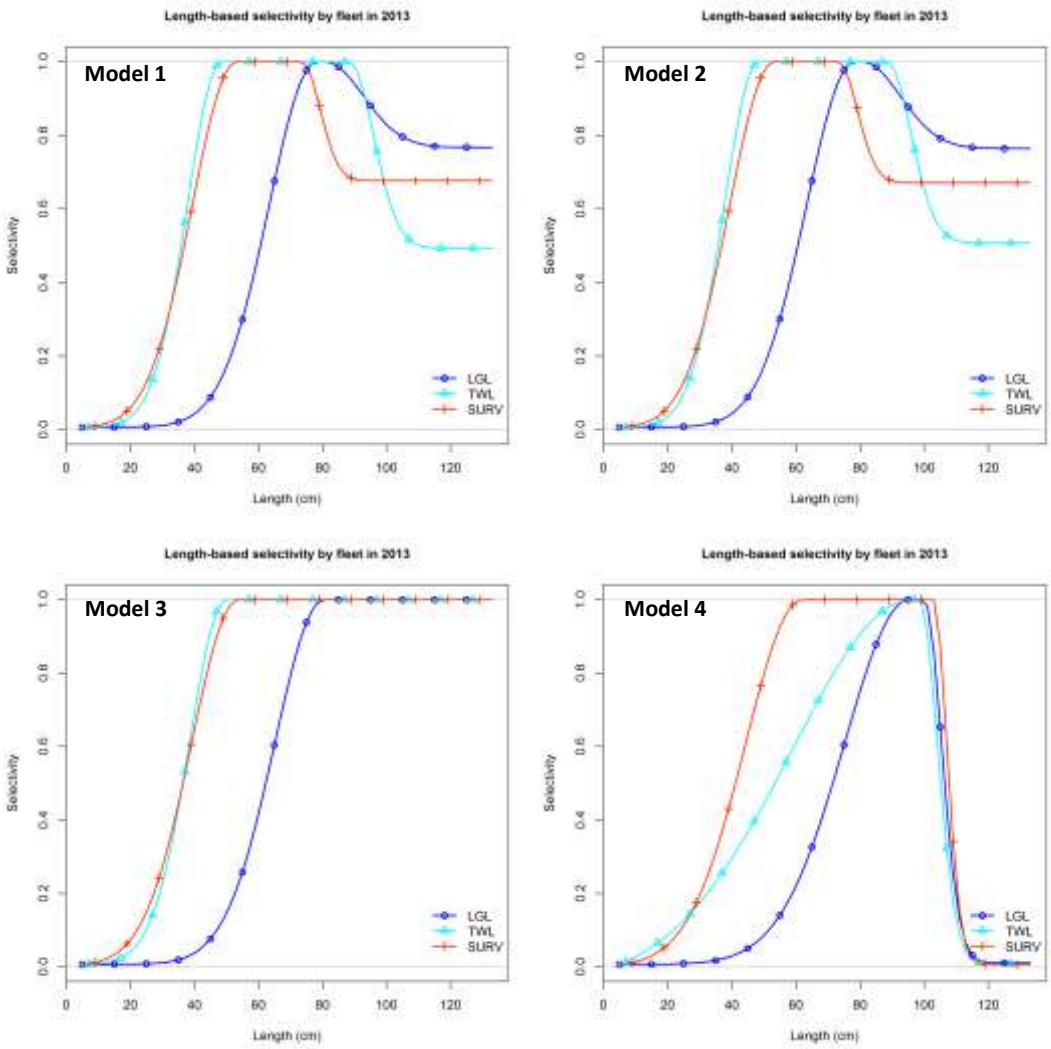


Figure 7. Selectivity functions for the four model alternatives. LGL = longline fishery, TWL = trawl fishery, SURV = trawl survey.

