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North Pacific Blue Shark Stock Assessment

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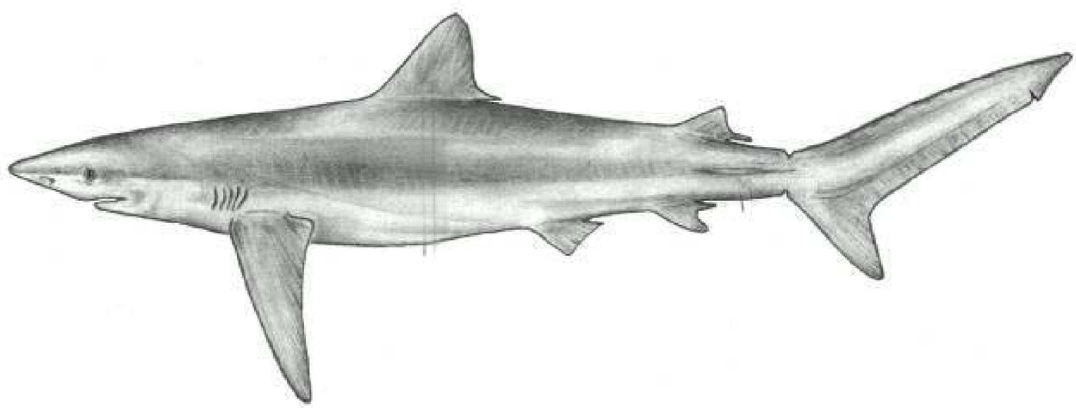

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ABSTRACT

A stock assessment of the blue shark (*Prionace glauca*) population in the North Pacific was conducted using catch and effort data from commercial longline and large mesh driftnet fisheries from the years 1971 through 2002 as well as small mesh driftnet fisheries operating primarily in the 1980s. Because reporting of shark catch has not been required in these fisheries, which target primarily tunas, a system for identifying the more reliable longline catch reports was utilized.

Two different assessment models were utilized, a surplus production model, and an integrated age and spatial structured model tested with a variety of structural assumptions. The two models were found to be in general agreement. The trends in abundance in the production model and all alternate runs of the integrated model show the same pattern of decline in the 1980s followed by recovery to above the level at the start of the time series. The integrated model analyses indicated some probability (around 30%) that biomass at the end of the time series was less than B_{MSY} (overfished) and that there was a lesser probability at that time that fishing mortality was greater than F_{MSY} (overfishing occurring). There was an increasing trend in total effort expended by longline fisheries toward the end of the time series, and this trend may have continued thereafter. It would be prudent to assume that the population is at least close to MSY level and fishing mortality may be approaching to the MSY level in the future.

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INTRODUCTION

Recent research on shark stocks and catch rates has raised concerns about their ability to withstand past and current levels of exploitation (Baum et al., 2003; Baum and Myers, 2004; Ward and Myers, 2005). Expansion of the shark fin trade (Clarke, 2004) and anecdotal reports of increased targeting of sharks for their fins have added to these concerns. Despite the prohibition of shark finning by several nations, there are few areas in which there are limits on the number of sharks caught. In parallel, reporting of shark catches is often not required or confounded by factors such as reporting of fin weights only, lack of species identification, and variable under-reporting. The lack of data quantity and quality has in many cases either prevented a rigorous quantitative assessment of shark population status, or has necessitated substantial caveats on preliminary quantitative conclusions.

The blue shark (*Prionace glauca*) is a common, wide-ranging pelagic species found in temperate and tropical waters worldwide (Nakano and Seki, 2003). Their relative abundance is low in equatorial and near coastal waters, and though they are present in high latitude waters, they are not common at latitudes above 50^{o}. This species ranges widely in the water column and has been found as deep as 400m (Last and Stevens, 1994). More is known regarding the biology and distribution of *P. glauca* in the North Pacific than in the South Pacific. On the basis of a low relative abundance in equatorial waters; evidence of pregnant females at mid-to-high latitudes in the North and South Pacific suggesting geographically separate parturition grounds; and tagging data from the Atlantic which indicate trans-equatorial movements are rare, the existence of separate northern and southern stocks in the Pacific is presumed pending further molecular genetic investigation (Kohler et al. 1998; West et al. 2004; Nakano and Stevens, in press).

According to comparative studies of demographic parameters, the blue shark has relatively higher rates of productivity than other sharks (Smith et al., 1998; Cortés, 2002) but lower rates than tunas and swordfish targeted by many fisheries which catch sharks (Froese and Pauly, 2005). In the North Pacific, *P. glauca* reaches 50% maturity at age 5-6 (140-160 cm precaudal length [PL]) for females, and age 4-5 (153 cm PL) for males. Parturition is believed to occur in May-June after a one year gestation period, and the average litter size is 26. Sex-specific distribution patterns observed in North Pacific blue sharks are believed to be linked to life stages. Parturition grounds appear to lie between 35-45^{o} N (i.e. within the North Pacific Transition Zone), whereas juvenile females are found northward to 50^{o} N, and in the Gulf of Alaska to 55^{o} N, and juvenile males are found southward to 30^{o} N. Mating is thought to occur in waters between 20-30^{o} N (Nakano and Seki, 2003).

Blue sharks are the most common, incidentally-caught shark in pelagic longline fisheries worldwide (Taniuchi, 1990; Bonfil, 1994). High seas drift net fisheries which operated through 1992 also caught large numbers of blue sharks (Nakano and Watanabe, 1991; Nakano et al. 1993; Nakano and Seki, 2003). Concerns regarding potential overfishing for sharks, motivated in part by campaigns against shark finning, have prompted several attempts to assess shark population status. Declines in catch-per-unit-effort (CPUE) of 60% were determined for blue sharks in the Northwest Atlantic over the past 15 years (Baum et al., 2003), and blue shark abundance in the central Pacific in the 1990s was found to be only 13% of its abundance in the 1950s (Ward and Myers, 2005). A yield-per-recruit analysis for blue shark in Australian waters concluded that the sustainably exploitable biomass is only a small portion of the unexploited biomass (West et al., 2004). While these studies suggest the stocks are vulnerable, a preliminary stock assessment for blue shark in the North Pacific found that the population appears to be in no danger of stock collapse (Kleiber et al., 2001). These results were echoed in the Atlantic by findings from the first shark stock assessment conducted by a regional fisheries management organization. In this assessment, blue shark populations in both hemispheres were found to be above the maximum sustainable yield (MSY) reference point, and in many model scenarios, close to unfished biomass levels (ICCAT, 2005). Despite an ongoing high level of uncertainty surrounding the available data, a recently completed assessment of these two stocks is consistent with previous findings, i.e., the 2008 assessment also found that the stock is not overfished status and overfishing is not occurring (ICCAT, 2008). This study revisits the assessment conducted by Kleiber et al. (2001) for the North Pacific.

MATERIALS AND METHODS

Area Boundaries and Spatial Structure

The study area for this North Pacific blue shark stock assessment was defined with reference to the distribution of the species and the availability of catch and effort data (Figure 1). The northern limit of the study area extended to 60°N based on Compagno (1984). The eastern limit was defined at 130°W to capture both the eastward extent of the Hawaii-based longline fleet and the major fishing grounds for the Japanese longline fleet. The western boundary was arbitrarily drawn at 140°E despite the presence of both blue sharks and fisheries which catch them in the area of the East China Sea between Kyushu, Japan and Mindinao, the Philippines. By focusing our efforts on fishing grounds east of 140°E we sought to avoid disproportionately increasing the uncertainty associated with estimating catch and effort for a number of different, poorly documented fleets operating west of this area.

Within the study area, 16 subareas were defined for the purposes of calculating catch and effort (Figure 1). The blue shark migration model proposed by Nakano (1994) suggested partitioning at 15°N, to delineate the southern extent of the mating ground, and 35°N, to delineate the southern extent of the parturition ground. These boundaries were adjusted to incorporate an additional stratum between 30-40°N corresponding to the North Pacific Transition Zone (Bigelow et al., 1999), thus four bands were delineated with boundaries at 0, 15, 30, 40 and 60°N. Given the importance of both latitude and longitude in determining the catch rates of blue shark (Bigelow et al., 1999), longitudinal boundaries were fixed at 20° intervals (30° for the easternmost subareas).

Catch and Effort Data Compilation

Data for this assessment were gathered from the national commercial fleet statistics of Japan, the U.S., Taiwan, the Republic of Korea and the Secretariat of the Pacific Community, and research and training vessel data from Japan. We attempted, but were unable, to obtain data from the People's Republic of China, although most of China's effort was said to occur in areas outside of the study area (Y.M. Wang, Food and Agriculture Organization, pers. comm.; X.J. Dai, Shanghai Fisheries University, pers. comm.) Gear types included large and small mesh drift net fisheries (1973–2002) and longline fisheries (1971–2002).

Drift Net Fisheries

Prior to the United Nations moratorium on high seas, large-scale, pelagic drift net fisheries, implemented as of 31 December 1992, Japanese high seas drift net fisheries in the North Pacific consisted of a large mesh fishery targeting striped marlin (*Tetrapturus audax*) and later albacore (*Thunnus alalunga*), and a small mesh fishery targeting flying squid (*Ommastrephes bartrami*) (Nakano et al., 1993). Korea and Taiwan also had small mesh drift net fisheries targeting flying squid. In addition, Taiwan had a large mesh fleet targeting albacore. The small mesh fisheries and Taiwan's large mesh fishery were closed after December 1992, but Japan's large mesh fishery continues to operate within Japan's Exclusive Economic Zone (EEZ).

Blue shark catches by large mesh drift net gear were estimated for the Japanese fleet for 1973–2002 on the basis of available landings data compiled by prefectural governments (Nakano et al., 1993). Japan's small mesh drift net fishery targeting squid is described by catch and effort data available since 1982 and an observer program operated in 1989–1991. Catches of blue shark by this fishery were estimated for 1989 and 1990 (Yatsu et al., 1993) and extrapolated based on available effort data to represent Taiwanese and Korean squid drift net fleets during the years 1981–1991 following methods outlined in Nakano and Watanabe (1991). Despite operating up until the imposition of the moratorium at the end of 1992, no records are available for any of the small mesh drift net fisheries in their final year. Therefore, catches for 1992 were estimated on the assumption that, in accordance with United Nations (UN) resolution 46/215 (Richards, 1994; UN, 1991), the fleets were reduced by 50% by 30 June 1992, and thus catches in 1992 were approximately half of those in 1991.

Lengths of blue sharks were measured by observers deployed on squid drift net vessels of Japan (1991), Korea (1990, 1991), and Taiwan (1991) and large-mesh drift net vessels of Taiwan (1991). When necessary, measured lengths were converted to precaudal length using conversion formulas for North Pacific from Nakano et al. (1985). Gender of sampled fish was undetermined. Accordingly, estimates of body weight were computed using sex-averaged length-weight conversion formulas of Nakano (1994) and used to convert catch in weight to catch in numbers. The average weights per individual blue shark applied in this analysis were 15.5 kg for large mesh gear and 4.7 kg for small mesh gear. Effort (in tans) by large mesh drift nets by month and area were available for the Japanese fleet in 1990 and the Taiwan fleet in 1990–1991 (Nakano et al., 1993). For small mesh drift nets, effort by month and area were available for 1990–1991 for Japanese, Taiwanese and Korean fleets (Gong et al., 1993). These data were used to define factors for partitioning annual catch data into quarterly values.

Longline Fisheries

Set-by-set catch and effort data at a resolution of 1x1 degree, and raised effort, i.e. extrapolated to account for vessels which do not submit logbooks, by 5x5 degree block, were obtained for Japanese longline fishery fleets from the Japan Fisheries Agency for 1971 to 2002. The Hawaii-based longline fleet's catch and effort was provided by the Pacific Islands Fisheries Science Center by quarter and area for 1990 to 2002. Catch and effort data agglomerated by month and 5x5 degree block were provided by the Taiwan Fisheries Administration for 1971 to 2002. Other effort was calculated from public domain, 5x5 degree resolution databases compiled by the SPC and subset by area for 1971 to 2002.

Estimation of Catch-per-Unit-Effort

The Japanese longline fleet provides the longest historical time series and broadest spatial coverage of shark catch data in the region. CPUEs estimated from catch records compiled for this fleet were used to compute catches for other fleets for which detailed catch records are lacking. The Japanese longline fleet is categorized into 3 vessel classes:

- the *Kogata* or *Engan* fleet is comprised of coastal fishing vessels less than 10 MT, with crews of one to three, and at sea for less than 1 week.
- the *Kinkai* fleet is comprised of vessels between 10 and 120 MT fishing offshore but west of the international dateline, with crews of less than 10, and at sea for periods ranging from 1 to 2 weeks to 1 month.
- the *Enyo* fleet consists of vessels larger than 120 MT, with crews of 15 to 20, at sea for periods of 2 to 3 months, and ranging farther from Japan than the offshore vessels.

Data on shark catches (in aggregate) have been recorded for the *Kinkai* and *Enyo* fleets since the mid-1960s. Electronic data are available from 1971 onward, and since 1994 species-specific reporting for blue shark has been required. However, logbooks are not required for the *Kogata* fleet. The *Enyo/Kinkai* database for 1971 to 2002 contains over 1.8 million set-by-set catch records including fields for year, quarter, latitude, longitude, shark catch (partitioned for some species, including blue shark, since 1994), gear configuration based on hooks between floats (hbf) and effort (hooks).

To estimate blue shark catches from total shark catches, a filtering method was applied which removes data from dubious logbooks through means of a calculated reporting rate per vessel cruise (Nakano and Clarke, 2006). A reporting rate filter of 80% was applied, i.e., logbooks from cruises which did not report sharks for at least 80% of all sets were discarded, leaving approximately 450,000 sets. According to previous analyses, given the dominance of blue sharks in the catch, application of the reporting rate filter to total shark catch data results in data that appropriately represent blue shark catch rates. For consistency, data for all years, regardless of species recording practices, were treated in the same manner (Nakano and Clarke, 2005; Matsunaga and Nakano, 2005).

In addition to catch data from commercial logbooks, nominal CPUE values were available from training vessels, i.e. research cruises, conducted by Japan from 1973-1999. These records did not require filtering but were otherwise standardized in a manner similar to commercial logbook catch data.

Before computing standardized CPUE using Generalized Linear Model (GLM) and statistical habitat model methods, records for which depth information was not recorded or for which corresponding oceanographic data were lacking were deleted from the database. The data were then divided according to number of hooks between floats (hbf): deep (7-20 hbf, n = 161,304) and shallow (4-6 hbf, n = 280,573) subsets.

The GLM method applied Poisson and log normal distributions to estimate standardized CPUE for annual (Eq. 1) and quarterly (Eq. 2) timeframes as follows:

$$E(Catch) = Effort \times \exp\begin{pmatrix} Intercept + (YearEffect \times Year) + \\ (AreaEffect \times Area) + (DepthEffect \times Depth) \\ + (QuarterEffect \times Quarter) \end{pmatrix} + \varepsilon \qquad (1)$$

$$E(Catch) = Effort \times \exp\begin{pmatrix} Intercept + \\ (Year:QuarterEffect \times Year:Quarter) + \\ (AreaEffect \times Area) + (DepthEffect \times Depth) \end{pmatrix} + \varepsilon \qquad (2)$$

where *E(Catch)* is a Poisson or log normal distributed variable representing the expected catch for a given time period, area and depth; *Effort* is an offset term of log(hooks); and ε is an error term. Terms for time period, area and depth were specified as factors. To avoid problems associated with zero catches, catch (x) was transformed to x+0.001 for the lognormal model.

An additional standardization was conducted using a statistical habitat model similar to that applied to Pacific bigeye and yellowfin tuna in Bigelow et al. (2004). In this model, habitat preferences were structured as noninformative, probabilistic parameters with uniform distributions and means of zero. Parameters included 15 ambient temperature preferences (2°C intervals from 3.5°C to 33.5°C) and 15 dissolved oxygen preferences (0.5 ml l^{-1} intervals from 0 to 7.5 ml l^{-1}). Furthermore, habitat priors were area-specific, thus there were 480 habitat parameters for the 16-area model. When accounting for the additional parameters for the year:quarter effects, the shallow (1971–2002) and deep (1975–2002) gear had a total of 608 and 592 parameters, respectively.

Predicted catch was compared to observed catch using two likelihood functions. A log-transformed least squares was used for direct comparison with the GLM as:

$$-\ln L\left(\boldsymbol{\theta} \mid \widetilde{\mathbf{C}}\right)=\left(\ln\left[\widetilde{C}_i+\delta\right]-\ln\left[C_i+\delta\right]\right) \tag{3}$$

and a lognormal likelihood as:

$$-\ln L\left(\boldsymbol{\theta} \mid \widetilde{\mathbf{C}}\right)=\sum_i \ln[\sigma]+\left[\frac{\left(\ln\left[\widetilde{C}_i+\delta\right]-\ln\left[C_i+\delta\right]\right)^2}{2\sigma^2}\right] \tag{4}$$

where $\widetilde{C}_i$ is the observed catch and C_i is the predicted catch for observation *i* and σ^2 is the lognormal variance weighted. A small constant δ (0.0001 for least-squares; 1.0 for lognormal) was added to the observed catch and predicted catch to avoid computational problems when the observed or predicted catch was zero. For individual observations (*i*) from an effort (*E*) series *j*, an estimate of catch (*C*) in year *y* is obtained as $C_{i,j,y}=E_{i,j,y}q_jB_y$ where *q* is overall catchability and *B* is abundance. Year effects ($q_j=qB_y$) are estimated because both *q* and *B* are unknown. The negative log-likelihood is minimized by simultaneously estimating various parameters with the function minimizer in AD Model Builder.

The vertical stratification in the statHBS model considered the oceanography from the surface to 600 m at 40 m intervals. For each observation, contemporary oceanographic ambient temperature and climatological oxygen content were obtained at a scale of 1 degree by month. Oceanographic temperature data were obtained from an Ocean General Circulation Model (SODA analysis, Carton et al. 2000a, 2000b, http://apdrc.soest.hawaii.edu). Oxygen data were obtained from the Levitus and Boyer (1994) climatology.

The vertical distribution of hooks within each gear configuration (4-20 hbf) was specified based on the operational gear characteristics in the Japanese longline fishery and an assumption that the longline gear conforms to a catenary shape (K. Yokawa, NRIFSF, pers. comm.).

Estimation of Effort

Raised effort for the Japanese *Kinkai* and *Enyo* longline fleets was subset by area and quarter. Unfiltered logbook data were similarly subset to calculate the proportion of shallow (< 6.5 hbf) and deep (>6.5 hbf) sets in each stratum. This proportion was then applied to the effort data to partition total raised hooks into shallow and deep categories. There were rare occurrences, i.e., 6 of 4,096 total strata, in which the unfiltered logbook data indicated zero hooks were fished but the raised effort database contained a non-zero entry. In this case the hooks recorded in the raised effort database were partitioned into shallow and deep categories based on the calculated proportion of deep and shallow hooks for all adjoining areas in the same year and quarter. There were also five strata for which effort was recorded in the unfiltered logbooks but not in the effort database. These strata were assigned the number of deep and shallow hooks recorded in the logbooks and therefore represent unraised effort.

For the Hawaii-based fleet, logbook coverage is nearly 100% and thus no raising of effort was required. Taiwan effort data were assumed to represent the best available fishing effort and applied without adjustment. All Taiwan effort was directed toward albacore (S.K. Chang, Taiwan Fisheries Agency, pers. comm.) and should thus be characterized as deep sets (Bigelow et al., 1999). Effort by longline fleets not contained in the Japan, Taiwan, or Hawaii databases was estimated by subtracting the effort in these three databases from the total effort by stratum in the SPC public domain 5x5 degree aggregated effort database for longline fisheries (SPC, 2005). In strata where the subtraction resulted in a negative number, the additional effort was set to zero. Alternative methods of adding a constant or using a multiplicative factor to raise all negative effort values to zero were considered but not applied due to apparent but unresolvable systematic biases in the data.

Calculation of Total Catch

The summed effort, in hooks, for the Japanese, Taiwanese and other fleets by deep and shallow strata was multiplied by the product of the standardized year coefficients and the antilog of the estimated intercept from the Poisson-based GLM to produce an estimate of catch per hook fished for these fleets. The *Kogata* estimate was derived by relating the effort of the *Enyo* and *Kinkai* fleets which is reported in Japanese fisheries statistics yearbooks (MAFF, 2004) in number of sets, to the *Kogata* effort which is reported in fishing days. It was assumed that vessels in the *Enyo* and *Kinkai* fleets fish an average of 2000 hooks per set, and *Kogata* vessels, due to their small size, fish only one set of 1000 hooks per day. By converting all three fleets' measure of effort to hooks, annual ratios of the effort in the undocumented *Kogata* fleet to the effort in the documented *Enyo* and *Kinkai* fleets were obtained, and *Enyo* and *Kinkai* catches were raised by these ratios in each year to account for *Kogata* catches. Catch data for the Hawaii-based longline fleet, estimated catches from the drift net fisheries, and an estimate of catches for the undocumented *Kogata* fleet were then added to produce total catch estimates by year and quarter.

Size Distribution Data

Data on blue shark precaudal lengths were compiled from Japanese training and research vessel cruises in the North Pacific from 1967 to 1973 (Taniuchi, 1990), 1978 to 1985 (JAMARC, unpublished data) and 1992 to 2002 (NRIFSF, unpublished data). Samples were also obtained by scientific observers on board Hawaii-based longline commercial vessels from 1994 to 2002. Lengths were partitioned by year, quarter, area and depth of the set in which they were caught, and then binned into 5 cm length categories and summed.

Stock Assessment Models

Two stock assessment models were applied: a Bayesian surplus production (BSP) model (ICCAT, 2003) and MULTIFAN-CL (Fournier et al., 1998).

Surplus Production Model

The BSP application software is based on the Schaefer model parameterized as:

$$B_{t+1} = rB_t - \frac{r}{K}B_t^2 - C_t \qquad (5)$$

where *B* is the biomass at time step *t*, *r* is the intrinsic rate of increase, *K* is the carrying capacity and *C* is the catch at time *t*. The required inputs are a continuous catch series and at least one catch rate series with coefficients of variation, if available. The model allows specification of priors for *K*, *r*, the biomass in the first modeled time step as a ratio of *K* ($B_{t=1}/K$), and the average catch (C_0) for missing catch data (if any) at the beginning of the time series. The constant of proportionality between each abundance index and the biomass trend (i.e., catchability, or *q*) was treated as having a non-informative prior and calculated using the numerical shortcut of Walters and Ludwig (1994). Under this method, in each draw from the importance function of the model-estimated parameters (e.g., *r* and *K*) the maximum likelihood estimate for *q* is computed and this in turn is used to compute the likelihood of the data given *r*, *K* and the other parameters. This is equivalent to specifying a prior for *q* and drawing samples of *q* from the importance function.

Parameter specification for the base case of the model is described in Table 1. Based on data availability, the initial year in the model is 1971 and the current year is assumed to be 2002. All informative priors were assigned a log normal distribution, and units of 10,000 fish were used for *K* (carrying capacity) and $B_{t=1}/K$ (biomass in the first year of the model as a proportion of *K*). A non-informative prior was specified for *K* using a uniform distribution on log(*K*) which allowed the value to range between the specified minimum and maximum values while weakly favoring smaller values. The population was assumed to be at carrying capacity at the beginning of the model time frame ($B_{t=1}/K$=1) and the specified standard deviation allowed this parameter ($B_{t=1}/K$) to range between 0.67 and 1.48 over the 95% prior probability of *K*. The prior for the intrinsic rate of increase (*r*) was set with reference to demographic analysis which indicated that the mean of *r* for blue shark is 0.34 yr^{-1} (95% confidence interval (C.I.) of 0.25-0.43; Cortés, 2002), however we assigned a less informative variance of 0.3 thus allowing *r* to take values between 0.19 and 0.63 yr^{-1}. This range encompasses the range of posterior predictions of *r* resulting from the ICCAT blue shark stock assessment (0.20–0.25), as well as most of the range of prior values used in that assessment (95% probability intervals (P.I.) of 0.10 to 0.37 yr^{-1} for the North Atlantic and 0.19–0.31 yr^{-1} for the South Atlantic; ICCAT, 2005).

For each CPUE series, the method of estimating σ (the standard deviation in the natural logarithm of the difference between observed and model predicted values) for each time step in the series (i.e., the weighting method) was specified by the maximum likelihood estimate (MLE) of σ for each series (i.e., weighting method #2 of McAllister and Babcock, 2002). The marginal posterior distributions for model parameters were calculated using the sampling-importance resampling algorithm (SIR), with the importance function defined as a multivariate *t* distribution (McAllister et al., 2001).

Sensitivity analyses were conducted to examine the impact of the priors on the results and selection of the weighting method. These tests included:

- Specifying the prior for *K* as uniform on *K* rather than uniform on log(*K*);
- Specifying a less informative prior for *r*, i.e., a variance of 0.81 gives a 95% P.I. on *r* of 0.06 to 2.0;
- Assuming the starting biomass ($B_{t=1}$) is well below K, i.e., $B_{t=1}/K$=0.6;
- Specifying an alternative weighting method consisting of equal weighting of each data point using a default coefficient of variation (CV) set at 0.2. This was implemented through specification of weighting method #6 of McAllister and Babcock, 2002). This alternative weighting method was chosen over other alternatives due to the fact that the available time series were neither long nor well-behaved and easily gave rise to numerically unstable results, therefore it was necessary to put a strong prior on the variance. The default value of 0.2 was considered a reasonable one based on other stock assessments and from initial spreadsheet exercises for the available north Pacific blue shark data.

Available diagnostic statistics for model runs were checked to verify low posterior correlations; a low number of discarded simulations (i.e., simulations are discarded if any of the parameters' values exceed the specified minimum or maximum); a low percentage value for the weight of the maximally weighted draw (i.e., a measure of the relative influence of the draw with the highest weight); and that the CV of the weights of the importance draws is less than the CV of the likelihood times the priors for the same draws (McAllister et al., 2004).

The decision analysis component of the model was used to project population parameters into the future based on a number of policy scenarios. Since there are currently no quotas or other management measures implemented for blue sharks in the North Pacific (aside from the prohibition of finning by all persons under U.S. jurisdiction), policies based on fishing mortality (*F*) were selected. Six *F* levels (0.05 to 0.30) were modeled over a 15-year time horizon.

