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STATUS OF SWORDFISH IN THE EASTERN PACIFIC OCEAN IN 2010 AND OUTLOOK FOR THE FUTURE

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1. SUMMARY

This report presents the status and trends of swordfish (*Xiphias gladius*) in the southeast Pacific Ocean (SEPO). The assessment was conducted with Stock Synthesis using data that were updated as of 22 April 2011.

The stock structure of swordfish is not well known in the Pacific. A number of specific regions of spawning are known, and analyses of fisheries and genetic data indicate that there is only limited exchange of swordfish between geographical areas, including between the eastern and western, and the northern and southern, Pacific Ocean, so it is considered that examinations of local depletions and independent assessments of the swordfish of the eastern Pacific Ocean (EPO) are meaningful. Though this assessment did not include parameters for trans-region movements of this or other stocks, it recognized that there may be limited exchange of fish between the southeast Pacific Ocean and stocks in adjacent regions.

Genetic and fishery data indicate that the swordfish of the southeastern Pacific Ocean (SEPO, south of 5°S) constitute a distinct stock.

Key results

1. The swordfish stock in the southeast Pacific Ocean is not experiencing overfishing and is not overfished.
2. The spawning biomass ratio is about 1.45, indicating that the spawning biomass is about 50 percent above the carrying capacity, and substantially above the level which is expected to produce catch at the level of maximum sustained yield (MSY).
3. Recent annual catch levels (~14,300 t) are significantly below the estimated MSY (~25,000 t).
4. There have been a series of recent high recruitments to the swordfish stock..

5. Catch rates and catches under current levels of fishing effort and fleet configurations will tend to decrease over the coming 10-year period, assuming average recruitment returns to pre-high recruitment levels, as those recruits pass through the fishery.

2. DATA

The principal fisheries that capture swordfish in the eastern Pacific Ocean (EPO) have been detailed in Hinton et al (2005). In the SEPO, the principal fisheries are those of Chile (Barbieri et al, 1998; Yáñez et al, 2003), Japan (Okamoto and Bayliff 2003; Yokawa 2005) and Spain (Mejuto and García-Cortés 2005). Chilean fisheries took a combined average annual catch of about 5,200 t during the 1990s and about 2,300 t since. Annual catch of Japanese fisheries harvests increased from about 1,500 – 2,000 t in the latter 1990s to about 5,000 t in the early 2000s, and since has decreased to about 2,000 t. The Spanish-flag fishery has dominated the catches made by individual fleets in recent years, with landings of about 5,700 t annually during the 2002-2009 period.

Figure 2 presents a general summary of the temporal coverage of the catch, effort, and size-composition data from 1945 through December 2010 by fishery (see below) that were used in the analyses.

2.1. Definitions of the fisheries

Six fisheries were defined for this assessment. These were based on the gear type, country, and/or spatial distributions of the fisheries so that, in general, there it is expected that there would be little change over time in their size-specific selectivity (Hinton and Maunder 2007).

The longline fisheries were separated into a coastal and an offshore fishery (Figure 2.1). These regions generally correspond to regions of spawning and juvenile rearing (offshore) and adults (coastal) identified in studies of Chilean fisheries (Anonymous 2005). Catches of longline fisheries that were considered similar in operation and targeting to the Japanese fisheries were compiled with those of Japan. These included catches in various years of Belize, China, Ecuador, French Polynesia, Korea, Uruguay, and Vanuatu.

The Spanish fleet changed from its traditional gear to American gear in about 2000- 2001, which changed the characteristics of the fishery (Mejuto and García-Cortes 2005). Therefore, the Spanish coastal fishery was modeled with a time-block separating the fisheries into pre- and post-2000.

The artisanal and longline fisheries of Chile capture fish of significantly different ages and operate in different areas (Yáñez et al. 2003), so they were modeled individually to account for differences in their selectivities using the categories established by the Servicio Nacional de Pesca (SERNAP)[1]. The artisanal fishery tends to catch larger fish using predominantly harpoon and gillnet gear, and the industrial longline fishery tends to capture somewhat younger, smaller fish. Though there is overlap in the regions fished by the industrial longline and artisanal fisheries, the longline fishery operates in waters to the west of those fished by the artisanal fisheries. The reported catches of Peru were pooled with those of the Chilean artisanal fishery in the analyses.

Fishery	Description	Principal area of operation[2]
F1	Chile industrial longline	Offshore
F2	Chile artisanal and Peru	Coastal
F3	Japan and Japan-like longline	Offshore
F4	Japan and Japan-like tuna longline	Coastal
F5	Spain longline	Offshore
F6	Spain longline	Coastal

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[1] Servicio Nacional de Pesca: http://www.sernapesca.cl/

[2] Coastal – east of 90°W; Offshore – west of 90°W

2.2. Catch

Total catch (t) by flag is provided in Table 2.2, and the catch (t) by fishery used in model is shown in Figure 2.2.

Catch data for Chinese Taipei, Japan, Korea and Spain were available in numbers of fish. Data for most years were available in both numbers and weight for Chinese Taipei, Japan, Korea and Spain. Data for Chile were available only in weight.

Catch[3] (numbers of fish and kilograms) for the Spanish-flag longline fishery was available for 1990-2009. Total catch by the Spanish-flag fishery in 2010 was assumed equal to and distributed as that taken in 2009.

Catch data for the Chilean fisheries are described in Table 2.2.1c of Hinton et al. 2005. This catch series was augmented by adding data for Peru (Weidner and Serrano 1997, Appendix B2a, Columns “Smith” and “FAO”, p. 401), and it was extended to 1945 for Chile (Weidner and Serrano 1997, Appendix E2a1, p. 776). Data for more recent years was obtained from catch reports posted on-line by SERNAP.

Data for each fishery were compiled by calendar quarter for the assessment. Generally this was accomplished using proportions of catch-by-quarter observed in catch and effort data aggregated at a resolution of month by 5° latitude by 5° longitude, or from tabled catch by month data. When these data were not available, catches were apportioned using the average distributions from the available data.

The Chilean- and the Spanish-flag fisheries display seasonality in annual catch, generally with peak catches occurring in calendar quarters two and three. In the case of the Chilean-flag fisheries, the distribution of catch-by-quarter from recent years (artisanal: 2002-2008; industrial: 2002-2009) was used to apportion the series of reported annual catch to quarter for years prior to 2002, for artisanal fisheries in 2009-2010, and industrial fisheries in 2010. In the case of Spanish-flag fisheries, the distribution of catch-by-quarter over the period 1998-2006 was used to apportion catch to quarter over the 1990-1997 period.

	Proportion of annual catch by calendar quarter			
Fishery	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**
Chile artisanal	0.0154	0.439	0.484	0.062
Chile industrial	0.0255	0.397	0.366	0.212
Spanish	0.0720	0.382	0.363	0.183

2.3. Discards

An observation of no discards was reported for Spanish-flag longline fisheries. There were no discard data available from other fisheries.

2.4. Indices of abundance

Indices of abundance were obtained using delta-lognormal models (Pennington 1983) fitted in TIBCO Spotfire S+ 8.1[4] for Windows. Initial identification of model parameters was made using functions “step.glm” and “stepAIC”. Final selection of model parameters was made by comparing the decrease in the Akaike Information Criteria (AIC) resulting from addition of the individual parameters suggested by the initial fittings, and including only those that resulted in a decrease in AIC of O(100) (Burnham and Anderson 1998). Initial model scopes included oceanographic parameters that might be expected to be correlated with the presence and vulnerability of swordfish (see e.g. et al. 2009). The general form fitted for both components of the delta-lognormal model was:

$$F(CPUE) = Year + Month + Latitude + Longitude + Environment + Interactions$$

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[3] Instituto Español de Oceanografía (IEO) (A Coruña, Spain)

[4] http://spotfire.tibco.com/products/s-plus/statistical-analysis-software.aspx

Interactions were considered only for significant main effects, and in the end, no significant interactions were identified for any model. Models fit to catch and effort data of Japan that included information on the number of hooks placed between floats on the mainline (HPB data) were compiled into four categories of gear configuration: $HPB < 8$; $8 < HPB < 12$; $12 < HPB < 16$; and $HPB \geq 16$. For the period prior to 1975, which brought the introduction of deep longline fisheries to the EPO, it was assumed that $HPB < 8$ (Hinton 2003).

Scaling of oceanographic parameters to the levels of available catch and effort data is problematic and not all oceanographic or environmental parameters are suitable for inclusion every models. A number of parameters were available or could be estimated on the scale of the one-degree catch and effort data, which is on the order of the linear dimension of a longline set (mainline length ~ 100 km). These were sea surface temperature[5] (sst: IGOSS); sea surface height (ssh), salinity, and meridional (tauy) and zonal (taux) surface velocities[6] (SODA 2.1.6); mixed-layer depth temperature and depth of the 20°C isotherm[7]; and the probability of encountering a temperature front in the area (FPI: frontal probability index)[8]. Estimates of these parameters on a five-degree grid level may be made, but at that level, they are not measures of the local conditions in the area of fishing operations and would not be expected to carry significant information on the relationship of catch rates to oceanographic conditions..

Environmental parameters with basin-wide extent and long timescales provide information on physical forcing and the general distributions of physical oceanographic parameters, and thus might be expected to correlate on these scales with the distribution of fisheries and swordfish. Such parameters that were included in standardization analyses were the Northern (NOIx)[9] and the Southern (SOIx) extra-tropical Oscillation Indices; the Southern Oscillation Index (SOI); and the Multivariate ENSO Index (MEI)[10]. As indicators of physical forcing and longer-term large scale ocean properties, it might be expected that correlations with catch rates on these larger scales may be realized via influence on future recruitment levels, therefore estimates of these parameters were included in the initial scope of the standardization models with lags of zero to six months.

Catch and effort data for fisheries of Chinese Taipei, Korea and Spain were available only at a 5-degree latitude x 5-degree longitude geographical resolution (5x5 data) and did not include data on gear configuration. Standardizations based on 5x5 data generally mirror closely the nominal catch rate series. Parameters for local environmental conditions that may influence the fishing operations, including such as decisions on where and when to initiate gear operations, do not scale in a meaningful way to the public-domain level 5x5 aggregated fishing data, so parameters such as sea surface temperature and height, current velocities, wind sheer and salinity were not included in attempts to standardize 5x5 data. In the end, no satisfactory standardized catch-per-unit effort series was found for fisheries of Chinese Taipei, Korea or Spain. Nominal CPUE time series for these fisheries and that of Japan based on 5x5 data is shown in Figure 2.4.1.

The nominal catch rates for Chilean fisheries (Serra et al. 2009: Tables 6 and 7) are shown in Figure 2.4.2. No data were available to develop standardized catch rate indices for Chilean fisheries, however Serra et al. (2009) present standardized indices for the Chilean longline fisheries which are generally consistent with and higher than the nominal rates, particularly in the offshore region.

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[5] Integrated Global Ocean Services System, Reyn_SmithOIv2 monthly sst; 1981-11 to 2010-; accessed 2011-04-09: http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst/http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.

[6] Simple Ocean Data Assimilation: soda pop 2.1.6; 1971-01 to 1981-10 (sst), 1971-2010; accessed 2011-04-08: http://apdrc.soest.hawaii.edu/dchart/

[7] European Centre for Medium-Range Weather Forecasts, Ocean Reanalysis, S3: yyyy-mm to yyyy-mm; accessed 2011-04-07: http://apdrc.soest.hawaii.edu/dchart/

[8] Pelagic Habitat Analysis Module:1971-01 to 2010: accessed 2011-04-07: http://phamlite.com/

[9] NOAA Pacific Fisheries Environmental Laboratory; 1971-01 to 2010: http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix.html

[10] NOAA/Earth Systems Research Laboratory. Wolter, K.: 19// to 2010: http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/

The offshore fishery of Japan began in the EPO in about 1952, but the geographical expansion did not reach the coastal regions of the SEPO (Hinton 2003, Figure 2, Area 4) until about 1967 (Joseph et al. 1974, Figure 1). Data series starting in the early 1950s were available for these fisheries as 5x5 data. Data series starting in 1971 with higher resolution, and series with and without gear-configuration information, were also available for these fisheries. The first of these was a series at 1-degree latitude x 1-degree longitude geographical resolution (1x1 data) starting in 1971 was available for the Japanese fisheries. Data series from these fisheries were also available with gear-configuration information as 5x5 data starting in 1975 and as 1x1 data starting in 1999. CPUE time series were generated for both the Japanese coastal and Japanese offshore fisheries (see Sec. 2.1 Fisheries).