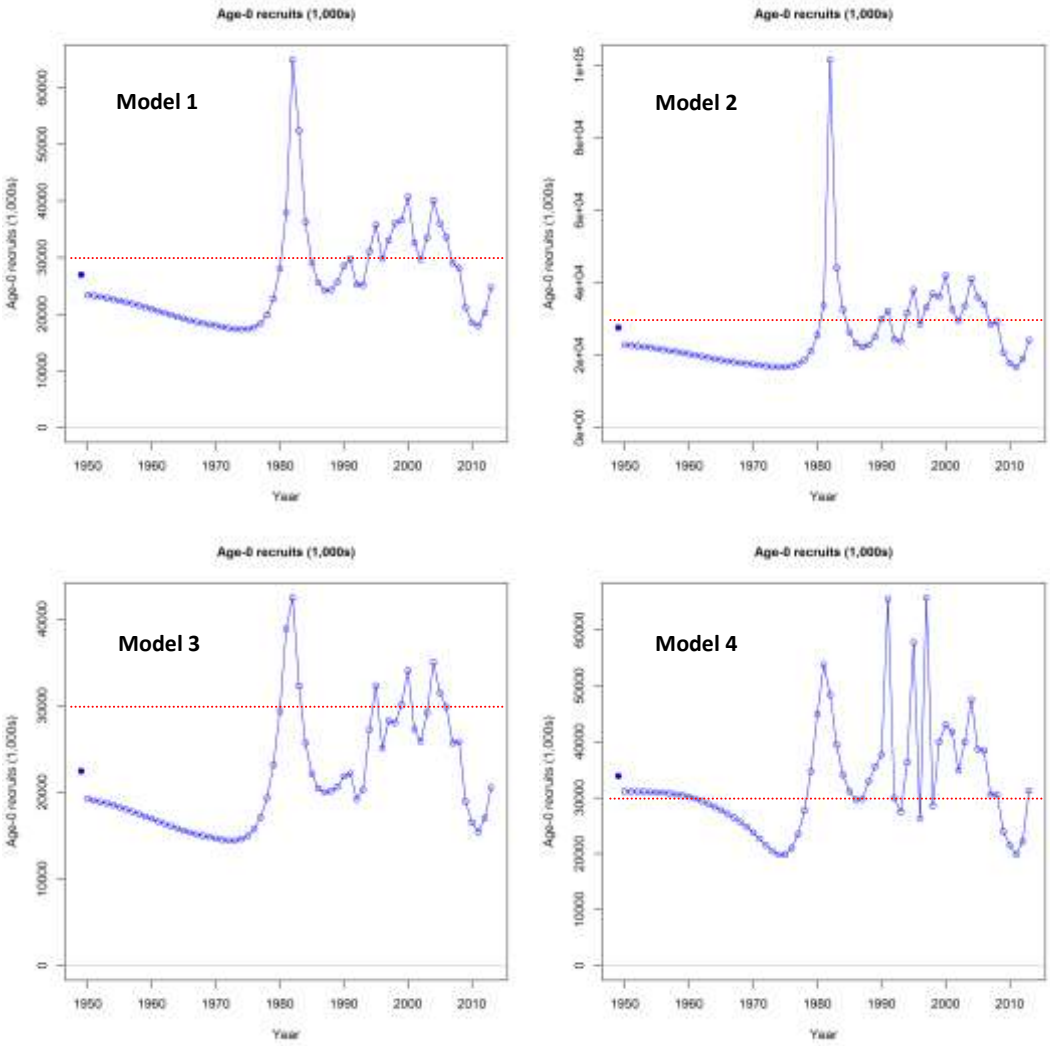


Figure 8. Time series of recruitment for the 4 alternative models. Filled blue circle indicates unfished recruitment. Vertical axis scales differ among plots; dashed red horizontal line indicates identical values among plots.

