ISC – Swordfish Working Group

Working Paper ____

MULTIFAN-CL Assessment of Swordfish in the North Pacific

Pierre Kleiber[1] and Kotaro Yokawa[2]

[1]Pacific Islands Fishery Science Center, NOAA Fisheries, Honolulu, Hawaii
[2]National Research Institute for Far Seas Fisheries, Shimizu, Japan

January 2004

1 Introduction

This paper presents results of a stock assessment of swordfish for presentation at the meeting of the Swordfish Working Group at ISC 4. The analysis was conducted with MULTIFAN-CL, a size-based, age- and spatially-structured population model (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org). Parameters of the model are estimated by maximizing an objective function consisting of both likelihood (data) and prior information components.

2 Data compilation

The data used in the assessment consist of catch, effort, and length-frequency data for 12 fleets defined in the analysis. The details of these data and their stratification are described below.

2.1 Spatio-temporal stratification

The geographic area considered in the assessment is a portion of the north Pacific Ocean subdivided into four regions as shown in Fig. 1. The time period covered by the assessment spans the years 1952 through first quarter of 2003 in quarterly time steps.

2.2 Definition of fisheries

Fourteen fisheries were defined for this assessment (Table 1). Japanese longline accounted for eight of the fisheries consisting of two types in each of four regions. The two types are the traditional shallow, *night* type and *other*, the deeper fishery that developed starting in 1970. The Hawaii longline was kept distinct from Japanese longline and divided into northeast and southeast sectors for another two fisheries roughly corresponding to swordfish targeting in the north and tuna targeting in the south. Finally, North Pacific driftnet fisheries in each region account for another four fisheries.

MULTIFAN-CL analyses were run with various combinations of the above fisheries, some with the Hawaii fisheries excluded and some with the Japanese "night" and "other" longline type combined.

2.3 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above. Catches were expressed in numbers of fish, and effort in hooks for longline and kilometres for driftnet.

Japanese longline catch and effort data were split into *night* and *other*. Records prior to 1970 and records showing fewer than 6 hooks per basket were assigned to *night* type, and remaining records were assigned to *other*. The data were also assigned to model region (Fig.1) and aggregated by type, region, year and quarter.

Hawaii longline data were aggregated by region, year, and quarter. Data from the commercial Japanese driftnet fishery of the 1980s and early 1990s were also aggregated by region, year, and quarter. Catch and nominal catch per unit effort (CPUE) for the various fisheries are shown in Figs. 2 and 3.

Treatment of effort in MULTIFAN-CL is affected by the fact that fisheries are assigned to catchability groups that share common catchability parameters. Effort for such groups is normalised to an average of 1.0 to assist numerical stability. For catchability groups consisting of more than one fishery, such normalisation across all fisheries in a group preserves the relative levels of effort among the fisheries.

2.4 Length-frequency data

Length frequency samples of Japanese longline catch were already separated into *night* and *other*. Samples data from Japanese training vessels were also available but not used because they were not supplied with information to separate them into *night* and *other*. There is also some question as to how representative they are of the Japanese commercial swordfish catch. Japanese driftnet sample data from the 1980s and early 1990s were not available. Sample data were obtained from commercial landings of the Japanese coastal driftnet fishery during 1999 to 2002, but it is questionable how well they represent the earlier, high seas, driftnet catch.

All sample data were assigned to fisheries according to criteria for the catch and effort data. They were then aggregated by fishery, year, and quarter as well as 5 cm size bins ranging from 35 to 310 cm. Samples within a fishery, year, and quarter containing fewer than 10 individuals were eliminated, as were some obviously erroneous measurements in the "other" longline fishery. The availability over time of sample data for the various fisheries is indicated in Fig. 4.

3 Model structure

The technical details of the population dynamic and statistical modelling craft underlying MULTIFAN-CL are given in Hampton and Fournier (2001) and Kleiber et al. (2003). Structuring an assessment model with MULTIFAN-CL involves setting a variety of input flags that determine the temporal, spatial, and many other details of the model structure as well as the fitting procedure and the content of output from the model. A guide for orchestrating a MULTIFAN-CL assessment is given by Kleiber et al. (2003). Here we describe the particular structural setup for this swordfish assessment.

3.1 Biological Structure

As already mentioned, this swordfish model incorporates up to 14 fisheries which harvest swordfish occurring in their respective regions. There are 20 age-classes in the model with age-class 20 comprising fish of age 20 and more years above age of recruitment. To calculate adult, or spawning, abundance, a maturity schedule is assumed with 50%, 75%, 95% in age-classes 4 to 6, and 100% thereafter.

Swordfish recruit to age-class 1 in the four regions in the third quarter of every year. The total recruitment and the proportion recruiting to each region vary with time and these time series are estimated by the model. To estimate a two-parameter Beverton-Holt spawning-recruit relationship (SRR) a lag of two quarters from spawning to recruit is assumed, and a beta distribution prior is placed on the steepness of the SRR curve. Steepness is the ratio of recruitment at *Bo/5* to recruitment at *Bo*, where *Bo* is the unfished equilibrium biomass. The mean and of the beta prior was set at 0.83 and 0.08 respectively.

The population age structure in the initial time period in each region is assumed to be in equilibrium as determined by the average of natural mortality plus fishing mortality during the first 5 years. Natural mortality (*M*) is an estimated parameter and is assumed to be constant with time. MULTIFAN-CL allows estimation of parameters for age variation in *M*, but this feature is not yet implemented for the swordfish assessment.

To relate age-structure to size structure in the model, swordfish are assumed to grow in length according to the von Bertalanffy growth curve. The average sizes of the first and last age-classes are estimated parameters as is the growth rate constant, *K*. Size at age is assumed to be variable about the von Bertalanffy curve according to an estimated median , and an additional estimated parameter governs the rate of change of the actual with age.

In the model, a proportion of the swordfish move from one region to another at the beginning of each quarter mediated by movement parameters (the proportions) connecting regions sharing a common boundary. There are four inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients. Thus 2×4×4 = 32 movement parameters are estimated. Age dependency can be accommodated with additional movement parameters, but this has not been implemented as yet in the swordfish model. The seasonal movement pattern is invariant from year to year.

3.2 Fishing

In the model, fishing mortality consists of selectivity, which governs the effect of age on fishing mortality; catchability, which scales fishing effort to fishing mortality; and effort deviations, which are time-independent random effects in the fishing effort–fishing mortality relationship.

The selectivity pattern is estimated as separate age-specific parameters (with a range of 0– 1). To avoid over-parameterization, the selectivity curves are constrained to be constant for the oldest three age-classes, and various smoothing constraints are also in effect. Because the selectivity is assumed to be a length-based process penalties on the overlap of sizes between adjacent age-classes imparts a degree of smoothness to the selectiviy curves. In addition penalties are appllied to the second and third differences along the selectivity curves to further encourage smoothness.

Individual selectivity curves are assumed for each fishery. However, fisheries are assigned to selectivity groups within which common selectivity curves apply. For ths assessment fisheries in the northwest region are grouped with their corresponding fisheries in the northeast region, and fisheries in the two southern regions are similarly grouped.

Catchability varies seasonally with four independent quarterly parameters. Longer term variation also occurs in a structural time series of annual steps with penalty constraints applied to the estimated changes from year to year.

As with selectivity, fisheries are assigned to catchability groups with shared catchability parameters. For this assessment "night" longline, "other" longline, and driftnet are grouped across all regions. However the Hawaii longline fisheries were kept in separate north and south groups.

Effort deviations constrained by prior distributions with zero mean, were used to model the random variation in the effort – fishing mortality relationship.

3.3 Observation models for the data

MULTIFAN-CL accepts four data components as contributors to parameter estimation– the total catch data, the length-frequency data, the weight-frequency data and the tagging data. In this swordfish analysis only the first two apply because sample data were all supplied as lengths and because no tagging data were available. The observed total catch data are assumed to be unbiased and relatively precise, with the SD of residuals on the log scale being 0.007.

The probability distributions for the length-frequency proportions are assumed to be approximated by robust normal distributions, with the variance determined by the effective sample size and the observed length-frequency proportion. Effective sample size is normally assumed to be 10% of the actual sample size with a maximum effective sample size of 100. Reduction of the effective sample size recognises that length-frequency samples are not truly random and would have higher variance as a result. For some runs, the effective sample size was reduced to 1% of the actual sample size for Japanese longlines in recognition of the fact that small swordfish are apparently omitted from the sampling

3.4 Parameter estimation

The parameters are estimated by maximizing an objective function which is the sum of the log-likelihood of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. Estimation proceeds in a series of phases, beginning with arbitrary starting values for most parameters. A shell script, dubbed the *doitall* file, orchestrates (and documents) the phased procedure. Some parameters were assigned specified starting values consistent with available biological information. The values of these parameters and other structural information are provided in an initial input file, the *ini* file[1]. To widely explore the parameter space, we applied a high penalty to deviations of the "overall exploitation rate" (total catch in number divided by total recruitment) from several specified target values. The penalty was removed in the final phase. This procedure ensures that a wide range of population sizes and average exploitation levels was explored by the optimization algorithm. In addition, we ran fits with various ordering of the phases, again ensuring that various fits proceeded through a variety of trajectories in parameter space.

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest.

3.5 Stock assessment interpretation methods

Ancillary analyses are conducted in order to interpret the results of the model for stock assessment purposes. These methods are summarized below and the details can be found in Kleiber et al. (2003). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach.

3.5.1 Fishery impact

Many assessments estimate the ratio of recent to initial biomass as an index of fishery depletion. The problem with this approach is that recruitment may vary considerably throughout the time series, and if either the initial or recent biomass estimates (or both) are "non-representative" because of recruitment variability, then the ratio may not measure fishery depletion, but simply reflect recruitment variability.

We approach this problem by computing biomass time series (at the region level) using the estimated model parameters, but assuming that fishing mortality was zero. Because both the *real* biomass B and the *unexploited* biomass B_0 incorporate recruitment variability, their ratio at each time step of the analysis $\frac{B}{B_0}$ can be interpreted as an index of fishery depletion.

3.5.2 Yield analysis and projections

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers, *Fmult*, the natural mortality-at-age (M_a), the mean weight-at-age (w_a) and the SRR parameters α and β. All of these parameters, apart from *Fmult*, which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to *Fmult* can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as limit reference points. These ratios are also determined and their confidence intervals estimated using a likelihood profile technique.

[1] Details of elements of the *doitall* and *.ini* files as well as other input files that structure a MULTIFAN-CL run are given by Kleiber, et al. (2003).

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 1999–2002. We do not include 2003 in the average because available catch and effort data are not complete for year 2003.

4 Variations in Model Structure

Several MULTIFAN-CL runs were conducted with a variety of flag settings and assembledges of data. For the purposes of this presentation, we consider the base, or nominal, case to be structure as described above and parameterized as described in Table 2. The *doitall* and *ini* files for this run are reproduced in Appendices A and B. The conditions of the various runs in relation to the nominal run are detailed in Table 3.

5 Results

5.1 Model fit diagnostics

All model fits proceeded till the maximum gradient of the objective function was less than 2e-6 of the value of the objective function, and some fits achieved a much lower gradient than that (Table 4).

The model is designed to fit the observed catches rather well which is confirmed for the base case (run A) in Fig. 2 where the predicted catches are compared with the observed catches. As a further diagnostic the residuals (Fig. 5) are small and show little evidenced of bias or trends.

The overall fit of predicted and observed size distributions is given in Fig. 6 for the base model run. In some fisheries the model is predicting somewhat larger sizes than were observed, particularly for the *other* Japan longline fishery in the two eastern zones. In addition the Hawaii longline fishery in the SE zone shows an observed peak of small (~70 cm) fishes which is missed by the model. The estimated selectivity patterns of the Hawaii fishery in the NE zone shows higher selectivity for small (young) fish than that of the other fisheries (Fig. 7) , but curiously this is not evident in the SE zone where the small fish mode is prominent.