2.5. Size composition data

Size-frequency data from the Spanish-flag longline fishery were available in lower jaw-fork length (LJFL), and from Japanese-flag fisheries in eye-fork length (EFL). Since the growth model used in the assessment was developed using measures of LJFL, and it has been found that the growth rates of swordfish in the southeastern and the central north Pacific (Hawaii region) are very similar (Cerna, 2009), EFL data were converted to LJFL using the method of Uchiyama et al. (1999: Table 1, pg. 19: LJFL = 8.0084 + 1.07064 × EFL).

Size frequency measurements were aggregated into 5 cm length bins by quarter for fisheries F3, F4, F5 and F6. These aggregates had observed sample sizes on the range of one to tens of thousands. Aggregates with 10 or fewer observations were excluded from the model. In the process of developing the assessment model, the effective sample size for the size frequency data estimated from the initial model runs was used to reweigh (Maunder 2011) the observed sample sizes used in a subsequent model fitting. The size frequency distributions in the assessment are presented below with the results of the assessment.

2.6. Age composition data

Age composition data for Chilean fisheries that was compiled for the previous assessment (Hinton and Maunder 2007) were included in this assessment. These included data for both the industrial and the artisanal fisheries of Chile. No updated or additional age composition data were available.

3. ASSUMPTIONS AND PARAMETERS

3.1. Biological and demographic information

3.1.1. Growth

Swordfish grow in length very rapidly, with both males and the faster-growing females reaching lower-jaw-fork lengths of more than a meter during their first year (DeMartini et al. 2007, Cerna 2009, Chong and Aguayo 2009).

Cerna (2009) and Chong and Aguayo (2009) present recent analyses of the growth rates of swordfish in the SEPO. The results of their independent analyses are consistent, though estimates of the asymptotic maximum length (L infinity: L_{inf}) from von Bertalanffy growth models by Cerna (2009) for both males (279 cm) and females (321 cm) were slightly higher than those of Chong and Aguayo (2009) (males, 275 cm; females, 305 cm). Estimates of the annual von Bertalanffy K by Cerna (2009) were lower (males, 0.158; females, 0.133) than those of Chong and Aguayo (2009) (males, 0.177; females, 0.153).

Considering the relatively high proportion of fish at lengths greater than 350 cm in the data, the parameters for the von Bertalanffy model of Cerna (2009) were used in the assessment.

The L_{inf} parameter may be estimated or specified, and in the assessment it was fixed for females at 321 cm, which equates to 290 cm at age 15, the maximum age in the model; and for males at 279 cm.

The von Bertalanffy equation in Stock Synthesis does not use the standard t_0 parameterization and instead it was parameterized with the length at age one equal to 118cm and 122 cm for females and males respectively.

There is no information about the variation of length at age and a constant coefficient of variation fixed at 0.1 was used in the assessment.

The choice of the length-weight relationship for the assessment was important, because it was used in calculating biomass and in making comparable the catch and the size-frequency data. The relationships used in the assessment were those of Cerna (2009), making them consistent with the growth model used in the assessment:

Females	Weight (kg) = $3.7 \times 10^{-6} \times$ [Lower-jaw-fork length (cm)]$^{3.26}$; and
Males	Weight (kg) = $4.5 \times 10^{-6} \times$ [Lower-jaw-fork length (cm)]$^{3.21}$

3.1.2. Natural mortality

The instantaneous natural mortality rate (M) of swordfish is not know. It has frequently been assumed that because of the large size attained by swordfish, M might be as low as 0.2 (Hinton et al. 2005). With the development of techniques for aging swordfish it has been found that most swordfish do not live longer than about 12 years (DeMartini et al. 2007, Chong and Aguayo 2009), which suggests that M is higher than the values that have been assumed in a number of previous studies. In the assessment we used a constant annual instantaneous natural mortality rate (M) of 0.4.

3.1.3. Recruitment and reproduction

A summary of the distributions of adult and juvenile swordfish and of spawning areas in the SEPO may be found in Anonymous (2005).

Swordfish in the SEPO spawn during the austral summer, principally during January and February (Claramunt et al. 2009). Size at 50 percent maturity for males is estimated to be about 115-120 cm LJFL, and for females, about 165-175 cm (DeMartini et al. 2007, Claramunt et al. 2009), which based on age-maturity studies corresponds to ages two to three.

The age of first maturity was assumed to be two. The maturity schedule in the assessment was set using a vector of proportion of females mature-at-age, with proportions for years zero through three of 0.0, 0.0, 0.6, and 0.8; and a value of 1 for ages greater than three.

The assessment model estimates spawning in season 1 and 2, with the estimate for season 2 relative to the level estimated for season 1.

It is generally considered that environmental conditions are the principal influence on recruitment levels of the pelagic tunas and tuna-like species, including swordfish, and that recruitment is not substantially reduced as a result of the level of the spawning biomass. Therefore, a Beverton-Holt stock-recruitment relationship (Beverton and Holt 1957) was used in the assessment. In the Stock Synthesis model, the Beverton-Holt relationship has been parameterized to include steepness (h) (Francis 1992, Appendix 1). Steepness equals that fraction of the recruitment to an unexploited stock (R0) that would be produced by a spawning biomass that has been reduced to 20 percent of the unexploited spawning biomass (S_0), viz. $hR_0 = F(0.2S_0)$, where F is the Beverton-Holt stock-recruitment relationship. Steepness can vary between 0.2 (in which case recruitment is a linear function of spawning biomass) and 1.0 (in which case recruitment is independent of spawning biomass). In practice it is often difficult to estimate steepness, because of a lack of contrast in observations of spawning biomass and because other factors (e.g. environmental) may cause extreme variability in recruitments from a given spawning biomass. Simulation analyses have shown that estimation of steepness is problematic, with large uncertainty and frequent estimates equal to one, even when the true steepness is moderately less than one (Conn et al. 2010).

There was no evidence that recruitment was related to spawning stock size for swordfish in the SEPO, so $h = 1$ in the assessment. A sensitivity analysis was carried out with h = 0.75 to investigate the effect of including a stock-recruitment relationship.

3.1.4. Movement

The assessment did not include explicit parameters for movement. There is very little information on the movements of swordfish. It was assumed that the population was randomly mixed at the beginning of each year, and though not explicitly modeled, some aspects of movement within the SEPO were accommodated by differences in selectivity and catchability by the spatial definition of fisheries. Though the assessment did not include parameters for trans-region movements of this or other stocks, it was recognized that from time-to-time there may be limited exchange of fish between the swordfish stock in the SEPO and those in adjacent regions.

3.1.5. Stock structure

The stock structure of swordfish is not well known in the Pacific. There have been a number of studies of stock structure of swordfish in the Pacific, and certain elements of the distribution of stocks seem more clear than others. A number of specific regions of spawning are known, and analyses of fisheries and genetic data indicate that there is only limited exchange of swordfish between geographical areas, including between the eastern and western, and the northern and southern, Pacific Ocean, so it is considered that examinations of local depletions and independent assessments of the swordfish of the eastern Pacific Ocean (EPO) are meaningful. Though this assessment did not include parameters for trans-region movements of this or other stocks, it recognized that there may be limited exchange of fish between the southeast Pacific Ocean and stocks in adjacent regions. In the eastern Pacific Ocean it is considered that there is a single stock in the SEPO (Alvarado Bremer et al. 2006), and the area chosen for the assessment, south of 5°S and east of 150°W, is expected to extend across the principal distribution of the stock.

3.2. Environmental influences

Environmental data were used in the catch-rate standardization (Section 2.4).

4. STOCK ASSESSMENT

The assessment was conducted using Stock Synthesis (Methot 2009). Stock Synthesis is a sex-specific, age-structured, integrated (fitted to many different types of data) statistical stock assessment model. Data included in the assessment were those available on 22 April 2011. The available data determined, to a great degree, the structure of the assessment model. In addition to the data, estimates of a number of population characteristics, such as natural mortality rate, growth rates, and age at first maturity, were obtained from studies and were included in the assessment as assumed or fixed parameters. Stock Synthesis was fitted to a suite of scenarios using the method of maximum likelihood. The value of the negative log-likelihood from each of the scenarios was used for evaluation and comparison of results.

4.1. Assessment model structure

The earliest data included in the assessment are the estimated catches in 1945. During the period from 1945 until 1965 the average annual catch was about 1,000 t. Over the next 10 years, as the longline fisheries of Japan, directed principally at tunas, extended operations into the eastern Pacific Ocean, the average annual catch of swordfish from the SEPO increased to about 1,600 t. These longline fleet operations continued to increase both in space and intensity, becoming the dominate harvesters of swordfish in the region by the mid- to late-1970s. In the late 1980s the fisheries for swordfish in the SEPO experienced significant increases with the development of industrial longline fisheries of Chile, followed closely thereafter by entry of longline fisheries of Spain into the region. As the fisheries expanded, desirable locations and conditions for capture of swordfish were identified. During the 10-year period ending in 2009, the average annual catch of swordfish from the SEPO was about 12,000 t.

A number of the basic assumptions common to most assessments become dubious in situations such as described above; for example, the assumption that standardized catch rates are proportional to abundance over the entire period, or that the geographical distribution of the stock has been identified and well sampled through time by the fisheries.

The steps taken to address these problems were to structure the assessment in temporal and spatial strata over which those basic assumptions were considered reasonable, while also extracting as much information as possible from the strata over which the assumptions were less tenable. This approach was consistent with that taken in stock assessments of striped marlin, and of yellowfin and bigeye tunas in the EPO.

The assessment model starts in 1945. Considering the given the low level of catch during the initial years of the data series and that it was unlikely catches had been higher or significantly different during the years of WWII which immediately preceded, the stock was assumed to be in an unfished virgin condition at the start of the model.

The model is gender-specific, which means that model parameters may differ for females and males, e.g. as noted in the sections on growth and maturity above. The assessment also included the following initial conditions, assumptions and fixed parameter values:

1. The model was a seasonal model, with four seasons each year, and with a single area.
2. Recruitment deviates beginning in 1964, six-years prior to the beginning of the size-frequency data, which includes information on the cohorts entering the fishery prior to the beginning of the data series.
3. Recruitment occurred in seasons 1 and 2, with that for season 2 estimated relative to recruitment in season Natural mortality (M) = 0.4.
4. Steepness (h) = 1.0
5. von Bertalanffy growth model parameters for females: $K = 0.113$ and $L_{inf} = 321$; and for males: $K = 0.158$ and $L_{inf} = 279$.
6. Length at age one was fixed at 118cm and 122 cm for females and males respectively. This was done because the growth function well described adult swordfish, but not the rapid allometric growth of juveniles. This caused problems with model fits due to the fairly high number of small fish (< 100 cm) taken in some of the fisheries
7. Coefficient of variation of length at age = 1.0
8. Age 15 was modeled as a plus group which accumulates all fish aged 15 and older.
9. The coefficients of variation (CVs) of the standardized catch rate observations for fisheries F3 and F4, which were used as indices of abundance, were fixed at 0.2.
10. Selectivities of fisheries F3, F4, F5 and F6 were estimated using a double-normal distribution function, which allowed estimation of domed shaped or asymptotic selectivities.
11. Selectivity of F2 was assumed asymptotic and estimated using a double-normal distribution with parameters for (1) the selectivity for the first size interval, (2) the rate of increase at the inflection point and (3) the age when selectivity equals one. Preliminary fitting of the assessment model, selectivity of F1 was asymptotic, so on the final model fitting, selectivity of F1 was made asymptotic, as discussed for F2. In addition the size at which selectivity reached its asymptote was fixed at the largest size in the model. This was done to reduce the number of parameters estimated in the final model.
12. The assessment included time blocks for selectivity of F6. In about 2000 the gear used in these fisheries underwent a complete change in configuration and operation. Examination of residuals in the size frequency data from preliminary analyses clearly indicated a change in selectivity, indicating the need for this additional structure in the model.

