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Application of the SEAPODYM model to swordfish in the Pacific Ocean

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Abstract

A SEAPODYM application to Pacific swordfish is developed. After definition of the population structure and initial parameterization, optimization experiments are conducted based on accessible fishing data (catch, effort and size frequency). Preliminary results are encouraging. Despite a lack of comprehensive fishing data, the model optimization experiments converged with reasonable estimated values of parameters defining the spawning and feeding habitat of the population at the Pacific basin scale, and provided a good fit between observed and predicted catch, and catch size. However, key parameters still remain unestimated and had to be set at fixed values, leading to very large uncertainty in biomass estimates. More progress could be quickly achieved if comprehensive fishing data were available at the scale of the Pacific Ocean. These data, including all available size frequency data, should be stratified by space, gear and target species. Compilation of such a comprehensive data set will require close collaboration between scientists across the Pacific and cooperation between WCPFC and IATTC.

Introduction

An application of the SEAPODYM model (Lehodey et al 2008, Senina et al 2008, Lehodey & Senina 2009) to swordfish in the Pacific Ocean is underway. The environmental forcing used for optimization experiments is provided by a simulation with an ocean circulation model (ORCA2) coupled to a biogeochemical model (PISCES) and forced by the NCEP-NCAR atmospheric reanalysis (http://www.cgd.ucar.edu/cas/guide/Data/ncep-ncar_reanalysis.html). ORCA2 is the standard configuration of the ocean general circulation model OPA (Version 9.0) for the global ocean

(<http://www.nemo-ocean.eu/>), and PISCES describes the marine biogeochemical cycles of carbon and the main nutrients (N, P, Si and Fe) which limit phytoplankton growth (Aumont et al. 2003; Bopp et al. 2005; Gorgues et al., 2005; Aumont and Bopp, 2006). This configuration has been used for applications to tuna species in Lehodey et al (2009).

The vertical layers were defined as: epipelagic layer between 0 and one euphotic depth (Z_{eu}), mesopelagic layer between 1 and $3Z_{eu}$ and bathypelagic layer between $3Z_{eu}$ and 1000m (see Lehodey & Senina 2009 and Lehodey et al. 2010 for a description of the various forcings). The model domain covers the Pacific Basin at a spatial resolution of 2deg x 2deg and a monthly time resolution. An update of this NCEP-ORCA2-PISCES configuration will be used later on, as it incorporates more recent years (1960-2008 vs 1945-2003), which will allow the use of longer and more accurate fishing data sets.

It should be noted that due to the coarse resolution of the model, these simulations do not reproduce mesoscale activity and underestimate the intensity of oceanic circulation in the most dynamical oceanic areas, e.g., Kuroshio and east equatorial Pacific (Lehodey & Senina 2009).

Several improvements were implemented in Seapodym (Lehodey et al. 2011):

- use of SST to estimate the spawning habitat, as most spawning preferences in the literature are expressed in terms of SST rather than temperature averaged over the whole epipelagic layer.
- a robustified formulation of the likelihood function to take better account of the size-frequency data in the cost function.

The model simulates age-structured swordfish populations with one length and one weight coefficient per age cohort obtained from independent studies (De Martini et al. 2007, Uchiyama et al. 1999). Different life stages are considered: larvae, juveniles and (immature and mature) adults. Due to the very rapid growth of swordfish and the monthly resolution of our forcing, the age structure was defined as follows: no larvae class; one monthly age class for juveniles; and 13 adult cohorts of varying duration, 6 for immature adults up to age 1.75 yr, when 50% of the fish are sexually mature (Courtney & Piner 2010), and 7 cohorts for mature adults up to age 9 yr and older (Fig. 1). After the juvenile phase, swordfish become autonomous, i.e., they have their own movement (linked to their size and feeding habitat) in addition to being transported by oceanic currents.

Due to the relatively long lifespan of swordfish, the parameter estimation is very sensitive to initial conditions. To mitigate this, the parameter optimization was conducted using historical fishing data over the period 1985-2000, with the first ten years excluded from the likelihood calculation.