It is reported that in the sampling of the commercial Japanese longline catch, small fishes are ignored, which is of some concern. We therefore tried run B in which the size sample data for the Japanese longline fisheries were de-weighted by a factor of 10. However, the small fish were still mostly missing in the predicted size distributions. Run B solved an evident problem with the results of run A wherein the fishery impact calculation (see below) gave negative numbers, which should be an impossibility. However, the catch residual plot (not shown) indicates a pattern of bias in the predicted catches.

Another model fit diagnostic is a plot of the effort deviations (Fig. 8) which show trends in the scatter for some fisheries. This could indicate some trend in catchability that has not been captured by the model but might be captured by lowering the penalty on catchability deviations for those fisheries. Fig. 9 shows the catchability trajectories as estimated in run A with the scatter of effort deviations (scaled in catchability units) superimposed. In Fig. 10 the catchability trajectories are smoothed to eliminate the seasonal variation, more easily showing the degree to which the long-term catchability trajectories capture trends in effort deviation.

5.2 Model parameter estimates

Because runs A and B are both problematic, we returned to a previous run done before the Hawaii data had been updated and processed for input to the model (run C). This is the basis of subsequent results presented here.

The estimated size at age shows a large increase with age in variability about the von Bertalanffy (VB) growth curve (Fig. 11). MULTIFAN-CL can estimate size at age as independent parameters for a number of the younger age classes, but for this assessment we did not find much departure from the VB curve; so for parameter parsimony, we applied the VB curve to all age-classes. The growth rate parameter, *K*, was estimated at 0.14 yr^{1} and natural mortality, *M*, at 0.64 yr^{-1} for run C. Estimates of these parameters and other results for all the runs are given in Table 4. For parameter parsimony, we did not attempt to estimate natural mortality at age.

A graphic representation of the estimated movement coefficients is shown in Fig. 12. The graphic shows no change in coefficient with age class because we did not attempt to estimate such changes. Almost all trans-boundary movement is estimated to occur in quarters 2 and 4. Some diffusive movement is indicated in the 2^{nd} quarter with movement in both directions between the NW and NE zones. Fig. 13 is a similar graphic showing movement in terms of number of animals crossing the boundary per quarter. This is dominated by the youngest age-classes because because these are the most numerous.

5.3 Stock assessment results

Estimated recruitment trajectories show somewhat different patterns by region (Fig. 14). A spurt of high recruitment seen early in the time frame in the NE whereas the NW region recruitment spurts throughout the time frame. The southern regions show a rising recruitment pattern.

The different regional recruitment patterns translate into corresponding trajectories of biomass (Fig.15). The impact of the fisheries on the population is seen to be minimal in all regions with the hypothetical unfished abundance estimated to be only marginally higher than the total abundance with fishing. A measure of fishery impact could be defined as the proportion by which the biomass without fishing is reduced in the presence of fishing. In run C (and most other runs), that measure of impact is small on average (Table 4) which is consistent with fishing mortality (*F*) being small relative to *M* in most runs.

Stock status is often reckoned by the relationship of fishing mortality (*F*) to the fishing mortality at MSY (F_{MSY}). To estimate these and other MSY related reference points, it is necessary to establish some form of a stock-recruitment relationship (SRR). The estimated Beverton-Holt SRR from run C is given in Fig. 16. The steepness parameter was estimated at 0.83, unchanged from the mean of its prior distribution.

With the SRR estimated, F_{MSY} and B_{MSY} were calculated, and for run C, the recent fishing mortality is seen to be a small fraction of F_{MSY}, while recent average biomass (*B*) is twice B_{MSY} (Table 4), confirming the picture of low impact of fishing. Runs Cx, Cxx, D, and Dx show that if the model is forced into a situation of substantive exploitation by the fisheries, and the forcing subsequently released, then the model returns to essentially the same low-impact scenario. That scenario is echoed yet again in the estimated yield curve for run C (Fig. 17) where the maximum yield is obtained at an *Fmult* near 40 and the lower boundary of the approximate confidence region is at maximum at an *Fmult* of more than 20.

This low fishery impact is a result of (or concomitant with) rather high estimates of natural mortality. The series of runs Cx1 through Cx5 show the result of forcing the model to adopt a series of fixed natural mortialities (Table 4). The associated yield curves are plotted in Fig.18. As expected the lower imposed values of *M* produce scenarios of greater fishery impact. Biomass trajectories for the same series of runs (Fig. 19) show substantial fishery impact with low *M* at the end of the time frame, but they also show an enormous impact at the start of the time frame.

For completeness we show tabular results of several additional runs (Table 4). The E and F run series, with de-weighted sample data for Japanese longlines was undertaken because of concern about the effect of truncated size sampling. The essential picture of low fishery impact is repeated, but the model fitting is somewhat unstable in that the model did not return as faithfully to its original fit when perturbed with an imposed exploitation rate and then released (runs Ex and Exx).

Run G addresses the question of the inapplicability of coastal driftnet samples to the high seas driftnet fishery operating a decade earlier. It appears not to have made much difference.

Run H examines the effect of simplifying the model by combining the *night* and *other* longline fisheries. The result is very low impact of fishing and low F/F_{MSY} yet the B/B_{msy} ratio is less than 1.0, which would normally be taken as a sign of an over fished state. Some of the other runs show a similar situation with not quite such a low B/B_{msy} (runs B, E, and F). In such cases the biomass must be low due to causes other than the direct effect of fishing. Juxtaposed biomass and recruitment trajectories show that biomass tracks declining recruitment relatively closely in these model runs (Fig. 20), leading to a low abundance in spite of small affect of the fisheries.

6 Discussion and conclusions

The main implication of the analyses presented here is that swordfish in the north Pacific are very lightly exploited by the fisheries. This conclusion is contingent on rather large estimates of natural mortality of 0.6 yr^{-1} or higher. If natural mortality is forced down in the model to levels as low as 0.2 yr^{1}, the estimated exploitation is increased, but the population would still not be overfished in recent times. However, in this case the model reports that there must have been unbelievably high exploitation in the early years of the time series.

Given a scenario of very low exploitation, variations in abundance must be driven by factors other than direct effects of fishing. Most of our output scenarios show biomass responding to variations in recruitment, which could be driven by any number of environmental factors besides fishing. However, another consequence of very low exploitation is lack of an informative signal in the fishery data. This can lead to unstable fits and other difficulties in the model, some of which we have seen in these swordfish analyses. So if we accept that exploitation is low, we must also be skeptical of the patterns of recruitment and abundance reported by the model. We have seen very different trends in bioamass in different runs of the model, but all with low exploitation. We have defined a measure of exploitation that depends on the ratio of estimated biomass to biomass without fishing (B/B_0). It is likely that this ratio is a more robust estimate than either its numerator or denominator.

Of course, another way that a signal of fishing impact could be lacking in the data, even in the presence of substantial fishery impact, would be if the data are incomplete or inaccurate. There are many factors that could be of concern in this regard including the truncation at the small end of the size distribution in longline sampling, and lack of sample data for driftnets. Another problem could be the lack of adequate sampling to deal with differential growth by sex and the need to incorporate into the model the ability to accommodate such data. Finally, there is a lack of tagging data which are probably the most powerful avenue of insight into the dynamics of a population when exploitation is low or when other data are problematic.

7 References

Fournier, D.A., Hampton, J., and Sibert, J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Can. J. Fish. Aquat. Sci.* **55**: 2105–2116.

Hampton, J., and Fournier, D.A. 2001. A spatially-disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean. *Mar. Freshw. Res.* **52**:937–963.

Kleiber, P., Hampton, J., and Fournier, D.A. 2003. MULTIFAN-CL Users' Guide. http://www.multifan-cl.org/userguide.pdf.

Table 1. Definition of fisheries for the MULTIFAN-CL analysis of north Pacific swordfish.

Fishery	***Gear***	***Region***	***Selectivity grouping***	***Catchability grouping***
JLL-NW-night	longline	1	a	a
JLL-NE-night	longline	2	a	a
JLL-SW-night	longline	3	b	a
JLL-SW-night	longline	4	b	a
JLL-NW-other	longline	1	c	b
JLL-NE-other	longline	2	c	b
JLL-SW-other	longline	3	d	b
JLL-SE-other	longline	4	d	b
Drift-NW	driftnet	1	e	c
Drift-NE	driftnet	2	e	c
Drift-SW	driftnet	3	e	c
Drift-SW	driftnet	4	e	c
HLL-NE	longline	2	f	d
HLL-SE	longline	4	g	e

Table 2. Main structural assumptions of the swordfish analysis, and details of estimated parameters, priors and bounds. Note that the number of estimated parameters shown is substantially greater than the effective number of parameters in a statistical sense because of the effects of priors, bounds and smoothing penalties.

Category	Assumptions	Estimated parameters (ln = log transformed parameter)	No.	Prior		Bounds	
				μ	σ	Low	High
Observation model for total catch data	Observation errors small, equivalent to a residual σ on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.1 times actual sample size (0.01 times actual for JPN longline in some runs).	None	na	na	na	na	na
Recruitment	Occurs as discrete events in the third quarter of each year. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior year via a Beverton-Holt SRR (beta prior for steepness with mode at 0.9 and σ of 0.08) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	52	SRR	0.7	-20	20
		Average spatial distribution of recruitment	3	-	-	0	1
		Time series deviations from average spatial distribution (ln)	152	0	1	-3	3
Initial population	A function of the initial recruitment and equilibrium age structure in each region, which is in turn assumed to arise from the natural mortality and average fishing mortality in the first 5 years of the time series.	Initial recruitment scaling (ln)	1	-	-	-8	8
Age and growth	20 annual age-classes, with the last representing a plus group. Age-class mean lengths constrained by VB curve. σ of length-at-age are log-linearly related to the mean length-at-age. Mean weights (W_j) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (a=0.00001585, b=3).	Mean length age class 1	1	-	-	10	100
		Mean length age class 20	1	-	-	20	500
		von Bertalanffy *K*	1	-	-	0.05	0.5
		Length-at-age σ	1	-	-	3	20
		Dependency on mean length (ln)	1	-	-	-0.69	0.69
Selectivity	Constant over time. Various smoothing penalties applied. Coefficients for the last 4 age-classes are constrained to be equal. Longline fleets share selectivity with the same region. Driftnet selectivity is shared over all regions.	Selectivity coefficients	136	-	-	0	1

Catchability	Seasonal variation for all fisheries. Japan "other" (deep) longline and dritnet fisheries have long-term variation, with catchability deviations occuring every year. Japan "other" longline has no long-term variation.	Average catchability coefficients (ln)	5	-	-	-15	1
		Seasonal parameters	20	0	2.2	-	-
		Catchability time series	367	0	0.1	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and σ 0.22 at the average level of effort for each fishery - σ inversely proportional to the square root of effort.	Effort deviations	1534	0	0.22	-15	15
Natural mortality	Constant over time and among regions.	Average natural mortality (ln)	1	0.2	0.5	-	-
Movement	Varies by quarter but constant among years.	Movement coefficients	32	0	0.32	0	3

Table 3. Definition of various MULTIFAN-CL runs for analysis of north Pacific swordfish.