13. Data that was for an annual, vs. seasonal, period were assigned to season 2. These included such as the annual abundance indices and the age-frequency for Chilean fisheries.

4.2. Assessment results

The assessment was conducted with Stock Synthesis[11] (SS-V3.20b-safe) using data and information available on 22 April 2011. The model was fit to the standardized abundance indices of F3 and F4; to the size-frequency data for F3, F4, F5, and F6; and to the age-frequency data for F1 and F2. The assessment model was quite unstable with convergence issues due to local minima. This instability was probably due to the selectivity parameterization. Several different starting values and phases of optimization were used to check that the final result was not a local minima. However, it is never certain that a better solution is not possible.

4.2.1. Fishing mortality

Estimated selectivity-by-size by fishery are shown in Figure 4.2.1. Fisheries 5 and 6, the longline fisheries of Spain, had the highest selectivity for small fish, with fish fully selected at sizes near 75 cm lower-jaw-fork length (LJFL). Swordfish remained fully selected across all sizes in Fishery 5, despite being allowed to be dome shape, while selectivity of Fishery 6 was dome-shaped, with selection dropping below 10 percent at sizes at and above about 275 cm. Fisheries 3 and 4, the Japanese longline fisheries, exhibited selection of swordfish at or above the 10 percent level at sizes of about 100 cm. Fishery 4, the Japanese fishery in the coastal region, exhibited asymptotic selectivity, despite being allowed to be dome shape,. Fisheries 1 and 2, the fisheries of Chile, were modeled with asymptotic selectivity and exhibited selectivity for large swordfish.

4.2.2. Recruitment

The trend in estimated annual recruitment is presented in Figure 4.2.2. Recruitment level estimates were started in 1964, decreasing immediately thereafter. They remained relatively stable until about 1999-2000, at which point they increased by a factor of almost two during a period of increasing harvests. They continued a general increasing pattern until peaking at about six-times the levels observed in the 1960s and 1970s. It is expected that this increase is a result of environmental conditions, since the annual catches of swordfish remained relatively constant at about 12,000 t during this period.

4.2.3. Biomass

The trend in estimated spawning biomass from the assessment is presented in Figure 4.2.3.1 along with the annual estimates of spawning biomass in the absence of fishing. It is clear that fishing has had a minor impact on the level of spawning biomass during the period. The level of spawning biomass expected to provide catches at the level of MSY (S_{MSY}) was about 11,000 t, which is significantly less than the lowest observed spawning biomass since 1945, which was about 43,000 t in 1993. Spawning biomass has steadily increased since 1993 and was estimated to be about 135,000 t in 2010.

The estimated ratio of the spawning biomass in 2010 to the spawning biomass in the unexploited stock (*SBR*) was about 1.45 (Figure 4.2.3.2), which was well above the estimated level expected to provide catches at the level of MSY ($SBR_{MSY} = 0.11$).

4.3. Comparisons to external data sources

No comparisons to external data were made in this assessment.

4.4. Diagnostics

4.4.1. Residual analysis

The assessment was fitted to the standardized abundance indices of Fisheries 3 and 4, the longline

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[11] http://nft.nefsc.noaa.gov/SS3.html

fisheries of Japan in the offshore and the coastal areas (Figure 2.1). The estimated trends in abundance fitted the index of abundance for the offshore Japanese fishery well, but fit the index of abundance for the inshore Japanese fishery poorly (Figure 4.4.1.1)

The assessment estimates of the size measurement data for the Japanese and Spanish longline fisheries are shown in Figure 4.4.1.2, and Pearson residual plots for these estimates are provided in Figure 4.4.1.3. (Japanese offshore and coastal fisheries) and Figure 4.4.1.4. (Spanish offshore and coastal fisheries). Estimates of the size frequency tended to underestimate the number of fish less than about 100 cm in a number of years in both the Japanese and Spanish coastal fisheries, though in general the assessment estimates fit the observed data fairly well.

The assessment estimates of age-frequency of catch in the fisheries of Chile are shown in Figure 4.4.1.5. In general, as was the case with the size-frequency data, the assessment-based estimates fit the observed age frequencies fairly well for the artisanal fishery, but there is a substantial residual pattern in the industrial fishery (Figure 4.4.1.6).

4.4.2. Sensitivity analyses

Uncertainty in assessment results, which can be difficult to quantify, occur due to sampling and process errors. In the first instance, the sample data could not perfectly represent the population parameters of swordfish in the SEPO, or more generally those of any population. In the second instance, the model structure used for the assessment provides only an approximation to the dynamics of the stock and the fisheries that harvest them. These approximations may result in process, or model-misspecification, errors. The confidence intervals for parameter estimates arising from the likelihood-based solution obtained for the assessment were estimated under the assumption that the population dynamics model "perfectly" (or at least adequately) represented the dynamics of the system. Since it was unlikely that this assumption could ever be satisfied, the estimates of uncertainty obtained from the assessment likely underestimate the "true" uncertainties.

A principal concern in this assessment was the potential for errors resulting from a failure of the assumption that the standardized indices of abundance used in the model were not proportional to the abundance of the population swordfish in the SEPO. In order to examine this potential, the model was fitted to the abundance indices with the last four years (2007-2010), the years showing the rapid increase, excluded from the analysis. This left only the size frequency data for those years in place to inform on the abundance of the stock during this period.

The results of this analysis are shown in terms of the spawning biomass ratio (Figure 4.4.2.1). It is clear that the increase in relative abundance was supported by the observed size-frequency data. It was also noted that the indicated increase in relative abundance from the standardized catch rate indices was consistent with increases seen in the nominal catch rates of other fisheries, particularly for the distant water nations and the offshore area (Figures 2.4.1 and 2.4.2).

The assessment was conducted with an assumed steepness of one. A sensitivity analysis with steepness of 0.75 was conducted, even though the stock has not been driven below a *SBR* of about 0.46, and as a result it would not be expected that there would be information in the data to estimate the impact of an incorrect assumption of steepness. The results of this sensitivity analysis are shown in Figure 4.2.2.2. in comparisons of the yield (t) and the *SBR* at levels of fishing effort (*F*) relative to current fishing effort for the assessment and for the model with steepness of 0.75.

4.5. Comparison to previous assessment

The previous assessment of swordfish in the southeast Pacific Ocean (Hinton and Maunder 2007) was conducted with data through 2003. That assessment indicated that the spawning biomass had declined significantly over the 1945-2003 period, and that it was then at about twice the level which would support fisheries at a maximum sustained yield of 13,000-14,000 metric tons. Catches had increased substantially since 2001, and recent annual harvests were on the order of 14,000-15,000 t.

This assessment was conducted with data through 2010. We found that the spawning biomass had decreased to a low of about 43,000 t in 1993 and had been increasing since, reaching about 135,000 t in 2010, a level at which *SBR* = 1.45. At the same time that there was an increasing spawning biomass, the annual catch by all fisheries was maintained at an average 12,000 t during the 10-year period ending in 2010.

A comparison of estimated *SBR* from the previous assessment and from this assessment is presented in Figure 4.5.

5. STOCK STATUS

The objective of the Antigua Convention is to"… ensure the long-term conservation and sustainable use of the fish stocks covered by [the] Convention, in accordance with the relevant rules of international law," and calls on the members to "… determine whether, according to the best scientific information available, a specific fish stock … is fully fished or overfished and, on this basis, whether an increase in fishing capacity and/or the level of fishing effort would threaten the conservation of that stock."

The parties to the Convention have not established specific biological or management reference points, so the status of the swordfish stock in the northeast Pacific Ocean has been, as in the past, presented in terms of commonly-cited management parameters based on MSY (Table 5). These estimates were made using the 3-year (2008-2010) average fishing mortality rates for each of the fisheries, thus they represented current operating conditions and practices in these fisheries.

The level of recent catch (~14,300 t) is less than half of the estimated MSY catch (~25,000 t); the recent biomass level (~424,300 t) is a factor of 10 higher than the biomass (~40,800 t) expected to support catches at the level of MSY, and the recent spawning biomass level (~158,000 t) is nearly 15 times the level expected to support catch at MSY levels.

The *F*-multiplier, the factor by which current fishing mortality would be changed in order to achieve the fishing effort expected to provide catches at the level of *MSY*, is about 18 in the assessment and about 7 in the model fit with steepness equal to 0.75. It is apparent that if steepness is one, then an increase in *F* by a multiple of 7 would achieve catch near the level of *MSY*, and that if *F* is 0.75, then an increase in *F* greater than 7 would result in catches less than those expected at *MSY*.

The trends of spawning stock biomass relative to MSY vs. *F* relative to MSY is shown in Figure 5 for the most recent 20-year period. The figure clearly shows that swordfish in the SEPO are not experiencing overfishing and are not being overfished.

The swordfish stock in the southeastern Pacific Ocean is in good condition, with spawning biomass at levels (SBR~1.45) well above those expected to yield catch at the level of *MSY* (~25,000 t). The assessment suggests that fishing effort would need to increase significantly to achieve catch at the level of *MSY* (Figure 4.2.2.2).

6. SIMULATED EFFECTS OF FUTURE FISHING OPERATIONS

The assessment indicates that there was a recent period of very high recruitment to the swordfish stock in the southeast Pacific Ocean. This high recruitment might be expected to provide catches at levels in excess of what might be expected from current fisheries operating with current estimated fishing mortality rates. However, such increased catch levels would be expected to decrease over time as the impact of their presence in the population wanes.

Estimates of current fishing effort were used to forecast the expected spawning biomass ratio (*SBR*) and the expected catch by fishery for the 2011-2020 period (Figure 6) were current levels to persist over that time period. The trend in *SBR* clearly shows the expected decline in the spawning biomass as the impact of the high recruitment passes through the stock. The trend in expected catch also shows the expected decrease in catch that results from decreasing catch rates at the assumed constant effort over the period.

7. FUTURE DIRECTIONS

7.1. Collection of new and updated information

It is not expected that the stock of swordfish in the southeast Pacific Ocean will be harvested at levels of MSY without a significant increase in fishing effort. We have no indication that such an increase is planned or will occur, but catch and catch rates should be monitored closely to ensure that any increase that may occur is recognized in time that analyses of impacts and assessments may be made before the stock can be overfished.

The assessment would have benefitted from standardized catch rate series for the fisheries of Chile and Spain, and from detailed size-frequency and age-frequency data for the fisheries of Chile (Serra et al. 2009). Efforts should be made to obtain these data prior to the next assessment.

Estimates of discards from fisheries were available only for the fisheries of Spain, in which there were no reported discards. An accurate estimate of total removals from a stock is necessary to an accurate assessment. Effort should be directed to obtaining information on discards from other fisheries.

7.2. Refinements to the assessment model and methods

The IATTC scientific staff will continue developing the assessment for swordfish. Much of the progress will depend on how the Stock Synthesis software is modified in the future. The ability to do the following would be desirable:

1. Determine appropriate weighting among the data sets;
2. Include data from conventional and satellite-based tagging.

There are continuing investigations of stock structure of swordfish in the Pacific and relevant information which may be found thereby should be incorporated into future assessments. These studies may also inform on whether the fishery for swordfish that occurs in the far western SEPO is on the same stock as that identified for this assessment. A collaborative effort may be made to more explicitly examine this element of the fisheries for swordfish in the south Pacific.