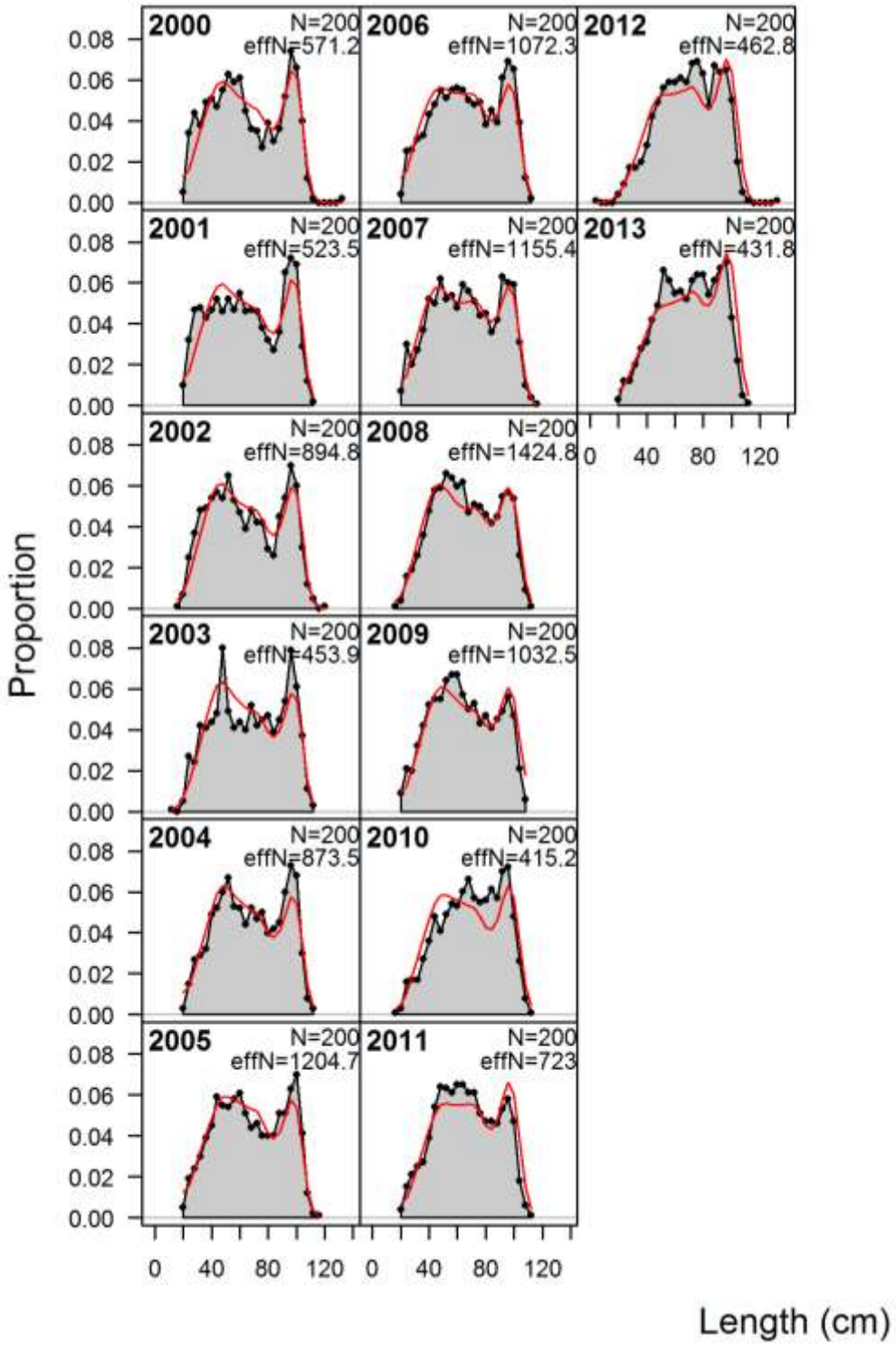


Figure 9. EBS shelf survey length compositions from 2000-2013. Grey shading = observed proportions; red line = model predictions. X-axis values are lengths in cm.

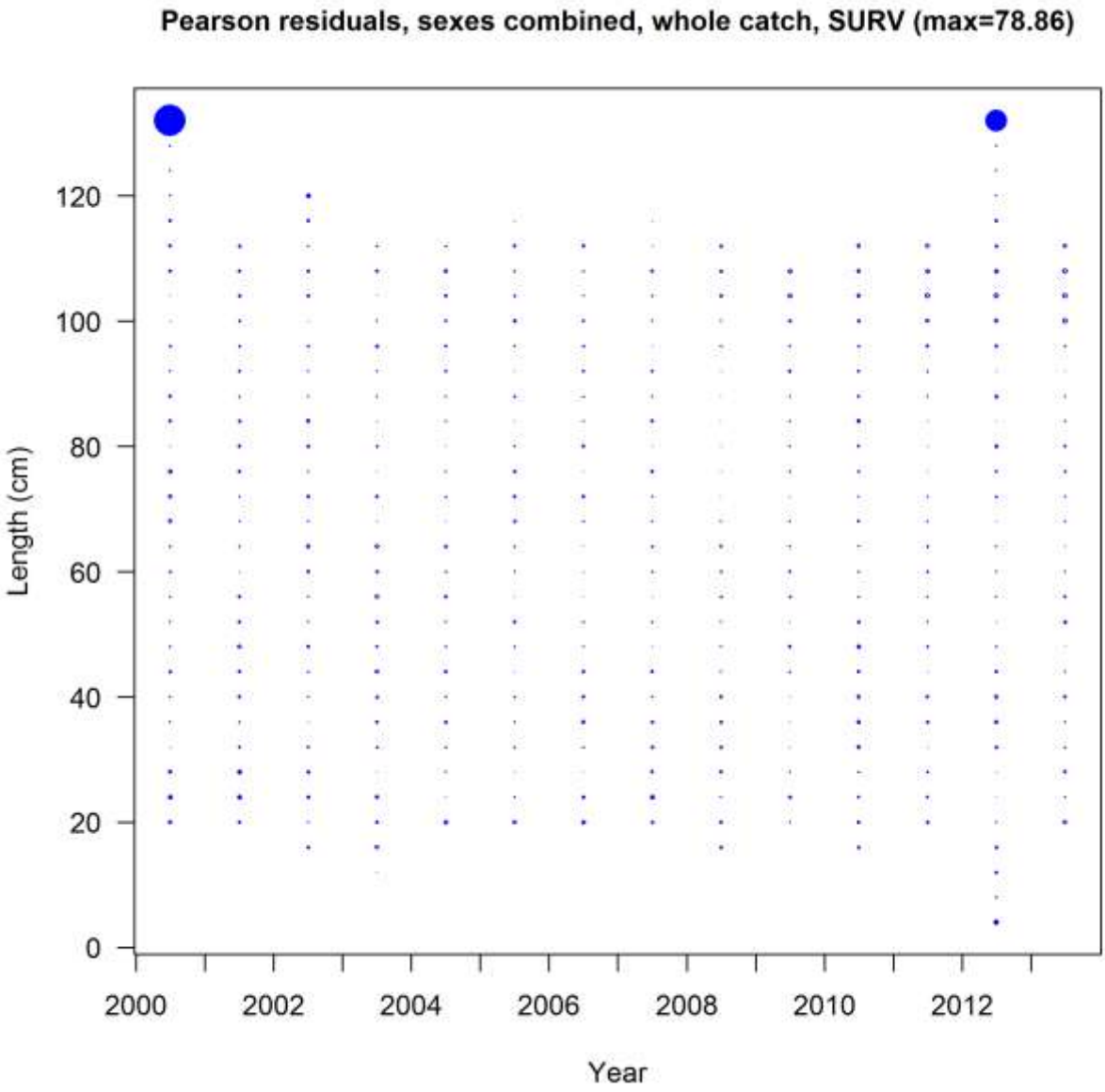


Figure 10. Pearson residuals for model fit to survey length composition data. Circles indicate the relative size of the residual, with the largest circle equivalent to a maximum residual value of 78.66. Solid circles indicate positive residuals, open circles indicate negative residuals.