Run Code	Run conditions
A	Base run. All 14 fisheries included.
B	Like run A but with Japan longline sample data de-weighted by an extra factor of 10.
C	Like run A but with Hawaii longline fisheries removed.
Cx	Added phase at end of run C with exploitation target of 20% imposed.
Cxx	Added phase at end of run Cx with exploitation target removed.
D	Like run C but with phases reordered and exploitation target set to 20% in first phase.
Dx	Added phase at end of run D with exploitation target removed.
Cx1	Added phase at end of run C with natural mortality fixed at 0.2 yr^{1}.
Cx2	Added phase at end of run C with natural mortality fixed at 0.3 yr^{1}.
Cx3	Added phase at end of run Cwith natural mortality fixed at 0.4 yr^{1}.
Cx4	Added phase at end of run C with natural mortality fixed at 0.5 yr^{1}.
Cx5	Added phase at end of run C with natural mortality fixed at 0.6 yr^{1}.
E	Like run C but with Japan longline sample data de-weighted by an extra factor of 10.
F	Like run E but with phases re-ordered.
Ex	Added phase at end of run E with exploitation target of 20% imposed.
Exx	Added phase at end of run Ex with exploitation target removed.
G	Like run C but with driftnet sample data removed and driftnet selectivities tied to Japan longline in corresponding regions.
H	Japan longline *night* and *other* fisheries combined into single fisheries in their respective regions, and no Hawaii longline, i.e. total of 8 fleets, 4 LL and 4 driftnet.

Table 4. Selection of parameter estimates from various model runs. "Final grad." is the final gradient achieved in the objective function as a proportion of the final objective function value. Fishery impact (1-B/B_0) is reckoned as the amount (as proportion) that the biomass is depressed by fishing on average in the recent year 1999—2002. *F*, *B*, and B_0, are averages over those same years, and F_{MSY}, B_{MSY}, are based on the average pattern of fishing effort by region and age class also over the same years.

Run Code	Run Conditions	Final grad.	*K* (yr^{-1})	*M* (yr^{-1})	*Impact* 1-B/B_0	*F* (yr^{-1})	F/F_{MSY}	B/B_{MSY}
A	14 fisheries	4e-8	0.13	0.75	-7 ???	0.0029	0.036	1.4
B	de-wt. JLL	8e-7	0.17	0.75	4E-5	2e-5	0.006	1.1
C	no HI fisheries	1e-9	0.14	0.64	0.030	0.0097	0.06	2.1
Cx	E-target	1e-9	0.14	0.43	0.192	0.046	0.20	2.1
Cxx	E-target removed	1e-9	0.14	0.62	0.030	0.0098	0.058	2.1
D	Δ phases, & E-targ.	1e-7	0.16	0.28	0.53	0.094	0.37	1.6
Dx	E-target removed	7e-6	0.16	0.65	0.030	0.010	0.06	2.0
Cx1	M .2	6e-8	0.16	0.2	0.488	0.067	0.33	1.7
Cx2	M .3	8e-9	0.14	0.3	0.317	0.055	0.23	2.1
Cx3	M .4	1e-6	0.14	0.4	0.170	0.036	0.17	2.2
Cx4	M .5	9e-10	0.14	0.5	0.083	0.022	0.11	2.2
Cx5	M .6	1e-9	0.14	0.6	0.038	0.012	0.067	2.1
E	de-wt. JLL	2e-7	0.27	1.44	~0	5E-7	0.006	1.1
F	Δ phases, de-wt. JLL	2e-6	0.23	1.27	3E-5	6E-6	0.006	1.1
Ex	E-targ., de-wt. JLL	2e-6	0.21	0.34	0.52	0.14	0.45	1.4
Exx	relax E-targ., de-wt. JLL	2e-6	0.25	1.2	0.022	0.14	0.10	1.7
G	no drift samples	2e-9	0.13	0.73	0.015	0.0055	0.03	2.0
H	JLL *night* ><JLL *other*	1e-7	0.14	0.79	6E-4	0.0003	0.008	0.7

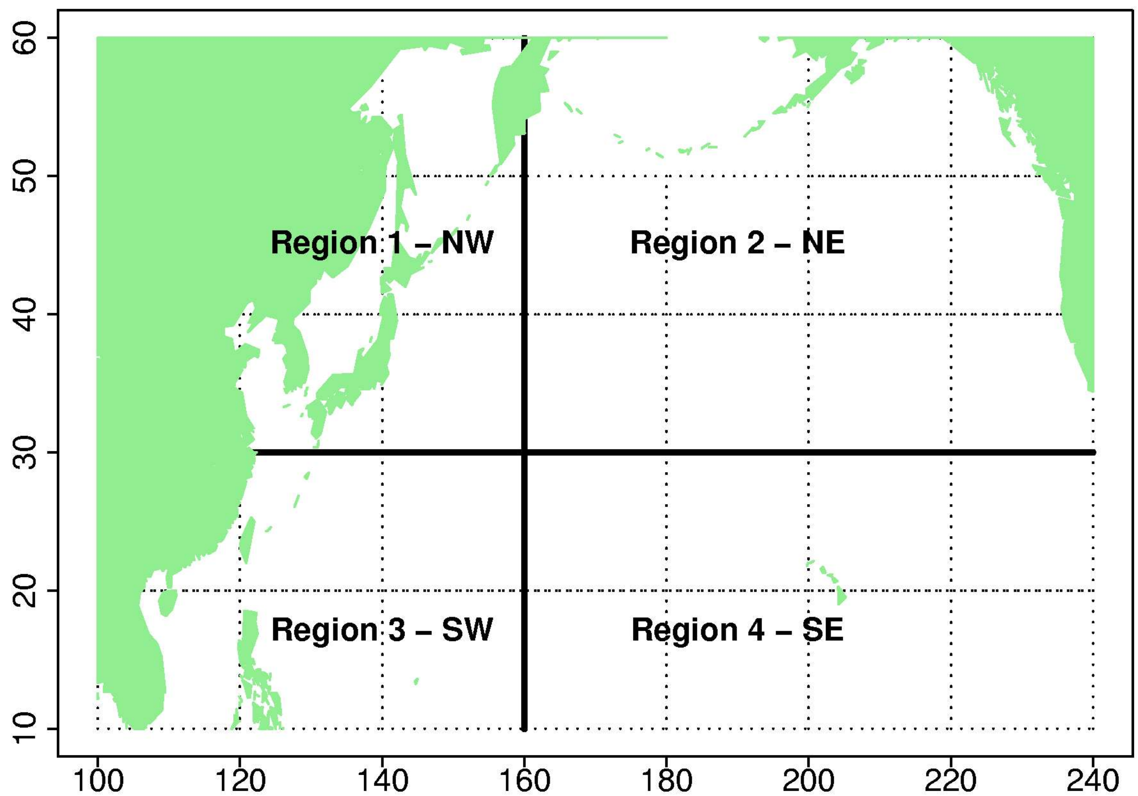

Figure 1. Subregions of the north Pacific used in the MULTIFAN-CL assessment.

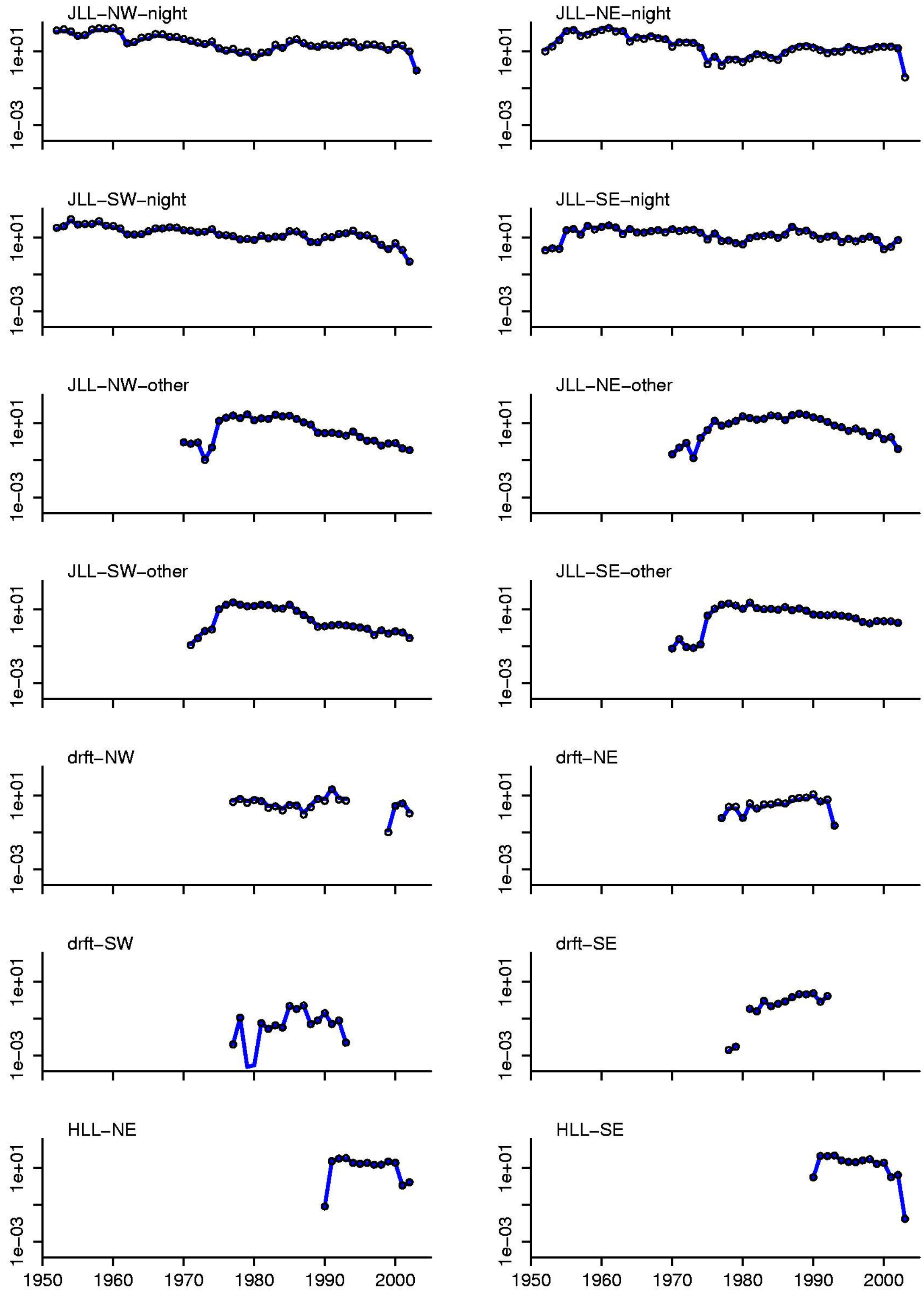

Figure 2. Annual catches, by fishery. Circles are observed and the lines are model predictions. Units are catch number in thousands for the longline fisheries and thousand metric tonnes for all other fisheries. . The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort.