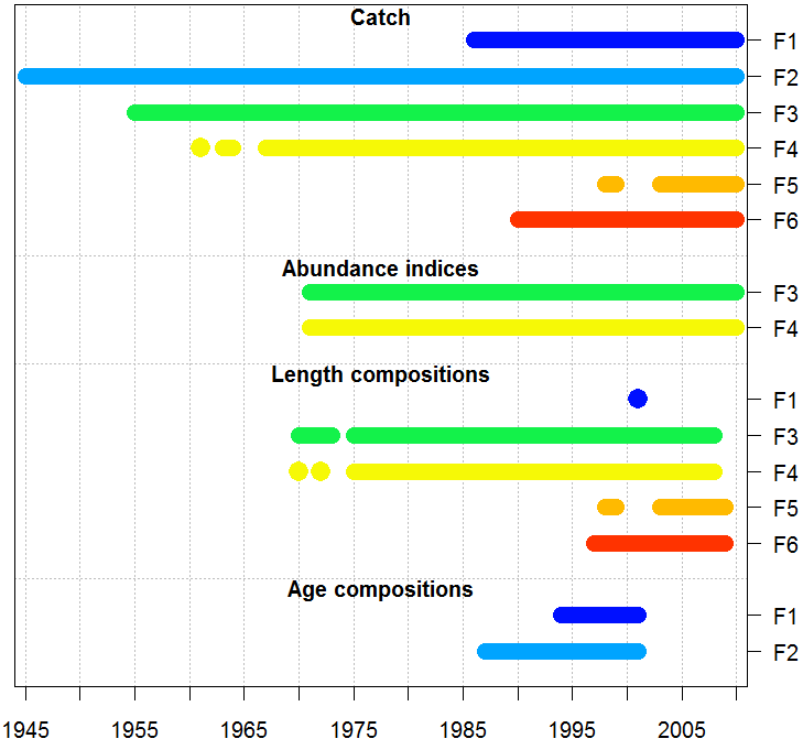

FIGURE 2. Temporal coverage of data used in the assessment by type and fishery. Note that the length composition data for Fishery 1were not used in the assessment.

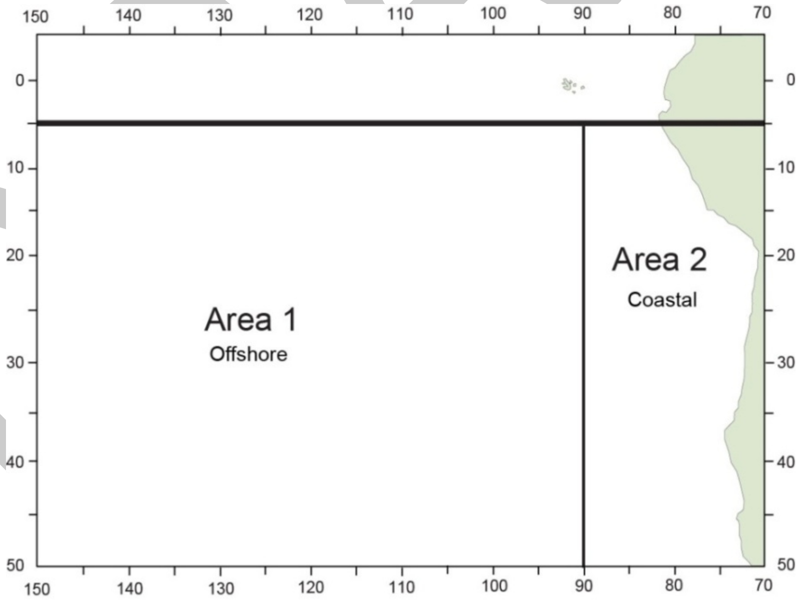

FIGURE 2.1. Area stratification for analysis of swordfish stocks in the eastern Pacific Ocean.

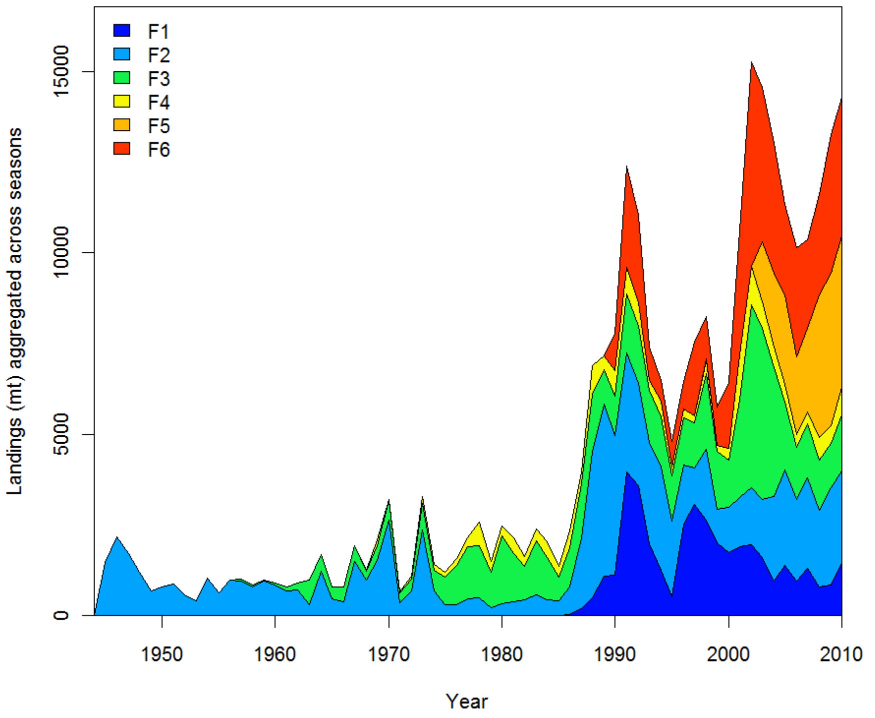

FIGURE 2.2. Catch (t) by fishery (see text for definitions) by year .

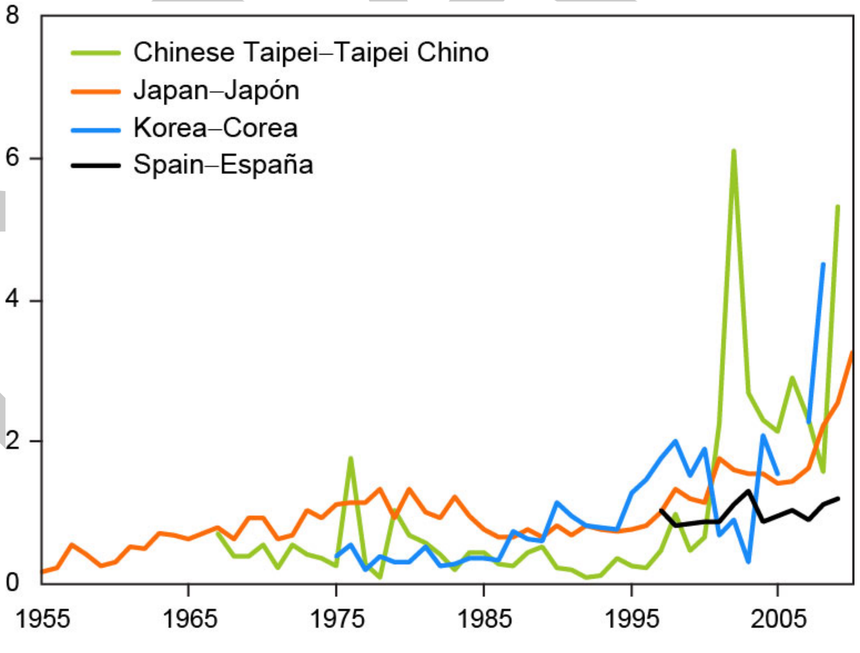

FIGURE 2.4.1. Nominal catch rates by year and flag scaled by the respective average catch rates.

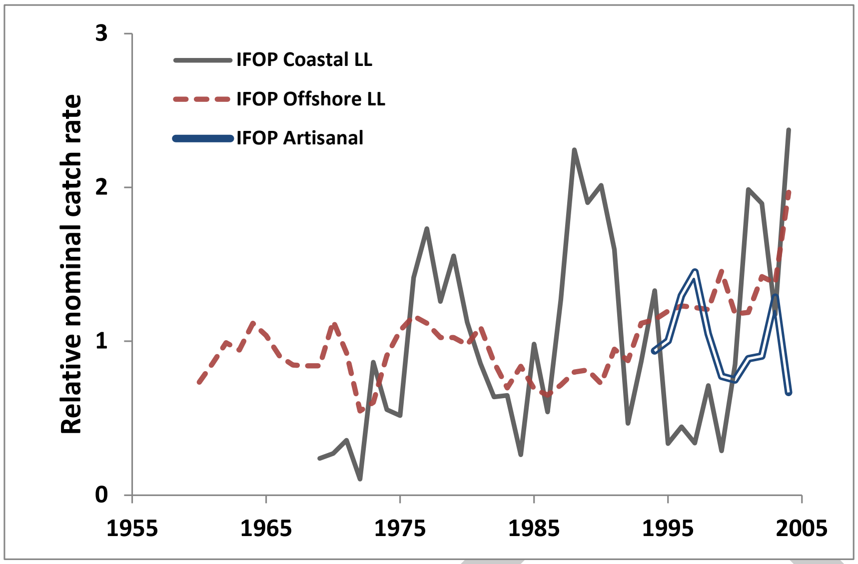

FIGURE 2.4.2. Nominal catch rates of Chilean longline and artisanal fisheries scaled by the respective average catch rate (Source: Serra et al. 2009).

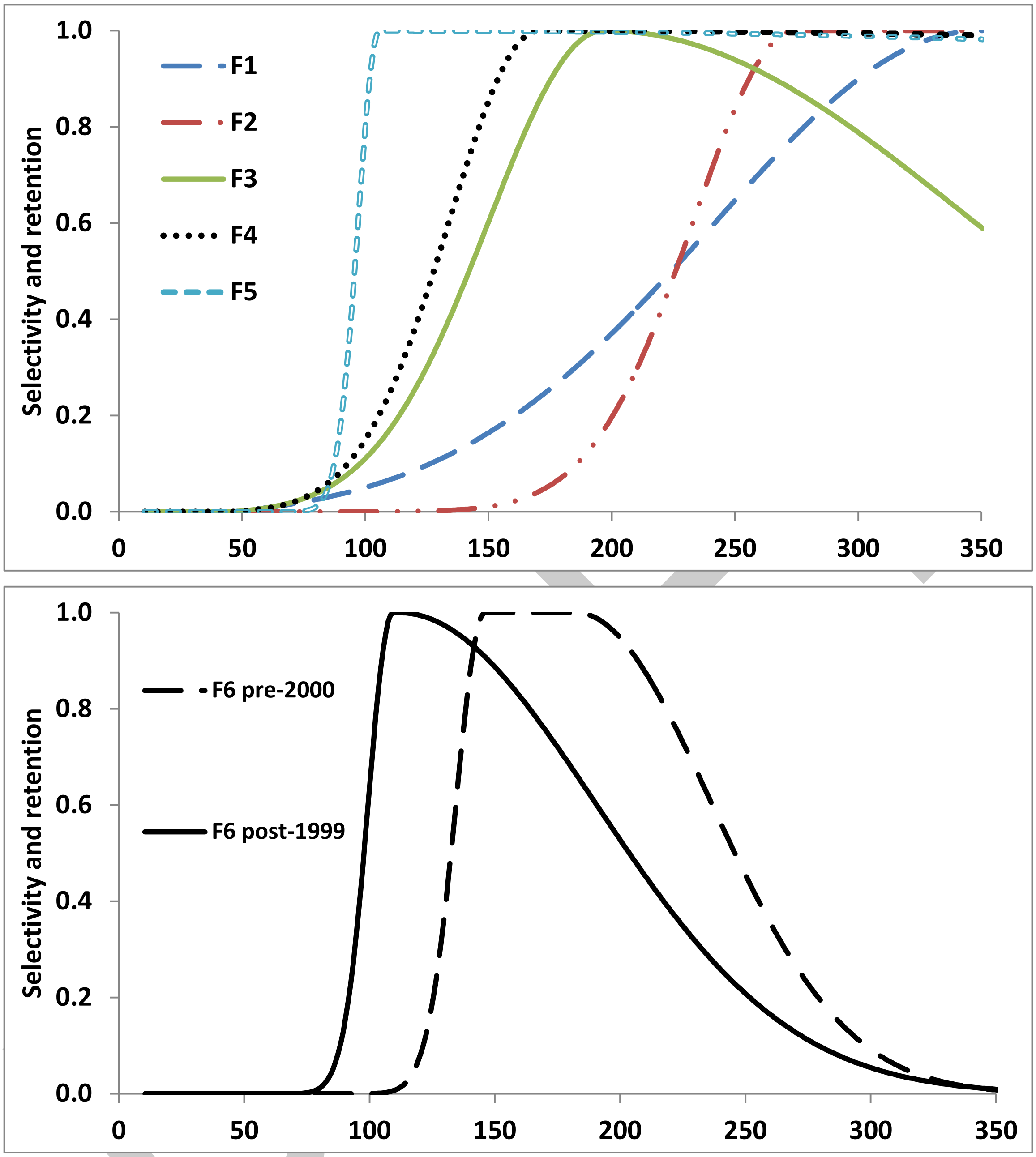

FIGURE 4.2.1. Selectivity for swordfish by lower-jaw-fork length for Fisheries 1-5 (upper panel), and for Fishery 6 (lower panel) prior to 2000 and after 1999 (see text for description of fisheries).