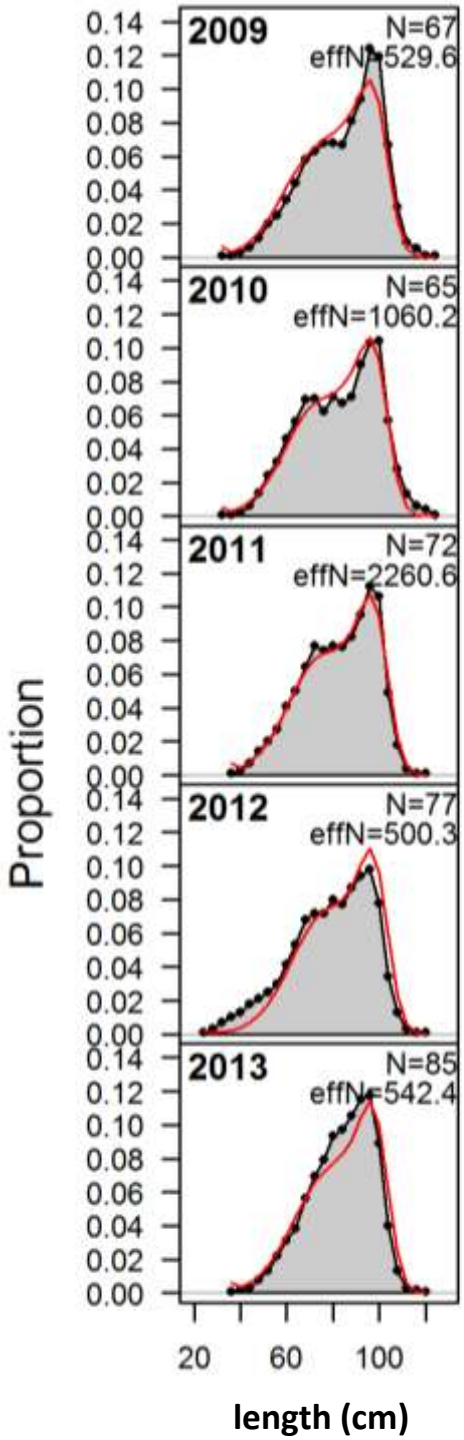


Figure 11. Observed and model-predicted length compositions from the 2009-2013 longline fisheries, with model predictions. Grey shading = observed proportions; red line = model predictions.