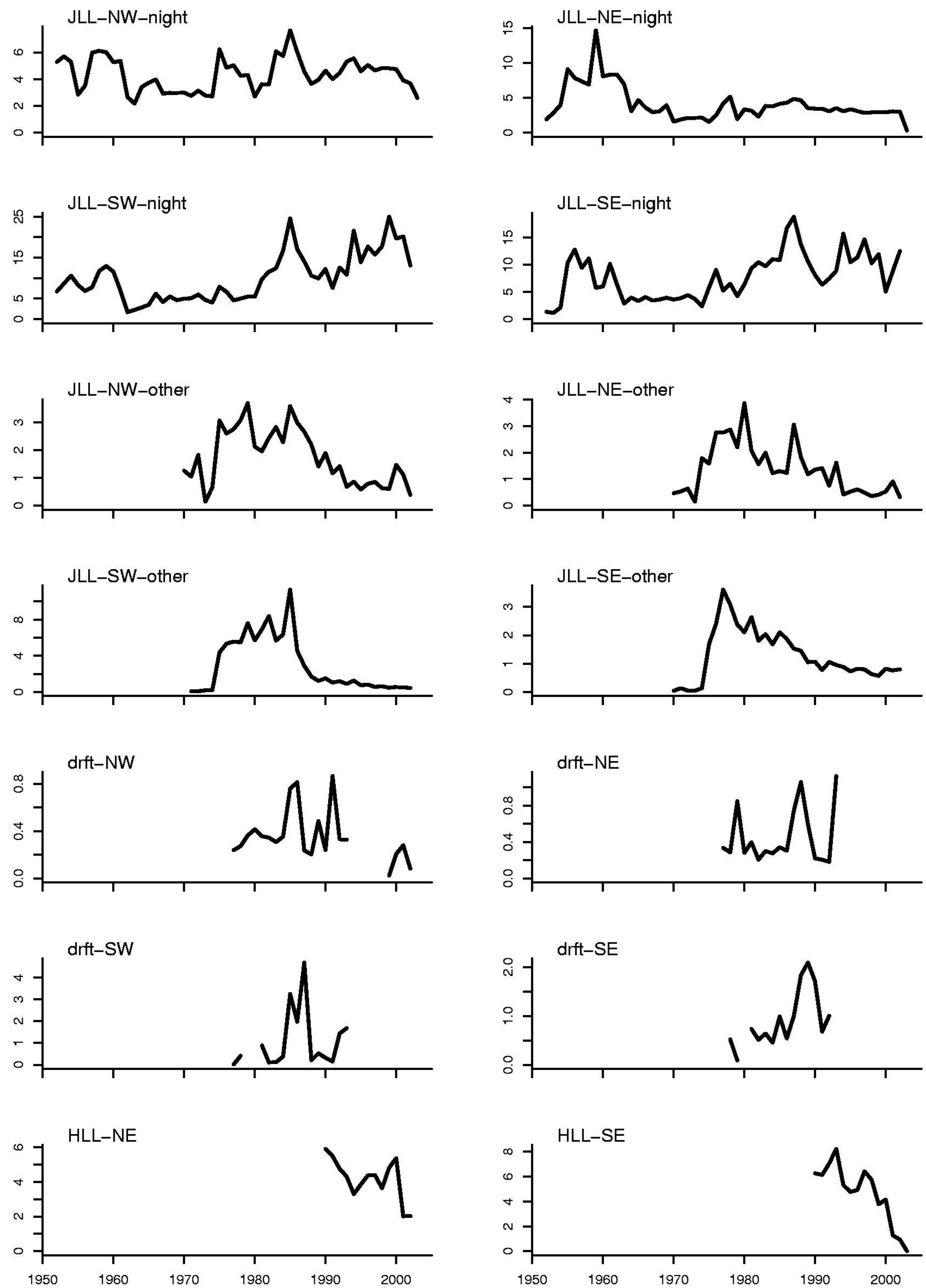

Figure 3. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL1–LL5), catch number per 100 nominal hooks (AU LL, CH/TW LL) and catch (t) per day fished/searched (all PS fisheries). Note that CPUE for PH RN, PH HL and ID are arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

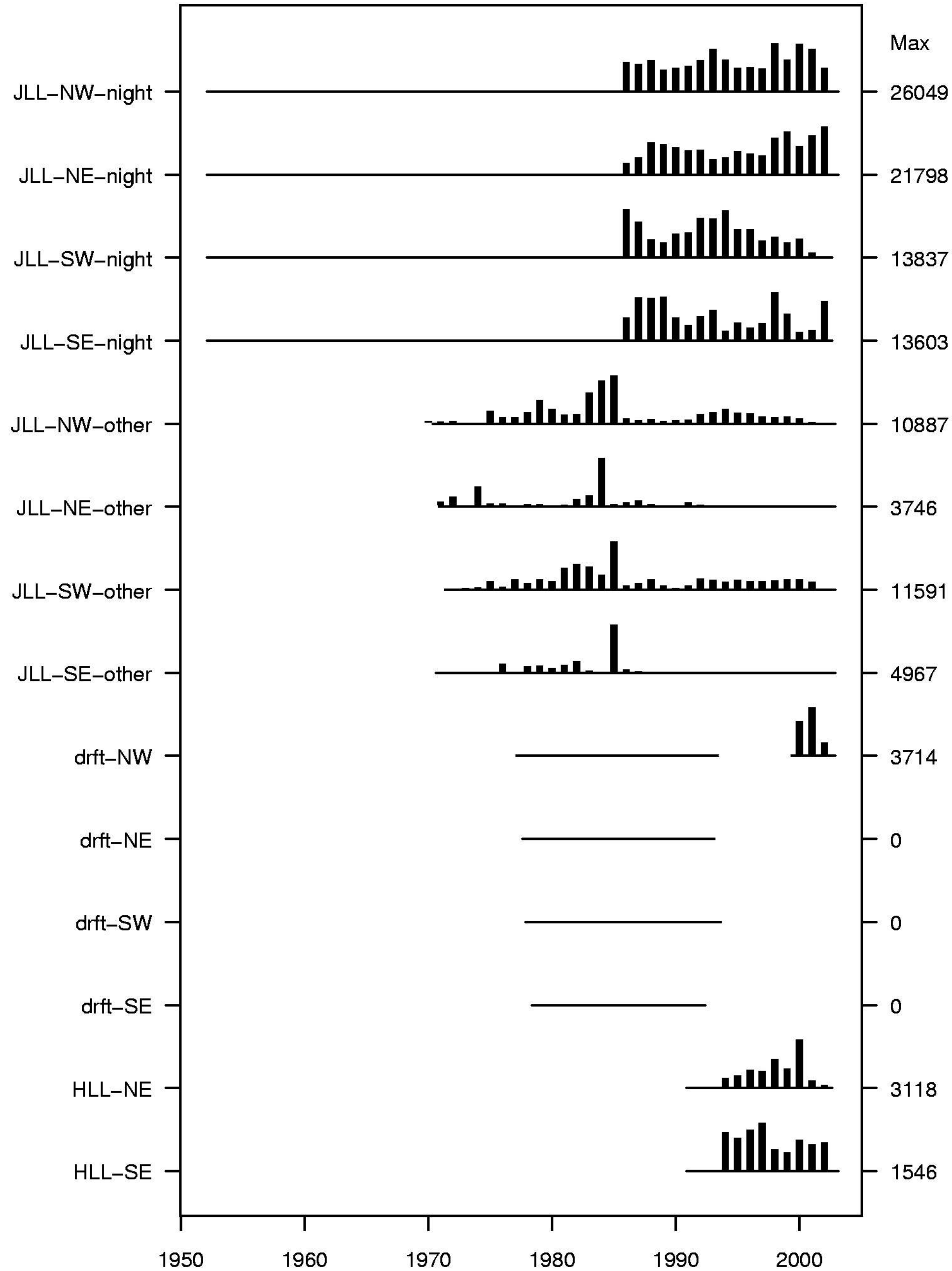

Figure 4. Number of fish size measurements by year for each fishery. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

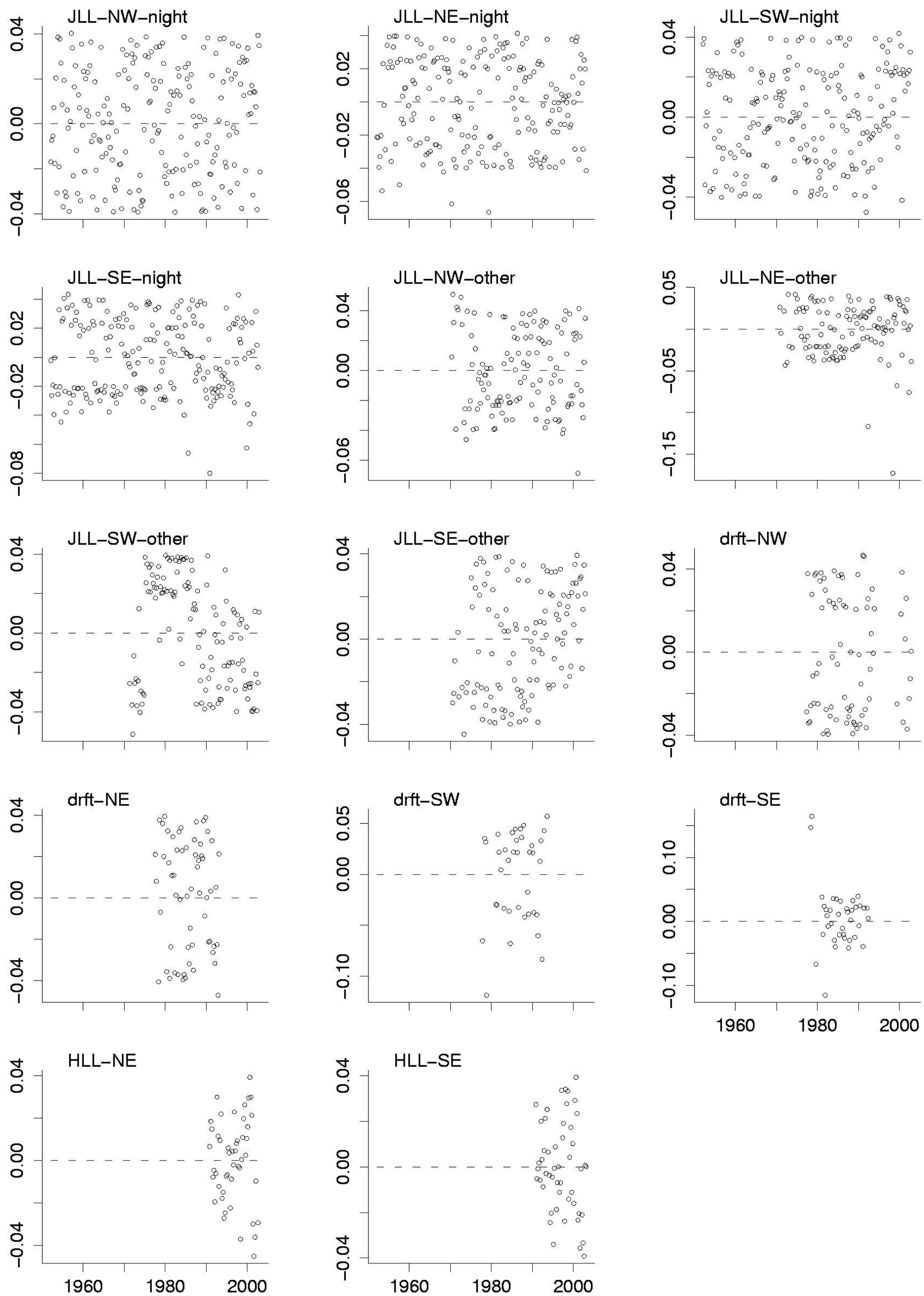

Figure 5. Residuals of ln (total catch) for each fishery in base run.