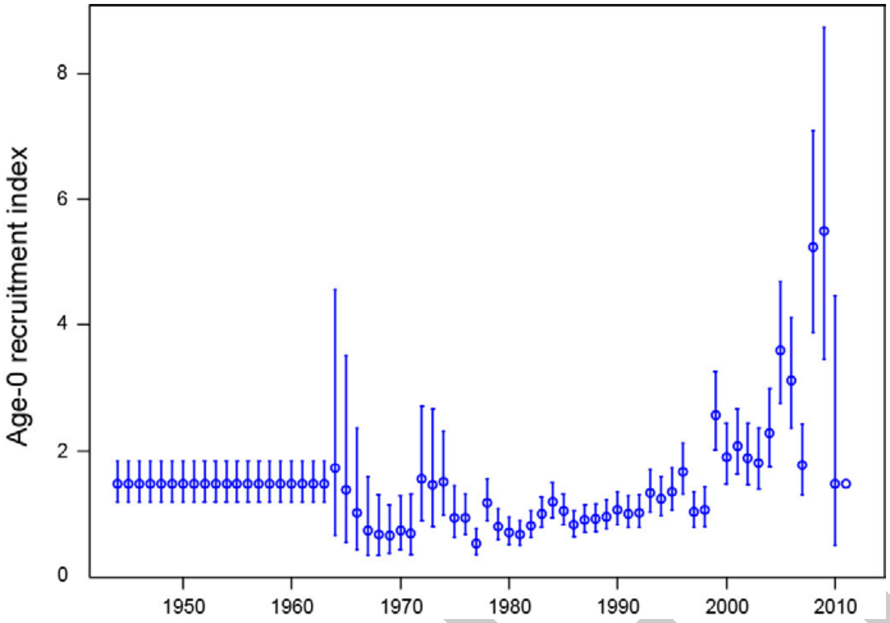

FIGURE 4.2.2. Relative annual estimated level of age-zero recruits and approximate 95 percent confidence levels.

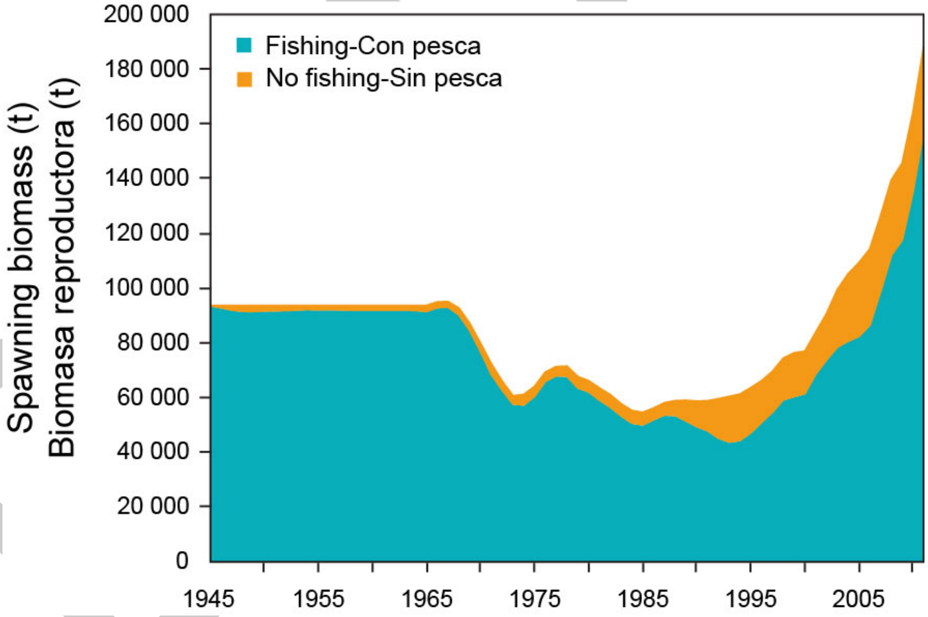

FIGURE 4.2.3.1. Estimated annual spawning biomass with and without fishing. The yellow shaded area represents the impact of the fisheries on the spawning biomass.

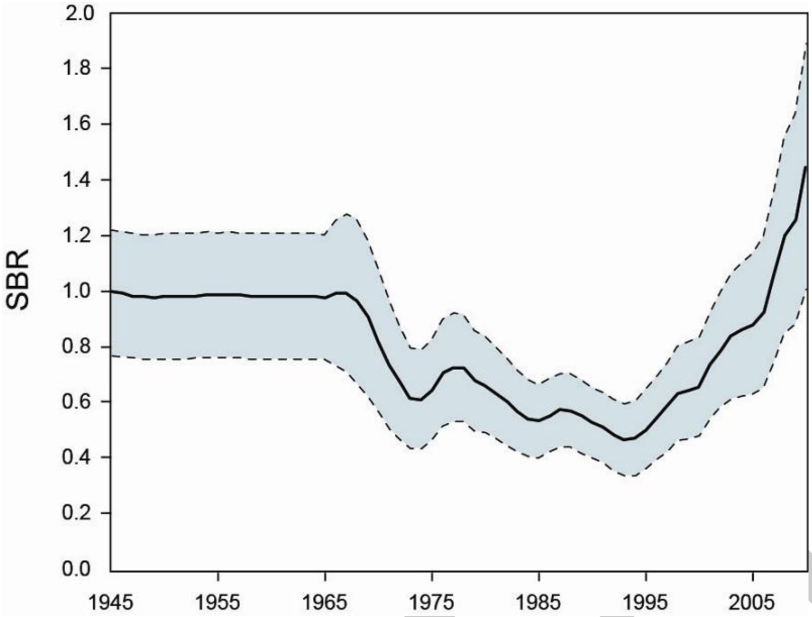

FIGURE 4.2.3.2. Estimated annual spawning biomass ratio and the approximate 95 percent confidence interval.

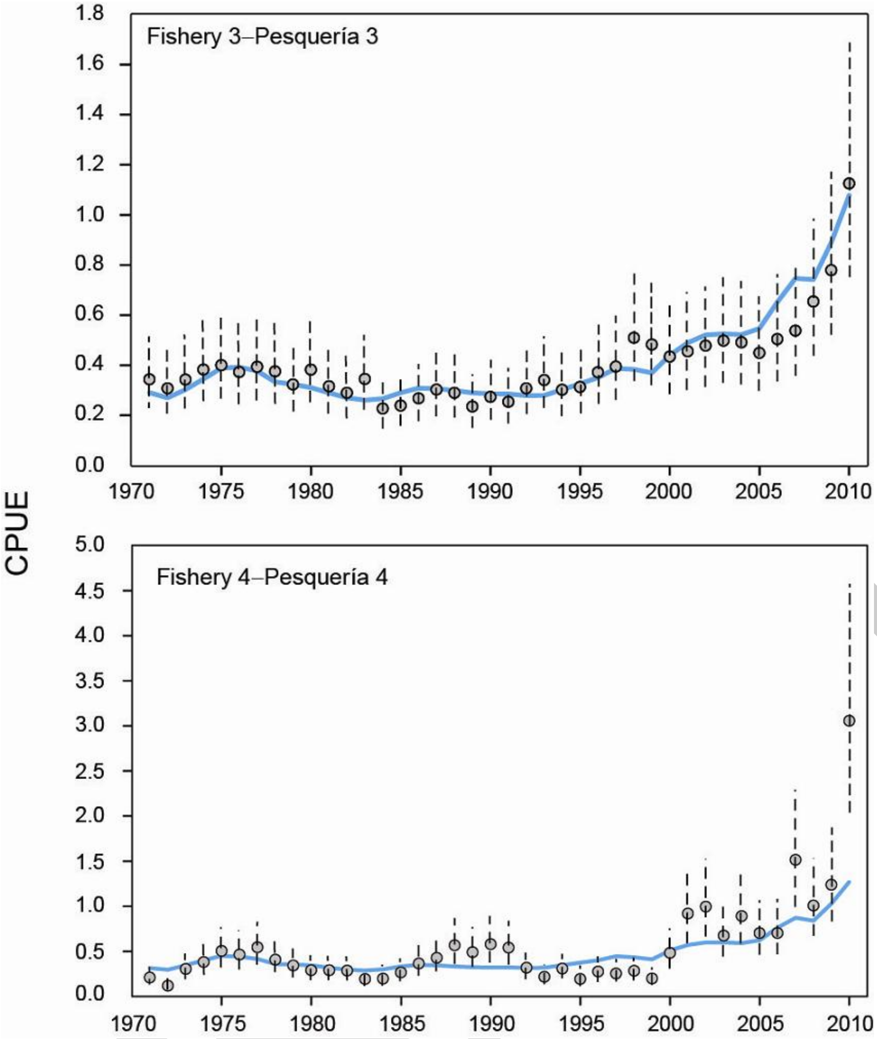

FIGURE 4.4.1.1. Estimated trends in annual abundance from the assessment (solid lines), and the standardized abundance indices (dots) with approximate 95 percent confidence intervals for the Japanese Offshore (F3) and Coastal (F4) longline fisheries.

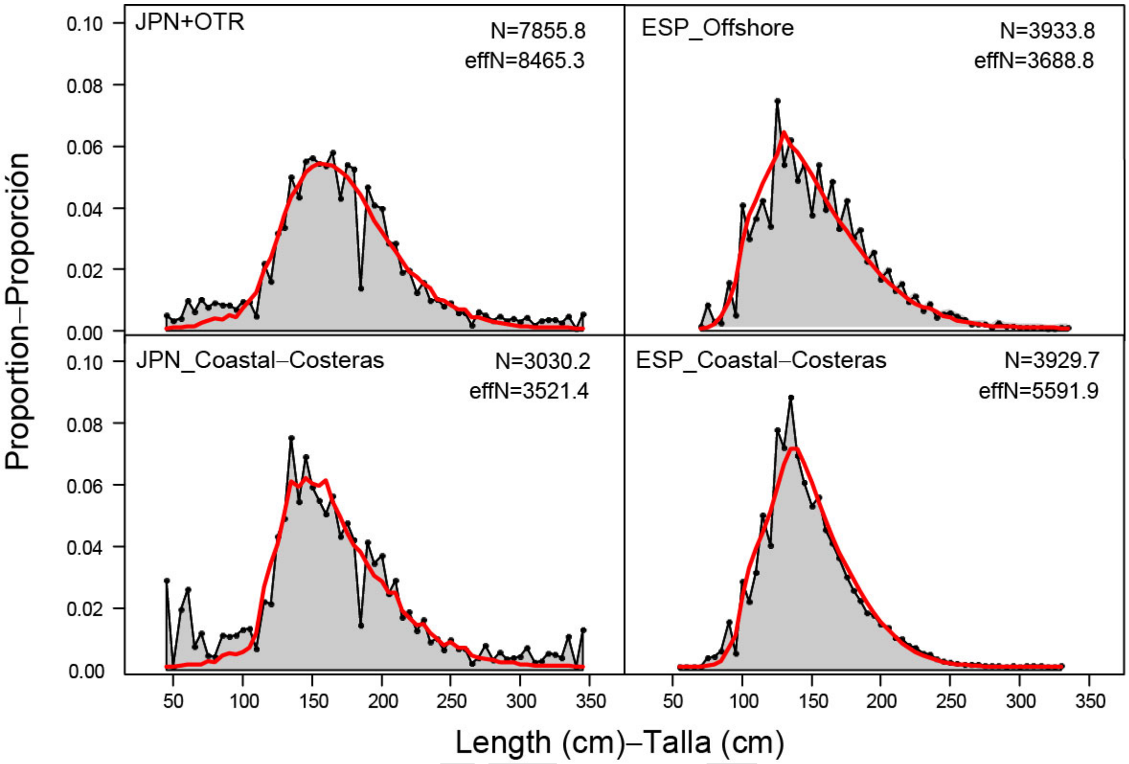

FIGURE 4.4.1.2 Observed (grey areas) and estimated (red lines) size-frequency distributions from the assessment for the Japanese and Spanish offshore and coastal fisheries averaged over all years for which the data are available