Integrated Model

MULTIFAN-CL was used to implement a model incorporating catch-effort and size sample data from multiple fisheries. MULTIFAN-CL integrates multiple data sources into a statistical, size-based, age-structured, and spatial-structured model of a spatially heterogeneous fish population harvested by a number of fleets operating within a number of regions that together comprise the geographic extent of the model universe (Fournier et al., 1998). The model encompasses the population dynamics of the fish, the variety and changeable nature of catchability and selectivity characteristics in various fishing fleets, observable data consisting of catch, effort, size samples, and tag data if available. The model is fit to catch, size, and tag recovery data by maximizing an objective function consisting of a robustified negative log-likelihood function of catch and effort deviations and size frequency deviations. Penalties or Bayesian priors are added to the objective function to constrain various parameters and to stabilize the estimation procedure. Gaps in the data are accommodated appropriately. Detailed operational and mathematical descriptions of the model are given by Hampton and Fournier (2001) and Kleiber et al. (2003).

Much of the model structure implemented by MULTIFAN-CL can be flexibly programmed in a multitude of ways. Various alternatives were tested in the course of this work in arriving at a "base-case" setup. Details described below refer to this base-case unless otherwise stated. Much of the structural detail for the base-case analysis is given in Table 2.

The model is structured with 4 regions in the North Pacific (Figure 1). The time frame is a span of 32 years from 1971 through 2002 in quarterly time steps. Twenty annual age classes are retained in the model, with the last one including age class 20 and older.

Fish recruit once per year to the first age class with average size L_1. They grow with age at a rate given by the von Bertalanffy K-parameter, and reach the last age class with average size L_2. Size within an age class is assumed to be normally distributed with the standard deviation, σ, varying with age. L_1, L_2, and K are estimated parameters, as is the mean σ and the rate at which σ varies with age. MULTIFAN-CL allows average size for a number of initial age classes to be estimated independently from the von Bertalanffy curve.

The population in each region in 1971 (the start of the time series) depends on initial recruitment estimates. The regional age distributions at the start are calculated assuming quasi-equilibrium conditions with seasonal movement among regions and average natural and fishing mortality by age, season, and region. The starting population structure therefore depends on the model estimates of recruitment, movement, natural mortality, catchability, and selectivity parameters. The promulgation of the fish population through the model time frame depends on those parameters as well.

Recruitment is estimated as an overall mean with penalized temporal and regional deviations from that mean. A different parameterization of recruitment using orthogonal polynomials is in development for MULTIFAN-CL. It was tested in a few of the alternate analyses.

Fish move among regions according to directional movement coefficients which are the proportion of fish in the origin region which move per time step to the destination region. Movement coefficients are assigned to both directions across each border between regions. Movement coefficients were assumed to be constant with age. Given the lack of direct information on movement, a penalty was applied to movement coefficients different from zero.

Attempts to estimate natural mortality within the MULTIFAN-CL framework gave unstable results. Natural mortality was therefore fixed at a constant 0.2 yr^{-1}.

Twenty five fleets (or "fisheries") are defined in the model and identified by alphanumeric fleet codes (Table 3): eight Japanese longline, six Hawaii-based longline, seven driftnet (Japanese, Korean, and Taiwanese combined), and four cryptic longline fleets (principally Taiwanese and Korean). The longline fleets are divided into deep and shallow setting, and driftnets are divided into large and small mesh. Fisheries are assigned to parameter-sharing groups for catchability and selectivity (Table 4). Catchability has two groupings, one for seasonal variation and one for longer-term. Selectivity parameters have a single grouping. The definition of fisheries and assignments to groups are made with a view to having fishing entities with relatively uniform characteristics in terms of catchability and selectivity.

Seasonal variation in catchability is parameterized by a sine function with estimated parameters for phase and amplitude. Longer term catchability trends are allowed for all but the Japanese longline fisheries and follow a constrained time series with biennial steps. Selectivity is parameterized as a 5-node cubic spline function. For the longline fisheries, selectivity was constrained to be non-decreasing with age and for the driftnet fisheries to be zero for age greater than 15 years.

The observed data consisted of estimated blue shark catch and effort by the fisheries defined in Table 3 plus length sample data obtained from various sources. Tag data were not available. Figure 2 shows the duration of activity by each fishery and the times and amounts of size samples taken from the catch of each fishery.

Errors in prediction of catch data enter in the likelihood function both as catch and as independent effort deviations, which are estimated parameters. The weighting of the catch and effort deviations is such that catch deviations tend to be small ($\sigma = 0.07$ on log scale). The effort deviations are penalized such that their standard deviation is assumed to be proportional to the square root of the effort. By default MULTIFAN-CL diminishes the influence of the sample data in the likelihood function relative to the catch/effort data by assuming that the effective number of fish measured for size is one tenth of the actual number with an additional limit of 100 effective measurements for any one sample event. A sample event is the accumulated fish measurements taken from one fishery over the course of one time step (one quarter year in this case).

The results from MULTIFAN-CL consist of estimates of mortality, growth, and movement parameters that go into calculating a reconstruction of the fish population, that is, the history of population abundance by age and region over the course of the model time frame. MULTIFAN-CL also calculates a hypothetical reconstruction of the population as it would have been without fishing. This hypothetical population construction will be referred to as the "unexploited population" to distinguish it from the "exploited population", which is an estimated reconstruction of the actual history of the population.

In addition to the basic parameters, those involved in constructing the population, a number of derived parameters are calculated such as maximum sustainable yield (MSY) and related quantities that are of fishery management interest.

Uncertainty in the results is addressed in part by approximations of statistical uncertainty of estimated results based on the inverse Hessian matrix as well as likelihood profiles for quantities such as the ratios of current biomass to biomass at MSY (B/B_{MSY}) and current fishing mortality to fishing mortality at MSY (F/F_{MSY}). Uncertainty in model formulation is addressed by examining the sensitivity of stock status indicators to alternate analyses with different structural settings.

Differences between the base-case and the way alternate analyses were set up are outlined in Table 5. Fish in some of the alternates were allowed to vary from von Bertalanffy growth with independent mean size parameters for the first five age classes. For most analyses, the effective sample sizes and effort penalties were set the same as the base-case, that is, the default rule for effective sample size of one tenth of the true sample size with a maximum of 100 and a more stringent effort deviation penalty for Japan longline than for the other fleets. But in recognition of the fact that the Japanese catch data for blue shark are expected to be less reliable than the catch data for more prominent commercial species, runs J–M were set up with less weight on catch/effort data and more on size data. In some analyses, including the base-case, a penalty was applied to regional differences in recruitment to stabilize a tendency of the model to put large transient peaks of recruitment in a single region. In another effort to stabilize recruitment, a new parameterization of recruitment was tested with orthogonal polynomials of varying degree.

RESULTS

Catch and Effort Estimates

Drift Net Fisheries

Estimated annual blue shark catches for large and small mesh drift net fisheries are shown in Figure 3. The large mesh fishery was required to submit catch records as of 1990, therefore catch estimates prior to this year are less reliable. Formerly, large mesh drift net catches peaked in April and May, and catches dropped in June as vessels converted to the squid drift net fishery (Nakano et al., 1993).

The small mesh squid drift net fishery operated between June and December with the greatest effort in the summer months (Yatsu et al., 1993). When the small mesh drift nets were operating, blue shark catches by the small mesh nets were estimated to be as high as 3.8 million annually and as much as an order of magnitude higher than blue shark catches in large mesh drift net catches.

Longline Fisheries

Estimation of catch-per-unit-effort--Estimates of CPUE were based on shark catches reported in filtered Japanese longline fishery logbooks. The filtering removed unreliable records, which averaged 76% of the total records in each year (Figure 4). A trend of decreasing number of sets per year was observed in both unfiltered and filtered data series from the mid-1980s onward (see Effort below). Since many of the records removed by the filter consisted of false zero catches (Nakano and Clarke, 2006), CPUE calculated on the basis of filtered records is higher and should more accurately reflect true catch rates. Both unfiltered and filtered data series suggest a rising trend in CPUE despite the expected suppression of catch rates in the unfiltered data due to under-reporting.

Potentially anomalous data points such as the low number of total (unfiltered) sets in 1992, and the low number of filtered sets and low filtered CPUE in 1993 were investigated but could not be resolved. One possible explanation lies in the change in logbook reporting requirements and record-keeping formats which occurred during these years which may have resulted in the loss of data.

When the effect of the filter is examined separately for shallow and deep sets, an increasing percentage of shallow sets pass the filter until the late 1980s and at the end of the study period nearly all the shallow sets pass the filter. In contrast, the number of deep sets passing the filter rises until the early 1980s then falls in parallel with the decreasing total number of deep sets. During the study period, the proportion of deep sets passing the filter ranges from 7–26%.

When data were separated by hook depth and standardized using several types of generalized linear models (GLM) and a habitat model, trends in CPUE were largely consistent between models Figure 5. However, the GLM with an assumed Poisson distribution had a higher explanatory ability than the GLM using the log transformed distribution (Table 6). When factors such as area and quarter are included, the various models' predictions conform even more closely than suggested by the year effects alone. In the shallow series, CPUE remained stable in the 1970s, declining slightly in the 1980s and rising gradually in the 1990s to a peak in 2002. The deep series was characterized by peaks in CPUE in 1980 (all models) and 1999 (habitat and log normal models only). In this series, the consistency of the models breaks down near the end of the timeframe with the greatest variability in the log normal model and the least variability in the Poisson model. On the basis of this model comparison, the GLM Poisson model was selected for use in the catch calculations described below.

As a further check on catch rates, blue shark catch data from training vessel cruises was also standardized using a Poisson-based GLM with factors year, area, depth and quarter (Figure 6). Although the shallow series shows a greater variability between years than the deep series, this is likely to be a reflection of the small sample size in some years (e.g., less than 10 sets per year for some years). The overall variability in the training vessel catch rates by year is very small compared to the logbook-based series, and on its own would suggest that catch rates have remained stable throughout the past three decades.

Estimation of effort--Longline fishing effort in the study area by fleets from Japan, Taiwan, the U.S., and other countries shows that until the early 1990s Japan's fleets were responsible for the majority of fishing effort in the North Pacific (Figure 7). After this time, Japan's fleet began to shrink under the effects of vessel de-commissioning, and the effort of other fleets began to comprise a greater proportion of total effort. In recent years, total effort has risen to over 250 million hooks per year but Japan has contributed less than half of the total effort. The effort associated with the Hawaii-based U.S. fleet was consistently less than 10% of the total recorded effort.

Fishing effort by depth changed rapidly in the late 1970s as Japanese longliners began shifting from shallow sets at 50 to 120m to deeper sets at 50 to 250m in order to target tuna species, such as bigeye (*Thunnus obesus*) found at greater depths (Bigelow et al., 2002; Suzuki et al., 1977) (Figure 8). By the mid 1980s, over 80% of all sets by the Japan fleet were deep. A similar proportion of the Hawaii-based fleet's effort, and reportedly all of the Taiwanese fleet's effort was targeting the deeper depths. Because Japanese fleet data were used to classify the effort of the "other" fleets, there is greater uncertainty in the depth data in the latter portion of the time series when the relative effort of the other fleets is higher.

Calculation of Total Catch

Total annual catches (Table 7) are the sum of offshore and coastal longline and drift net catches. As indicated by the effort statistics, the offshore longline catches for deep set gear exceeded the catches for shallow set gear as of 1981, reflecting a shift in targeting practices. Japan's coastline longline catches were estimated to comprise approximately 16% of its offshore longline catches at the beginning of the time series, but with offshore vessel decommissioning in the 1990s, the proportion grew steadily to 38% in 2002. When the small mesh squid drift net fishery was operating, catches by this gear dominated total catches (Figure 9) particularly in the northeast part of the study area (Figure 1). Longline catches, which had fallen and then remained constant while the squid drift net fishery was operating, rose for all fleets after imposition of the drift net moratorium in 1992. Nevertheless, the highest post-drift net catches, 2.8 million blue sharks in 2001, represented only 52% of the catches during 1989 when all gear types were in operation.

Size Distribution Data

Pre-caudal lengths by latitudinal band and sex are shown for four time periods in Figure 10. A comparison between recent data and data from the 1970s is only available for the area near the equator (0 – 15^{o}N), and this comparison shows a statistically significant increase in mean size since 1967–1973 (male mean length 163.8 cm vs.

166.0 cm; female mean length of 156.3 cm vs. 158.32 cm; $p<0.001$). In the large sample from 1992–2002, male mean length is greater than female mean length in all latitudinal bands except the northern-most (40–60°N) area, conforming to the nursery area hypothesis of Nakano (1994). Males outnumber females in each band, but in the North Pacific Transition Zone (30–40°N) the sex ratio of males to females is greater than 6:1, whereas in the other bands the ratio lies between 1.2:1 and 1.8:1.

Surplus Production Model

Simple spreadsheet surplus production models were executed to derive reasonable starting values for the Bayesian parameter estimation. Since shallow and deep sets are likely to represent different types of operations with different blue shark catchability coefficients, initially shallow and deep series were examined separately. As suspected, each series on its own produced substantially different parameter estimates for K and r. For the shallow series, K was less than half of the deep series' K (24.3 versus 56.4 million sharks), and the estimated r values were near 0.60 yr^{-1} for the shallow series but only 0.24 yr^{-1} for the deep series. The variance between the observed and estimated biomass (σ) suggests some problems with the estimation in the shallow series ($\sigma = 0.154$), with autocorrelation apparent at lags greater than 10. No such problems were apparent with the estimation based on the deep CPUE series ($\sigma = 0.077$ and no apparent autocorrelation).

Based on these preliminary results, base and sensitivity trials of the BSP model were conducted for the shallow and deep CPUE series separately. The evaluation of diagnostics for each run indicated convergence and reliable estimation for the deep series but, as expected, some problems with estimation based on the shallow series. Specifically, the CV of the weights (167) was considerably larger than the CV of the prior times the likelihood (28) for the shallow series. This suggests that the importance function may not be appropriately sampling the posterior distribution. Although this problem may be overcome by increasing the number of iterations, there may be mis-specification such that coding of an alternative importance function may be required. Due to this indicated unreliability of the importance sampling function, the posterior parameter estimates for the shallow runs are likely to be unreliable (McAllister et al., 2002). In addition, examination of the Hessian matrix revealed a high (-0.972) correlation between K and r in both shallow and deep estimations. While potentially problematic, the influence of this correlation on parameter estimation is minimized when an informative prior for r can be specified as was the case in this assessment. The fit of the base-case predictions of CPUE, as derived from the BSP model, to the observed deep and shallow CPUE series is shown in Figure 11.

The numeric results of base case and sensitivity runs for both shallow and deep series are presented in Table 8. Given the observed problems with model diagnostics for the shallow-based estimates, the shallow results must be treated with caution. Results for the deep series show little variation among the scenarios, with estimates of K near 50 million sharks and MSY estimates near 3.5 million sharks yr^{-1}. The current biomass is estimated as being approximately 70–75% of K and the values of r (0.27 – 0.32 yr^{-1}) are in the range of previously estimated values for this species. For the shallow CPUE the estimates of MSY and B_{cur}/K are similar to those from the deep series. This is expected given the use of the same catch series for both deep and shallow model runs, and the high observed correlation between r and K. In contrast to the catch estimates, however, estimates of K in the shallow runs are 24.6 to 33.5 million sharks, approximately half as large as those in the deep runs, and estimates of r are 0.52–0.62 yr^{-1}, nearly double those for the deep runs.

The remaining results are based on estimates for the deep CPUE series only under the base case scenario. Posterior probability distributions are shown for the parameters of interest in Figure 12. The 95% P.I.s for the distributions of K and r from the deep series do not encompass the expected values for these parameters as estimated using the shallow series, further reinforcing the differences in information signals from the two series. Other model parameters estimated from the deep series (but not graphically presented) indicate that the current catch is 74% of the MSY catch level (CV=0.05), the current biomass is 102% of the biomass at the beginning of the time series (in 1971; CV=6.44), and the current fishing mortality is 51% of the fishing mortality at MSY (CV=0.11). Since under the Schaefer model the harvest rate at MSY closely approximates the fishing mortality at MSY and can be calculated as $r/2$ (Hilborn and Walters, 1992), the harvest rate at MSY is approximately 0.296/2=0.145.

In addition to these key parameters, using decision analysis, a variety of stock assessment reference points were produced for various levels of fishing mortality (Table 9). These results indicate the blue shark population will drop below its MSY levels (i.e., $B_{fin}/B_{MSY}<1.0$) once fishing mortality (F) exceeds 0.15 yr^{-1}. If fishing mortality remains near 0.15 yr^{-1}, however, the population will be maintained at half of its carrying capacity and above MSY levels over a 15-year horizon (Figure 13).

Integrated Model

Indicators of Model Performance

As expected, the correspondence is very close between observed catches and catches predicted by the model (Figure 14) except for the cryptic longline fisheries (Cp1 – Cp4; see fleet codes in Table 3) for which catches are unknown and plotted as zero in the figure[1]. The catch residuals are small (Figure 15 — note the scale) and for the most part scattered around zero. There is some pattern to the residuals with time indicating some dynamic effects not captured by the model, and a couple of the fisheries have consistently biased residuals. The latter cases, HI1s and DF4sm, amount to a small catch relative to

[1] The latter are included in the figure to show that based on the reported effort in the cryptic fisheries the model predicts moderate catch relative to other fisheries, except for the large spike at the end of the time series by Cp4. This results from a very large longline effort reported by Taiwan in region 4 and may be anomalous.

other fisheries in the model. They also represent a small amount of fishing in a region neighboring a principal region of operation of the particular gear type. For example, only a small portion of Hawaii longline fishing occurs west of the dateline in region 1, and that which is west of the line is located not far from it. In retrospect, it would make sense to eliminate HI1s and include its catch and effort in HI2s, even though it occurred over the border in region 1. A similar situation exists for DF4sm with respect to the border at 30°N.

Effort deviations are larger than catch deviations (Figure 16). They show most of the divergence between the model's notion of abundance and that implied by the catch and effort of a fishery. The cryptic fisheries are not included in Figure 16 because their effort deviations are necessarily all zero. Ideally, there would be unpatterned scatter about zero in the effort deviations. This is less true for some fisheries than others. Again, HI1s and DF4sm stand out in this regard as they do for the catch residuals.

Predicted and observed age distributions in the catch, as derived from the size distribution data, are summarized for the base case over all years in Figure 17. The actual size data seen by the model are the samples within quarterly time steps. The fit between predicted and observed age distributions is poor for some fisheries for which the total of effective sample sizes is less than a few hundred. As explained above, the effective sample sizes shown in Figure 17 are reduced to at least a tenth of the actual sample sizes. In some of the alternate analyses, this heavy restriction on sample size is relaxed for some or all of the fisheries, thereby increasing the importance of the size data in the model fit.

Table 10 gives information on the quality of fit achieved by the model. In particular the final gradient is the maximum slope of the objective function at the maximum point found on the function. That slope should be close to zero. Two alternates, Runs B and H, were not able to converge to as low a gradient as one would like. Other attempted alternate runs, not shown in this or other tables, were rejected for various reasons including even worse convergence as well as converging with parameter values against imposed bounds. All but two of the runs involving orthogonal polynomials were rejected for this reason. The rejected runs account for gaps in the alphabetical series of run labels.

Basic Model Results

The von Bertalanffy growth curve for the base case (Figure 18) was estimated to have an L_∞ of 199 and growth rate coefficient of 0.21yr^{-1}. Some alternate analyses estimated size at age as separate parameters for the first five age classes, but the base-case shown here conformed to the von Bertalanffy model for all age classes.

Selectivity estimated for 8 fishery groups (Table 4) shows a clear difference between driftnet and longline gear with the driftnets favoring smaller (younger) fish (Figure 19). Long-term and seasonal variations in catchability are shown in Figure 20 for all except the cryptic longline fleets (Cp1–Cp4), whose catchability parameters are linked to those of corresponding Japanese longline fleets (Table 4). Catchability in the Japanese longline fleets is assumed constant in the long-term because the catch and effort data for these fleets was standardized and therefore assumed to be representative of fish abundance. Long-term variation was estimated in the Hawaii longline fishery and the driftnet fisheries. Seasonal variability was estimated in all fisheries, although with the cryptic longline fisheries linked to corresponding Japanese longline fisheries (Table 4). Seasonal variation was more pronounced in the longline than in the driftnet fisheries.

Selectivity and catchability combine with effort to determine quarterly, age-specific fishing mortality for each fishery. These are summarized in Figure 21 as annual fishing mortalities by all fleets in each region for juvenile and adult age classes. The episode of high juvenile fishing mortality in the northern regions during the 1980s and early 1990s is a reflection of driftnet effort which flourished in that time period and which predominantly selected young fish. The catch resulting from the estimated fishing mortality is summarized in Figure 22 with the bulk of the catch in the northern regions, particularly region 1, and the episode of high driftnet effort again manifested in the catch.

Recruitment is estimated to be variable with a sharp rise beginning in the mid 1990s (Figure 23). For the base-case, by far the major amount of recruitment is estimated to occur in region 1. Regions 2 and 3 are particularly low in recruitment. Most of the alternate model runs showed more significant recruitment in the other regions, but all having highest recruitment in region 1. Seemingly low recruitment in a region can be made up for by movement from neighboring regions. Large movement coefficients up to 32% per quarter are shown in Figure 24. Applying estimated movement coefficients to the average biomass distribution late in the time frame gives a summary pattern of movement flow among regions (Figure 25) indicating large exchange of fish throughout the year between regions 1 and 2 and seasonal exchange between 1 and 3, 2 and 3, and 3 and 4. The movement patterns estimated by many of the alternate runs are quite different from the base-case pattern indicated in Figures 24 and 25.

Indicators of Stock Status

Parameters of a Beverton-Holt stock-recruitment relationship (SRR) were estimated from model estimates of spawning stock and recruitment (Figure 26) subject to a Bayesian prior on steepness of the SSR. Steepness in an SRR is defined as the ratio of recruitment at 20% of the equilibrium, unexploited spawning stock to recruitment at 100% of the equilibrium, unexploited spawning stock. A steepness of 1.0 implies that recruitment is independent of spawning stock, and the population would therefore be highly robust to exploitation. For steepness approaching 0.2, the population would be barely maintaining itself at all levels of spawning stock and would therefore be highly vulnerable to exploitation. In estimating the SRR, a nonstandard beta probability distribution was specified as a steepness prior. The resulting posterior estimate of steepness was 0.92 (Figure 27). In the estimated SSR (Figure 26), the rapid rise at low spawning stock levels for the base-case indicates a degree of robustness to exploitation, though there is high uncertainty in the SRR at those low spawning stock levels.

The estimated exploited and unexploited biomass trajectories for each region, and all regions combined, are shown in Figure 28. Following a rise in the early year of the time frame, the exploited biomass by region and overall shows a prominent dip in the middle of the time frame with an overall rising trend in total biomass in the last several years. A similar but milder trend occurs in spawning biomass. Trajectories of unexploited total and spawning biomass (biomass in absence of fishing) echo the steep early rise of the exploited biomass and then remain relatively stable. The vertical distance between the pairs of solid and dotted lines in Figure 28 is therefore indicative of the impact of fishing on the population. Fishery impact measured as the ratio of exploited to unexploited biomass is shown in Figure 29 with the maximum impact occurring around 1990 in all regions and overall.

The maximum sustainable yield (MSY) is obtained from the yield curve (Figure 30) which plots equilibrium yield as a function of fishing mortality, *F*, expressed as a fishing mortality multiplier $F/F_{current}$, where $F_{current}$ is the average *F* prevailing near the end of the time frame. The average covers the four years 1998 through 2001. The final year of the time frame (2002) is excluded because input data and time-specific model estimates are more uncertain in that year than throughout the time frame. The maximum point of the yield curve indicates that fishing mortality at MSY (F_{MSY}) is 1.4 × $F_{current}$. Given the uncertainty region around the curve, the actual value of F_{MSY} is uncertain though it is very unlikely to be greater than $F_{current}$.

The uncertainty in current biomass relative to B_{MSY} (B/B_{MSY}) was examined using a likelihood profile, a technique by which likelihood levels evinced by the model are recorded when the model is forced to accommodate a range of B/B_{MSY} values, giving an approximate probability distribution. The results (Figure 31) show that the bulk of the B/B_{MSY} distribution is greater than 1, but almost 30% is less than 1, implying a 30% chance that the population is in the "overfished" state. The corresponding technique for F/F_{MSY} within MULTIFAN-CL is in a state of disrepair, but a distribution of sorts was obtained from F/F_{MSY} values reached when the B/B_{MSY} profile was generated. For F/F_{MSY}, approximately 6% of the distribution is above 1, i.e., in the "overfishing" zone. A true likelihood profile for F/F_{MSY} would presumably be at least as wide as that shown in Figure 31.

Table 11 summarizes information about the sensitivity results for B/B_{MSY} and F/F_{MSY}, as well as for fishery impact, for the base-case and alternate analyses. Note that Run H estimates the population to be in the overfished state, as does Run K, which also shows that overfishing is occurring. Table 11 also shows estimates of the parameter *Tm*, which denotes the age at maturity that maximizes lifetime fecundity. This was calculated using the formula derived by Roff (1984) in investigating evolutionary pressure on age at maturity in fishes:

$$Tm = \{1/k\}\log((3k+M)/M)$$

where *Tm* is age at maturity, *k* is the Brody growth coefficient, and *M* is natural mortality. *M* was fixed in all model runs to 0.2 per yr, and the Brody coefficient was estimated in each run. *Tm* was calculated not to advance an estimate of age at maturity but to check the consistency of growth estimates with assumed age of maturity. Maturity is determined in MULTIFAN-CL by an input vector of fecundity at age which for this analysis puts 50% maturity between ages 5 and 6 years and 99% maturity by age 7 for the base-case and all alternative runs. Of the values of *Tm* in (Table 11), Run K is the most inconsistent with the assumed maturity schedule in the model. Also included in Table 11 are the ratios of exploited and unexploited biomass in the final 3 years of the time frame, on average, to their average values in the first 3 years. In all cases the biomass at the end of the time frame is larger than at the beginning, and the increase in abundance was considerably greater in the unexploited population than in the exploited one, particularly in Run K.

A phase plot of F/F_{MSY} versus B/B_{MSY} (Figure 32) shows how the situation of an exploited population sits with respect to overfishing and being overfished. The point for the base-case (an average over years 1998–2002) falls within the desirable quadrant ($F/F_{MSY} < 1$ and $B/B_{MSY} > 1$), that is, the quadrant in which the population is not overfished and in which overfishing is not occurring. The base-case is within a cluster of similarly located alternate runs. There are four outliers, two of which are noted above and located in either the overfished quadrant or the overfished plus overfishing quadrant. The two other outliers are located far from the overfished and overfishing boundaries. Figure 33 shows a similar plot of results for spawning biomass (SB/SB_{MSY}) with similar locations of the base-case and alternate analyses. Histories of the population on the phase plot over the model time-frame are shown in Figures 34 and 35 for total biomass and spawning biomass, respectively. The trajectories show the base case spending some time in all quadrants and ending in the "overfished" quadrant, though the last point is an average of only two years (2001 and 2002). All trajectories show the worst part of their history (farthest in the overfishing and overfished direction) during the 1980s, when the driftnet fishery was active.