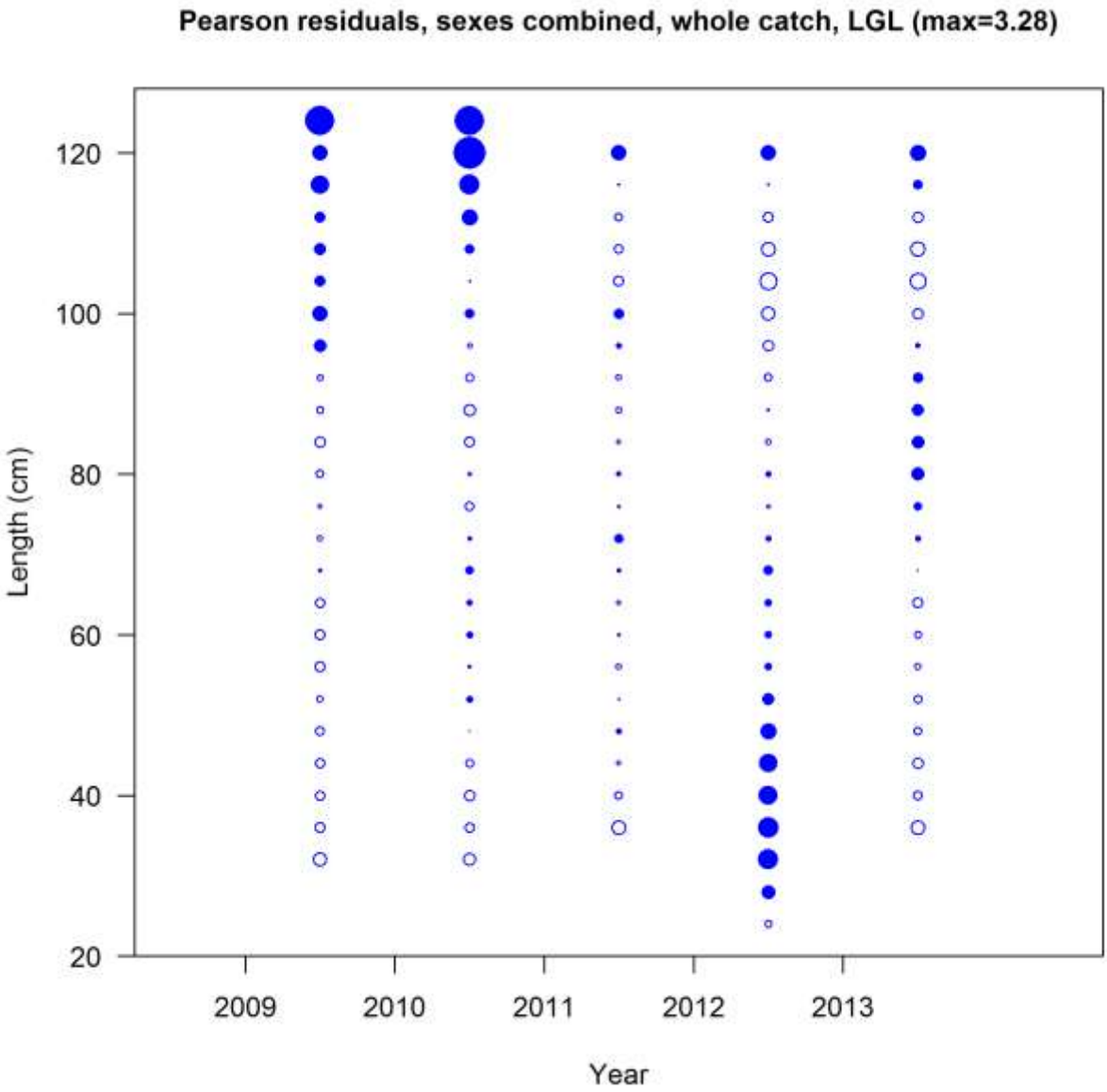


Figure 12. Pearson residuals for model fit to longline fishery length composition data, 2009-2013. Circles indicate the relative size of the residual, with the largest circle equivalent to a maximum residual value of 3.28. Solid circles indicate positive residuals, open circles indicate negative residuals.

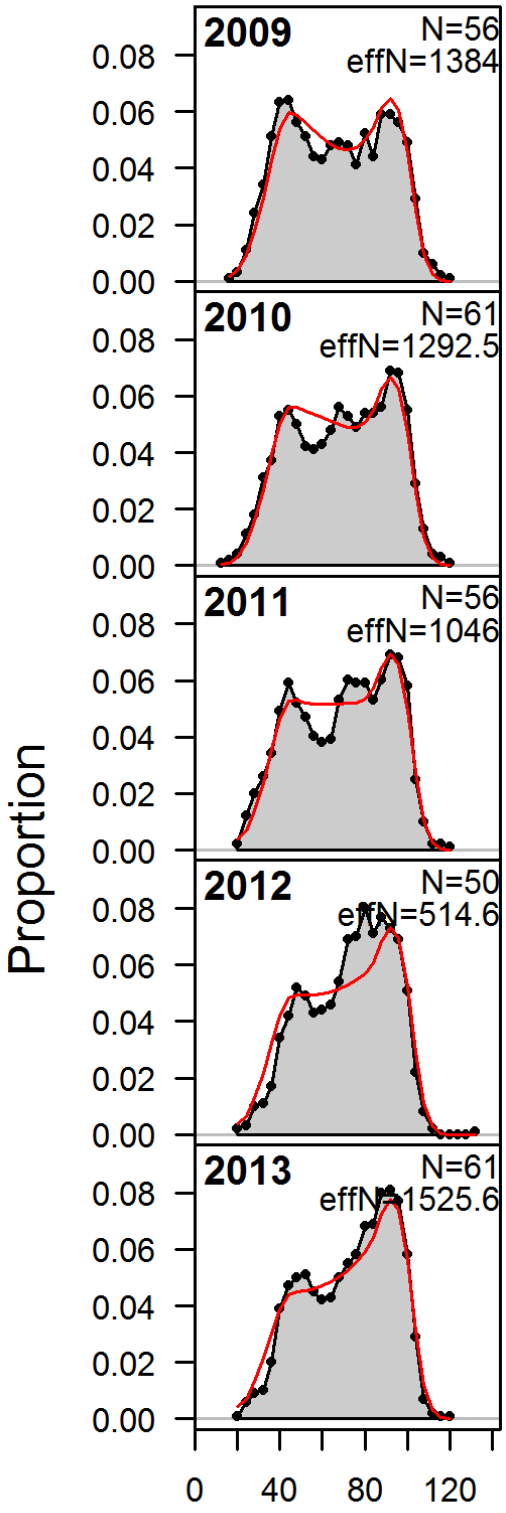


Figure 13. Observed and model-predicted length compositions from the 2009-2013 trawl fisheries, with model predictions. Grey shading = observed proportions; red line = model predictions.