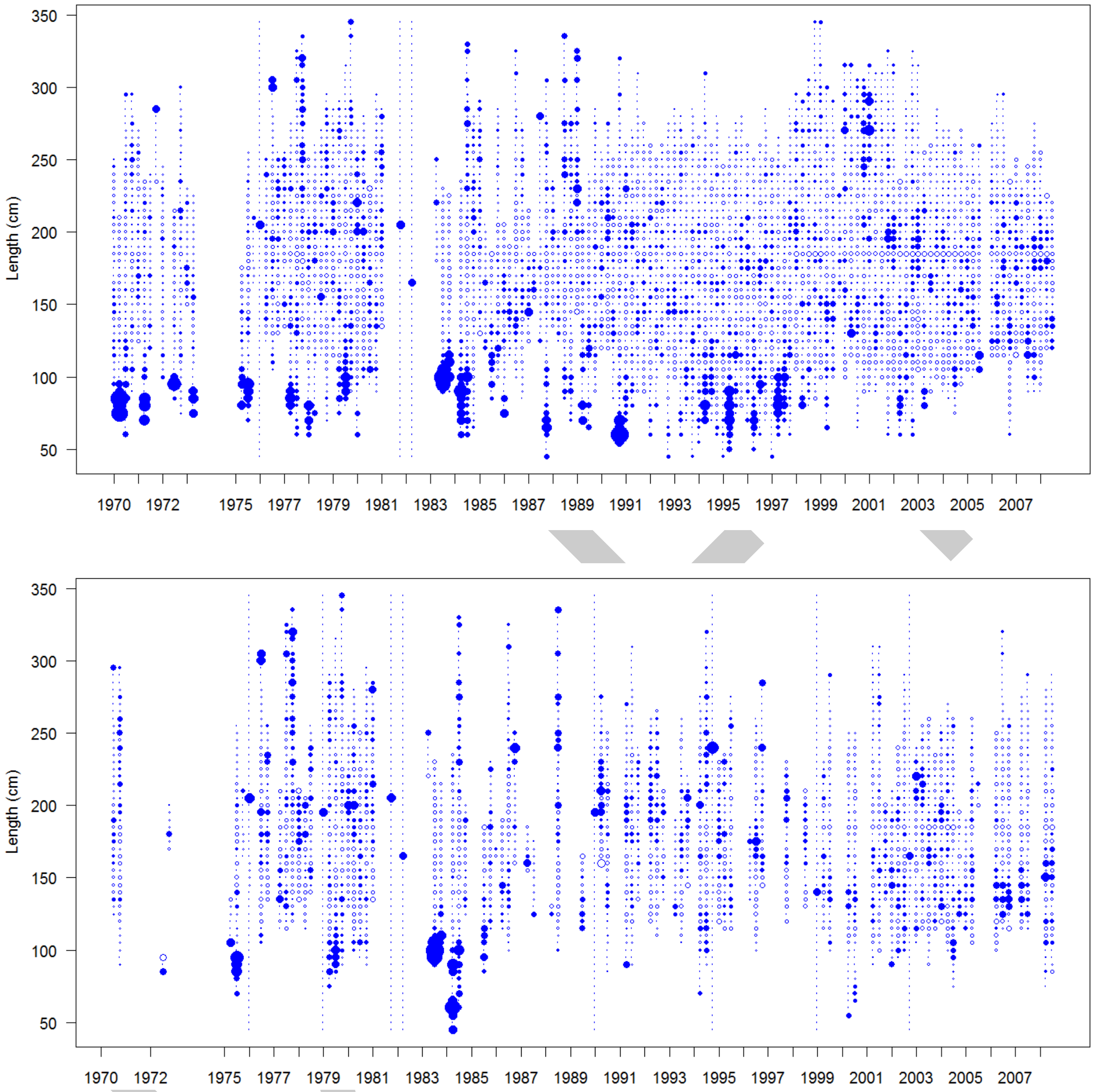

FIGURE 4.4.1.3. Pearson residuals from the estimates from the assessment of the size frequency data for the offshore (upper panel) and coastal (lower panel) longline fisheries of Japan. . The open circles represent observed values that are greater than predicted values and the open circles represent observed values that are less than the predicted values.

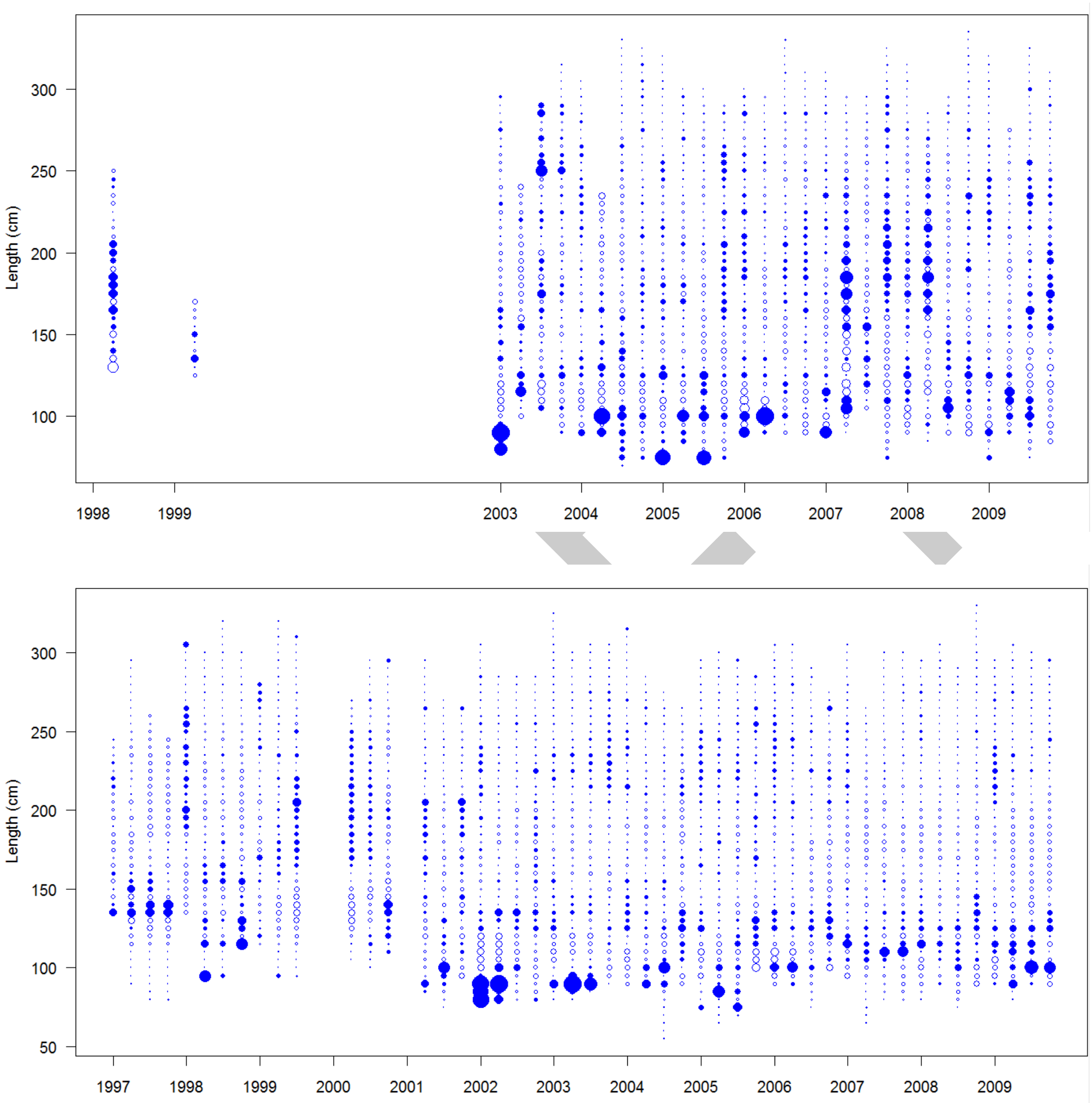

FIGURE 4.4.1.4. Pearson residuals for the estimates from the assessment of the size frequency data for the offshore (upper panel) and coastal (lower panel) longline fisheries of Spain. . The open circles represent observed values that are greater than predicted values and the open circles represent observed values that are less than the predicted values.

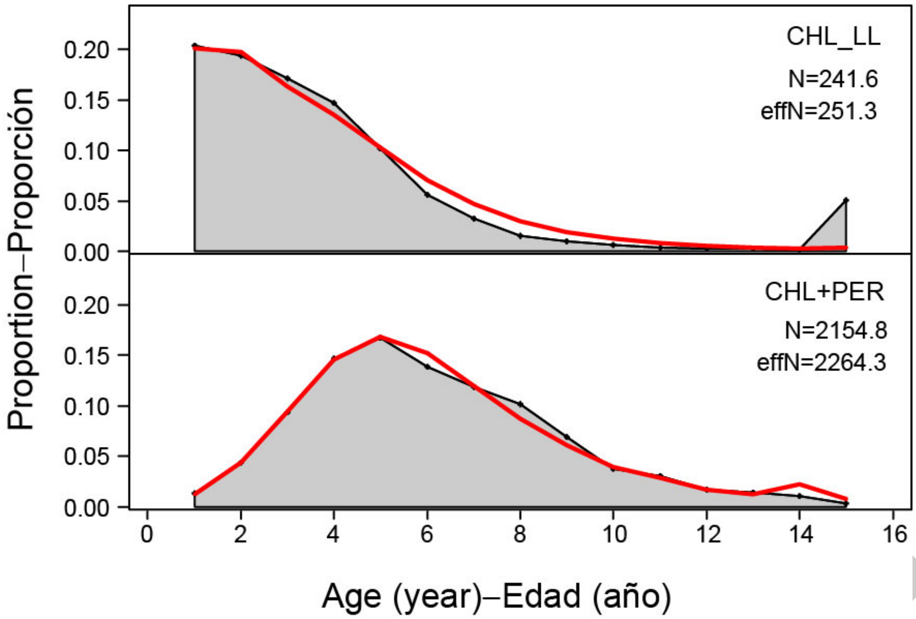

FIGURE 4.4.1.5. Assessment-based estimates (red lines) and observations (shaded area) of the age-frequency distribution distributions of the industrial longline (upper) and artisanal (lower) fisheries of Chile averaged over all years for which the data were available.