In addition to fishery impact, B/B_{MSY}, and F/F_{MSY}, a variety of other management reference points and reference point ratios are shown in Tables 12 and 13 for the base-case and for two alternates represented by the extreme points of the scatter in Figure 33.

DISCUSSION

Blue Shark Catch and Catch Rate Estimates

Accurate estimates of total catch and catch rates are arguably the most important elements of any stock assessment. For blue sharks in the North Pacific, catch estimates must be based on longline fisheries, which have operated at effort levels between 150 – 250 million hooks through the period 1971–2002 (Figure 7) and drift net fisheries, which contributed substantially to overall catches during their peak years of operation in 1981–1992, but were rather small contributors in other years (Figs. 1 and 9).

In estimating longline catches, this study relied heavily on Japanese historical logbook data. For much of the timeframe, i.e., until the early 1990s, Japan's longline fisheries comprised the major portion of catches, however, in more recent years other fisheries, which are not as well documented, have formed an increasing share of the overall effort (Figure 7). Therefore, while Japan's records became more detailed in the early 1990s through the implementation of species-specific reporting requirements for blue sharks, the overall estimates of catch for this study may have become less accurate due to the increasing need to extrapolate catches from the Japanese fleets to other fleets which may or may not share similar characteristics.

Methods for filtering unreliable catch records from the Japanese longline logbook database prior to analysis are also possible sources of uncertainty in catch and catch rate estimates. The filter is designed to improve the accuracy of catch estimation from logbook data (Nakano and Clarke, 2006) and resulted in CPUE estimates two or more times higher than unfiltered (nominal) CPUE estimates in most years (Figure 4a). A potential bias in the filter, manifested as a disproportionate inclusion of shallow sets (which show a higher blue shark CPUE than deep sets) in the filtered database (Figure 4b), is likely to inflate the CPUE rates further. Another potential bias in the filter concerns the assumption that unspecified shark catches are dominated by blue sharks (Nakano and Clarke, 2006). As there is no species-specific recording until 1994 in either commercial or training/research vessel databases, there are limited data with which to assess whether the species composition of shark catches has changed over time. While it is possible that blue shark populations have declined and been replaced in the catches by other shark species, on the basis of the relatively higher production capacity of blue sharks (Smith et al., 1998; Cortés, 2002), and the lack of shark-specific targeting, this seems unlikely.

After filtering, Japanese longline logbook data were used to construct CPUE indices which formed the basis of catch estimation for Taiwan and "other" (undocumented) fleets fishing in the North Pacific, as well as the major catch rate indices for the stock assessment modeling. When standardized, both shallow and deep CPUE series showed relatively flat trends indicating that if CPUE is proportional to standing stock, there have been no major changes in populations during the timeframe of the study. While the assumptions outlined above indicate there is some uncertainty in interpretation of the commercial logbook series, the similar, flat trend in CPUE compiled from deep sets by training/research vessels (Figure 6) reinforces the trend observed in the commercial database.

Inconsistent reporting is one of the most important biases when dealing with catch data for non-target species. In the case of blue sharks, for most fisheries it is unclear whether an increase in mortality to hooked sharks, expected as a result of the increase in the fin trade, would be reflected in an increase in catches recorded in logbooks. By applying the filter, this study has removed records from vessels suspected to be underreporting shark catches, whether or not these vessels were finning sharks. Blue shark catches in the filtered records were either retained whole, finned or released alive but in any case were treated as mortalities in our analysis. Given that the extent of underreporting in the filtered records is expected to be minimal, and given the possibility that some hooked sharks are released alive, the filtering may serve to slightly inflate CPUE rates.

While the foregoing discussion has focused on Japanese longline data due to its use in both catch and catch rate estimation, there is also some uncertainty associated with the other data sets used in this analysis. In particular, the estimates of blue shark catches by the small mesh (squid) drift net fishery (Figure 3) appear high in comparison to global estimates for the same time period in Bonfil (1994), and are based on only 2 years of data for the Japanese fleet only but extrapolated over 11 years and three fisheries. There is also uncertainty surrounding the effort figures for Taiwan and "other" fisheries as they may represent only the reported portion of the total effort (i.e., unraised), and obviously do not account for any illegal, unregulated and unreported fishing operations.

Despite the various sources of uncertainty, the catch and catch rate estimates applied in this study are believed to represent the best practicable and substantiated estimates available. Where possible, uncertainties in catches and catch rates have been reflected in stock assessment model inputs but did not result in substantially different conclusions.

Stock Assessment

Bayesian Surplus Production Model

The findings of the BSP model, while based on a limited range of sensitivity tests, suggest that the blue shark population in the North Pacific is being fished at harvest rates below MSY levels and that the current population levels are similar to those at the beginning of the 1970s. The model was run using number of sharks rather than biomass which may produce biased results if the average size of individuals has changed over time. Analysis of size data was possible for the equatorial region only, and showed statistically significant increases of 2 cm length in both males and females from the late 1960s to the 1990s. This result stands in contrast to the finding of Ward and Myers (2005) who concluded that biomass of blue sharks had more than halved between the 1950s and the 1990s. Another recent analysis of Japanese data for the entire western Pacific for the 1930s, 1960s and 1990s indicated a slight decline in body size (13% by length, 36% by weight) only in equatorial regions, with no statistically significant changes in other areas (Matsunaga et al., 2005). Given the findings of this study and Matsunaga et al. (2005), it seems reasonable to conclude that using number rather than biomass in the BSP model has not substantially affected the conclusions.

The BSP model proved adequate in this application to fit parameters for at least one of the available time series (i.e., deep sets), and the parameter estimates were similar to those found in previous studies. The estimated intrinsic rate of increase (r=0.30) was similar to that calculated from demographic methods (0.34) and from application of this model to Atlantic blue shark stocks (0.20–0.25) (Cortés, 2002; ICCAT, 2005). A previous assessment of the North Pacific blue shark stock using an age-structured model (MULTIFAN-CL) estimated that MSY catch levels were 170 to 300% of current catch levels, and fishing mortality at MSY was 2 to 8 times current levels of fishing mortality (Kleiber et al., 2001). Analogous estimates from the present study are more pessimistic, with estimates of current catches at 74% of MSY and current F at 50% of F_{msy}, but both studies concur that the stock is in no danger of collapse.

Finally, we contrast the results of this assessment with a recent yield analysis of blue shark which suggests that only 4% of the total biomass, or 6% of the unexploited fishable biomass, can be sustainably harvested (West et al., 2004). Our median estimate of MSY

(3.58 million sharks yr^{-1}) represents 7% of our median estimate of K (49.15 million sharks) which is larger than but reasonably consistent with the results of the yield analysis. As a further check, under the Schaefer model we can compute the MSY catch as fraction of unfished abundance (*K*) as *r*/4, or given our results, as 7.4%.

Integrated Model

The alternate analyses echo for the most part the base-case pattern of exploited population trajectories, with a rise in the 1970s, a decline in the 1980s and rise again in the 1990s. The same is true for the estimates of unexploited population, with a rise in the 1970s followed by only mild ups and downs in the remaining time. Exceptions to this are the two most extreme outliers, Runs K and L.

Run K is the analysis with the greatest fishing impact (Table 11), and is located farthest into the zone of overfished and overfishing. In its scenario, the unexploited population rises steadily through most of the time frame and reaches stability only in mid 1990s. The magnitude of the supposed rise is large, with implication that the blue shark population would have grown by a factor of 3.4 from 1970 till year 2000 (Table 11) had it not been for fishing. The estimated high impact of fishing in Run K is largely explained by growth in the unexploited population due to some unknown factor, rather than to a decline in the exploited (actual) population, which in fact also grew, but only by a factor of 1.6 over the time frame (Table 11). The exploited populations in all the other analyses also grew by about the same amount, and in all cases that growth was exceeded by the growth of the unexploited population, but Run K stands out in the degree of excessive growth of the unexploited population.

The opposite outlier, Run L, shows the least fishery impact. The unexploited population is this case echoes the rises and the fall in the exploited population. Again, the fact that the unexploited population varies with time implies that the population has been subjected to factors other than, or in addition to, fishing. The fact that the exploited and unexploited populations vary more or less in synchrony implies the factors driving the variations are primarily other than fishing.

Interestingly, Runs K and L represent similar manipulations of the base-case setup (Table 5). In both runs, more weight is given to size samples and less to the catch/effort data in the likelihood function. In Run K that manipulation is applied to all fleets, and in Run L it is applied only to the Japanese longline fleets. The sensitivity to the weighting implies a conflict between the information in the catch/effort data and in the size data. This conflict might in part be due to the fact that most of the size samples come from Japanese longline training vessels and may not be entirely representative of catch by the Japanese commercial vessels from which the bulk of the catch/effort data were obtained.

Why these two outliers are at opposite extremes is not clear. It is also not clear why Run J was seemingly little affected even though its relative weighting of catch/effort and size data was manipulated to the greatest extent (Table 5). Run M had the same manipulation of relative weighting as did Run L, and it strayed a little from the main cluster on the phase plots (Figs. 34 and 35) towards Run L, but the fact that recruitment in its case was estimated by orthogonal polynomials may have kept it from moving very far. In Run H, the only manipulation from the base-case was use of orthogonal polynomials, and it strayed at bit in the opposite direction and toward Run K on the phase plots. Perhaps there is an innate tendency for recruitment estimates based on the current implementation of orthogonal polynomial in MULTIFAN-CL to drive the analysis upward and leftward on control rule plots, i.e., toward the overfished and overfishing states. However, the orthogonal polynomial recruitment in MULTIFAN-CL is a feature that is still under development.

The other manipulations of the model setup (Table 5) appeared to have much less effect in that the other alternate runs are clustered close to the base-case in the control rule plots.

Another way in which the outlier, Run K, stands out is that *Tm*, the age at maturity which maximizes lifetime fecundity, implied by its estimate of the Brody growth coefficient *k* and the fixed natural mortality, is 9 years (Table 12). This is rather older than published values of 5 to 6 years for females and 4 to 5 years for males in the north Pacific (Nakano and Seki, 2003). Run K shares that inconsistency to some extent with Runs J and B. Estimates of *Tm* for other alternate runs range down from there towards the value of 6 years, which is approximately the age at maturity set in all the model runs. Run L was the most consistent in that regard.

Given the sensitivity to manipulations of the model setup evident in the variability among the base-case and alternate results and given the spread of the outliers, it is obvious that coming to a definite conclusion regarding overfishing and overfished state is a matter of judgement. One could justify discounting Run K because of its foibles and Run H because it is based on the still experimental use of orthogonal polynomials, or they could both be discounted simply because they are outliers. However, even if one were to rely on just the base-case, the likelihood profiles imply that there is some probability (around 30%) that biomass is less than B_{MSY} and that there is some (though lesser) probability that fishing mortality is greater than F_{MSY}.

CONCLUSIONS

Conducting an assessment of incidental or non-target species is fraught with problems of poor reporting of catch by fisheries as well as changes in operational characteristics of the fishing gear. We have attempted to compensate for under-reporting of blue shark catch by one of its major fisheries (Japanese longline) by use of a reporting rate filter, and to compensate for changing depth of deployment in that fishery by effort standardization. For the other major fishery (small mesh drift net) we were provided with catch estimates based on scientific observer data. Nevertheless, considerable uncertainty remains in the fishery data used in our analysis. In addition, there was uncertainty in how best to structure our assessment models.

When a variety of structural assumptions were tested with two different assessment approaches, a surplus production model and an integrated age- and spatially-structured model, the results show the production model to be in general agreement with the bulk of evidence from the integrated model. The trends in abundance in the production model, and all alternate runs of the integrated model, show the same pattern of decline in the 1980s followed by recovery to above the level at the start of the time series. It must be acknowledged that the base-case results by the integrated model analyses indicates some probability (around 30%) that biomass is less than B_{MSY} (overfished) and that there is a lesser probability that fishing mortality is greater than F_{MSY} (overfishing is occurring). There was a slight increasing trend in the recent total effort expended by longline, and this trend may have continued thereafter. It would be prudent to assume that the population is at least close to MSY level and fishing mortality may be approaching the MSY level in the future. In this regard, further refinements of model development and the collection of accurate data on catch and fishing gear are essential. The uncertainty could well be reduced by a vigorous campaign of tagging.

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REFERENCES

Baum, J. K., and R. A. Myers.
2004. Shifting baselines and the decline of pelagic sharks in the Gulf of Mexico. Ecology Letters **7**:135–145.

Baum, J. K., R. A. Myers, D. G. Kehler, B. Worm, S. J. Harley, and P. A. Doherty.
2003. Collapse and conservation of shark populations in the Northwest Atlantic. Science 299:389–392.

Bigelow, K. A., C. H. Boggs, and X. He.
1999. Environmental effects on swordfish and blue shark catch rates in the U.S. North Pacific longline fishery. Fish. Oceanogr. 8:178–198.

Bigelow, K. A., J. Hampton, and N. Miyabe.
2002. Application of a habitat-based model to estimate effective longline fishing effort and relative abundance of Pacific bigeye tuna (*Thunnus obesus*). Fish. Oceanogr. 11:143–155.

Bigelow, K., A. Langley, and T. Patterson.
2004. Relative abundance indices of the Japanese longline fishery for bigeye and yellowfin tuna in the western and central Pacific Ocean (Working Paper SA-7). 17th Meeting of the Standing Committee on Tuna and Billfish. Majuro, Marshall Islands, 9–18 August 2004.

Bonfil, R.
1994. Overview of World Elasmobranch Fisheries. FAO Fisheries Technical Paper 341, Food and Agriculture Organization, Rome, Italy.

Carton, H., G. Chepurin, and X. Cao.
2000a. A simple ocean data assimilation analysis of the global upper ocean 1950 – 95. Part I: Methodology. J. Phys. Ocn. 30:294:309.

Carton, H., G. Chepurin, and X. Cao.
2000b. A simple ocean data assimilation analysis of the global upper ocean 1950 –95. Part II: Results. J. Phys. Ocn. 30:311:326.

Clarke, S.
2004. Understanding pressures on fishery resources through trade statistics: a pilot study of four products in the Chinese dried seafood market. Fish and Fisheries 5**:**53–74.

Compagno, L. J. V.
1984. Sharks of the World, Parts I *(Hexanchiformes* to *Lamniformes) and II (Carcharhiniformes).* FAO Species Catalogue, Vol. 4, Food and Agriculture Organization, Rome, Italy.

Cortés, E.
2002. Incorporating uncertainty into demographic modeling: application to shark populations and their conservation. Conserv. Biol. 16:1048–1062.

FISHSTAT.
2005. FISHSTAT Plus (v. 2.30), Capture Production Database, 1970–2003, Food and Agriculture Organization, Rome, Italy, available online at www.fao.org/fi/statist/FISOFT/FISHPLUS.asp.

Fournier, D. A., J. Hampton, and J.R. Sibert.
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.

Froese, R., and D. Pauly (eds.)
2005. FishBase -WorldWideWeb electronic publication, accessed at www.fishbase.org.

Gong, Y., Y. S. Kim, and S.J. Hwang.
1993. Outline of the Korean squid gillnet fishery in the North Pacific. Bulletin of the North Pacific Commission 53:45–69.

IATTC (Inter-American Tropical Tuna Commission).
2005. Resolution on the conservation of sharks caught in association with fisheries in the eastern Pacific Ocean (Resolution C-05-03). IATTC, La Jolla, California, USA. (downloaded in August 2005 from http://www.iattc.org/PDFFiles2/C-05-03-Sharks.pdf).

ICCAT (International Commission for the Conservation of Atlantic Tunas).
2003. Bayesian surplus production model with importance sampling (BSP 3.0). Available for download at http://www.iccat.es/downloads.htm#catalog.

ICCAT.
2005. Report of the 2004 Inter-sessional meeting of the ICCAT Subcommittee on by-catches: shark stock assessment. *Col. Vol. Sci. Pap. ICCAT* **58(3): 799-890.**

ICCAT.
2008. Report of the 2008 Shark Stock Assessment Meeting (1-5 September 2008, Madrid Spain. ICCAT SCRS/2008/017.

Ito, R., and W. A. Machado.
1999. Annual Report of the Hawaii-based Longline Fishery for 1998. National Marine Fisheries Service, Honolulu, Hawaii, U.S.A. 62 pp.

Kleiber, P., Y. Takeuchi, and H. Nakano.
2001. Calculation of plausible maximum sustainable yield (MSY) for blue sharks (*Prionace glauca*) in the North Pacific. Honolulu Lab., Southwest Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396. Southwest Fish. Sci. Cent. Admin. Rep. H-01-02, 10 pp.

Kohler, N. E., J. G. Casey, and P. A. Turner.
1998. NMFS Cooperative Shark Tagging Program, 1962–93: an atlas of shark tag and recapture data. Marine Fisheries Review 60(2):1–87.

Last, P. R., and J. D. Stevens.
1994. Sharks and Rays of Australia. Commonwealth Scientific and Industrial Research Organization, Canberra, Australia.

Lawson, T. A.
2004. Tuna Fishery Yearbook 2003, Secretariat of the Pacific Community, Noumea, New Caledonia, 184 pp.

Levitus, S., and T. Boyer.
1994. World Ocean Atlas. 1994, Vol. 2: Oxygen. NOAA Atlas NESDIS 2. Washington, D.C.: U.S. Government Printing Office.

MAFF (Ministry of Agriculture, Forestry and Fisheries).
2002. 漁業・養殖業生産統計年報, 平成 14 年 (Capture Fisheries and Aquaculture Production Statistics Yearbook 2002), 農林水産省統計部 (Ministry of Agriculture, Forestry and Fisheries), Tokyo, Japan.

Matsunaga, H., H. Shono, M. Kiyota, and Z. Suzuki.
2005. Long-term changes in CPUE of sharks and size of blue sharks caught by tuna longlines in the western North Pacific Ocean. Scientific Committee Paper EB WP-11, Western and Central Pacific Fisheries Commission, August 2005.

Matsunaga, H., and H. Nakano.
2005. Estimation of shark catches by Japanese tuna longline vessels in the Atlantic Ocean. Col. Vol. Sci. Pap. ICCAT 58(3): 1096-1105.

McAllister, M. K., and E. A. Babcock.
2003. Bayesian surplus production model with the sampling importance resampling algorithm (BSP): a user's guide. Available for download at http://www.iccat.es/downloads.htm#catalog.

McAllister, M. K., E. A. Babcock, and E. K. Pikitch.
2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci. 58:1871–1890.

McAllister, M. K., E. A. Babcock, E. K. Pikitch, and R. Bonfil.
2002. Importance sampling issues with the 1998 Large Coastal Shark Assessment. 2002 Shark Evaluation Workshop, National Marine Fisheries Service, Panama City, Florida.

McAllister, M. K., S. L. Hill, D. J. Agnew, G. P. Kirkwood, and J. R. Beddington.
2004. A Bayesian hierarchical formulation of the De Lury stock assessment model for abundance estimation of Falkland Islands' squid (*Loligo gahi*). Can. J. Fish. Aquat. Sci. 61:1048–1059.

McCoy, M. A., and H. Ishihara.
1999. The Socio-economic Importance of Sharks in the U.S. Flag Areas of the Western and Central Pacific. National Marine Fisheries Service, Long Beach, California, United States.

Molony, B.
2005. Estimates of the mortality of non-target species with an initial focus on seabirds, turtles and sharks. Scientific Committee Paper EB WP-1, Western and Central Pacific Fisheries Commission, August 2005.

NOAA (National Oceanic and Atmospheric Administration).
2005. 2004 Report to Congress Pursuant to the Shark Finning Prohibition Act of 2000 (Public Law 106-557). NOAA, Silver Spring, Maryland, USA.

Nakano, H.
1994. Age, reproduction and migration of blue shark in the North Pacific Ocean. Bulletin of the National Research Institute for Far Seas Fisheries 31:141–256.

Nakano, H., and S. Clarke.
2005. Standardized CPUE for blue sharks caught by the Japanese longline fishery in the Atlantic Ocean, 1971-2003. Col. Vol. Sci. Pap. ICCAT 58(3): 1127-1134.

Nakano, H., and S. Clarke.
2006. Filtering method for obtaining stock indices by shark species from species-combined logbook data in tuna longline fisheries. Fish. Sci. 72:322–332.

Nakano, H., and M. P. Seki.
2003. Synopsis of biological data on the blue shark (*Prionace glauca* Linnaeus). Bulletin of the Fisheries Research Agency of Japan 6: 8–55.

Nakano, H., and J. D. Stevens.
In press. A summary of the biology and ecology of the blue shark. In: M. Camhi and E.K. Pikitch (eds.). Sharks of the Open Ocean, Blackwell, Oxford.

Nakano, H., and Y. Watanabe.
1991. Effect of high seas driftnet fisheries on blue shark stock in the north Pacific (Working Paper J011), Scientific Review of North Pacific High Seas Driftnet Fisheries, 11–14 June 1991, Sidney, British Columbia, Canada.

Nakano, H., K. Okada, Y. Watanabe, and K. Uosaki.
1993. Outline of the large-mesh driftnet fishery of Japan. Int. N. Pac. Fish. Com. Bull. 53:25–37.

Richards, A. H.
1994. Problems of drift-net fisheries in the South Pacific. Mar. Pollut. Bull. 29:106–111.

Roff, D. A.
1984. The evolution of life history parameters in teleosts. Can. J. Fish. Aquat. Sci. 41:989–1000.

Smith, S. E., D. W. Au, and C. Snow.
1998. Intrinsic rebound potentials of 26 species of Pacific sharks. Mar. Freshw. Res. 49:663–678.

SPC (Secretariat of the Pacific Community).
2005. Oceanic Fisheries Program Public Domain Data, 5x5 Aggregated Catch and Effort Data, accessed in August 2005 at http://www.spc.int/OceanFish/html/statistics/index.htm#Public

Suzuki, Z., Y. Warashina, and M. Kishida.
1977. The comparison of catches by regular and deep tuna longline gears in the Western and Central Equatorial Pacific. Bulletin of the Far Seas Research Laboratory 15:51–89.

Taniuchi, T.
1990. The role of elasmobranches in Japanese fisheries. pp. 415-426 *In*: H. L. Pratt Jr., S. H. Gruber, and T. Taniuchi (eds.). *Elasmobranchs* as Living Resources: Advances in the Biology, Ecology, Systematics, and the Status of the Fisheries. NOAA Technical Report NMFS 90, Silver Spring, Maryland, U.S.A.

UN (United Nations).
1991. Large-scale pelagic drift-net fishing and its impact on the living marine resources of the world's oceans and seas. United Nations General Assembly Resolution 46/215, accessed in August 2005 at http://www.intfish.net/treaties/ga46_215.htm.

Walters, C. J., and D. Ludwig.
1994. Calculation of Bayes posterior probability distributions for key population parameters: a simplified approach. Can. J. Fish.Aquat. Sci. 51:713–722.

Ward, P., and R. A. Myers.
2005. Shifts in open ocean fish communities coinciding with the commencement of commercial fishing. Ecology 86:835–847.

West, G., J. Stevens, and M. Basson.
2004. Assessment of blue shark population status in the western South Pacific. Australian Fisheries Management Authority and CSIRO Marine Research Project R01/1157.

Yatsu, A, K. Hiramatsu, and S. Hayase.
1993. Outline of Japanese squid driftnet fishery with notes on the by-catch. Int. N. Pac. Fish. Com. Bull. 53:5–24.

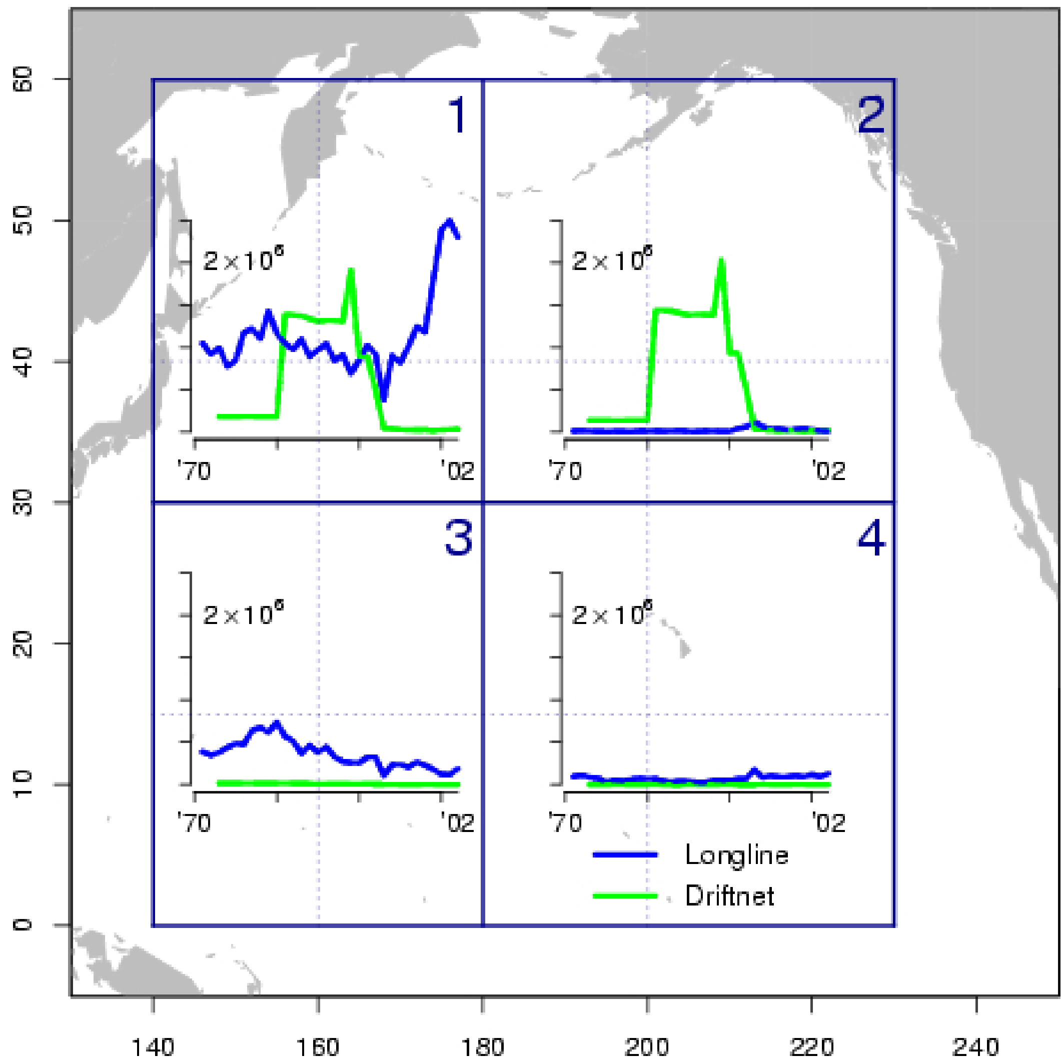


Figure 1.--The study area showing 16 subareas used in CPUE standardization modeling (delineated by dotted lines) and four subareas used in the MULTIFAN-CL analyses (delineated by solid lines). Longitudes are shown as degrees east from the Greenwich meridian (0^o). Also shown are annual blue shark catches in numbers aggregated by MULTIFAN-CL region and by longline and driftnet components of the fisheries for years 1970 to 2002.