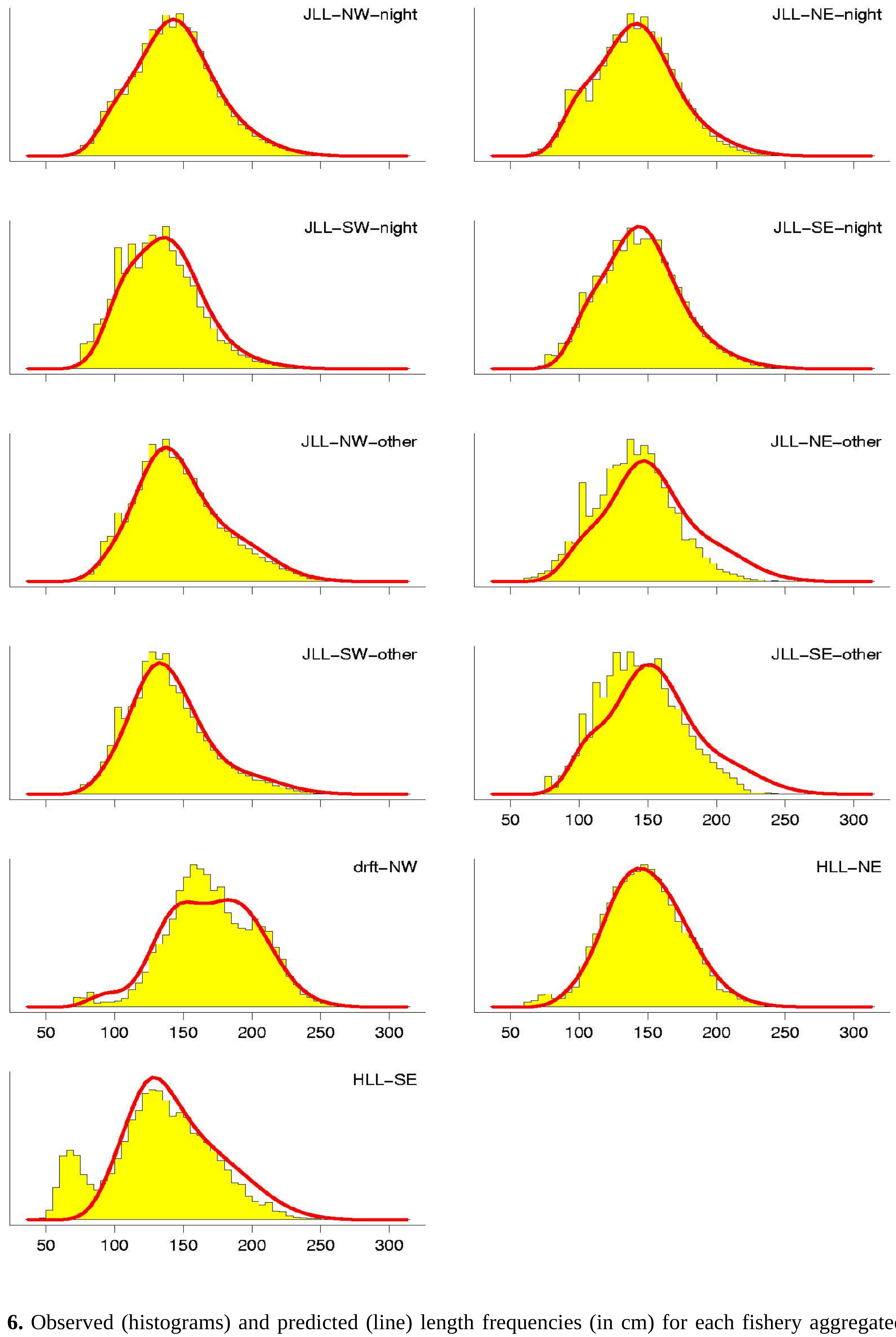

Figure 6. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time. Run A

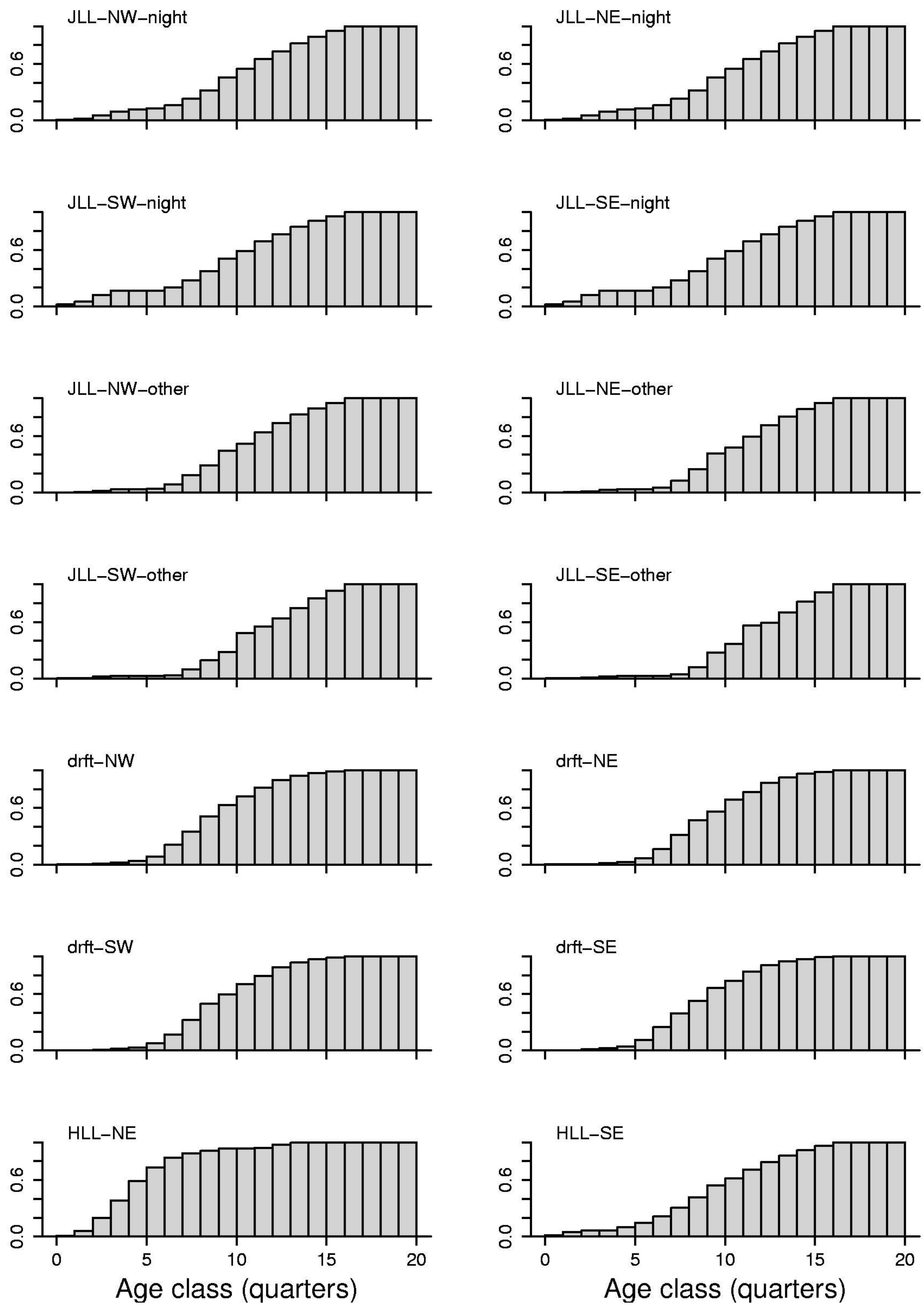

Figure 7. Selectivity coefficients, by fishery. Run A.

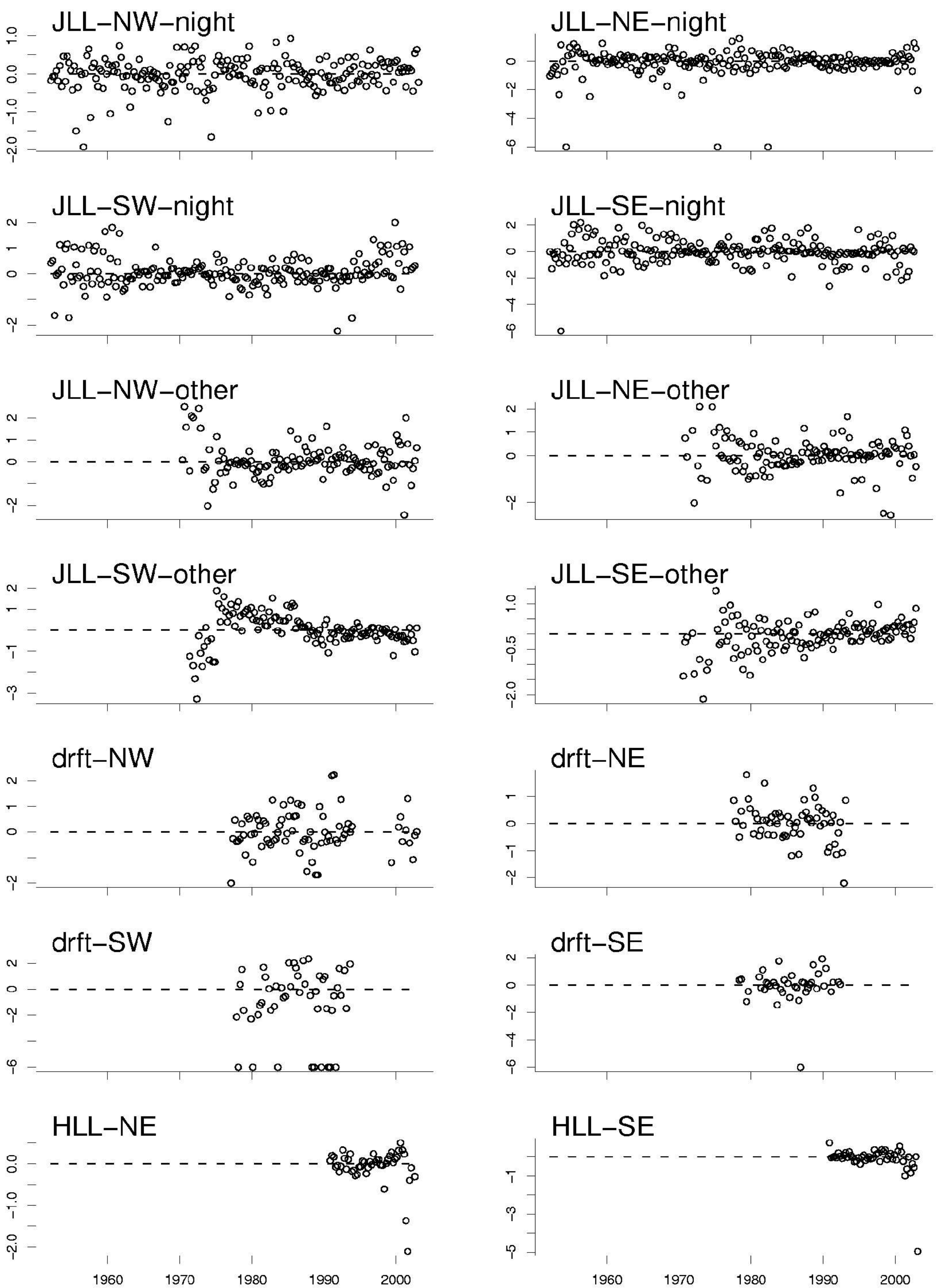

Figure 8. Effort deviations for each fishery. Run A.