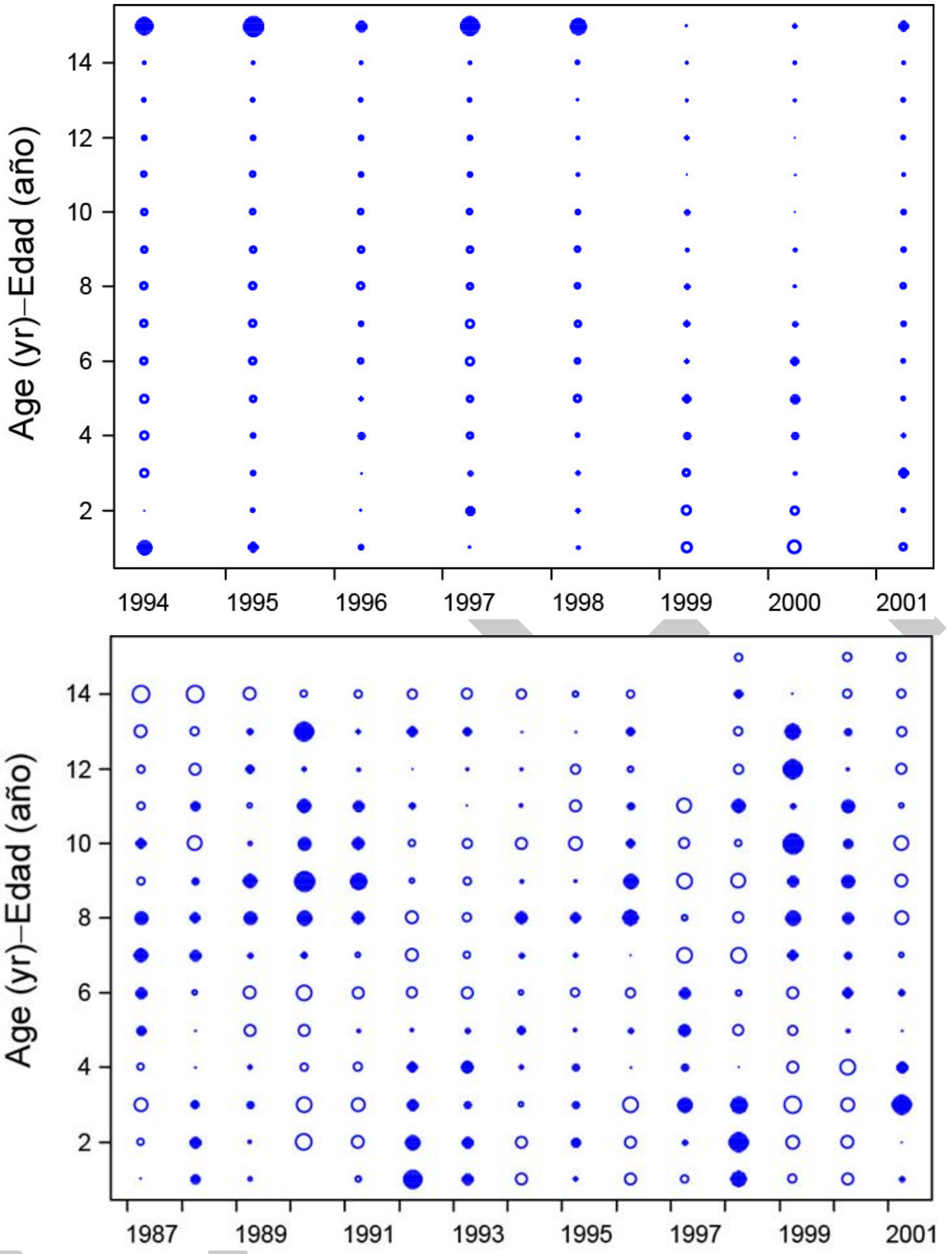

FIGURE 4.4.1.6. Pearson residuals for the estimates from the assessment of the size frequency data for the industrial (upper panel) and artisanal (lower panel) fisheries of Chile. . The open circles represent observed values that are greater than predicted values and the open circles represent observed values that are less than the predicted values.

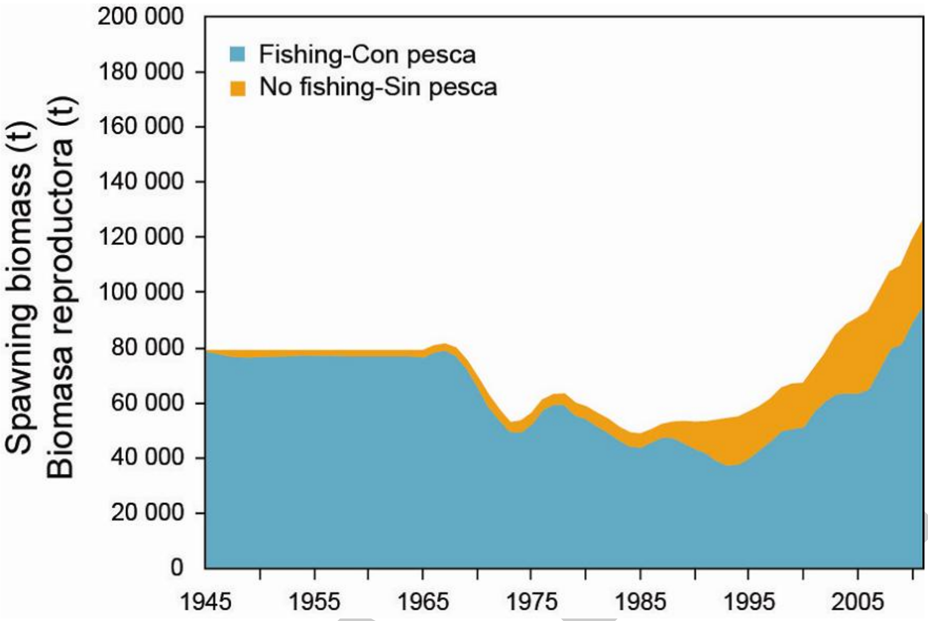

FIGURE 4.4.2. Estimated trends in spawning biomass, with and without fishing, from fits of the assessment without catch rate indices for the recent (2007-2010) period. The yellow shaded area represents the impact of the fisheries on the spawning biomass.

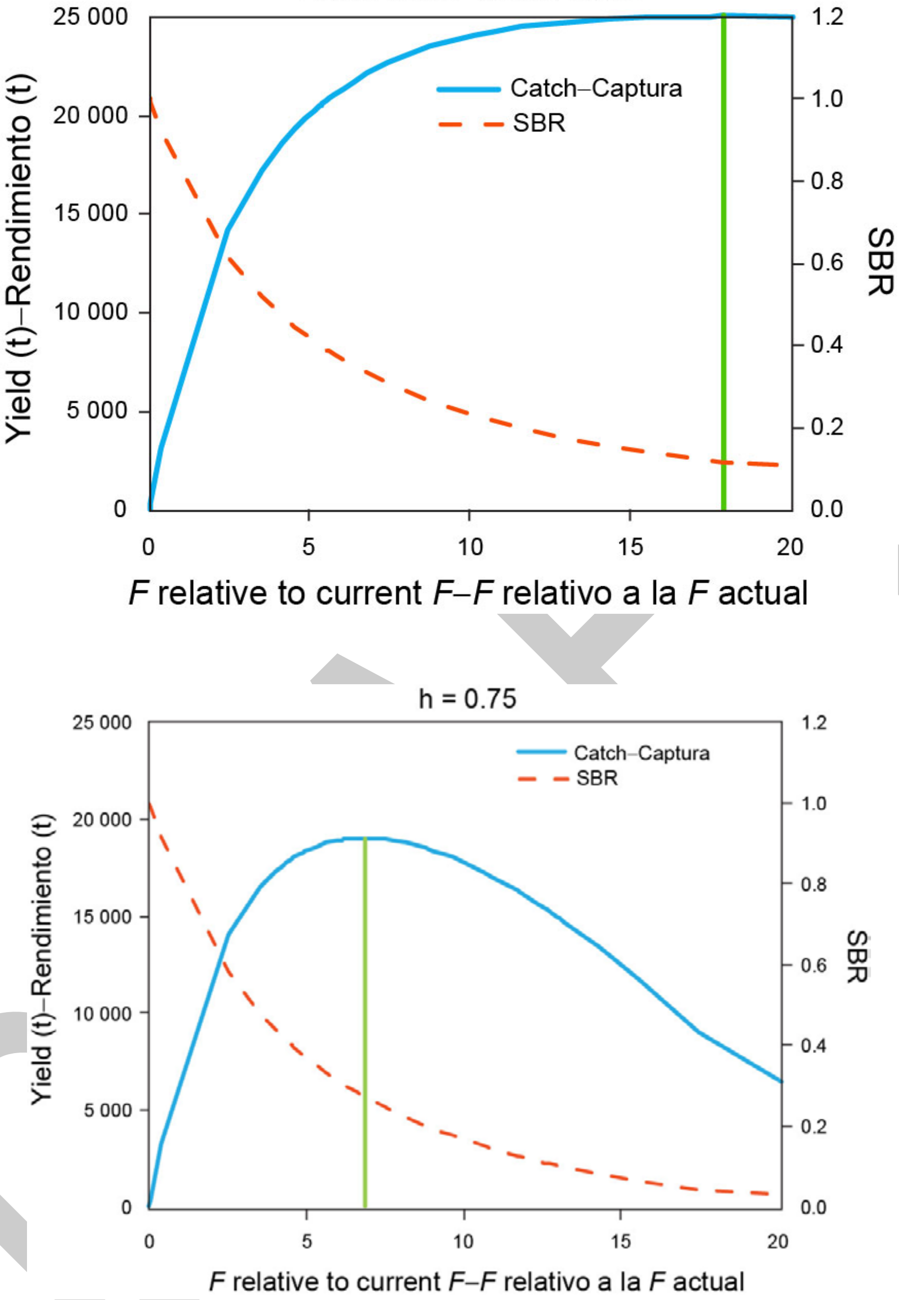

FIGURE 4.2.2.2. Estimated yield and *SBR* from the assessment (upper panel) and from the model with steepness of 0.75 (lower panel) as a function of fishing mortality relative to the current level of fishing mortality. The green vertical bar indicates the relative fishing mortality expected to provide catch at the level of *MSY*.

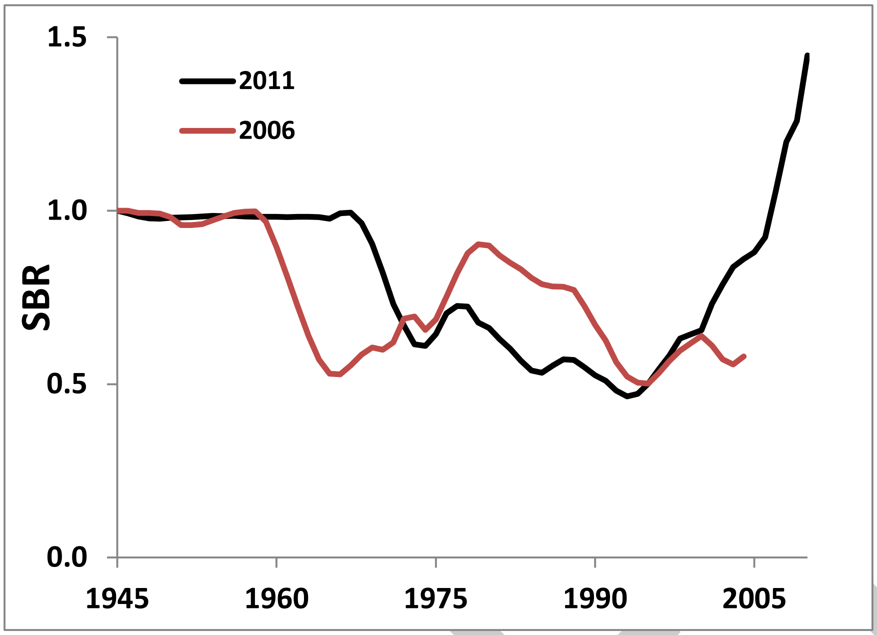

FIGURE 4.5. Comparison of the estimated spawning biomass ratios (SBR) from assessments of swordfish in the SEPO in 2006, which used data through 2003, and from the assessment in 2011, which used data through 2010.