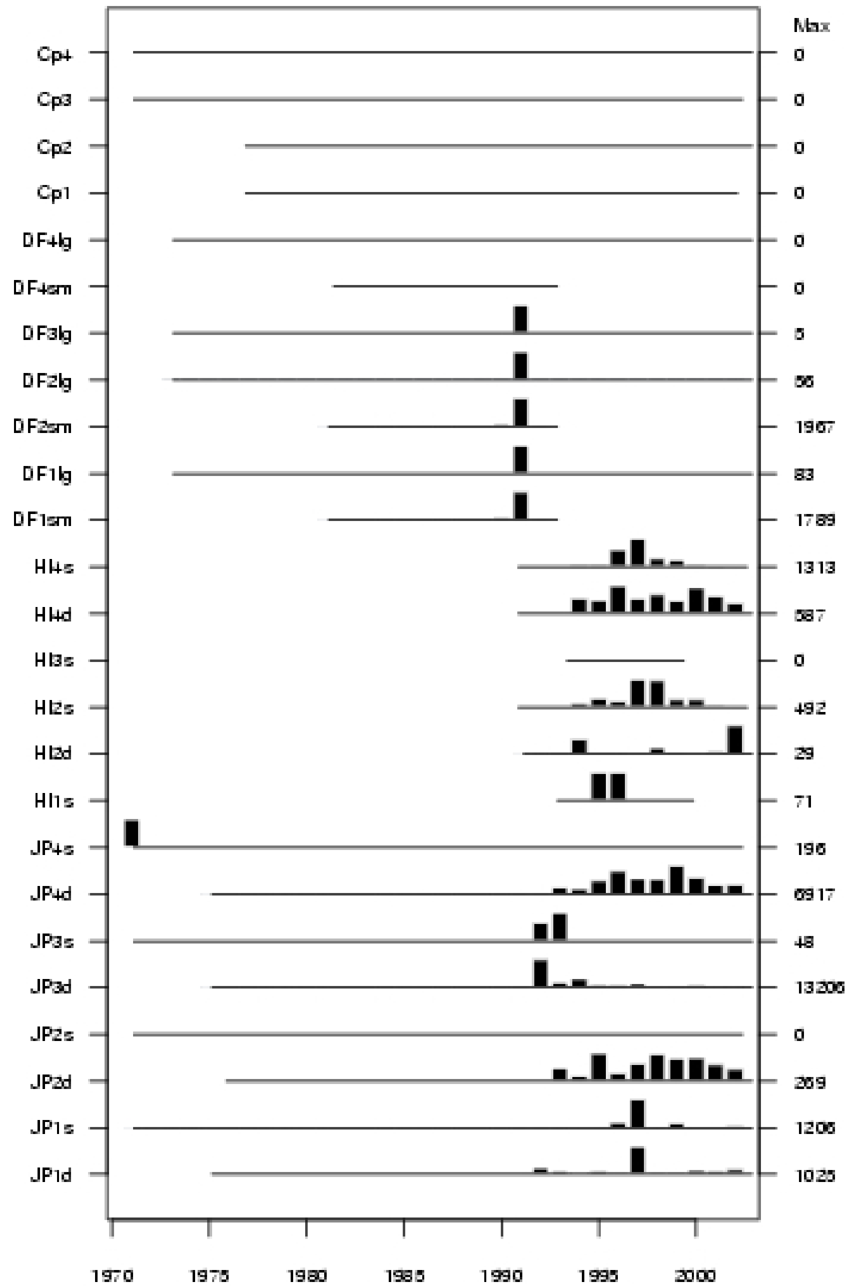


Figure 2.--Number of fish size measurements by year for each fishery. The black bars represent length measurements. The sample size corresponding to the maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

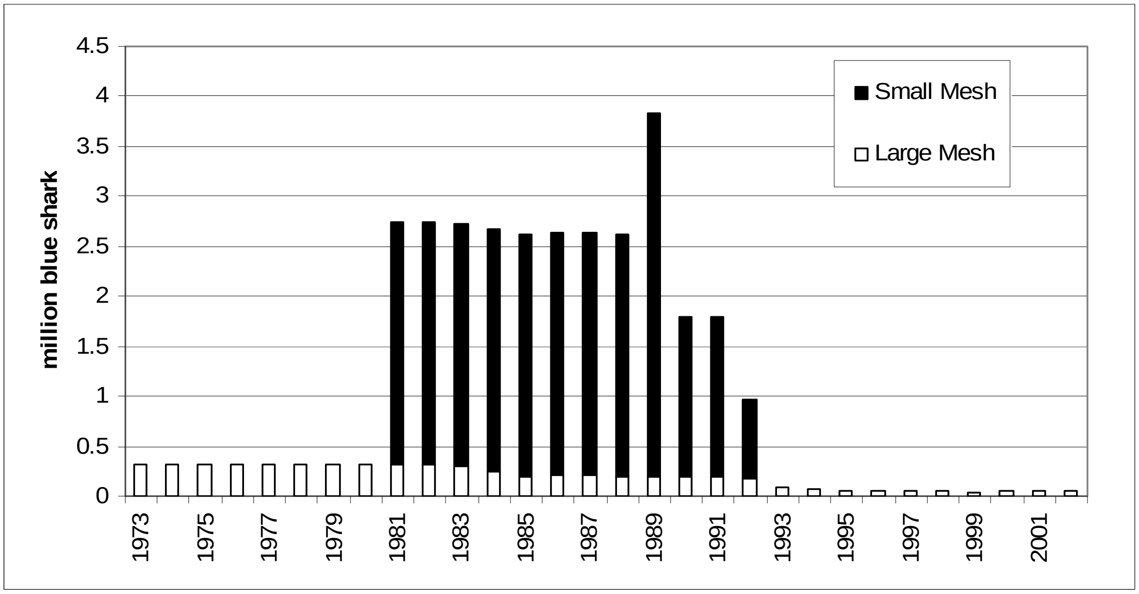
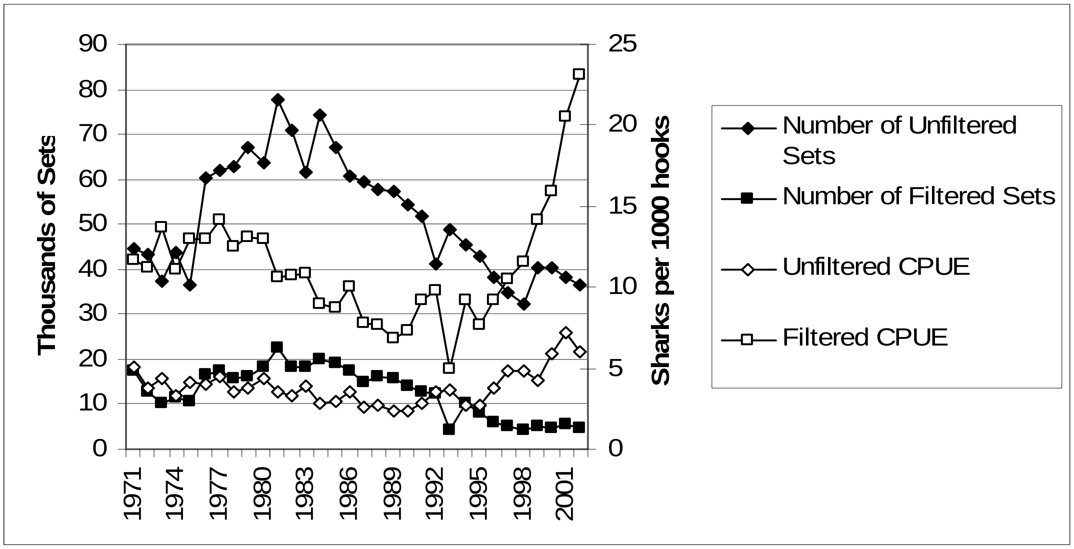


Figure 3.--Estimates of the number of blue shark caught by large mesh (Japanese fleet) and small mesh (Japanese, Taiwanese and Korean fleets) drift net fisheries in the North Pacific, 1973–2002.

(a)



(b)

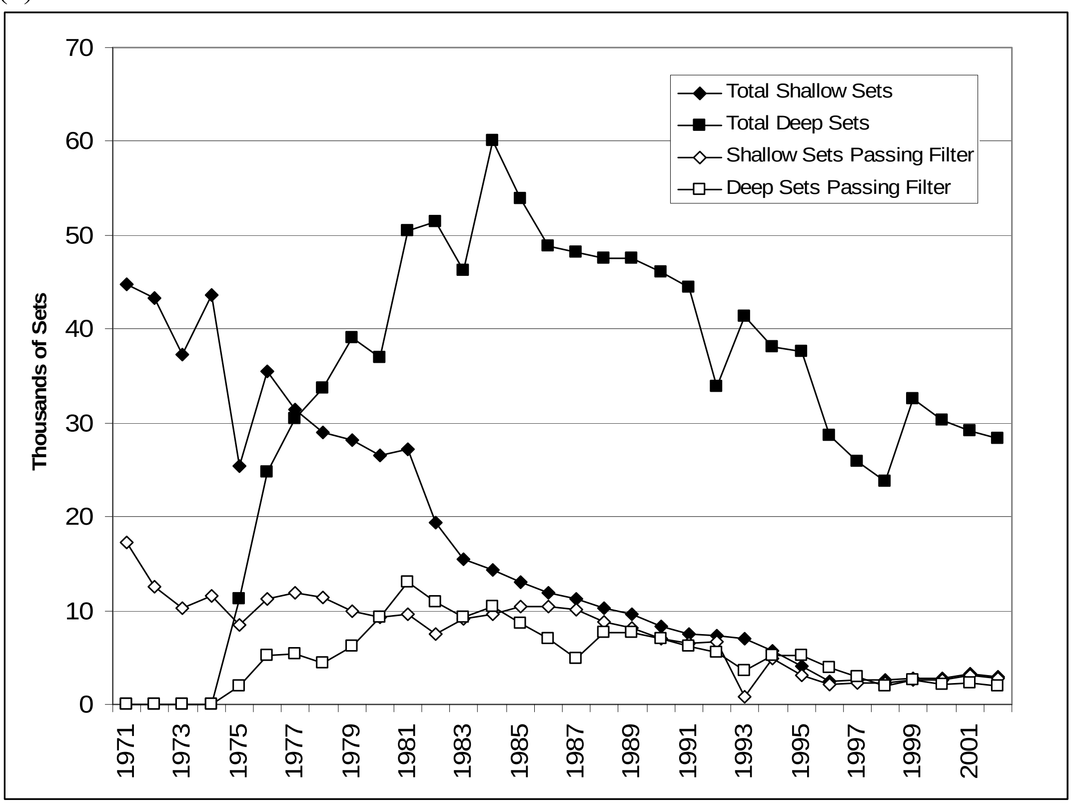


Figure 4.--The effect of filtering Japanese longline fishery logbooks, 1971–2002, using a reporting rate of 80% (i.e., discarding records from vessels which did not report shark catches for at least 80% of all sets) for (a) number of sets and unstandardized CPUE and (b) number of shallow and deep sets.

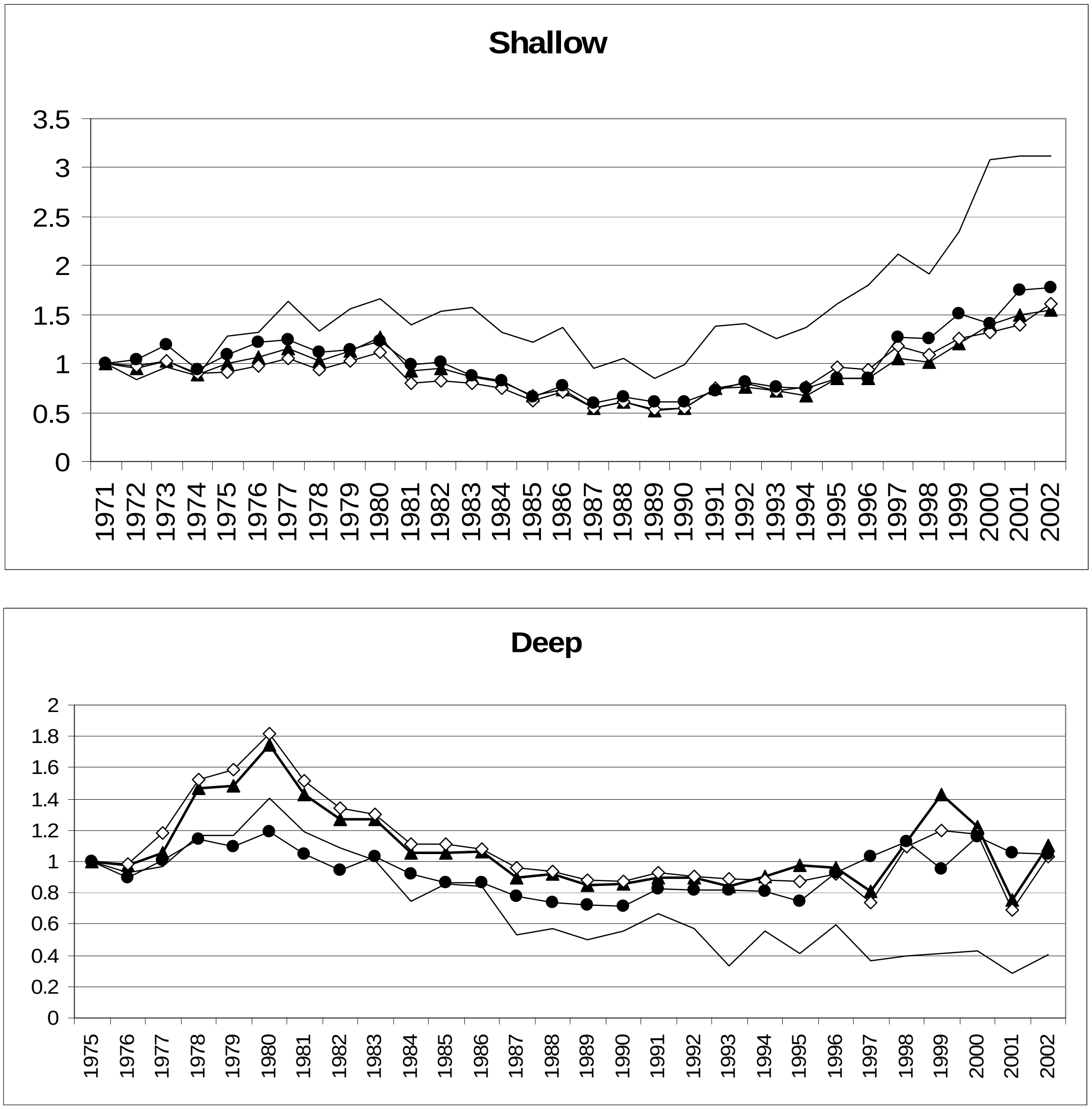


Figure 5.--Standardized CPUE for shallow (< 6.5 hbf) and deep (> 6.5 hbf) produced by four alternative models: nominal model using the factor year only (); GLM based on the log normal distribution (▲); GLM based on the Poisson distribution (●); and statistical habitat model (◊) for filtered Japanese longline fishery logbook data, 1971–2002.

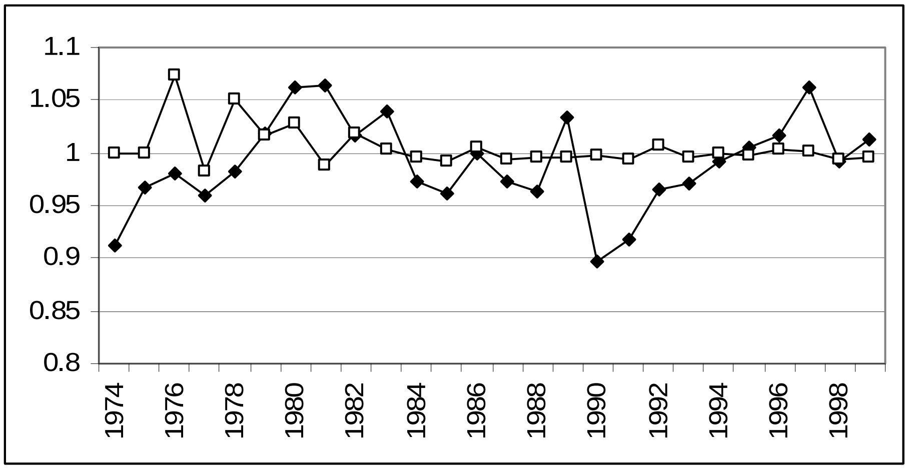


Figure 6.--Standardized CPUE for blue shark from training vessel records, 1973–1999, categorized by shallow (▲; n = 8303) and deep (□; n = 44,842) hook depths.

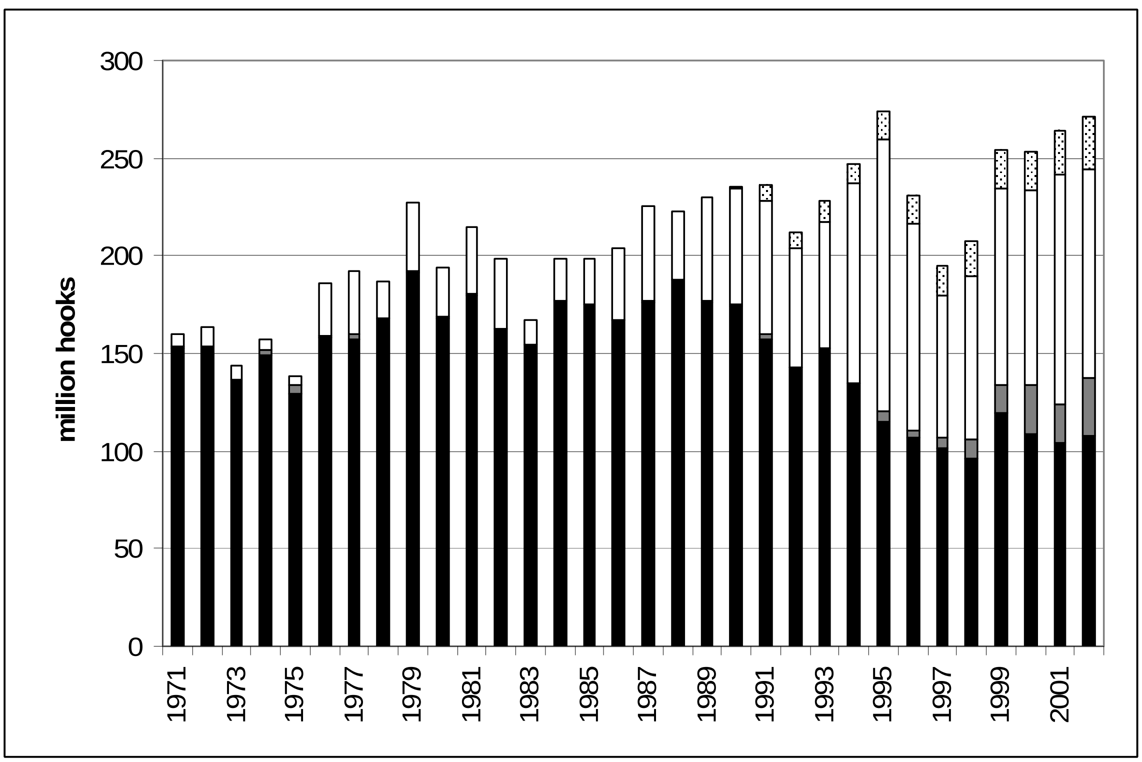


Figure 7.--Total annual longline effort (in million hooks) in the North Pacific study area, 1971–2002. Japan (black), Taiwan (gray) and U.S. Hawaii (speckled) fleet effort are derived from national databases, whereas the effort for other fleets (white) was calculated by subtracting these three fleets' effort from an overall effort estimate.

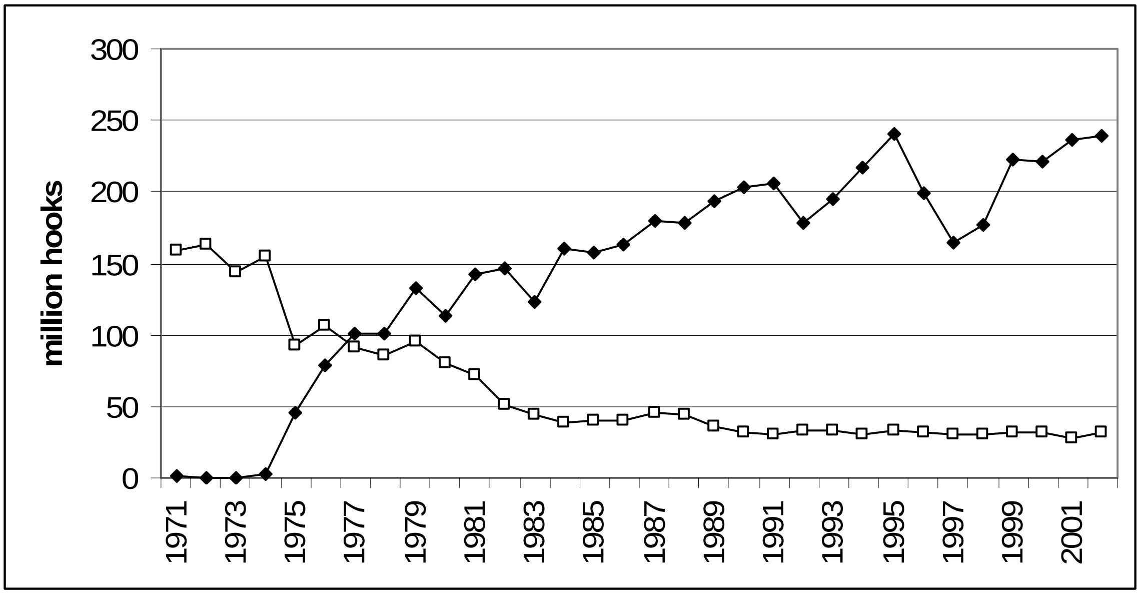


Figure 8.--Effort (in million hooks) by fishing depth (♦-deep, □ - shallow) and year in the study area for Japan, Taiwan, U.S. Hawaii and other fleets combined, 1971–2002.

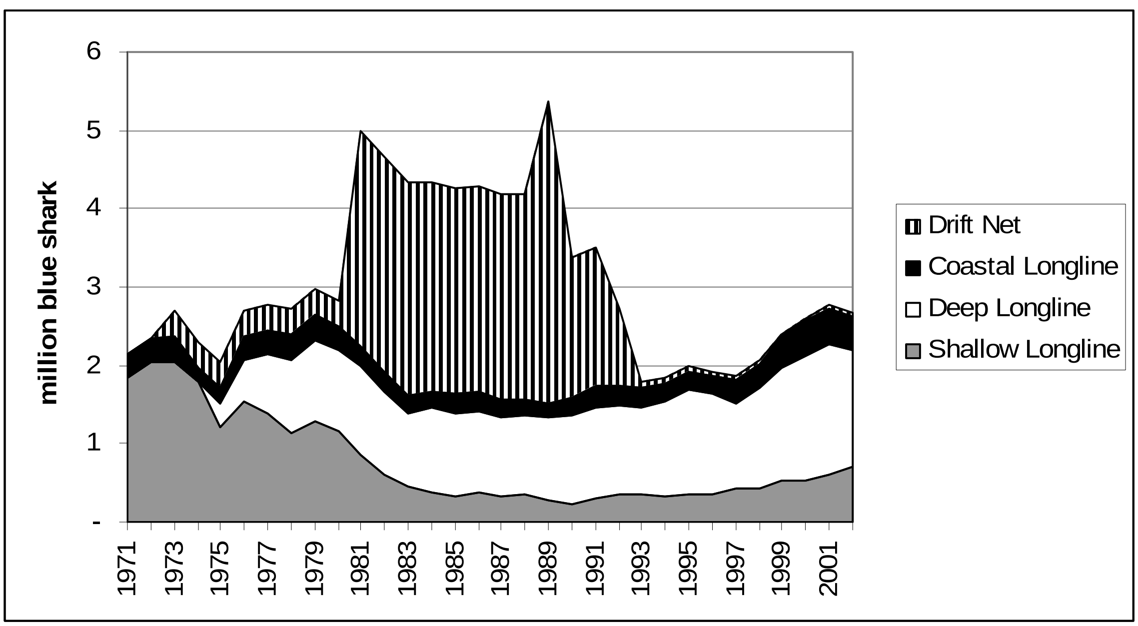


Figure 9.--Total catch of blue shark by gear type in the study area, 1971–2002.