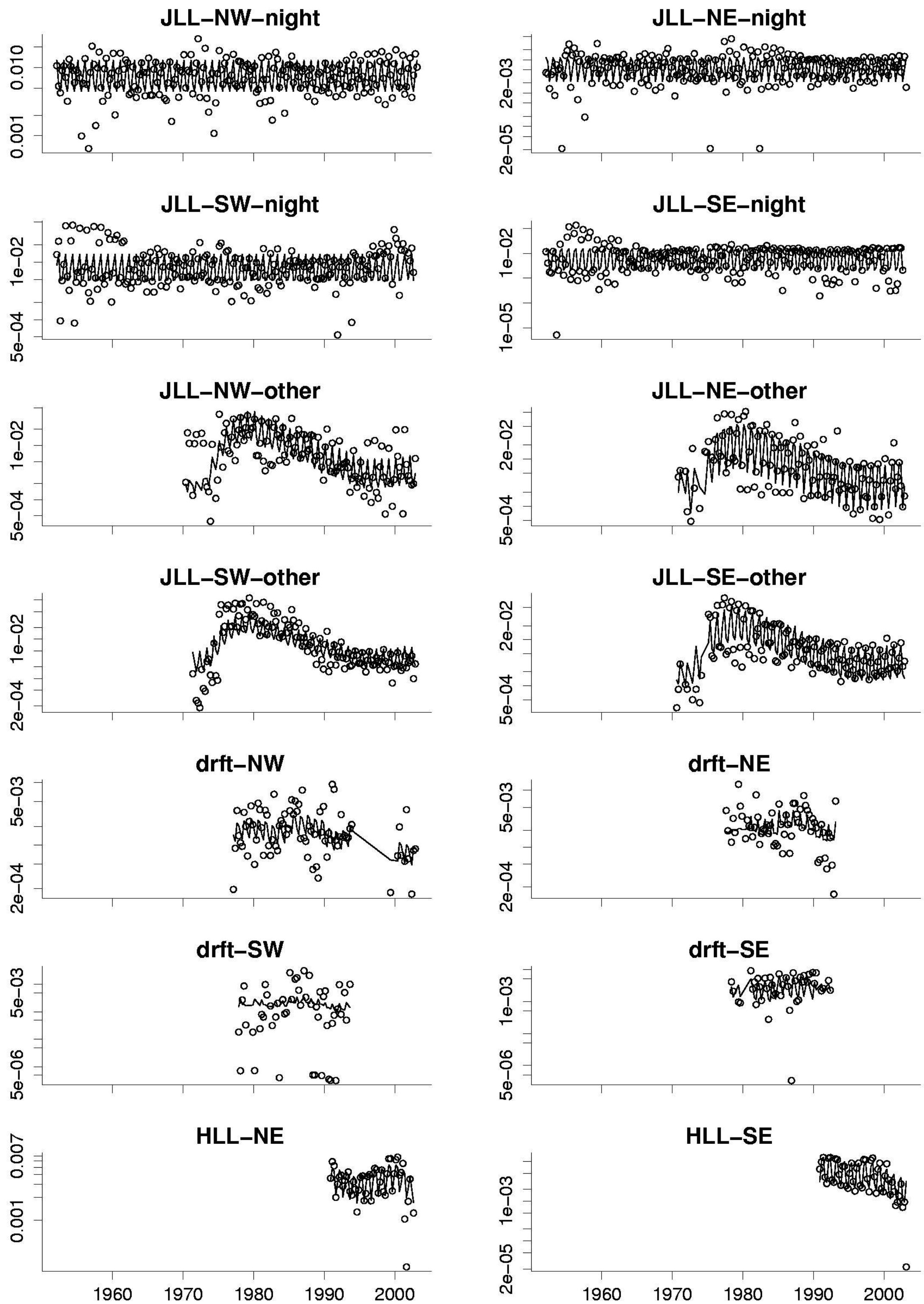

Figure 9. Effort deviations for each fishery surroundingestimated catchability trajectories. Run A.

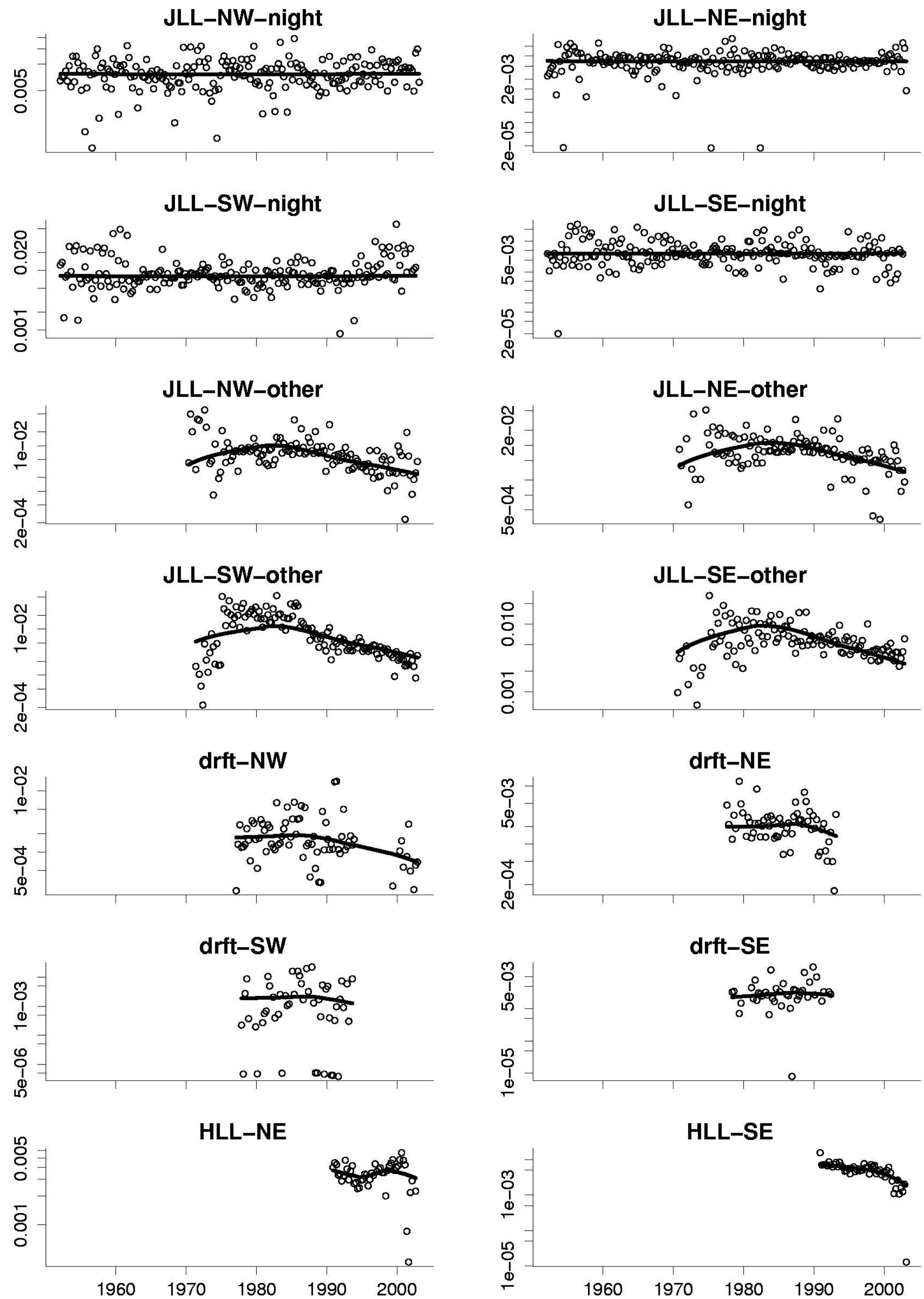

Figure 10. Effort deviations for each fishery surrounding smoothed catchability trajectories. Run A.

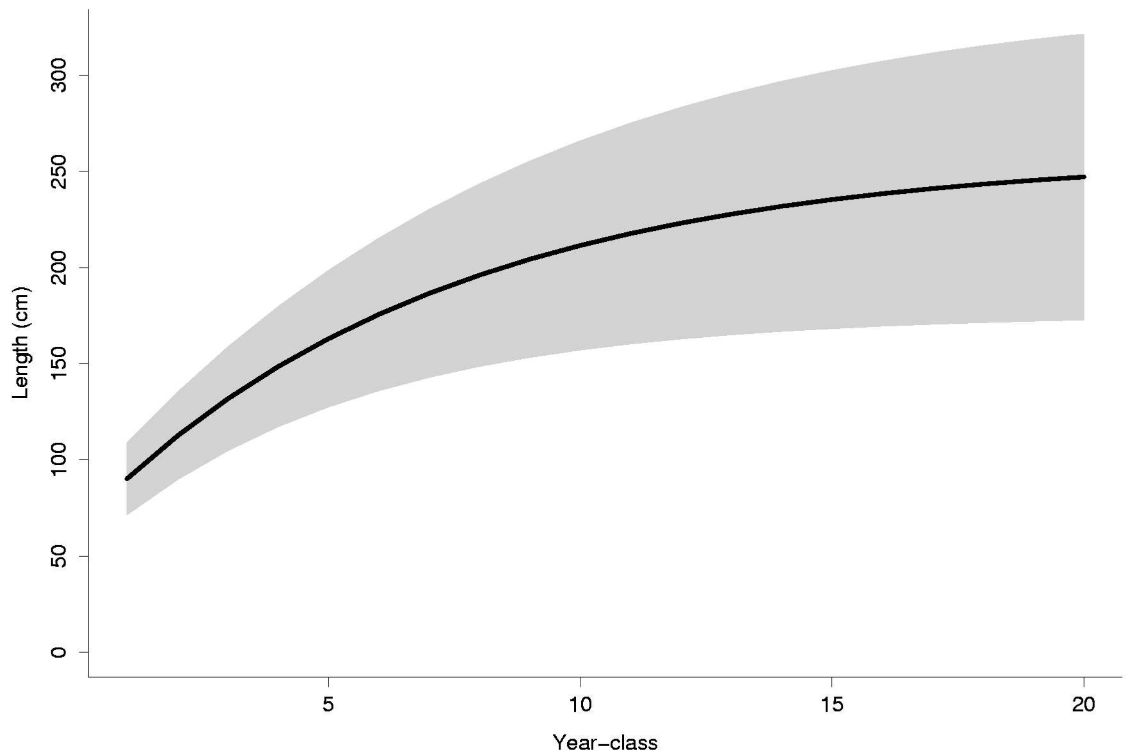

Figure 11. Estimated mean lengths-at-age. The shaded area represents approximate 95% confidence region (±2). Run C.

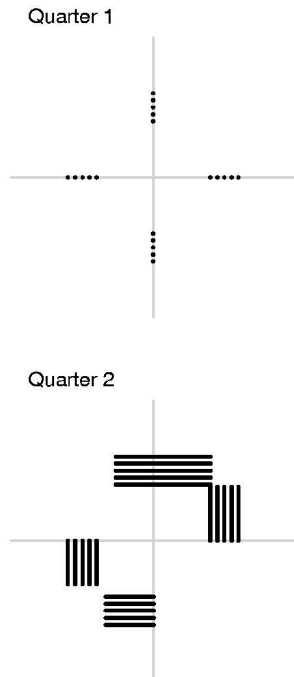

Figure 12. Movement coefficients by quarter. Grey lines indicate boundary between model regions. Dark bars indicate direction of movement, and their lengths indicate the value of the movement coefficient (averaged over 5 even subsets of the age classes). Their position (left to right or bottom to top) indicate youngest to oldest subset of age classes. The maximum movement coefficient has a value of 0.087 per quarter. Run C.

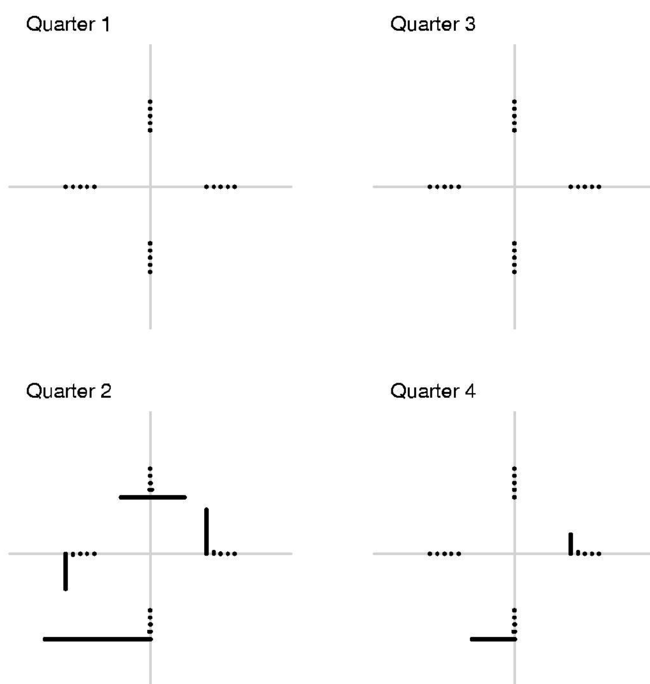

Figure 13. Numbers of fish crossing boundaries per quarter. Graphic is organized as in previous figure. Longest line is equivalent to 3.6e5 fish migrating per quarter. Run C.