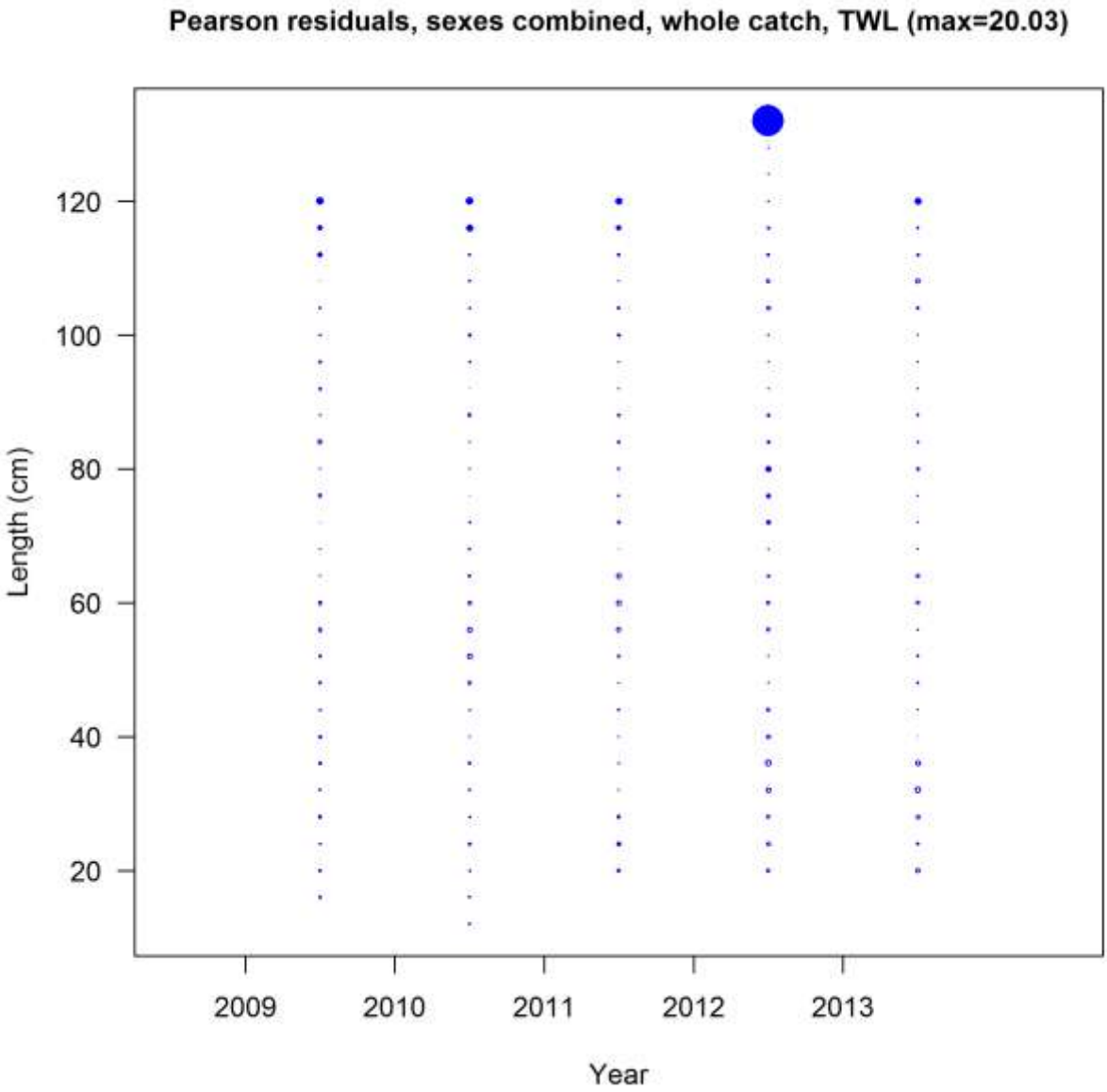


Figure 14. Pearson residuals for model fit to trawl fishery length composition data, 2009-2013. Circles indicate the relative size of the residual, with the largest circle equivalent to a maximum residual value of 20.03. Solid circles indicate positive residuals, open circles indicate negative residuals.