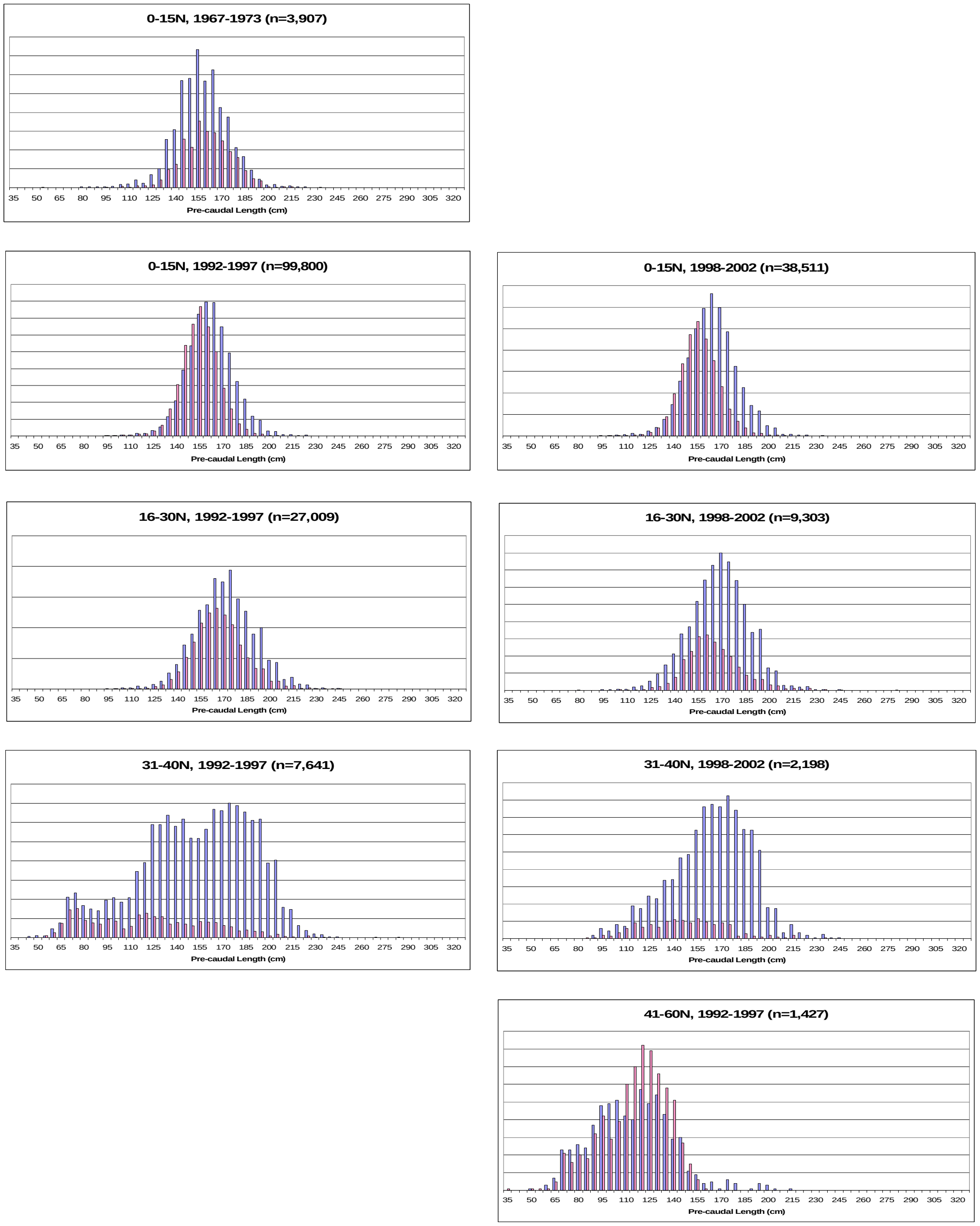


Figure 10.--Precaudal lengths (in cm) for male (blue) and female (pink) blue sharks by latitudinal bands for 1967–1973, 1992–1997, and 1998–2002.

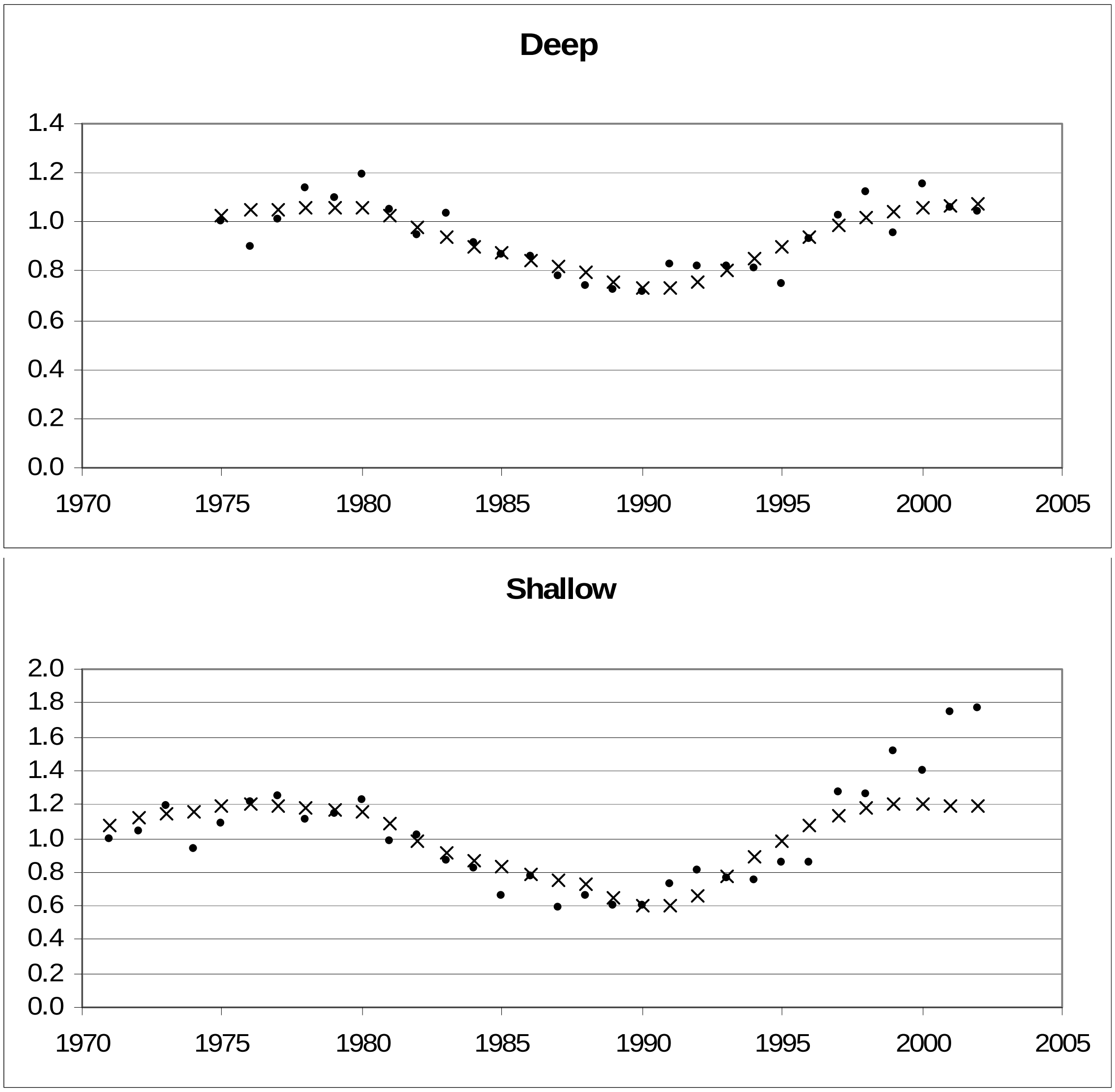


Figure 11.--Fit of the BSP model predicted CPUE (×) for deep (1975–2002) and shallow (1971–2002) sets to the observed deep and shallow CPUE indices (•).

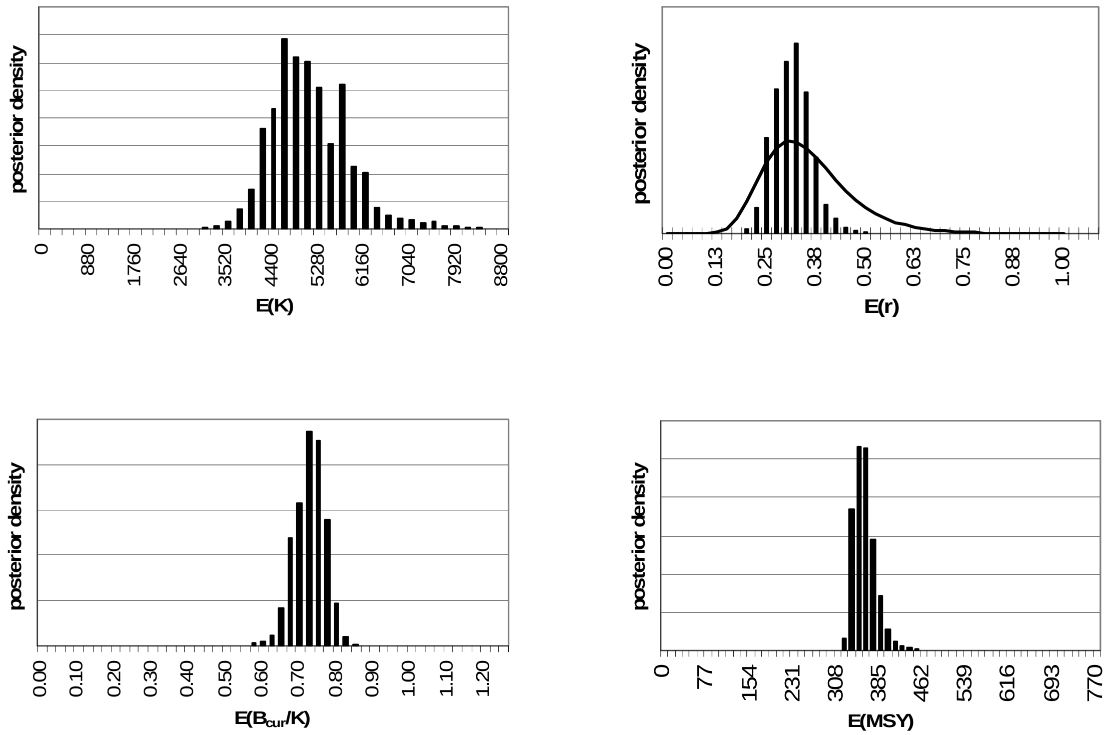


Figure 12.--Posterior probability density functions estimated by the BSP model for key parameters based on the base case for the deep CPUE series. In the graph showing the intrinsic rate of increase (r), both the posterior probability density function (columns) and the prior probability density function (line) are shown.

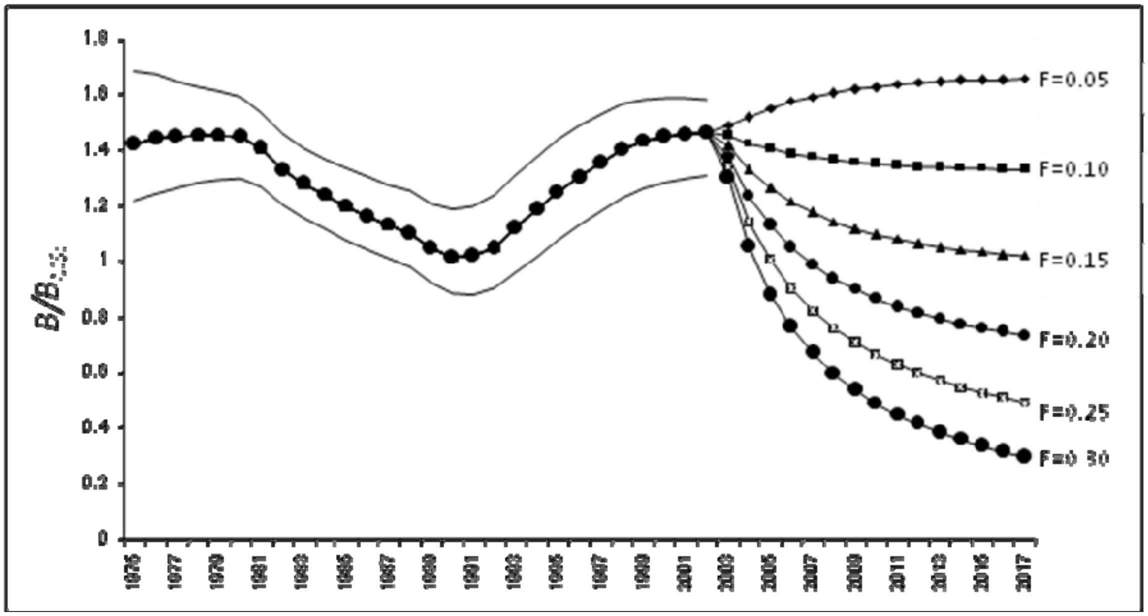


Figure 13.--Median values (annotated thick lines) for stock size as a proportion of stock size at maximum sustainable yield (B/B_{MSY}) under various scenarios for *F*, fishing mortality, projected for 15 years. 90% probability intervals (thin lines) are shown for historical data only. These projections are based on the base case for the deep catch rate series only.

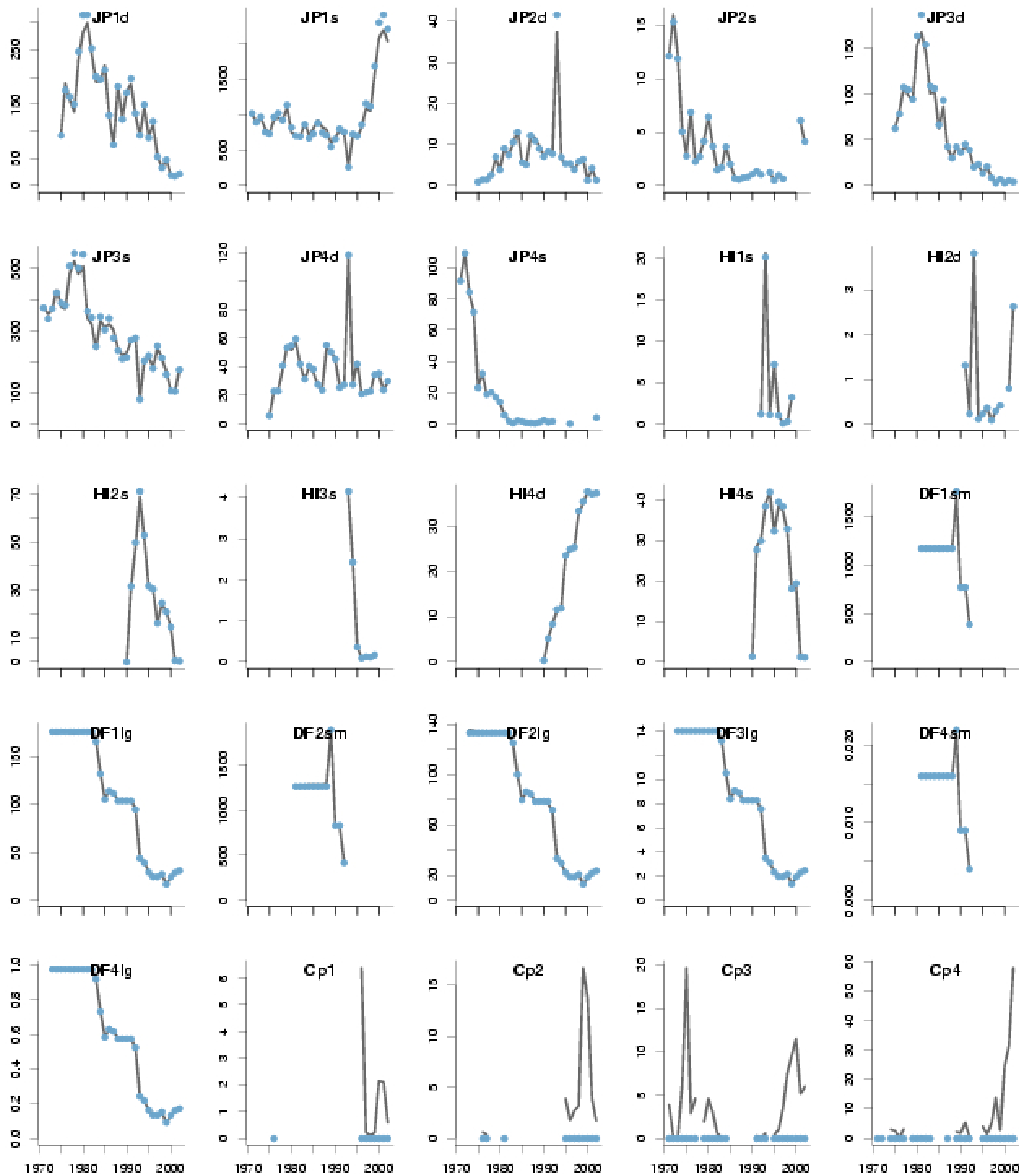


Figure 14.--Annual catches, by fishery. Points are observed and the lines are model predictions. Units are number caught in thousands. Figure labels are fleet codes for the MULTIFAN-CL analysis, described in Table 3.

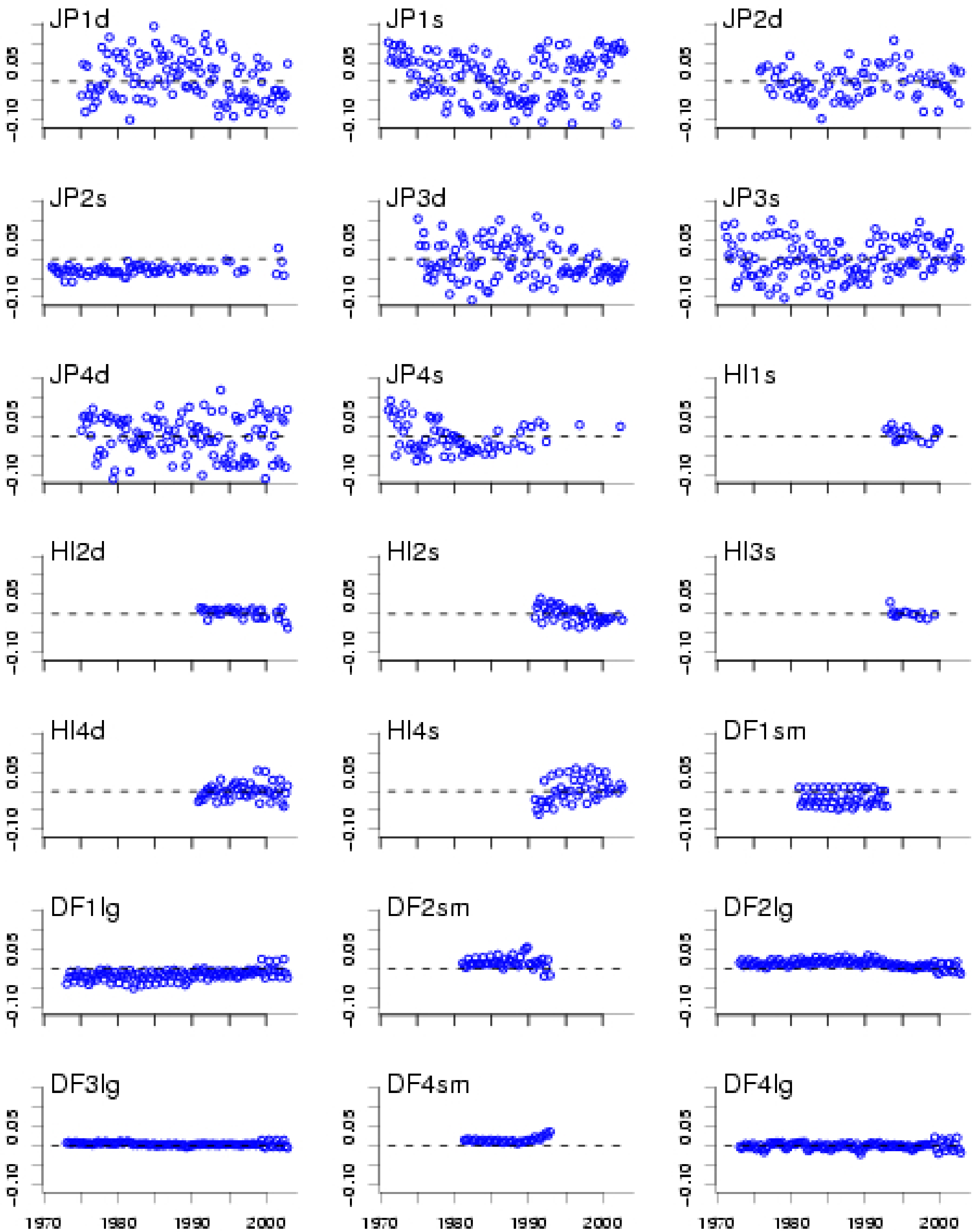


Figure 15.--Residuals of log (total catch) for each fishery.

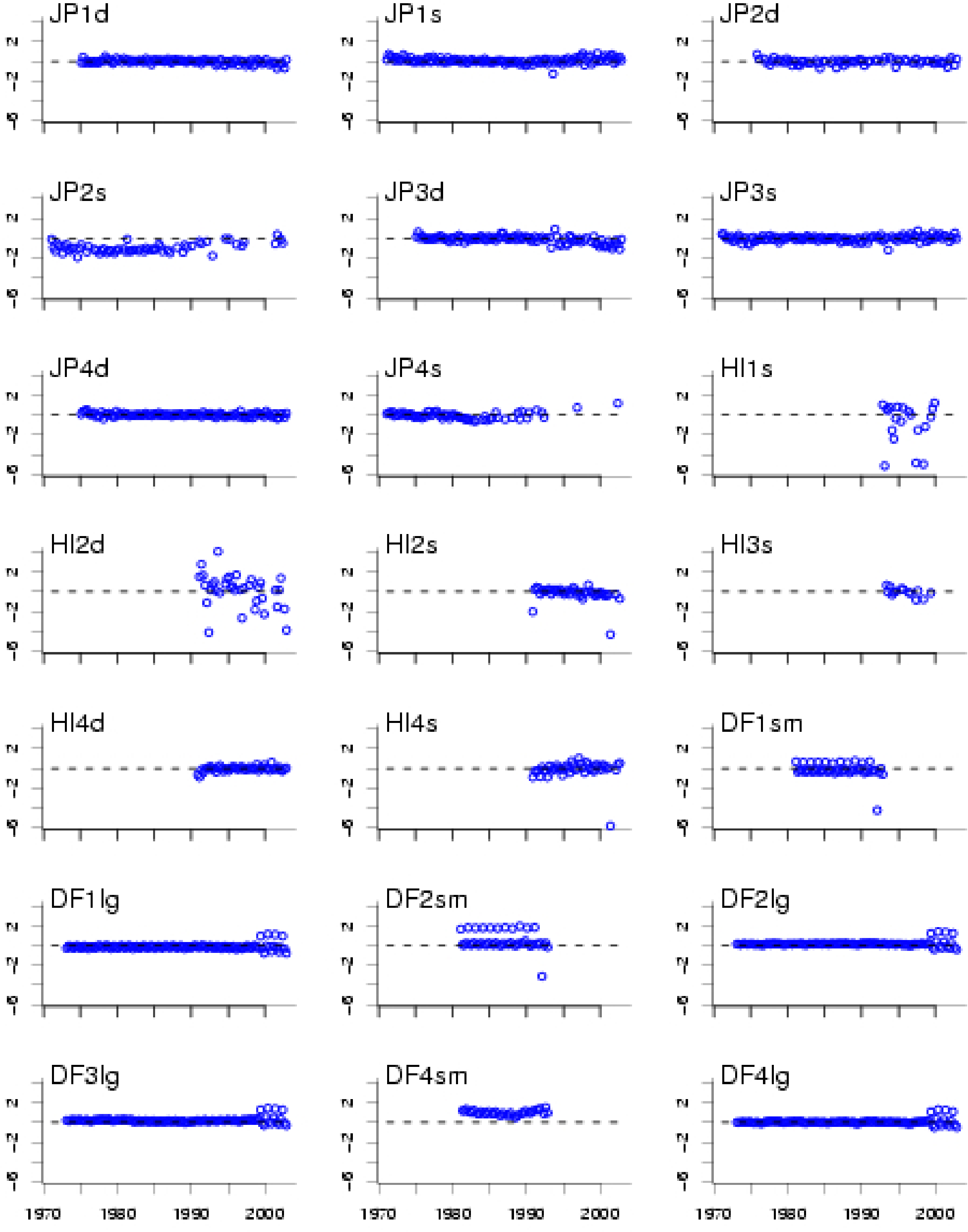


Figure 16.--Effort deviations - log((corrected effort)/effort) - for each fishery.

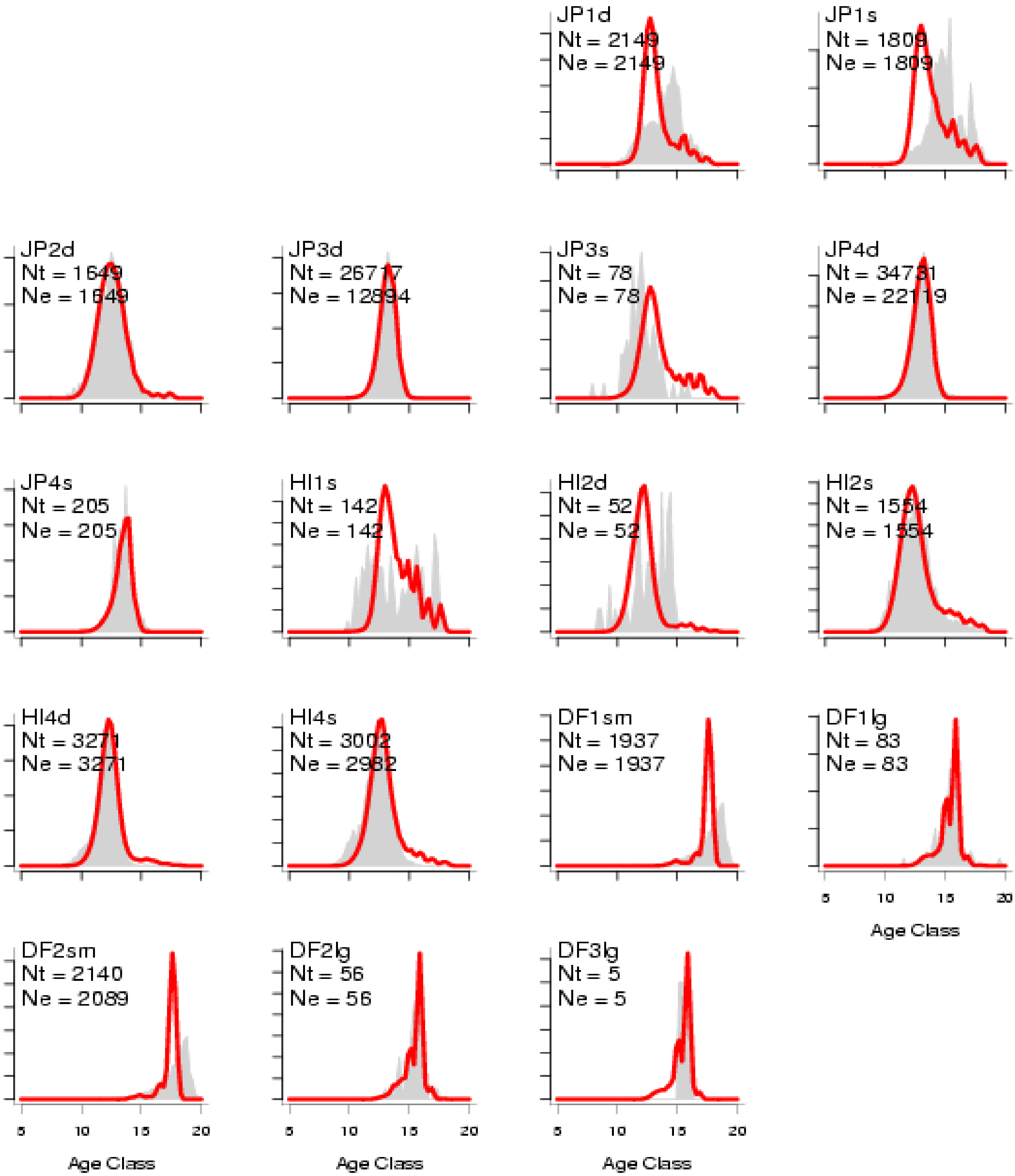


Figure 17.--Observed (histograms) and predicted (line) age frequencies (age in yrs) for each fishery aggregated over time. Total and effective sample sizes for observed length data are indicated by "Nt" and "Ne", respectively.