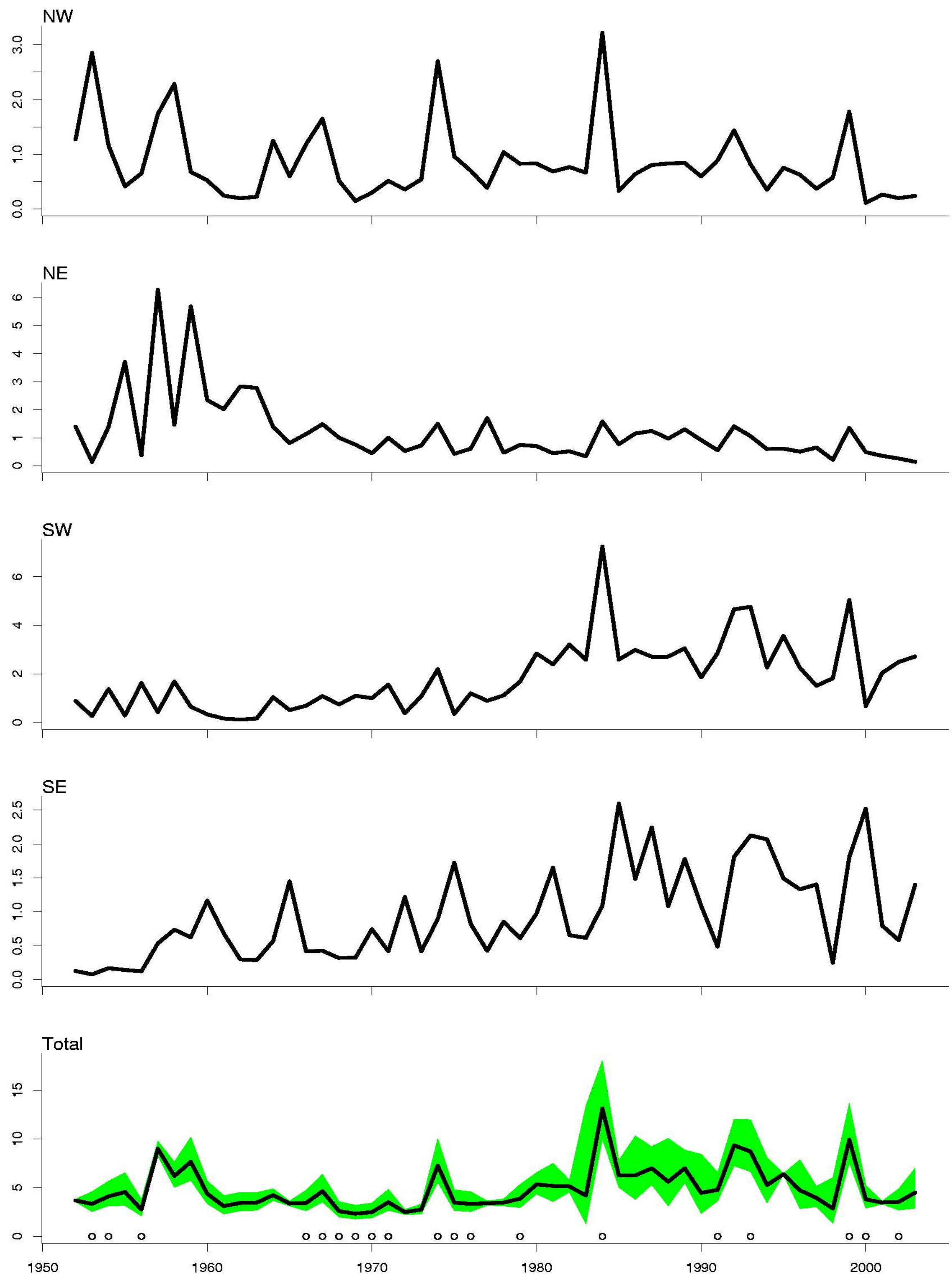

Figure 14. Estimated annual recruitment (millions) by region and total. The shaded area on the bottom figure indicates approximate 95% confidence region (±2 determined from inverse hessian). Circles on the x-axis indicate where an average was assumed because the estimated at that poin was ill-determined. Run C.

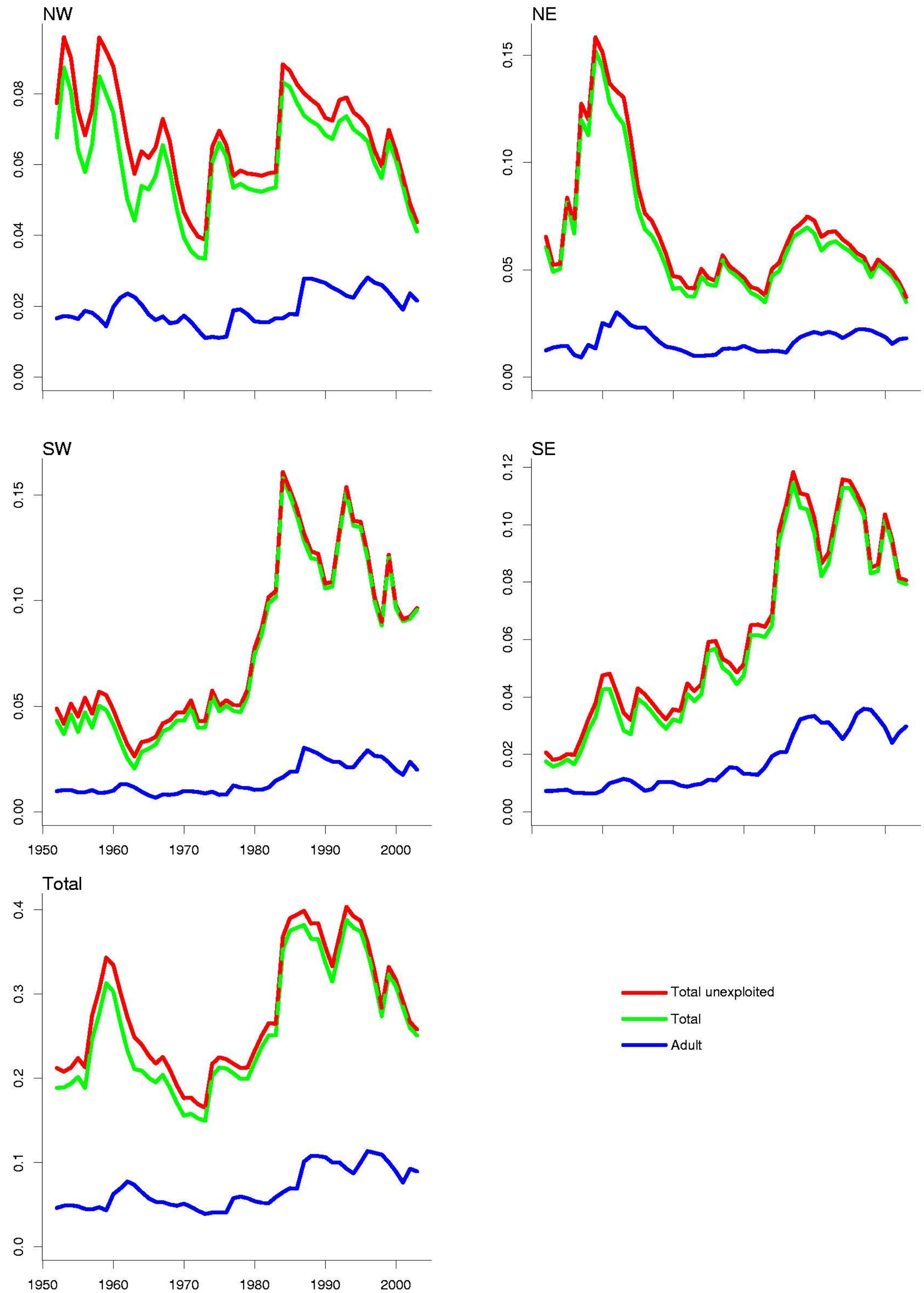

Figure 15. Estimated biomass (thousand t) by region and whole model area. The "Total unexploited" lines are the estimated biomass trajectories that would have occurred had there been no swordfish harvest.

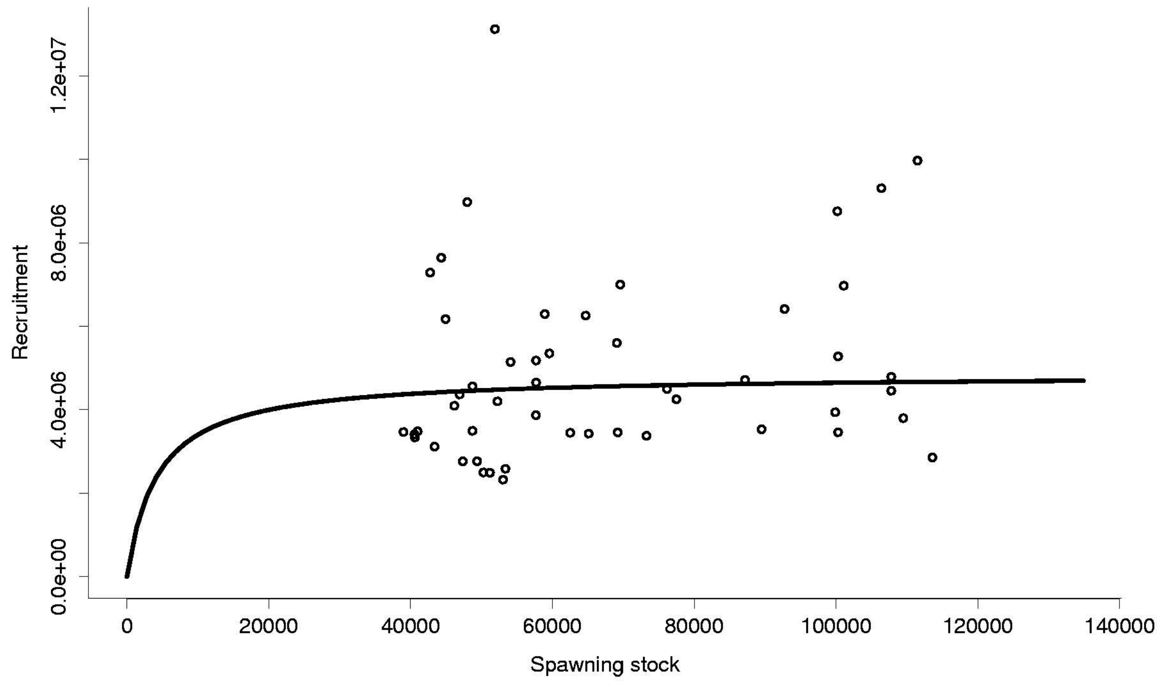

Figure 16. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. Estimated recruitment-spawning biomass points are plotted as open circles. Run C.

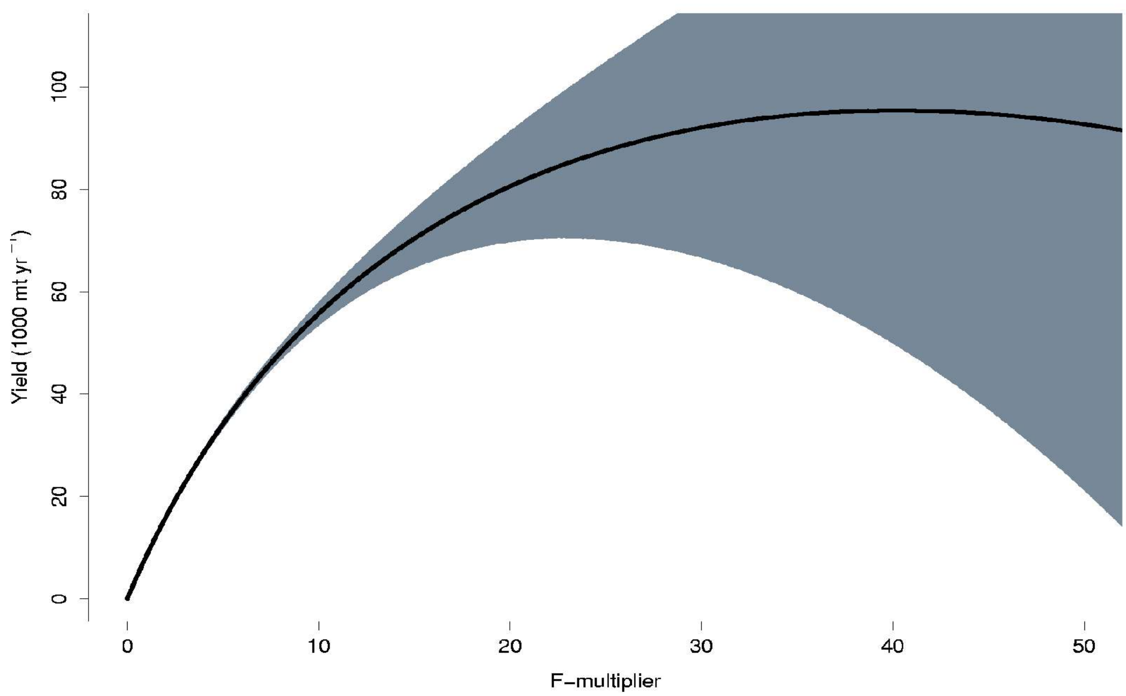

Figure 17. Equilibrium yield as a function of fishing mortality multiplier. The shaded area represents approximate 95% confidence region. Run C.