Fishing data available for optimization

The only fishing data sets available for this study were public domain, spatially-disaggregated monthly catch data provided by the Oceanic Fisheries Program of the Secretariat for the Pacific Community (SPC) and high-resolution catch data provided by NOAA/NMFS for the Hawaii-based longline fisheries. Quarterly length frequency data associated with each fishery over the historical fishing period were also available. Table 1 summarizes the fisheries included in this analysis. The data used include catches by fleets providing data to the Western and Central Pacific Fisheries Commission (WCPFC). Swordfish catch data for fleets fishing in the eastern Pacific and reporting catches to the Inter-American Tropical Tuna Commission (IATTC) were not available for the study.

Fishing data provided by NMFS included high-resolution catch data ($0.1^\circ \times 0.1^\circ \times 1$ day degraded to $1^\circ \times 1^\circ \times 1$ month) for 3 Hawaii-based longline fisheries (deep, mixed and shallow sets). The spatial resolution for Hawaii fisheries was further degraded to $2^\circ \times 2^\circ$ to avoid problems fitting the diffusion and advection parameters to the patchy high-resolution data. To reduce numerical errors in the simulation, the number of iterations was increased to 18.

The SPC data are $5^\circ \times 5^\circ \times 1$ month aggregated by flag. Figure 2 shows the composition of catch by flag for the SPC data. Unfortunately, no information on target species or hooks per float is available with which to stratify the SPC catch data by set depth, except for Australia, New Zealand, and Taiwan (only for the period 2005-2008 for Taiwan). Swordfish CPUE can vary greatly between night-time shallow longline sets targeting swordfish and daytime deep sets targeting tuna (sometimes by as much as a factor 100 in the Hawaii-based longline fisheries). The absence of information on the target species makes it very difficult to fit pooled catch data in SEAPODYM, where each fishery is modeled with a unique selectivity function and a unique catchability coefficient. In addition, data provided by the SPC only account for parts of the swordfish catch in the Pacific Ocean (Courtney & Piner 2010, Hinton & Maunder 2011 draft, Figs. 3-6). As mentioned, catch data for non-WCPFC fisheries were not available. Because our analysis did not include these catch data, the fishing mortality in our model is likely underestimated in the eastern Pacific.

Australian data were not used in the likelihood for this set of optimization experiments, as 1995-2000 represents the period during which the swordfish longline fishery was developing in Australia, with a switch to bigger boats and a regular effort to better target swordfish (Ward 2000). Such a rapid change in fishing techniques makes the data unsuitable for the optimization. However, the Australian catch was taken into account for the calculation of the fishing mortality. A linearly changing coefficient of catchability was used to account for the change in the fleet.

High-resolution length-frequency data were available from the Hawaii longline observer program for the three Hawaiian fisheries. The length-frequency data provided by the SPC, on the other hand, only covered a small portion of the areas fished by the main fisheries (Japan, Korea, Taiwan) and only some years between 1987 and 2007. The Australian fishery was not included in that length-frequency dataset. The number of observations of length-frequency was artificially increased (keeping the same size distribution) for fisheries L3, L4 and L6 to increase their weights in the likelihood and obtain a better fit. Spatial distributions of available size frequency data are shown in Figure 7.

Results

Current estimates of the parameters are presented in Table 2. As a result of the lack of information on gear for all fisheries other than the Hawaii-based ones, a number of parameters had to be fixed and some of the estimated parameters are close to the bounds. In particular, diffusion, natural mortality and recruitment could not be estimated all at the same time, and thus were fixed to values that were biologically plausible.

Natural mortality rates and recruitment are the most difficult parameters to estimate in population dynamic models. For swordfish, recent stock assessment studies use a rate between 0.4/yr for younger fish and 0.35/yr for fish older than 7 years (Courtney & Piner 2010). Hinton & Maunder (2011) mention that natural mortality for swordfish could be as low as 0.2/yr but used a constant annual instantaneous natural mortality rate of 0.4/yr. In SEAPODYM, natural mortality is defined by the

combination of a predation and a senescence function allowing the mortality rates to vary with age (size) but also spatially and temporally within a range of values related to the habitat index (which varies between 0 and 1). The parameters estimated in the optimization experiments produced very low natural mortality coefficients resulting in unreasonable biomass values, so they were initially fixed at values close to 0.4/yr for adults. With such high levels of natural mortality of adults, the model was predicting only catches of younger fish. Mortality of adults had to be greatly reduced to improve the fit to the length frequency data. The resulting natural mortality curve is shown in Fig. 8.