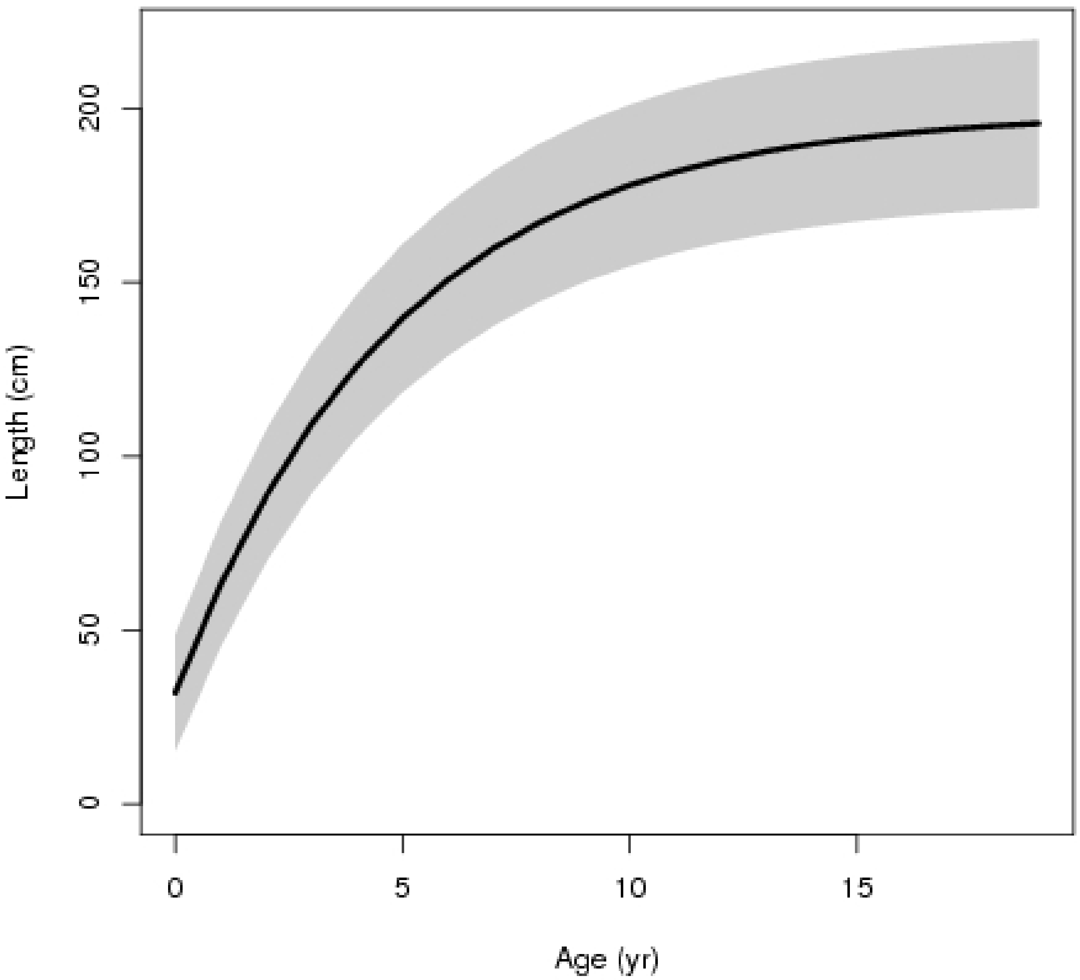


Figure 18.--Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD).

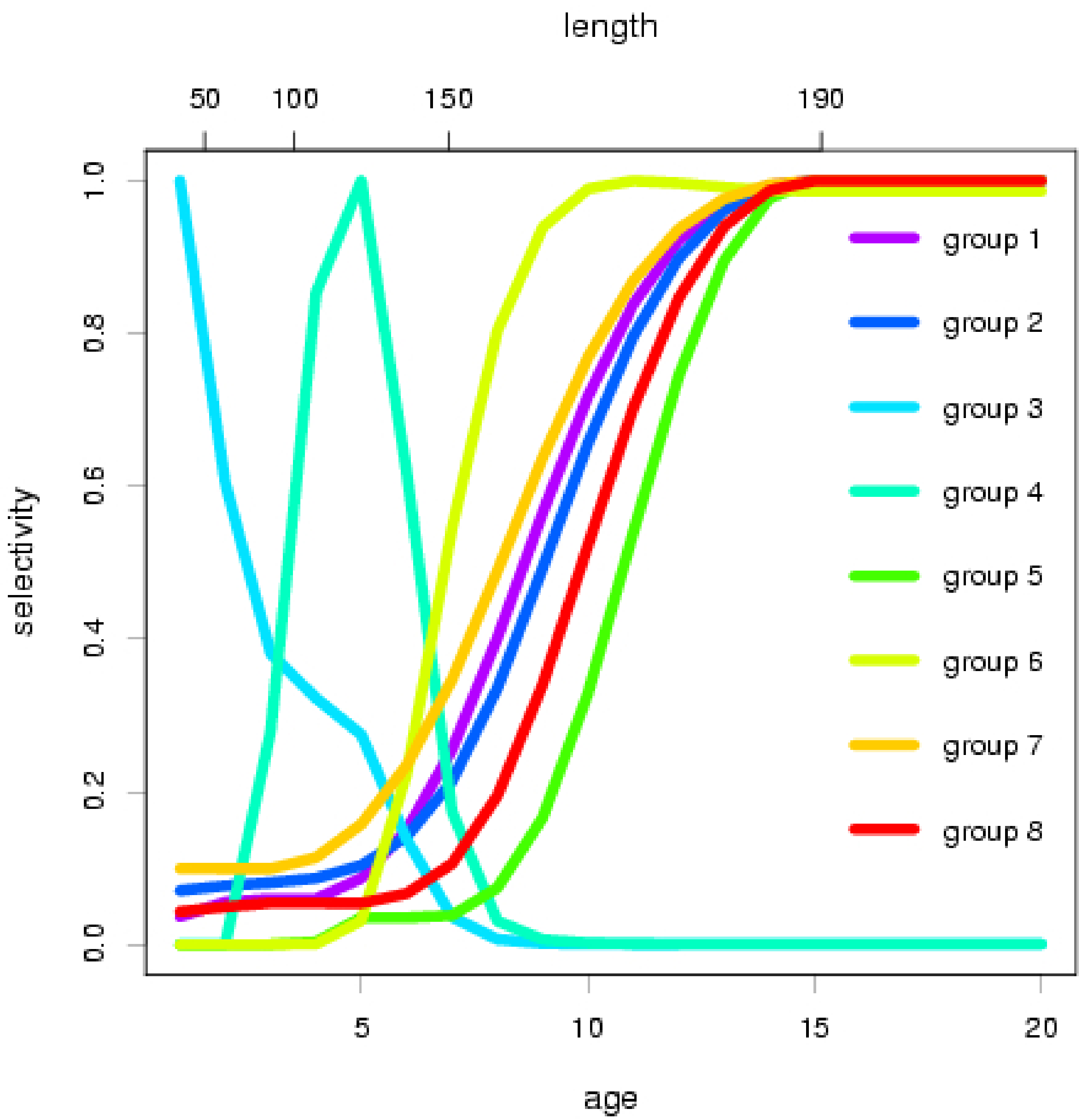


Figure 19.--Selectivity curves, for selectivity groupings defined in Table 3. Relationship of length and age scales given by growth curve above (Figure 18).

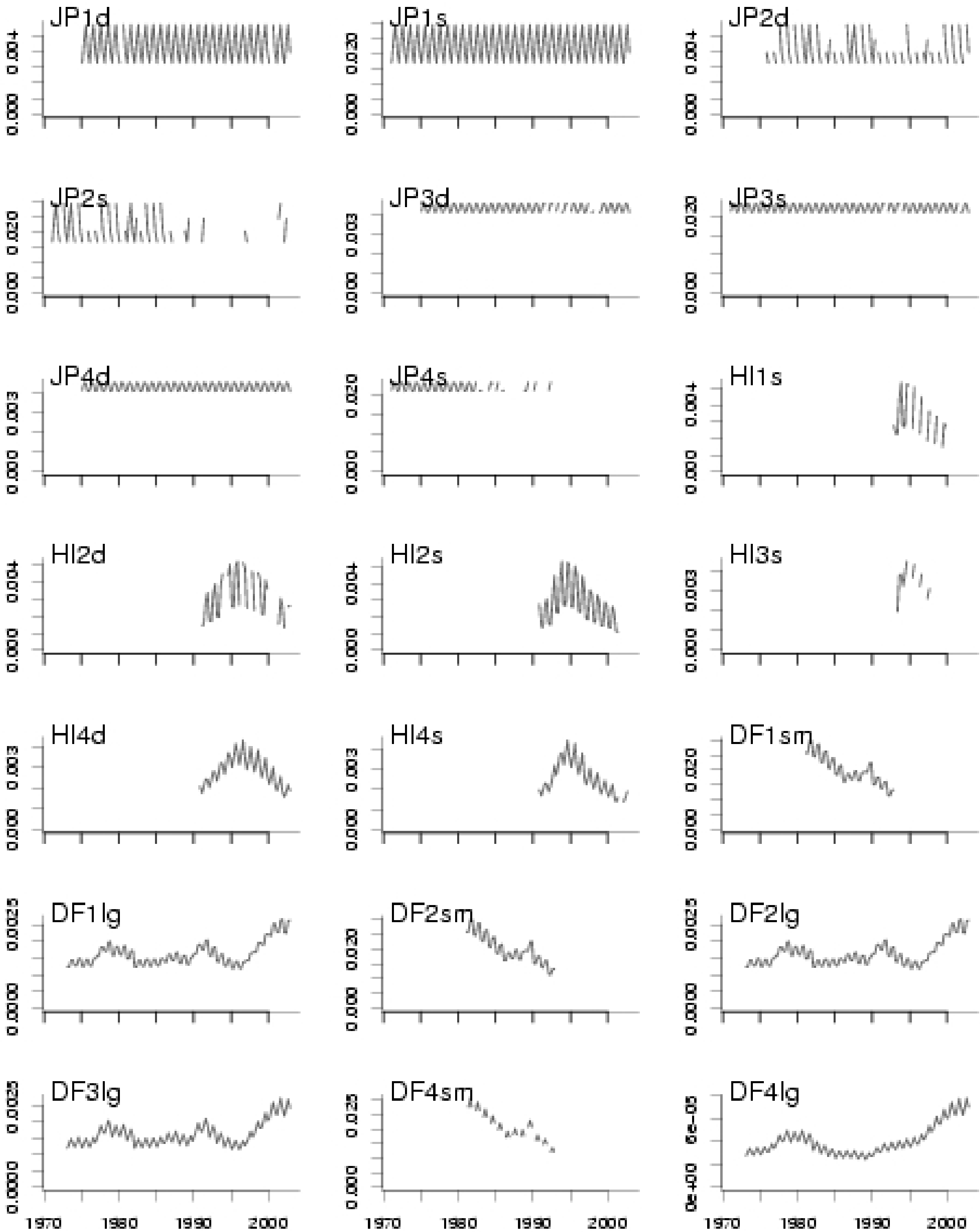


Figure 20.--Catchability time series, by fishery.

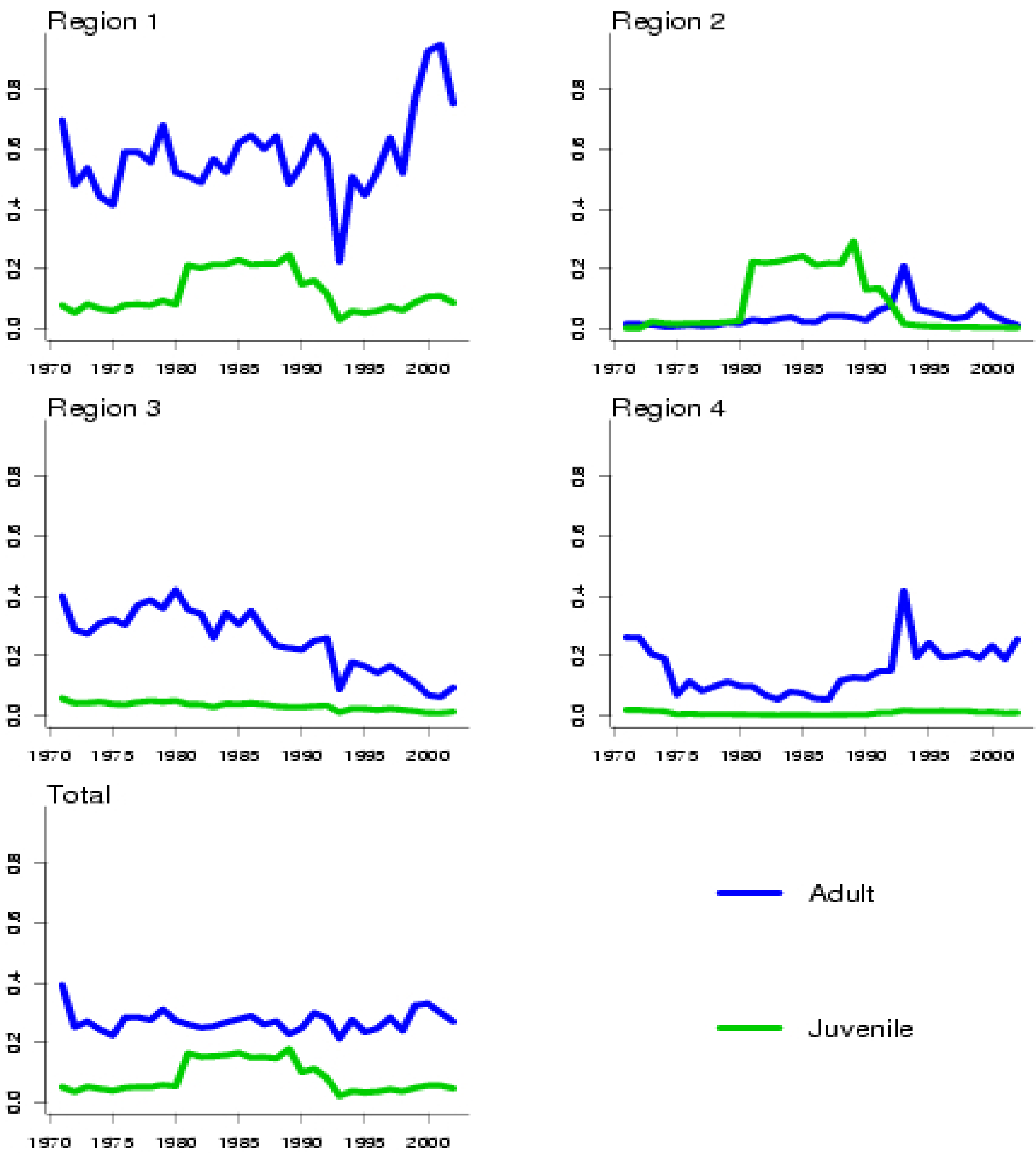


Figure 21.--Estimated annual average juvenile and adult fishing mortality, all fleets combined, by region and total.

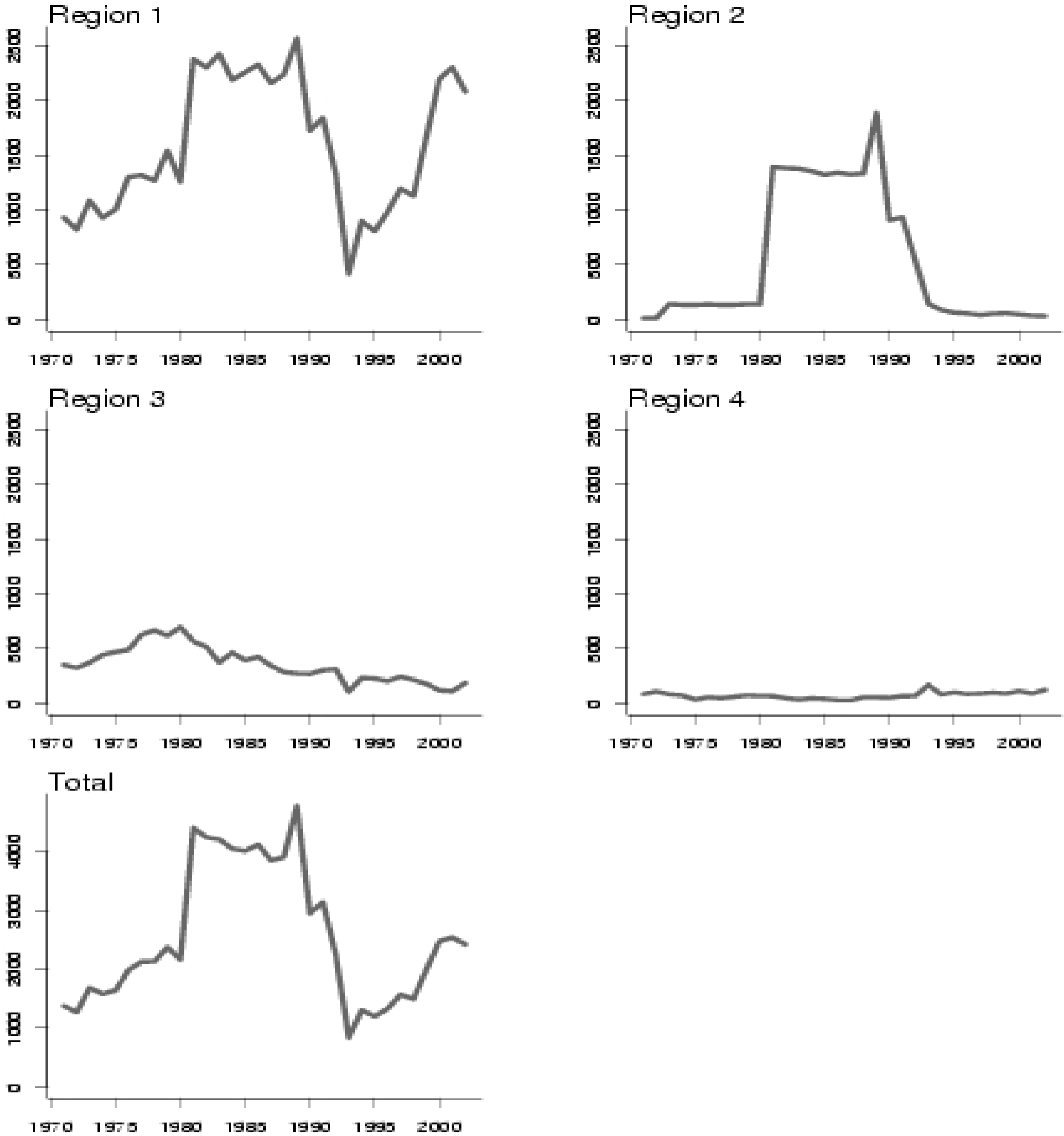


Figure 22.--Estimated annual catches (thousands of fish), all fleets combined, by region and total.

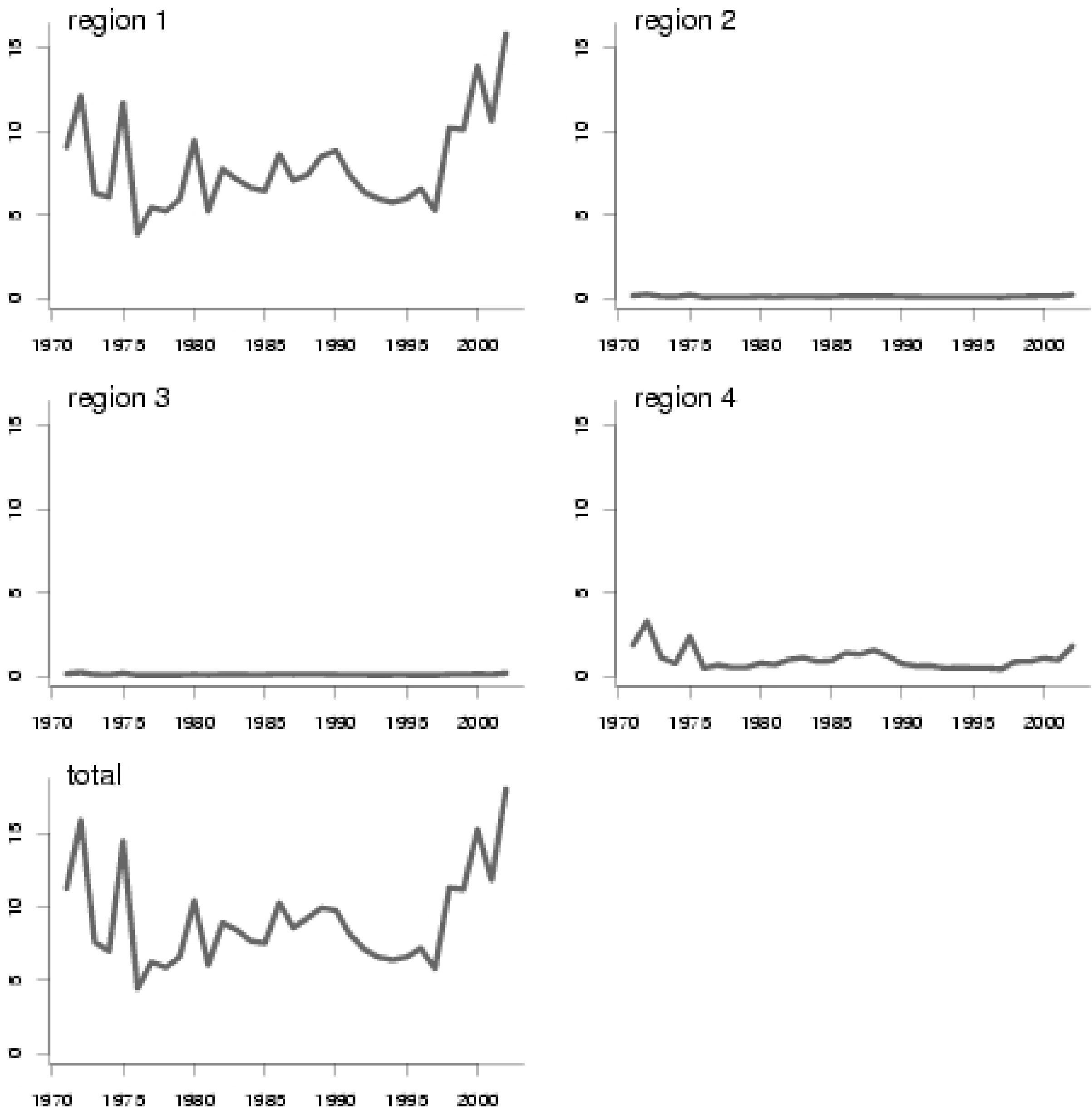


Figure 23.--Estimated annual recruitment by region and total (millions of fish per year).

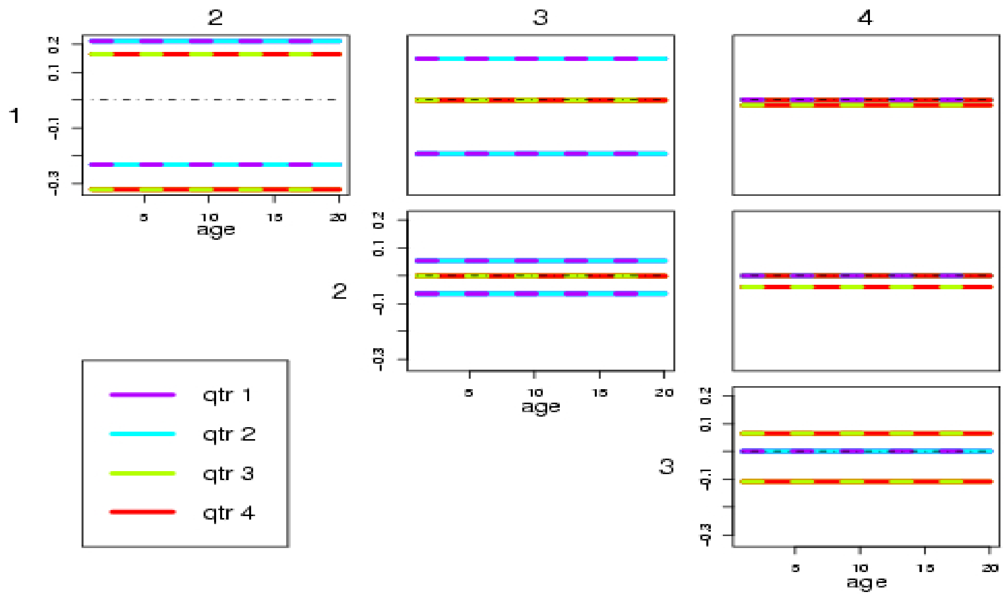


Figure 24.--Movement coefficients. Color indicates the quarter of the year in which movement occurs. Positive values represent movement from the regions indicated on the left to regions indicated on the top, and negative values represent movement in the reverse direction.