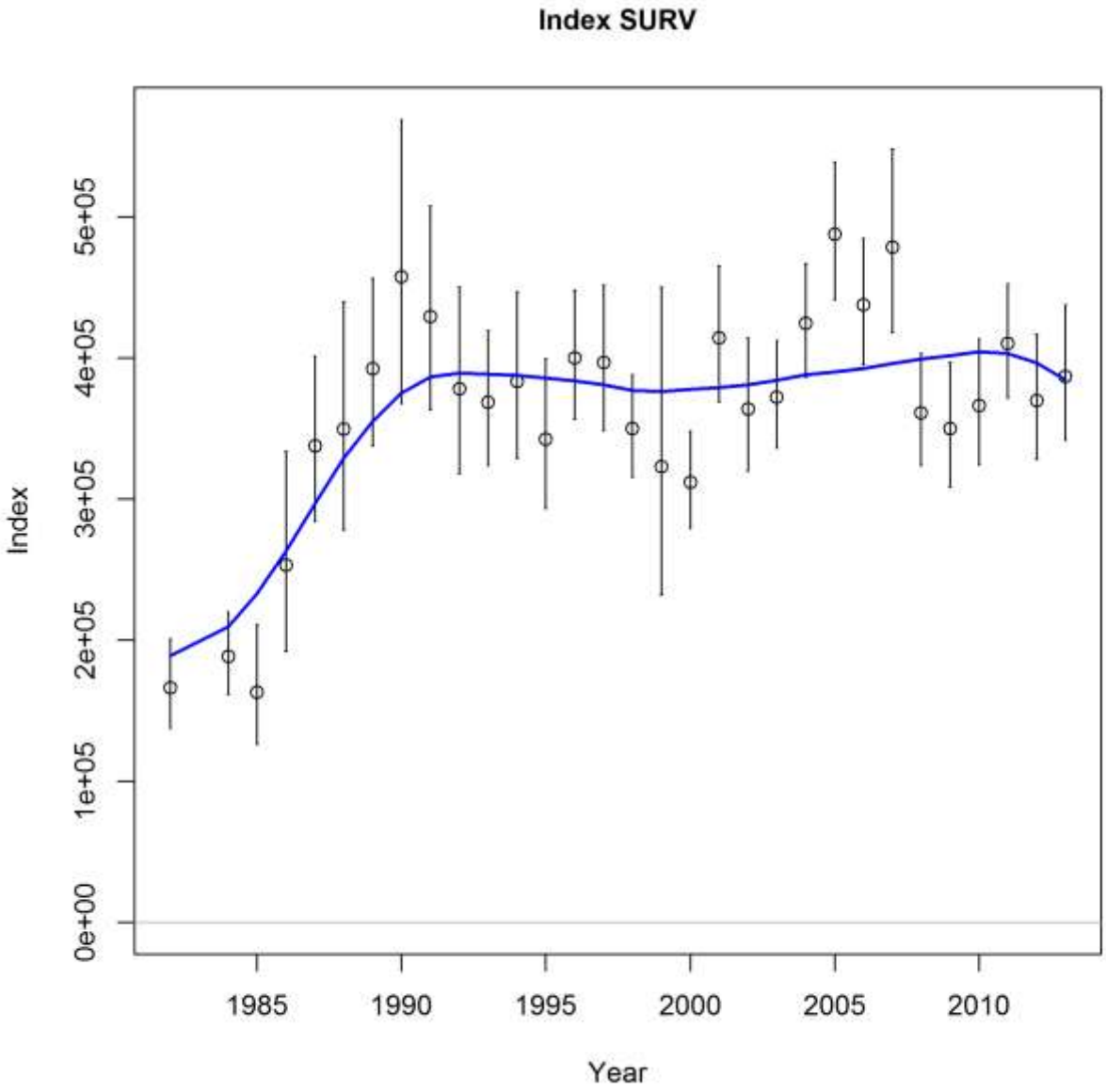


Figure 15. Observed biomass (circles) from EBS shelf surveys 1982-2013, with confidence intervals (± 2 SE), and predicted survey biomass from the model (blue line).