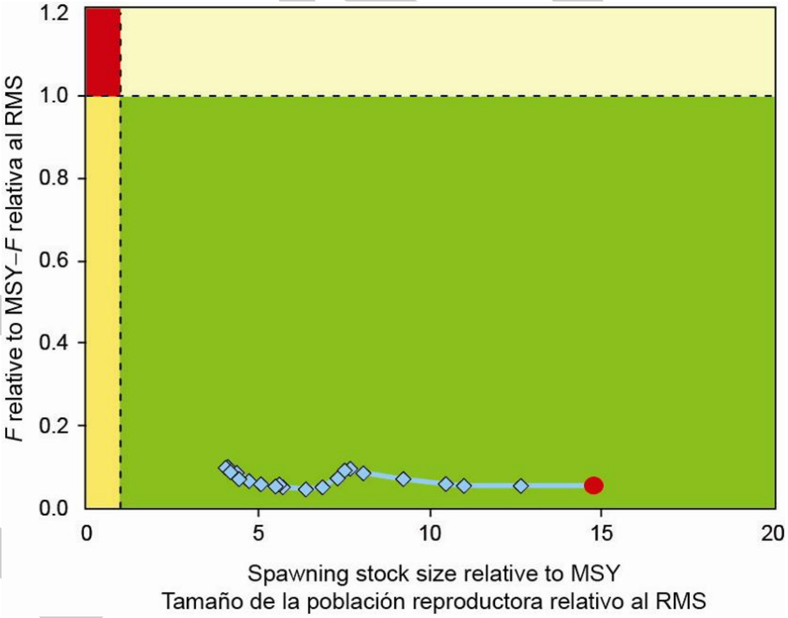

FIGURE 5. The relationship between spawning stock biomass relative to MSY and fishing mortality rate (*F*) relative to MSY.

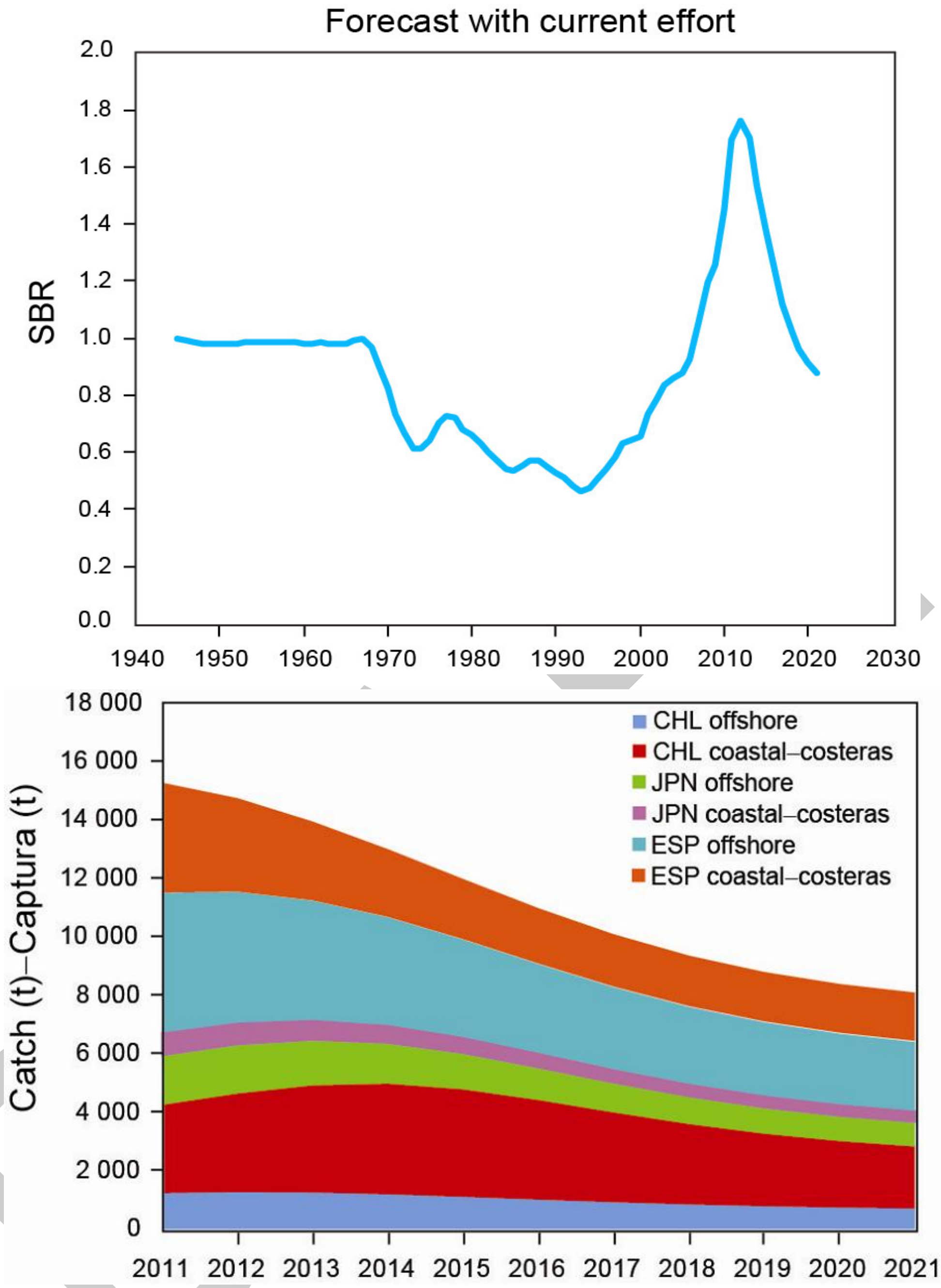

FIGURE 6. Projected spawning biomass ratio (*SBR:* upper panel) and catch by fishery (lower panel) by fishery for the 2011-2020 period, assuming current (average 2008-2010) levels of fishing mortality and effort by fishery persist over the period.

TABLE 2.2. Catches of swordfish from the SEPO, in metric tons.

	CHL	CHN	CRI	ESP	JPN	KOR	PER	PYF	TWN	OTR	Total
1945	1,455	-	-	-	-	-	-	-	-	-	1,455
1946	2,166	-	-	-	-	-	-	-	-	-	2,166
1947	1,701	-	-	-	-	-	-	-	-	-	1,701
1948	1,209	-	-	-	-	-	-	-	-	-	1,209
1949	690	-	-	-	-	-	-	-	-	-	690
1950	786	-	-	-	-	-	-	-	-	-	786
1951	870	-	-	-	-	-	-	-	-	-	870
1952	570	-	-	-	-	-	-	-	-	-	570
1953	416	-	-	-	-	-	-	-	-	-	416
1954	334	-	-	-	0	-	700	-	-	-	1,034
1955	237	-	-	-	1	-	400	-	-	-	638
1956	386	-	-	-	3	-	600	-	-	-	989
1957	357	-	-	-	54	-	600	-	-	-	1,011
1958	392	-	-	-	64	-	400	-	-	-	856
1959	555	-	-	-	32	-	400	-	-	-	987
1960	456	-	-	-	36	-	400	-	-	-	892
1961	394	-	-	-	104	-	300	-	-	-	798
1962	297	-	-	-	211	-	400	-	-	-	908
1963	94	-	-	-	676	-	200	-	-	-	970
1964	312	-	-	-	471	-	900	-	-	-	1,683
1965	151	-	-	-	344	-	300	-	-	-	795
1966	175	-	-	-	401	-	200	-	-	-	776
1967	203	-	-	-	390	-	1,300	-	31	-	1,924
1968	175	-	-	-	261	-	800	-	18	-	1,254
1969	314	-	-	-	569	-	1,200	-	6	-	2,089
1970	243	-	-	-	542	-	2,396	-	26	-	3,207
1971	181	-	-	-	261	-	185	-	18	-	645
1972	141	-	-	-	368	-	550	-	38	-	1,097
1973	410	-	-	-	912	-	1,941	-	30	-	3,293
1974	218	-	-	-	694	-	470	-	34	-	1,416
1975	137	-	-	-	882	3	158	-	9	-	1,189
1976	13	-	-	-	1,209	15	295	-	36	-	1,568
1977	32	-	-	-	1,654	16	420	-	31	-	2,153
1978	56	-	-	-	2,045	29	436	-	8	-	2,574
1979	40	-	-	-	1,226	13	188	-	30	-	1,497
1980	104	-	-	-	2,103	32	216	-	17	-	2,472
1981	294	-	-	-	1,653	79	91	-	32	-	2,149
1982	285	-	-	-	1,143	26	154	-	31	-	1,639
1983	342	-	-	-	1,771	28	238	-	9	-	2,388
1984	103	-	-	-	1,538	37	343	-	15	-	2,036
1985	342	-	-	-	868	70	55	-	12	-	1,347
1986	764	-	-	-	1,473	60	21	-	12	-	2,330
1987	2,059	-	-	-	1,661	144	73	-	28	-	3,965
1988	4,455	-	-	-	2,233	110	54	-	38	-	6,890
1989	5,824	-	-	-	1,216	42	3	-	74	-	7,159
1990	4,955	-	-	1,007	1,596	170	1	-	24	-	7,753
1991	7,255	-	107	2,794	1,896	402	3	-	28	29	12,514
1992	6,379	-	27	2,435	2,020	172	16	2	27	-	11,078
1993	4,712	-	20	928	1,505	159	76	2	19	-	7,421
1994	3,801	-	27	576	1,627	121	310	16	44	-	6,522
1995	2,594	-	29	698	1,213	290	7	25	6	-	4,862
1996	3,145	-	315	772	1,186	332	1,013	25	12	-	6,800
1997	4,040	-	1,072	2,018	1,169	250	24	23	37	-	8,633

	CHL	CHN	CRI	ESP	JPN	KOR	PER	PYF	TWN	OTR	Total
1998	4,492	-	419	1,238	2,005	361	98	20	78	6	8,717
1999	2,925	-	99	1,092	1,257	401	15	30	84	-	5,903
2000	2,973	-	407	1,807	1,184	354	2	46	109	3	6,885
2001	3,262	111	653	3,426	2,436	154	2	47	462	536	11,089
2002	3,523	321	638	5,629	2,363	146	14	4	2,080	661	15,379
2003	3,848	815	286	5,913	2,286	136	26	87	1,454	320	15,171
2004	3,268	236	179	5,607	1,783	583	19	63	799	476	13,013
2005	3,979	308	191	4,962	1,254	146	28	51	561	34	11,514
2006	3,147	*	444	5,149	1,153	*	63	64	614	19	10,653
2007	3,741	147	242	4,730	1,309	159	46	51	246	119	10,790
2008	2,792	335	44	6,718	1,678	94	124	60	129	90	12,064
2009	3,514	*	37	8,011	1,617	89	25	59	91	*	13,443
2010	*	*	*	*	2,312	*	*	*	*	*	2,312

CHL: Chile; CHN: China; CRI: Costa Rica; ESP: España-Spain; JPN: Japan-Japón; KOR: Republic of Korea-República de Corea; PER: Perú; PYF: French Polynesia-Polinesia Francesa TWN: Chinese Taipei-Taipei Chino.
OTR: Includes Belize, Colombia, Ecuador, El Salvador, Guatemala, Mexico, Nicaragua, Panama and Vanuatu. Incluye Belice, Colombia, Ecuador El Salvador, Guatemala, México, Nicaragua, Panamá y Vanuatú.

TABLE 5. Estimates of selected model outputs and MSY-based parameters from the assessment and from sensitivity analyses in which h = 0.75 and in which the high catch rates observed in the 2007-2010 period were not included in the model.

Estimate – Estimación	**Assessment – Evaluación**	**h = 0.75**	**2007-2010 cpue excluded**
MSY	25,044	19,029	21,046
B_{MSY}	40,782	72,717	34,111
S_{MSY}	10,705	26,772	8,920
B_{MSY}/B_0	0.20	0.34	0.20
S_{MSY}/S_0	0.11	0.27	0.11
$\text{C}_{\text{RECENT}}/\text{MSY}$	0.57	0.75	0.68
$\text{B}_{\text{RECENT}}/\text{B}_{\text{MSY}}$	10.40	5.14	6.40
$\text{S}_{\text{RECENT}}/S_{\text{MSY}}$	14.76	5.99	10.68
F_{mult}	17.92	6.86	11.67

RECENT = average value for the three most recent years.

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