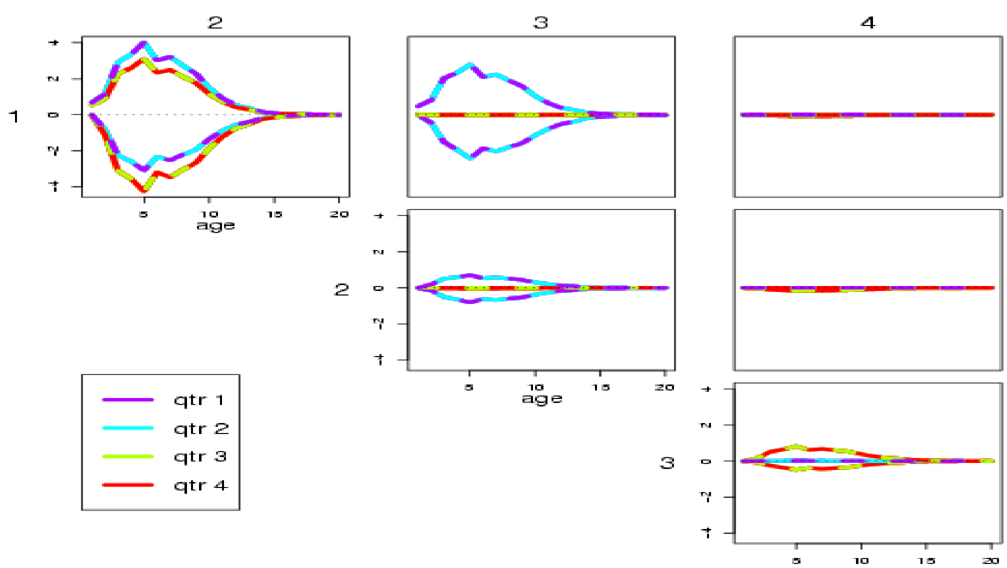


Figure 25.--Example movement flow in thousands of mt per quarter with movement coefficients applied to average population by age and region in years 1995 through 2000. Color indicates the quarter of the year in which movement occurs. Positive values represent flow from the regions indicated on the left to regions indicated on the top, and negative values represent flow in the reverse direction.

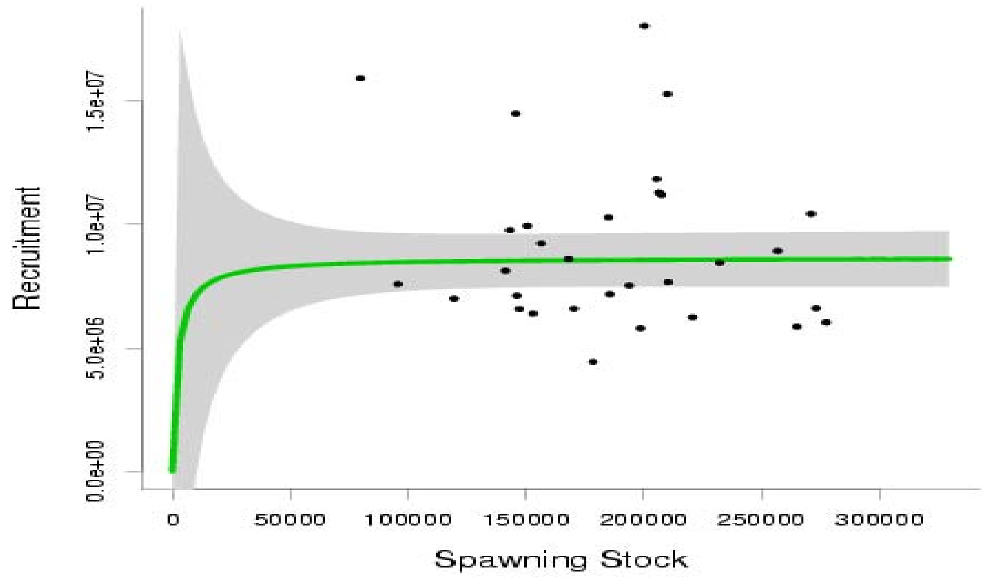


Figure 26.--Point estimates of recruitment and spawning biomass. Beverton-Holt stock-recruit relationship fittted to those points given by green line grey area indicating the 95% confidence region.

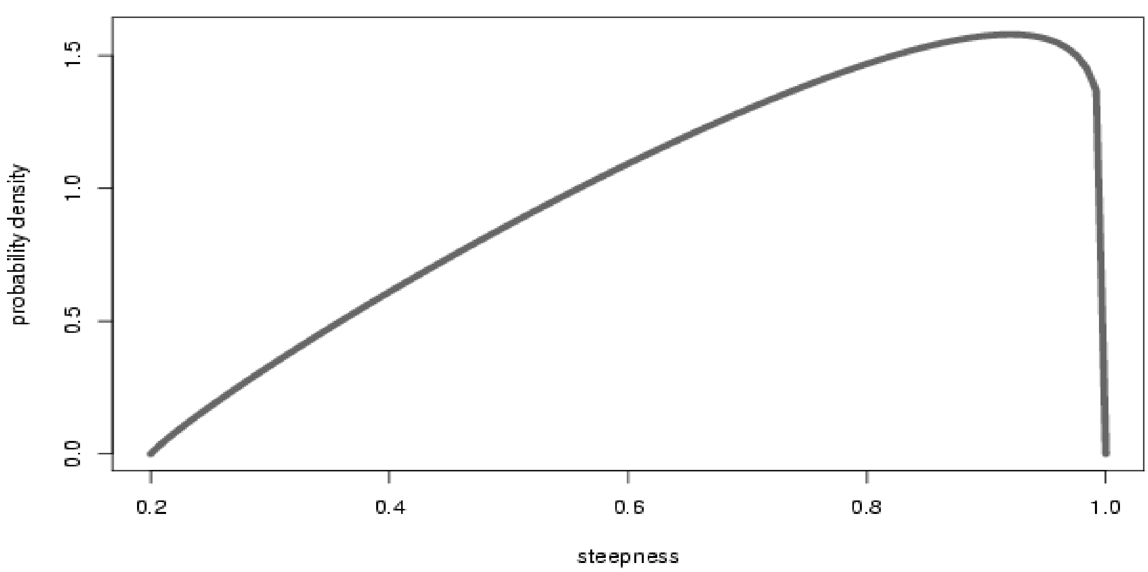


Figure 27.--Bayesian prior on steepness of the stock-recruit relationship - a non-standard beta distribution on interval [0.2 - 1.0] with mean 0.707 and standard deviation 0.193.

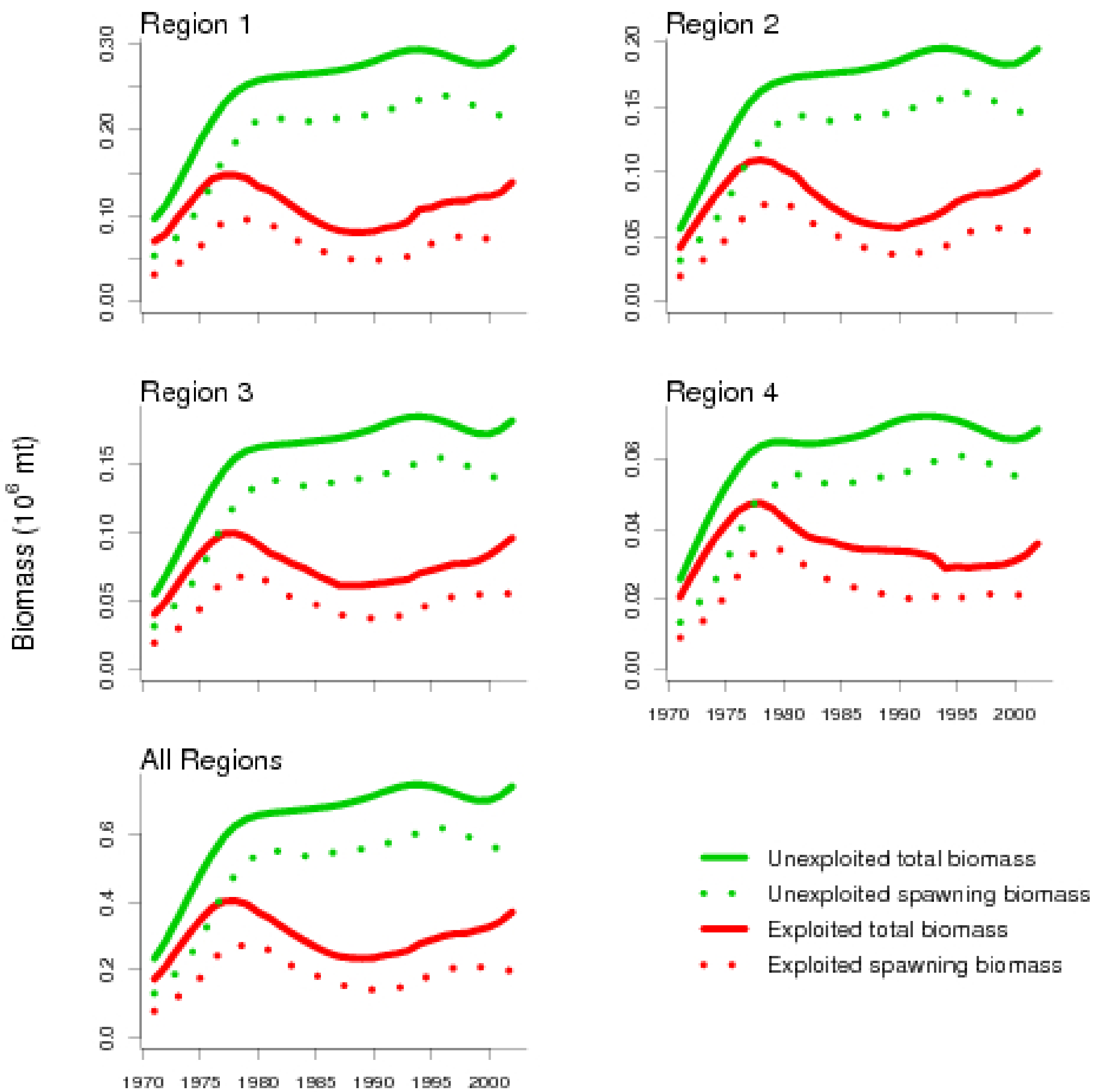


Figure 28.--Biomass and fishery impact. Annual average total biomass and spawning biomass by region and for all regions combined. The lower and upper solid and dotted lines indicate estimated biomass trajectories with fishing and without fishing, respectively. Vertical distance between pairs of lines indicates fishery impact.

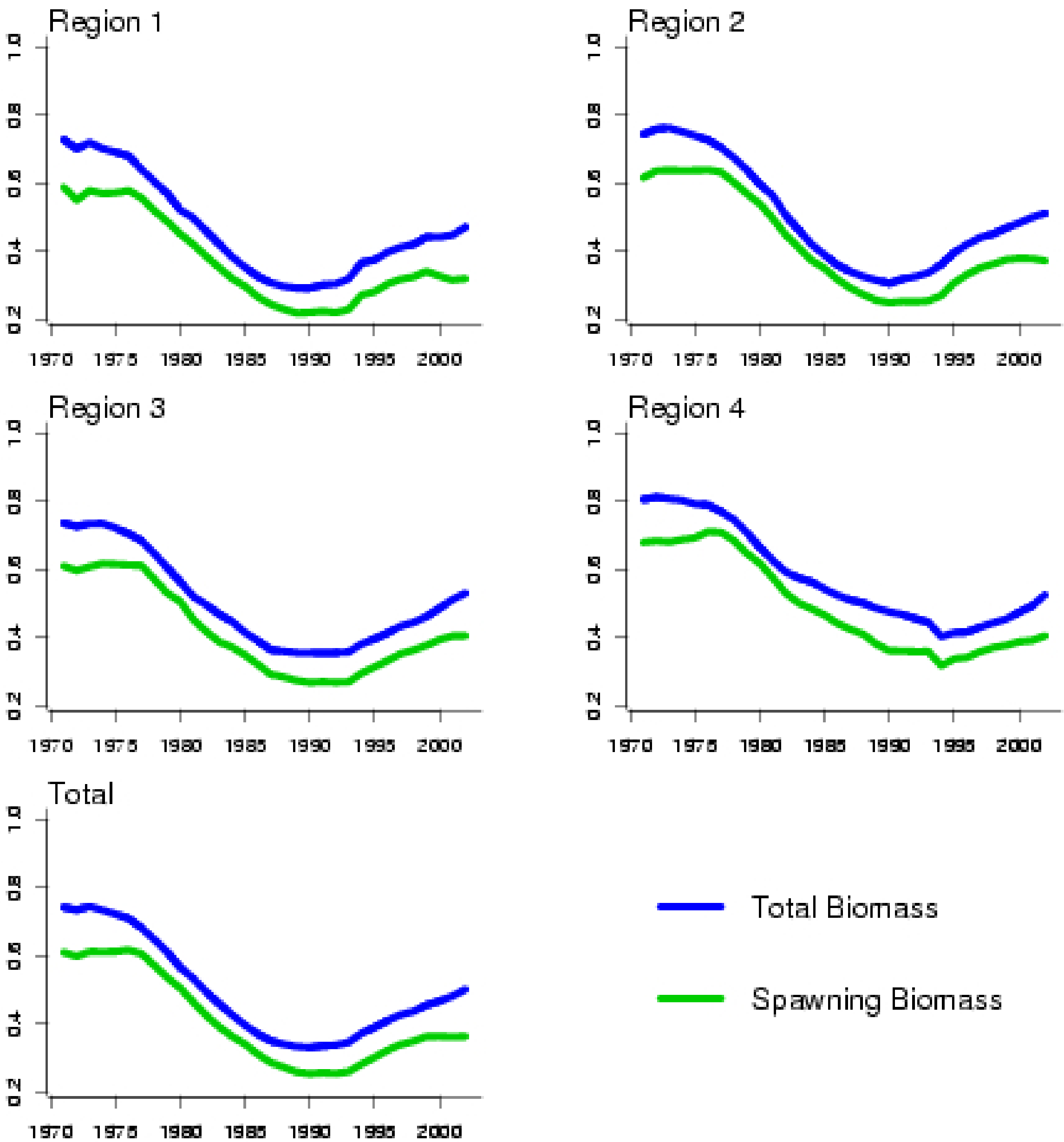


Figure 29.--Fishery impact measured by the proportional reduction of biomass from what it would be without fishing, i.e., *biomass(exploited)/biomass(unexploited)*.

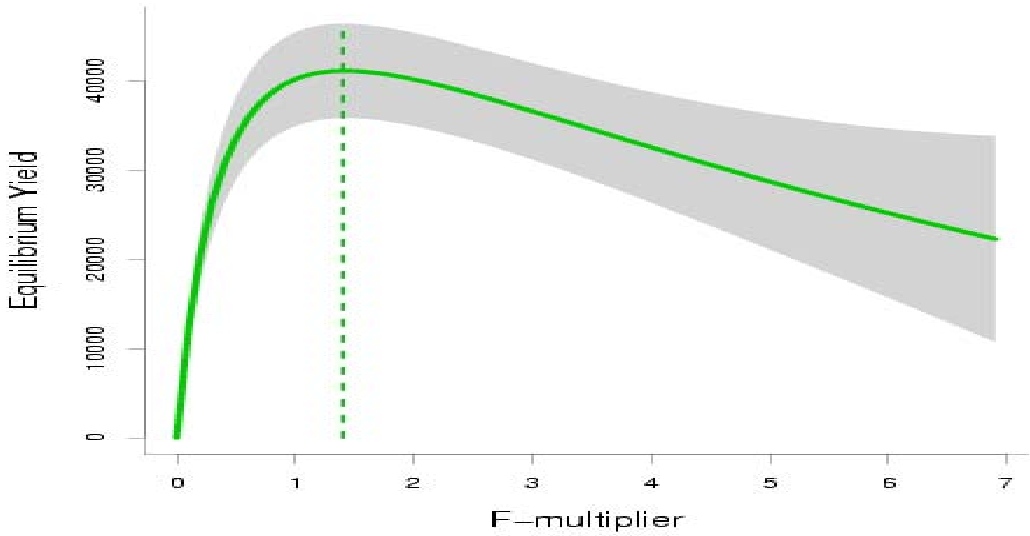


Figure 30.--Equilibrium yield (1000 mt) as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals. Dashed line indicates F_{MSY}, the point of maximum yield.

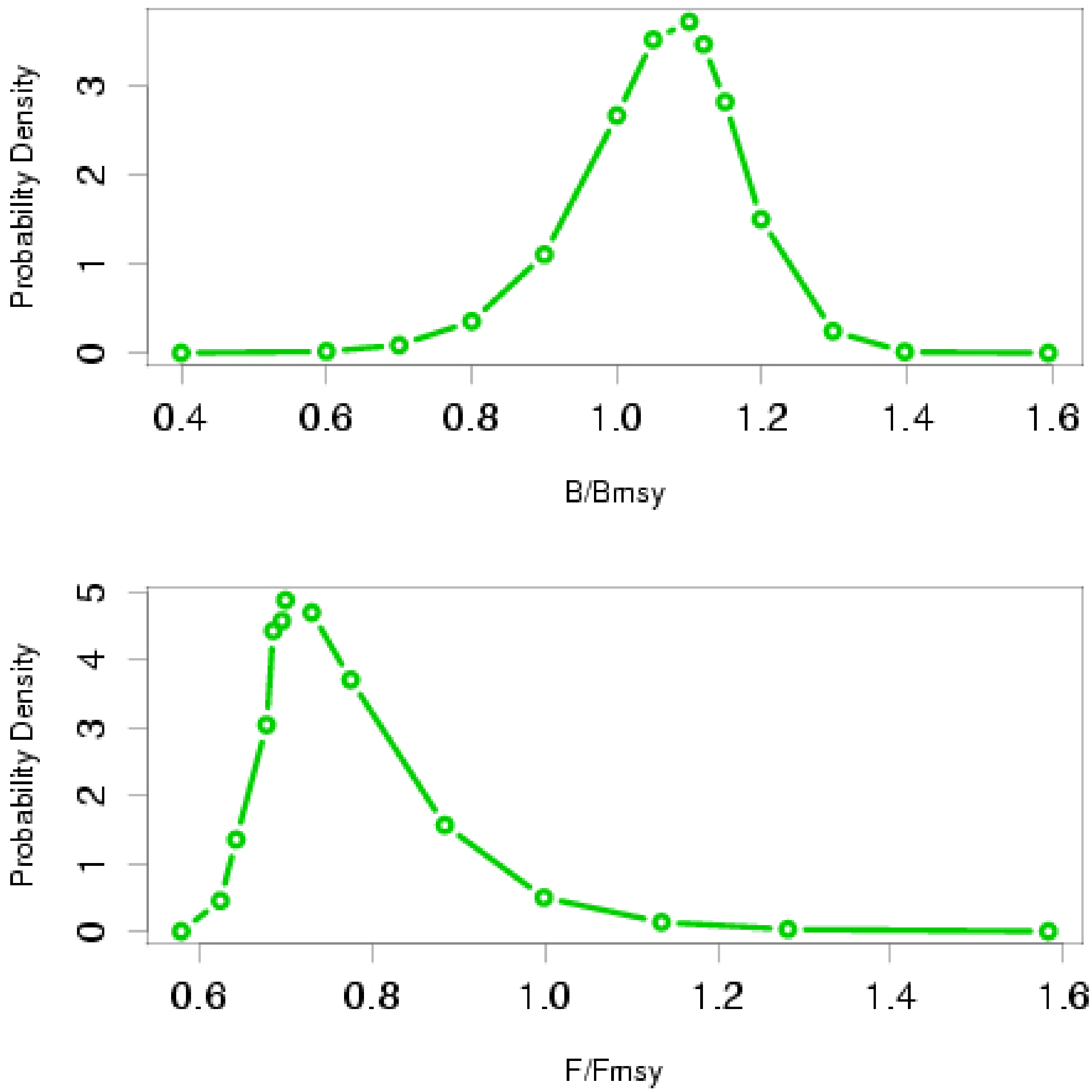


Figure 31.--Likelihood profile of B/B_{MSY} (upper panel) and minimal profile for F/F_{MSY} (lower panel) based on average conditions over years 1998 through 2001.

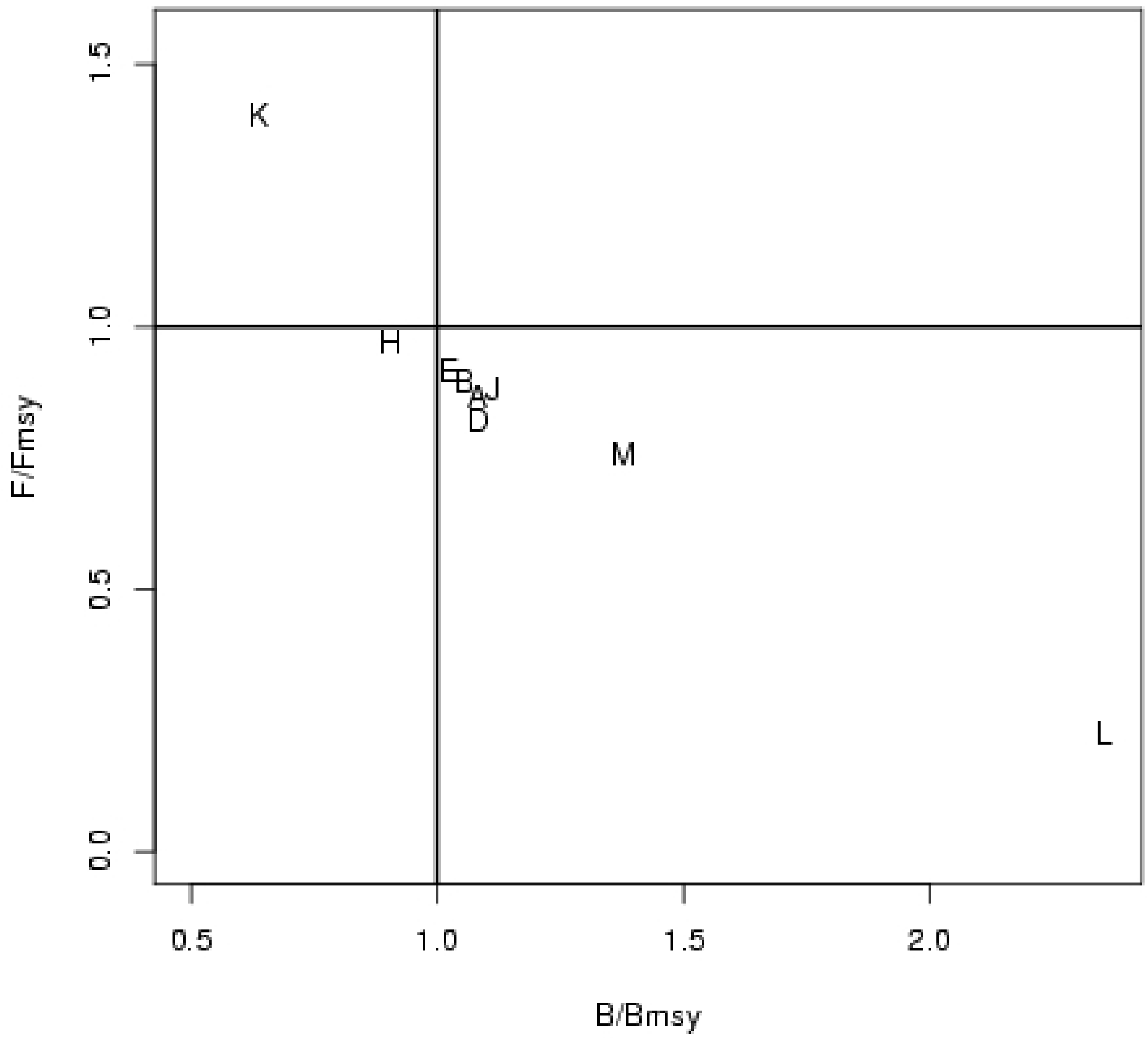


Figure 32.--Average (1998–2002) F/F_{MSY} vs. B/B_{MSY} for a range of alternate model fits conducted under a variety of constraints and conditions. "A" is the base-case.

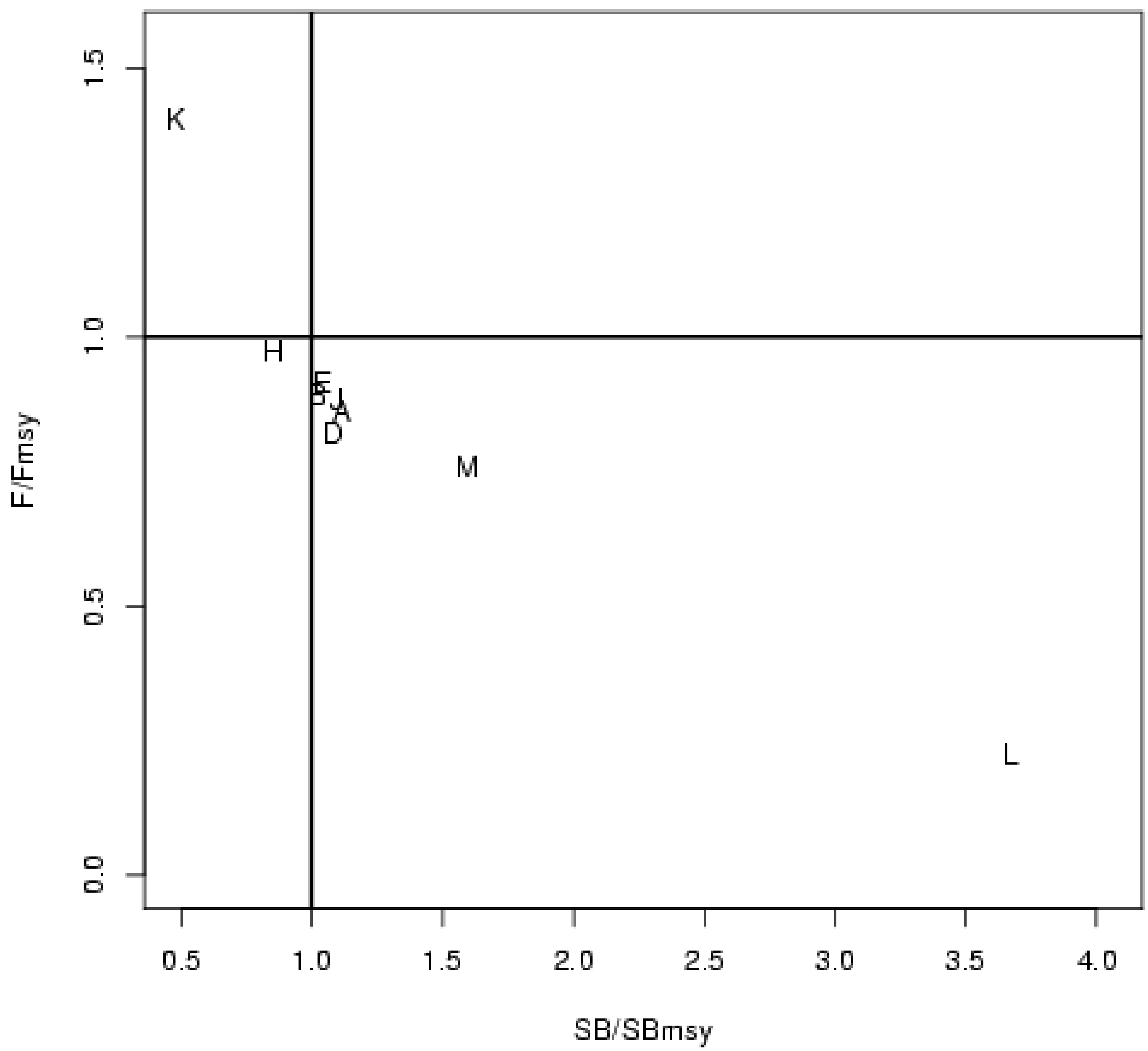


Figure 33.--Average (1998–2002) F/F_{MSY} vs. SB/SB_{MSY} for a range of alternate model fits conducted under a variety of constraints and conditions. “A” is the base-case.