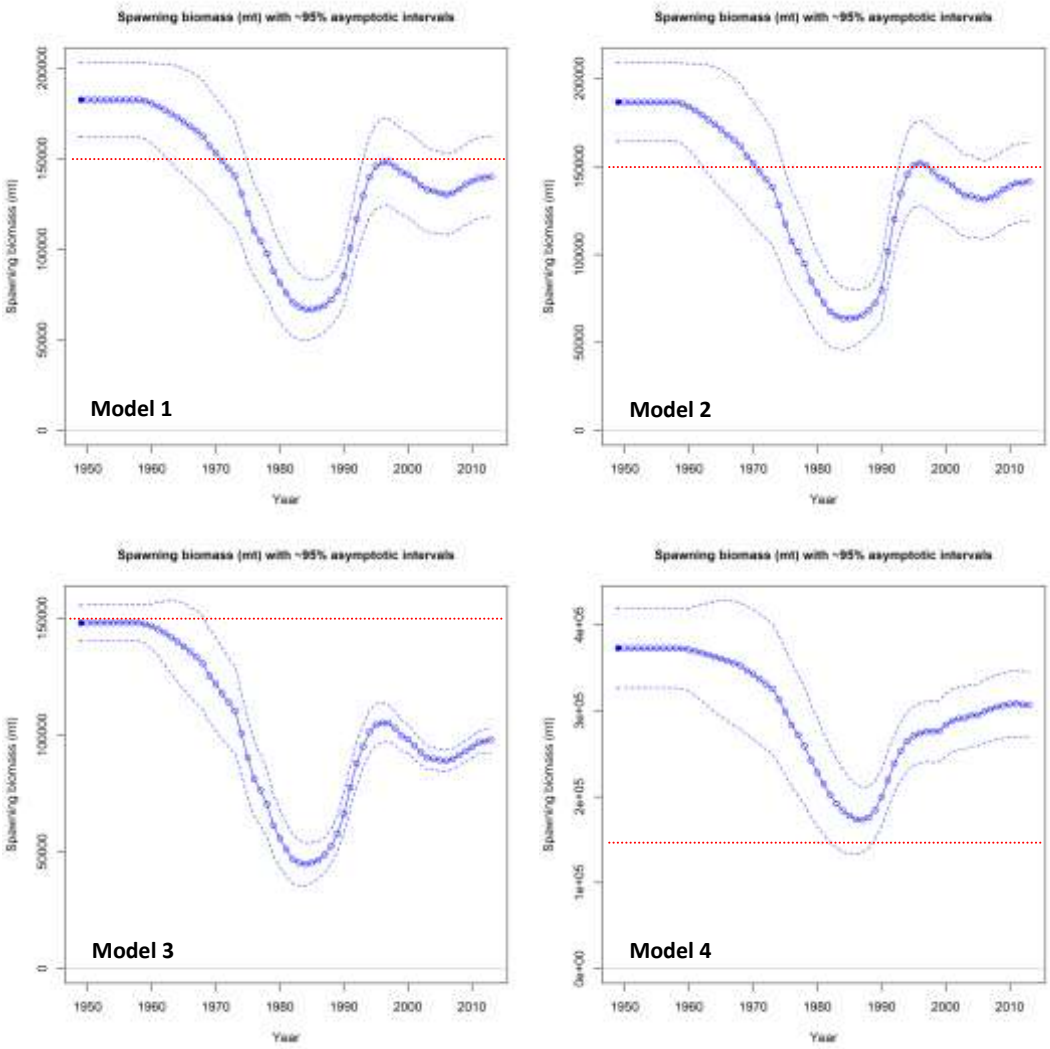


Figure 16. Time series of female spawning biomass for the 4 model alternatives. Vertical axis scales differ among plots; dashed red horizontal line indicates identical values among plots.

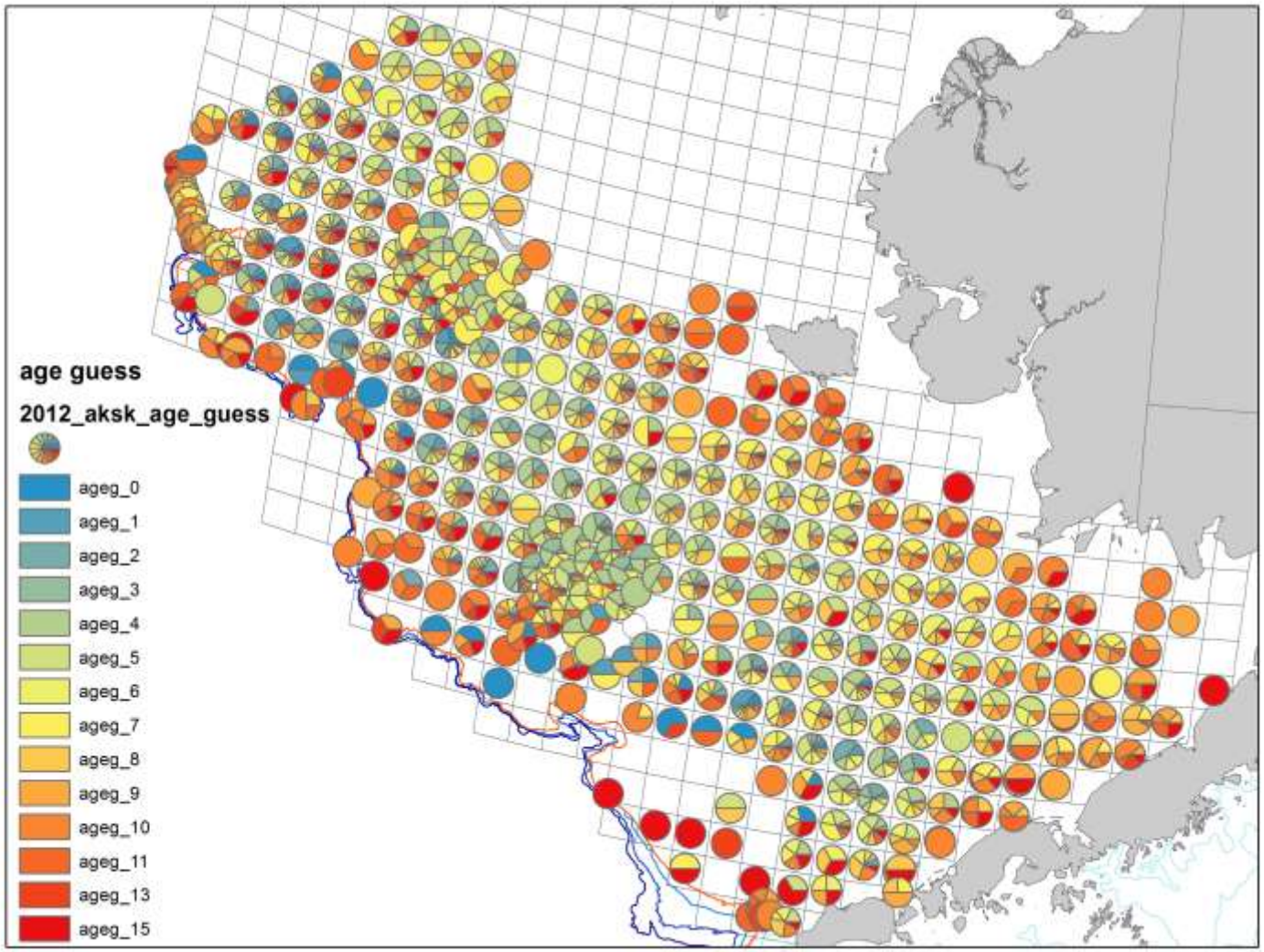


Figure 17. Proportional distribution of Alaska skates in the BSAI by estimated age ("age guess"). Data include the EBS shelf and slope surveys, and each circle indicates a survey haul. Length data were converted to estimated age by interpolating mean length-at-age data from the 2009 survey