The **stock-recruitment** relationship is also difficult to estimate in population dynamics models. It defines the number of larvae released in each cell of the grid in relation with spawning biomass and weighted by the spawning index. This relationship, together with the mortality rates, determines the total level of the population. Stock assessment studies use a stock-recruitment steepness of 1 for swordfish, indicating that recruitment is not reduced at lower levels of spawning biomass (Courtney & Piner 2010, Kolody et al 2008, Hinton & Maunder 2011). Similarly we fixed it at 1. Recruitment was fixed at the lowest possible level to sustain catches from all fisheries (Fig. 9). The resulting biomass of adults predicted by the model is much higher than the biomass predicted by the various stock assessments. However, it should be noted again that not all the catch and fishing effort was available for these optimization experiments, therefore likely leading to underestimated fishing mortality.

The stock synthesis model described in Courtney & Piner (2010) estimated a biomass of swordfish age 2 and over around 30,000 and 70,000 mt in areas NP1 and NP2 respectively (Fig. 3) between 1995 and 2000. The stock synthesis model of Hinton & Maunder (2011) estimated the spawning biomass to be around 60,000 mt during the same period in the eastern Pacific (areas SE1 and SE2 in Fig. 3). And the Multifan-CL stock assessment of Kolody et al. estimated maximum spawning biomass around 25,000 mt in the southwest Pacific (areas SW and SC in Fig. 3). Ignoring the overlap between the three assessments regions, this would amount to about 185,000 mt of adult swordfish in the Pacific Ocean. The first biomass of adult swordfish predicted by our SEAPODYM configuration was quite unrealistic (appr. 35 million mt). The latest ongoing experiment predicts biomasses around 7 million mt, which is still an order of magnitude higher than stock assessment predictions. Further analysis is required to understand such a difference.

The **temperature habitat** by age resulting from the optimization experiment is shown on Fig. 10. The optimal spawning temperature is estimated at 28.3°C by the model with a high standard deviation (3.6°C). The optimal habitat temperature of the oldest cohort was estimated to be 11.3°C. The estimated temperature range for spawning is in agreement with published values since swordfish are known to spawn in waters with sea surface temperature between 24 and 29 °C, with a peak during quarter 2 in the North Pacific (Ward 2000, Courtney & Piner 2010).

The peak of the **spawning season** was set in June in the northern hemisphere to obtain distributions of adults that match the seasonality of catches north of Hawaii : high catches in quarters 1 and 2, virtually no catches in quarter 3, and few or no catches in quarter 4 (Hawaii Longline Fishery Logbook Summary Reports, <http://www.pifsc.noaa.gov/fmb/reports.php>).

The **oxygen** threshold parameter estimated by the model is 3.84 ml/l. This seems quite high since satellite tracking data suggest that swordfish are more tolerant to low ambient dissolved oxygen concentration than most tuna species (Abecassis et al. 2011 subm., Dewar et al. 2011).

All **fishery** parameters (catchability and selectivity) were estimated from the model (Fig. 11) and despite the lack of contrast in the fishing data that was available, the experiments showed a generally good fit to the fishing data both for monthly catch time series (Fig. 12) and length frequency distribution of catch (Fig. 13). Figure 14 shows a map of the R-squared goodness of fit metrics and of the mean error on the fit of catches over our optimization period. Some areas, especially the area covered by the Hawaii-based longline fishery are very well fitted by the model.

Examples of spatial distribution of predicted biomass of young and adults are presented in Fig. 15 for year 1996. When compared with Fig. 16 (Fonteneau 2005, pers. comm.) the distribution of adults exhibits a gap in the equatorial Pacific. This is most likely because we did not incorporate any fishing data from that region.