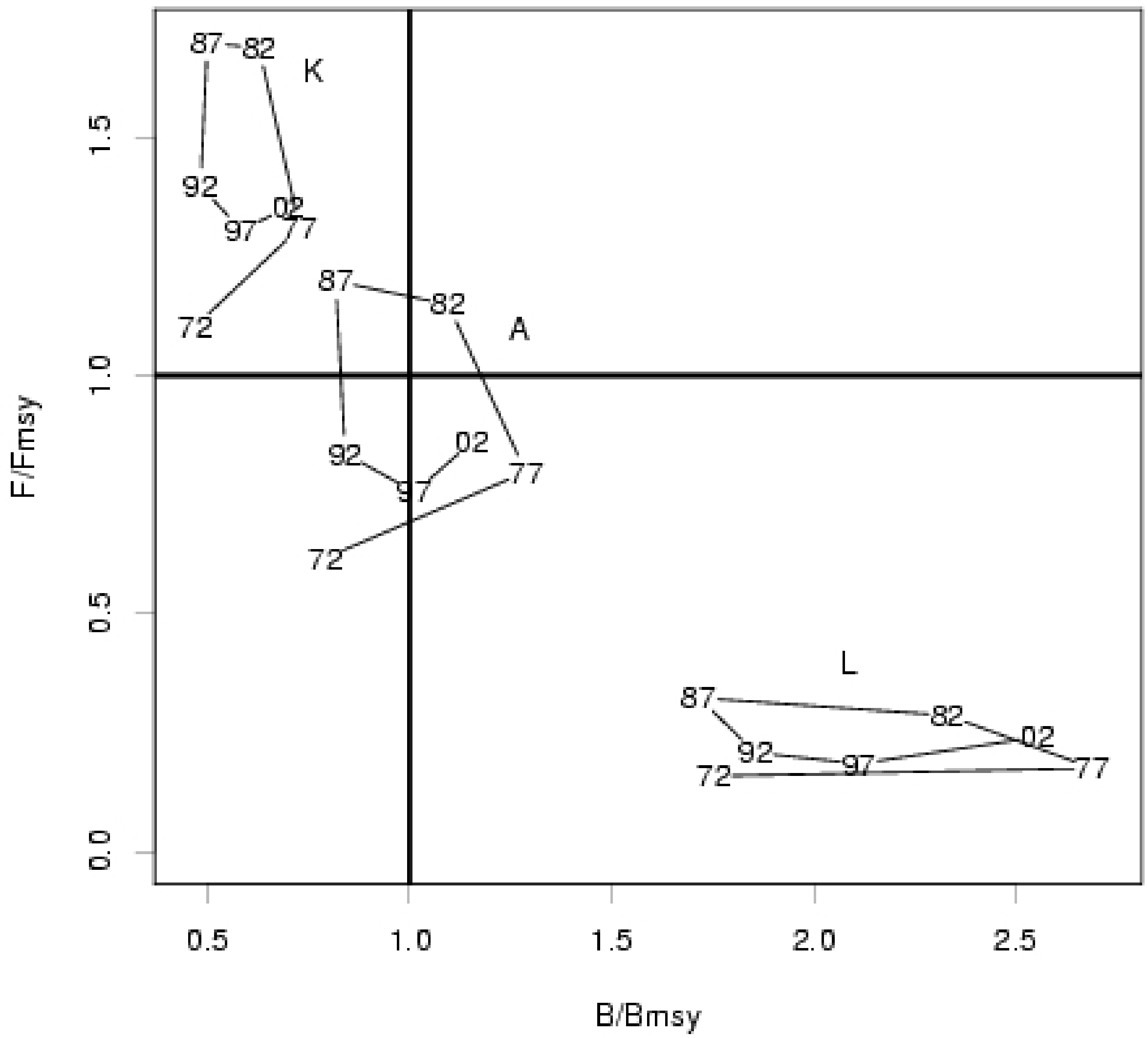


Figure 34.--Average F/F_{MSY} vs. SB/SB_{MSY} for sequence of 5-yr periods for the base case (A) and the extreme alternate runs (K and L). The middle year of each 5-yr period is indicated except for the first period, which begins in 1972 and the last period, which ends in 2002.

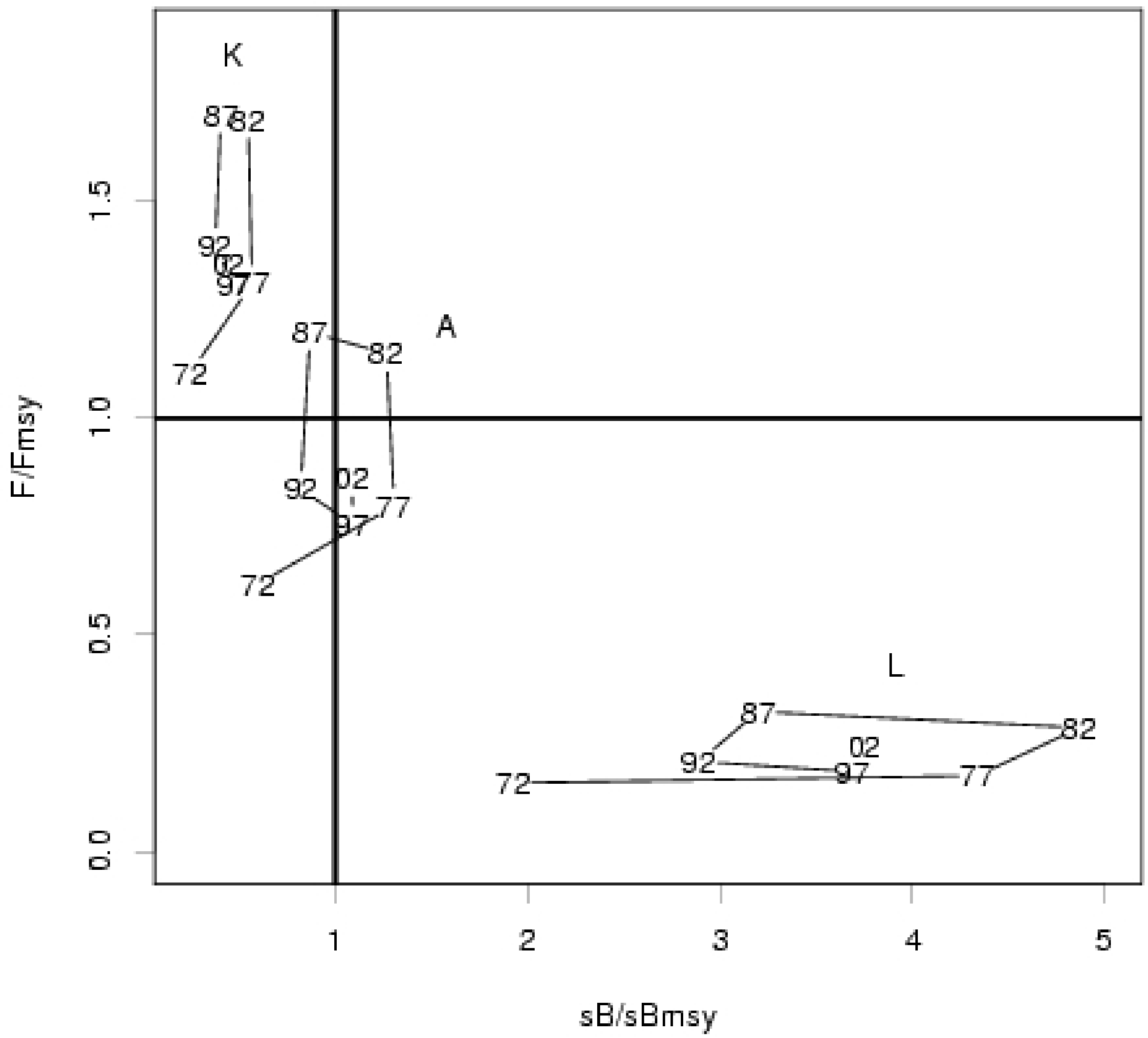


Figure 35.--Average F/F_{MSY} vs. SB/SB_{MSY} for sequence of 5-yr periods for the base case (A) and the extreme alternate runs (K and L). The middle year of each 5-yr period is indicated except for the first period, which begins in 1972 and the last period, which ends in 2002.

Table 1.--Parameter specification for the deep and shallow base cases of the BSP model.

Parameter	Distribution	Mean	Standard Deviation	Range (Input Minimum and Maximum)
K (10^4 fish)	Uniform	-	-	400 to 1,000,000
$B_{t=1}/K$	Log normal	1.0	0.2 (gives a 95% P.I. of 0.67 to 1.48)	0.3 to 3.5
r	Log normal	0.34	0.3 (input as variance =0.09; gives a 95% P.I. of 0.19 to 0.63)	0.001 to 2

Table 2.--Main structural assumptions of base-case MULTIFAN-CL 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 catch data	Observation errors small, equivalent to a residual SD 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 with a maximum effective sample size of 100.	None	na	na	na	na	na
Recruitment	One recruitment per 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 SD of 0.2). The spatial distribution of recruitment in each year 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)	32	SRR	0.7	-20	20
		Average spatial distribution of recruitment	4	-	-	0	1
		Time series deviations from average spatial distribution (ln)	123	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 total mortality estimated for 1971–75 and movement rates.	Initial recruitment scaling (ln)	1	-	-	-8	8
Age and growth	20 annual age-classes, with the last representing a plus group. Adult age-class mean lengths constrained by VB curve. SD 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*=0.0000043, *b*=3.1 >>reference<<).	Mean length age class 1	1	-	-	30	80
		Mean length age class 20	1	-	-	170	280
		von Bertalanffy *K*	1	-	-	0.01	0.3
		Independent mean lengths	0	0	0.7		
		Length-at-age SD	1	-	-	3	15
		Dependency on mean length (ln)	1	-	-	-0.69	0.69

Category	Assumptions	Estimated parameters (ln = log transformed parameter)	No.	Prior		Bounds	
				μ	σ	Low	High
Catchability	Sinusoidal seasonal variation within years. Catchability parameters shared within various fleet groupings (see Table 4). Except for Japanese longline, catchability allowed to vary with time in a constrained structural time series of biennial steps.	Average catchability coefficients (ln)	7	-	-	-15	1
		Seasonality amplitude (ln)	25	0	2.2	-	-
		Seasonality phase	25	-	-	-	-
		Structural time series	255				
Selectivity	Constant over time. Selectivity at size estimated as a 5-node cubic spline. Selectivity constrained to be constant for size greater than size at age 15 and for driftnet constrained to zero. Longline selectivities non-decreasing with increasing age. Selectivity parameters shared within various fleet groupings (see Table 1).	Selectivity coefficients	40	-	-	0	1
Fishing effort	Effort deviations constrained by prior distributions. SD inversely proportional to the square root of normalised effort.	Japan longline (ln)	788	0	0.10	-6	6
		Other fleets (ln)	984	0	0.22	-6	6
Natural mortality	Constant with age and time. Fixed in this analysis.	None	na	na	na	na	na
Movement	Varies by quarter but constant among years and age	Movement coefficients	32	0	0.10	0	3

(Table 2 – continued.)

Table 3.--Definition of fisheries for the MULTIFAN-CL analysis of blue sharks.

				Grouping codes		
				Catchability		
	Fleet code	Fleet description	Region	long-term	seasonal	Selectivity
1	JP1d	Japan LL, deep	1	Cy1	Cs1	S1
2	JP1s	Japan LL, shallow	1	Cy2	Cs1	S2
3	JP2d	Japan LL, deep	2	Cy1	Cs1	S5
4	JP2s	Japan LL, shallow	2	Cy2	Cs1	S2
5	JP3d	Japan LL, deep	3	Cy1	Cs2	S6
6	JP3s	Japan LL, shallow	3	Cy2	Cs2	S7
7	JP4d	Japan LL, deep	4	Cy1	Cs2	S6
8	JP4s	Japan LL, shallow	4	Cy2	Cs2	S8
9	HI1s	Hawaii LL, shallow	1	Cy3	Cs3	S2
10	HI2d	Hawaii LL, deep	2	Cy4	Cs3	S1
11	HI2s	Hawaii LL, shallow	2	Cy3	Cs3	S2
12	HI3s	Hawaii LL, shallow	3	Cy3	Cs4	S2
13	HI4d	Hawaii LL, deep	4	Cy4	Cs4	S1
14	HI4s	Hawaii LL, shallow	4	Cy3	Cs4	S2
15	DF1sm	DriftNet, small mesh	1	Cy5	Cs5	S3
16	DF1lg	DriftNet, large mesh	1	Cy6	Cs5	S4
17	DF2sm	DriftNet, small mesh	2	Cy5	Cs5	S3
18	DF2lg	DriftNet, large mesh	2	Cy6	Cs5	S4
19	DF3lg	DriftNet, large mesh	3	Cy6	Cs6	S4
20	DF4sm	DriftNet, small mesh	4	Cy5	Cs6	S3
21	DF4lg	DriftNet, large mesh	4	Cy7	Cs6	S4
22	Cp1	Cryptic LL, deep	1	Cy1	Cs1	S1
23	Cp2	Cryptic LL, deep	2	Cy1	Cs1	S5
24	Cp3	Cryptic LL, deep	3	Cy1	Cs2	S6
25	Cp4	Cryptic LL, deep	4	Cy1	Cs2	S6

Table 4.--Grouping of fisheries for common aspects of catchability variation and for selectivity.

Group	long-term catchability	seasonal catchability	selectivity
1	JP1d, JP2d, JP3d, JP4d, Cp1, Cp2, Cp3, Cp4	JP1d, JP1s, JP2d, JP2s, Cp1, Cp2	JP1d, HI2d, HI4d, Cp1
2	JP1s, JP2s, JP3s, JP4s	JP3d, JP3s, JP4d, JP4s, Cp3, Cp4	JP1s, JP2s, HI1s, HI2s, HI3s, HI4s
3	HI1s, HI2s, HI4s,	HI1s, HI2d, HI2s	DF1sm, DF2sm, DF4sm
4	HI2d, HI4d,	HI3s, HI4d, HI4s	DF1lg, DF2lg, DF3lg, DF4lg
5	DF1sm, DF2sm, DF4sm	DF1sm, DF1lg, DF2sm, DF2lg	JP2d, Cp2
6	DF1lg, DF2lg, DF3lg	DF3lg, DF4sm, DF4lg	JP3d, JP4d, Cp3, Cp4
7	DF4lg		JP3s
8			JP4s

Table 5.--Set-up information for base-case (Run A) and alternate analyses.

Run	Extra growth parameters	Effective sample size	Effort penalty	Region recruitment penalty	Orthogonal polynomial degree	Note
A	-	min(N/10, 100)	-50 for JPN -10 for others	50	-	
B	5	min(N/10, 100)	-50 for JPN -10 for others	0	-	
D	-	min(N/10, 100)	-50 for JPN -10 for others	50	-	Eliminate steep increase in Cp4 effort in final years
E	5	min(N/10, 100)	-50 for JPN -10 for others	0	-	Cp1—4 grouped with JP1—4 shallow instead of deep
H	5	min(N/10, 100)	-50 for JPN -10 for others	0	10	
J	-	min(N, 1000)	all 1	50	-	
K	-	min(N/2, 500)	all 5	50	-	
L	-	JPN: min(N/2, 500) HI & DN: min(N/10, 100)	5 for JPN -50 for others	50	-	
M	-	JPN: min(N/2, 500) HI & DN: min(N/10, 100)	5 for JPN -50 for others	50	8	

Table 6.--Comparison of GLM and statistical habitat models for estimating blue shark catch.

	Shallow gear		Deep gear	
	Pseudo-R^2	Parameters	Pseudo-R^2	Parameters
GLM (log transformed least-squares)	0.272	145	0.294	137
GLM (Poisson)	0.335	145	0.294	137
statHBS (log transformed least-squares)	0.282	608	0.306	592

Table 7.--Catch of blue shark in number by gear, 1971–2002. Shallow longline catches reflect Japan, Hawaii and other fleets, whereas deep longline catches reflect these fleets and the Taiwan fleet. The coastal longline catches are those from Japan's *Kogata* fleet only. Drift net catches are the sum of large and small mesh gear type estimates.

Year	Shallow longline	Deep longline	Coastal longline	Driftnet	Total
1971	1,847,900	-	283,440	-	2,131,340
1972	2,033,522	-	304,070	-	2,337,591
1973	2,039,357	-	323,664	324,008	2,687,030
1974	1,795,575	-	178,303	324,008	2,297,887
1975	1,205,711	304,841	201,694	324,008	2,036,254
1976	1,526,201	539,690	298,836	324,008	2,688,735
1977	1,378,656	754,827	313,319	324,008	2,770,810
1978	1,131,295	939,501	316,328	324,008	2,711,133
1979	1,297,306	1,031,380	315,167	324,008	2,967,862
1980	1,166,493	1,025,275	310,094	324,008	2,825,870
1981	860,242	1,126,540	259,996	2,749,597	4,996,374
1982	614,552	1,053,451	240,084	2,749,597	4,657,685
1983	452,769	924,025	226,330	2,730,552	4,333,676
1984	381,502	1,074,881	208,750	2,668,846	4,333,979
1985	328,503	1,062,738	239,697	2,619,247	4,250,185
1986	384,007	1,033,301	239,166	2,635,581	4,292,056
1987	316,884	1,020,380	213,826	2,630,922	4,182,012
1988	350,092	1,010,081	214,744	2,616,373	4,191,290
1989	267,990	1,065,101	190,551	3,833,715	5,357,357
1990	234,332	1,132,100	227,105	1,784,345	3,377,881
1991	290,411	1,180,720	255,765	1,784,345	3,511,241
1992	361,482	1,114,320	273,080	971,098	2,719,981
1993	347,094	1,103,208	265,860	80,446	1,796,609
1994	324,530	1,201,078	249,739	71,894	1,847,240
1995	358,765	1,332,834	234,903	53,665	1,980,166
1996	349,944	1,282,737	242,146	44,680	1,919,507
1997	438,445	1,084,824	288,939	44,583	1,856,791
1998	425,003	1,285,372	307,689	50,031	2,068,095
1999	530,704	1,432,482	405,328	30,419	2,398,933
2000	529,918	1,581,446	449,090	44,303	2,604,757
2001	593,628	1,671,748	456,946	52,928	2,775,250
2002	697,004	1,493,918	434,024	56,677	2,681,623

Table 8.--BSP model results for various scenarios based on deep and shallow CPUE series separately. The results are presented as the expected value from posterior probability distributions for each parameter. Figures in parentheses, where shown, represent standard deviations.

	K (10^{-4} fish)	*r* (yr^{-1})	*MSY* (10^{4} fish yr^{-1})	B_{cur}/K	*σ (MLE)*	*q* (yr^{-1} $hook^{-1}$)
Deep						
Base	4,915 (1,103)	0.30 (0.045)	358 (79)	0.73 (0.042)	0.075	3.13E-4
K prior not log normal	5,202 (7,783)	0.28 (0.038)	358 (664)	0.70 (0.041)	0.075	3.10E-4
Less informative *r*	5,109 (1,623)	0.28 (0.049)	355 (142)	0.72 (0.044)	0.075	3.08E-4
Starting biomass well below *K*	5,187 (684)	0.27 (0.040)	344 (13)	0.68 (0.051)	0.074	3.23E-4
Alternative weighting method	5,233 (8,947)	0.32 (0.067)	405 (733)	0.77 (0.051)	0.074	3.12E-4
Shallow						
Base	2,798 (,1191)	0.54 (0.083)	366 (99)	0.77 (0.020)	0.159	5.80E-4
K prior not log normal	3,351 (19,030)	0.57 (0.141)	423 (1,695)	0.78 (0.025)	0.160	5.71E-4
Less informative *r*	2,463 (1,097)	0.62 (0.118)	373 (114)	0.78 (0.016)	0.158	6.36E-4
Starting biomass well below *K*	2,831 (431)	0.52 (0.080)	361 (17)	0.75 (0.024)	0.156	6.00E-4
Alternative weighting method	2,636 (284)	0.56 (0.067)	366 (8)	0.77 (0.015)	0.158	5.94E-4

Table 9.--Biomass as a proportion of carrying capacity (B_{fin}/K) and biomass as a proportion of MSY(B_{fin}/B_{msy}) as estimated by decision analysis for the deep catch series over a 15-year time frame.

Horizon	**Policy:** F (yr^{-1})	**E(B_{fin}/K)**	**E(B_{fin}/B_{msy})**
5-year	0.05	0.79	1.58
	0.10	0.68	1.37
	0.15	0.58	1.17
	0.20	0.49	0.98
	0.25	0.41	0.82
	0.30	0.33	0.67
10-year	0.05	0.82	1.63
	0.10	0.67	1.33
	0.15	0.53	1.05
	0.20	0.4	0.81
	0.25	0.3	0.59
	0.30	0.21	0.41
15-year	0.05	0.82	1.65
	0.10	0.66	1.32
	0.15	0.5	1.01
	0.20	0.36	0.73
	0.25	0.25	0.49
	0.30	0.15	0.3

Table 10.--Model fit information for base-case (Run A) and alternate analyses.

Run	No. parameters	Objective function	Final gradient
A	1946	26601	0.000971
B	1950	26345	0.776238
D	1946	26579	0.000947
E	1916	26470	0.000914
H	1809	26428	0.826824
J	1946	39859	0.000863
K	1946	36204	0.000864
L	1946	31656	0.000918
M	1805	31623	0.000556

Table 11.--Derived information for base-case (Run A) and alternate analyses. Fishery impact is current exploited biomass as fraction of current unexploited biomass. *Tm* is the estimated age at maturity (yrs).

Run	Fishery Impact	*F/Fmsy*	*B/Bmsy*	*Tm*	B_{end}/B_{start}	
					exploited	unexploited
A	0.44	0.86	1.11	6.8	1.6	2.5
B	0.43	0.89	1.02	7.9	1.6	2.6
D	0.42	0.82	1.08	6.9	1.7	2.5
E	0.41	0.92	1.04	6.8	1.6	2.5
H	0.36	0.97	0.85	7.4	1.7	2.8
J	0.37	0.88	1.09	8.1	1.6	2.5
K	0.21	1.40	0.47	9	1.6	3.4
L	0.64	0.22	3.67	6.6	1.6	1.8
M	0.49	0.76	1.59	7.6	1.6	2.4

Table 12.--Reference point results for base-case (Run A) and two alternate fits chosen from extremes of scatter in Figure 33. An overhead tilde (~) indicates an equilibrium value approached under a long-term stable fishing regime. An overhead bar (—) indicates a "current" value calculated as the average over the years 1998–2001.

Reference point	Symbol	Units	Run A	Run L	Run K
Maximum sustainable yield (MSY)	$\tilde{Y}_{MSY}$	mt/yr	41130	100000	55770
Equilibrium yield at current fishing mortality (F)	$\tilde{Y}_F$	mt/yr	40200	50840	49770
Current biomass with fishing	$\overline{B}_F$	mt	323412	1270290	213345
Current biomass with no fishing	$\overline{B}_0$	mt	703577	1634128	901006
Equilibrium biomass with current F	$\tilde{B}_F$	mt	355500	1221000	213100
Equilibrium biomass with no fishing	$\tilde{B}_0$	mt	753300	1585000	952900
Equilibrium biomass at MSY	$\tilde{B}_{MSY}$	mt	299800	539600	334000
Current spawning biomass with fishing	$S\overline{B}_F$	mt	205907	743497	87014
Current spawning biomass with no fishing	$S\overline{B}_0$	mt	573741	1094292	757919
Equilibrium spawning biomass with current F	$S\tilde{B}_F$	mt	233400	805000	81350
Equilibrium spawning biomass with no fishing	$S\tilde{B}_0$	mt	611000	1158000	792900
Equilibrium spawning biomass at MSY	$S\tilde{B}_{MSY}$	mt	184900	202700	183700

Table 13.--Reference point ratios for base-case (Run A) and two alternate fits chosen from extremes of scatter in Figure 33.

Reference point	Run A	Run L	Run K
$\overline{F} / F_{MSY}$	0.86	0.22	1.40
$\overline{B}_F / \widetilde{B}_{MSY}$	1.08	2.35	0.64
$\overline{B}_F / \overline{B}_0$	0.46	0.78	0.24
$\overline{B}_F / \widetilde{B}_F$	0.91	1.04	1.00
$\overline{B}_F / \widetilde{B}_0$	0.43	0.80	0.22
$\widetilde{B}_F / \widetilde{B}_0$	0.47	0.77	0.22
$\widetilde{B}_F / \widetilde{B}_{MSY}$	1.19	2.26	0.64
$S\overline{B}_F / S\widetilde{B}_{MSY}$	1.11	3.67	0.47
$S\overline{B}_F / S\overline{B}_0$	0.36	0.68	0.11
$S\overline{B}_F / S\widetilde{B}_F$	0.88	0.92	1.07
$S\overline{B}_F / S\widetilde{B}_0$	0.34	0.64	0.11
$S\widetilde{B}_F / S\widetilde{B}_0$	0.38	0.70	0.11
$S\widetilde{B}_F / S\widetilde{B}_{MSY}$	1.26	3.97	0.44

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(October 2007)

13 Corrected catch histories and logbook accuracy for billfishes (Istiophoridae) in the Hawaii-based longline fishery.
W. WALSH, K. BIGELOW, and R. ITO
(December 2007)

14 Hawaiian Archipelago Marine Ecosystem Research (HAMER).
HAWAII DIVISION OF AQUATIC RESOURCES, PAPAHĀNAUMOKUĀKEA MARINE NATIONAL MONUMENT, NOAA PACIFIC ISLANDS FISHERIES SCIENCE CENTER, UNIVERSITY OF HAWAII, U.S. FISH AND WILDLIFE SERVICE, WESTERN PACIFIC REGIONAL FISHERY MANAGEMENT COUNCIL (compilers)
(February 2008)

15 Rationalizing the formula for minimum stock size threshold (B_{MSST}) in management control rules.
P. KLEIBER
(April 2008)

16 Shark deterrent and incidental capture workshop, April 10-11, 2008.
Y. SWIMMER, J. H. WANG, and L. McNAUGHTON (comps. and eds.)
(November 2008)