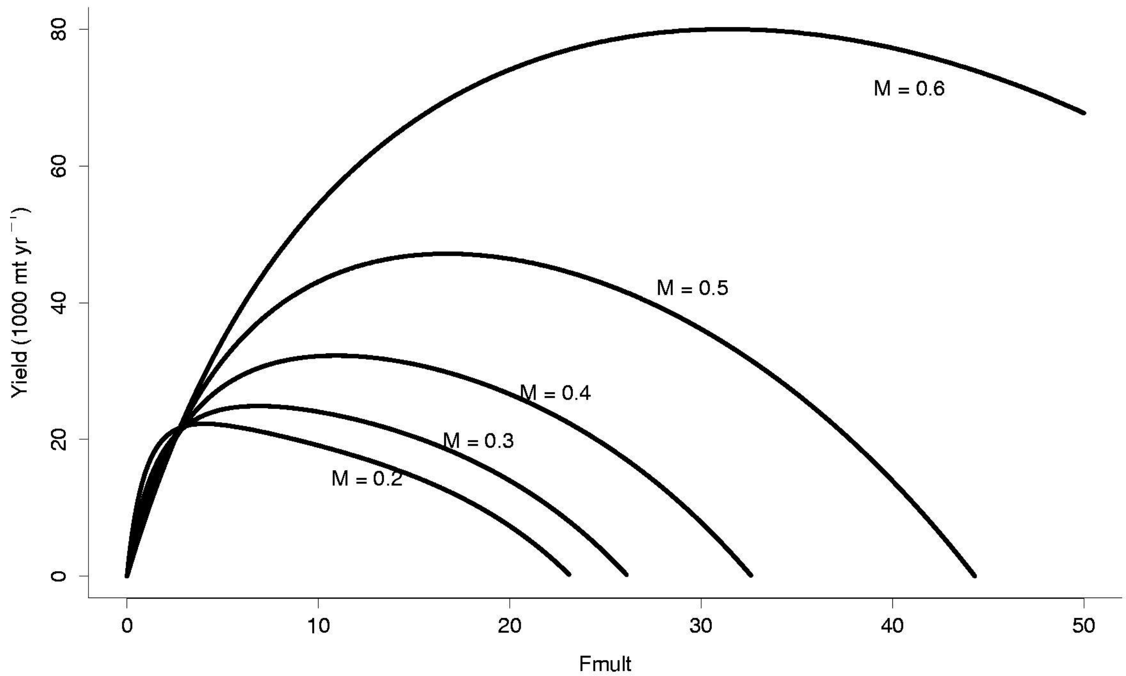

Figure 18. Equilibrium yield as a function of fishing mortality multiplier for fixed levels of natural mortaliy ranging from 0.2 to 0.6 yr^{-1}.

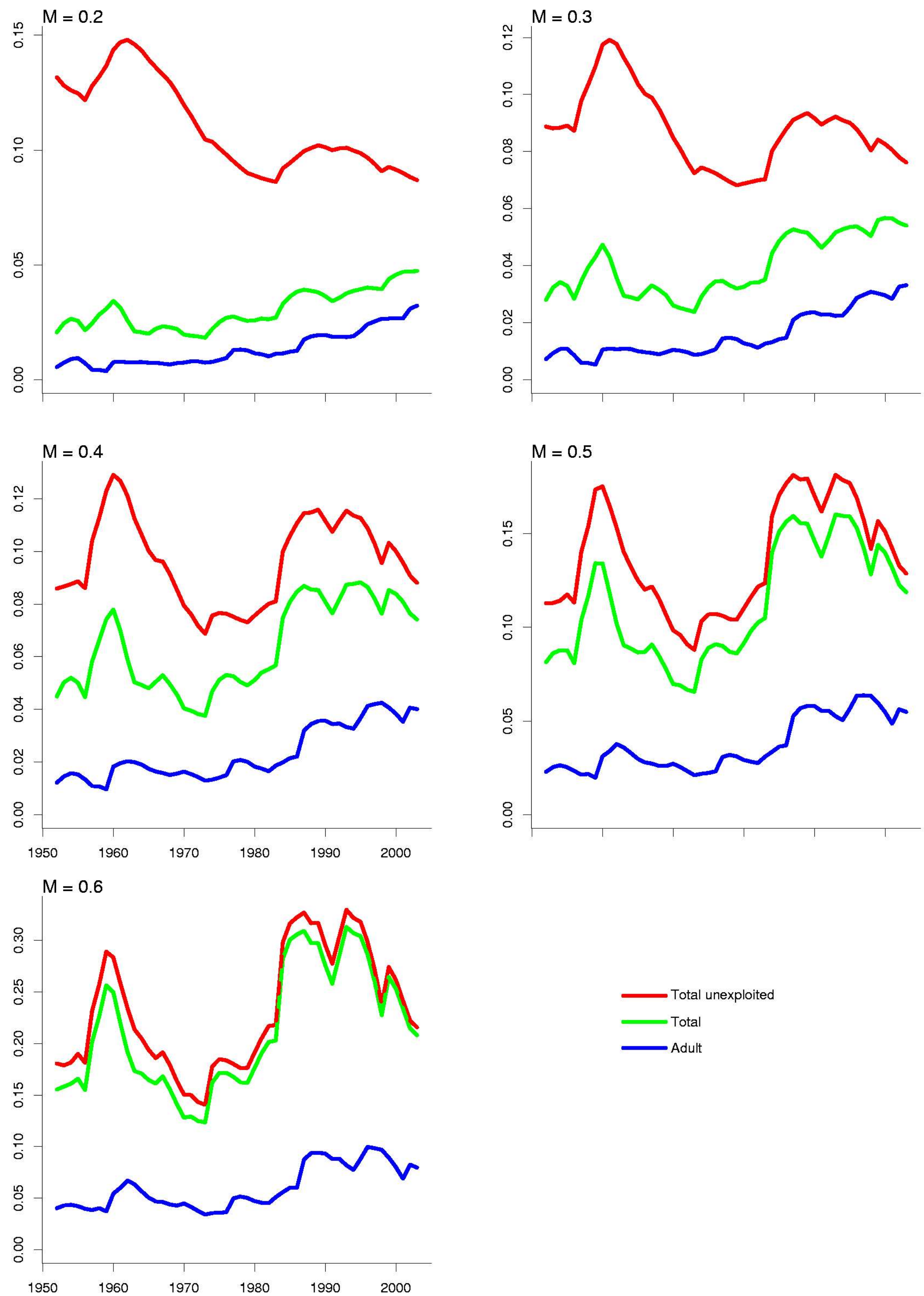

Figure 19. Estimated total biomass (1000 t) for series of assumed values of natural mortallity. The "Total unexploited" lines are the estimated biomass trajectories that would have occurred had there been no swordfish harvest.

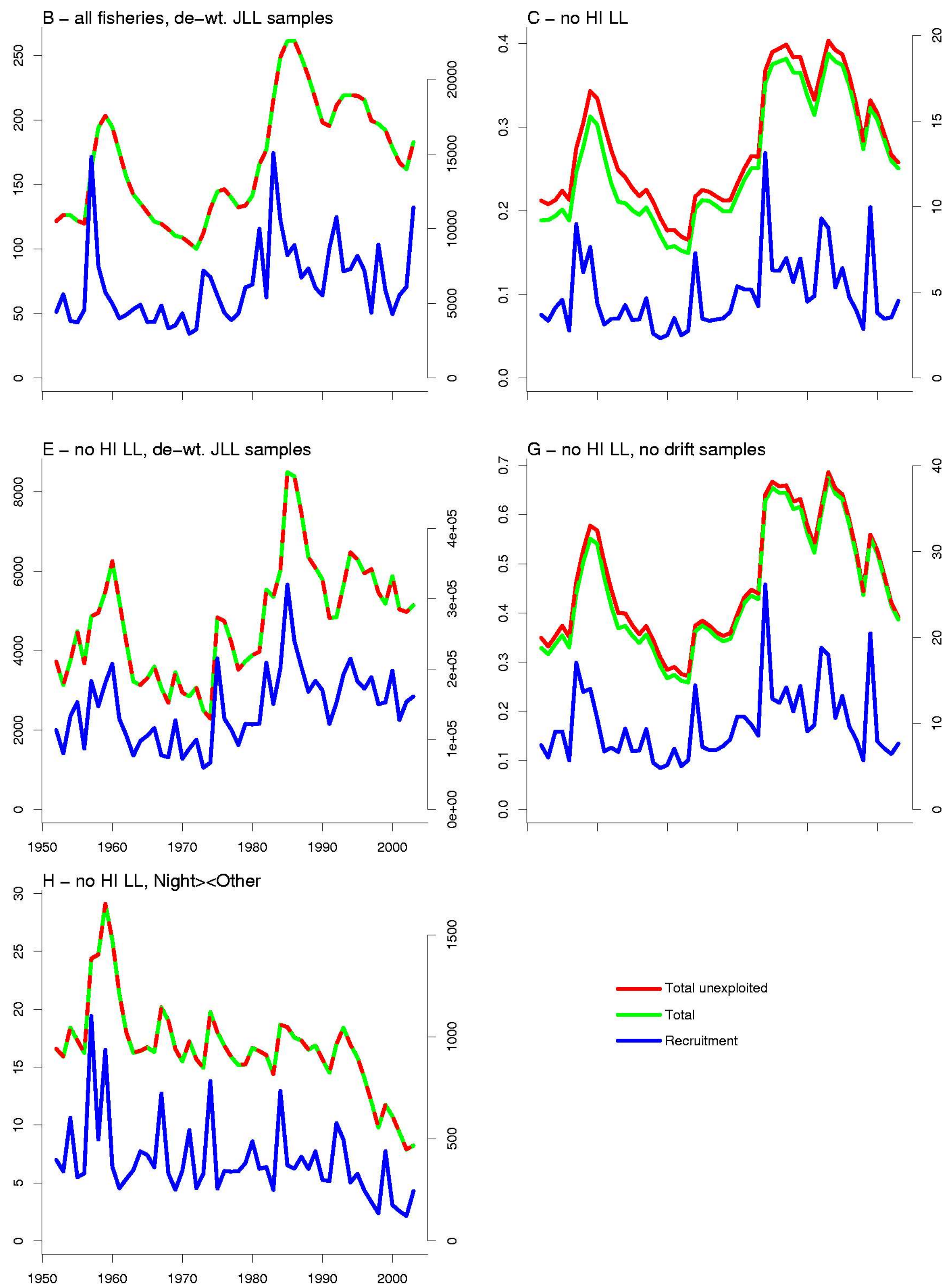

Figure 20. Estimated total biomass (1000 t) and recruitment in millions (axis scale on right) for a selection of model runs. The "Total unexploited" lines are the estimated biomass trajectories that would have occurred had there been no swordfish harvest.