Conclusion

These preliminary results are encouraging. Despite a lack of comprehensive fishing data, the model optimization experiments converged with reasonable estimated values of parameters defining the spawning and feeding habitat of the population at the Pacific basin scale. However, key parameters still remain unestimated and had to be fixed leading to very large uncertainty, especially in the total biomass and distribution of adults. We have been working with incomplete fishing data (lacking data for Chile and Mexico in the Eastern Pacific), and data that pools all types of gear together for most fisheries. Such an aggregation is problematic for swordfish as CPUE can vary by as much as two orders of magnitude between deep daytime sets and shallow night-time sets. This “blurring” of the catchability makes it very difficult for the model to constrain habitat parameters.

Much progress could be quickly achieved if more comprehensive fishing data were available at the scale of the Pacific Ocean. These data, including all available size frequency data, should be stratified by space, gear and target species. Compilation of such a comprehensive data set will require close collaboration between scientists across the Pacific and cooperation between the WCPFC and IATTC.

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Tables

L1	Hawaii – shallow sets
L2	Hawaii – mixed sets
L3	Hawaii – deep sets
L4	Japan
L5	Korea
L6	Taiwan
L7	Australia

Table 1. Longline fisheries included.

N	Name	min	max	Start, $n = 0$	Finish, $n = 100$
1	N_{FE}			0	164
2	L (types 3 3 3 3 3 3 3)			20136.4	20016.2
3	G_{max}			6608.82	0.303174
4	Food for age(0)	0	1	1	1
5	a sst spawning(0)	0.5	4	3.02319	3.6214
6	b sst spawning(0)	24	30	28.5705	28.2553
7	alpha spawning(0)	0	5	1.11022e-15	5.55112e-16
8	a sst habitat(0)	0.5	6	1.19325	1.14131
9	b sst habitat(0)	8	20	11.3943	11.2973
10	a oxy habitat(0)	1e-10	0.1	5.26002e-09	2.94267e-10
11	b oxy habitat(0)	0.01	4	3.95605	3.95819
12	MSS species(0)	0.001	3	1.7469	1.81483
13	q(0,0)	0	0.5	0.0157809	0.036007
14	q(0,1)	0	0.5	0.0161892	0.0280753
15	q(0,2)	0	0.035	0.00200116	0.00366397
16	q(0,3)	0	0.01	0.00071313	0.000867601
17	q(0,4)	0	0.001	0.000166926	0.000193875
18	q(0,5)	0	0.001	0.000318782	0.000366039
19	s sp fishery(0,0)	0.04	1	0.04	0.0402983
20	length threshold(0,0)	33.084	222.67	172.799	192.492
21	s sp fishery(0,1)	0.04	1	0.0437735	0.0474703
22	length threshold(0,1)	33.084	222.67	177.038	182.835
23	s sp fishery(0,2)	0.01	1	0.0241799	0.029066
24	length threshold(0,2)	33.084	222.67	222.67	222.67
25	s sp fishery(0,3)	0.03	1	0.0672714	0.0622492
26	length threshold(0,3)	33.084	222.67	156.362	158.156
27	s sp fishery(0,4)	0.03	1	0.0759784	0.0777456
28	length threshold(0,4)	33.084	222.67	121.573	121.923
29	s sp fishery(0,5)	0.03	1	0.0309274	0.0337575
30	length threshold(0,5)	33.084	222.67	189.934	184.489
31	s sp fishery(0,6)	0.03	1	0.733746	0.721748
32	length threshold(0,6)	33.084	222.67	33.084	33.084

Table 2. Estimated parameters

N	Name	Parameter
1	Mp mean max(0)	0.028
2	Mp mean exp(0)	0.75
3	Ms mean max(0)	0.025
4	Ms mean slope(0)	-0.03
5	Ms mean half(0)	100
6	M mean range(0)	1.0196e-12
7	hp cannibalism(0)	5
8	sigma species(0)	0.09
9	c diff fish(0)	2.25
10	nb recruitment(0)	0.0025
11	a adults spawning(0)	1
12	q sp fishery(0,6)	4e-06

Table 3. Fixed parameters. The catchability for the Australian fishery was fixed at $4e-6$ with a linear increase of 125% over the 5 years used in the optimization experiment.

Figures

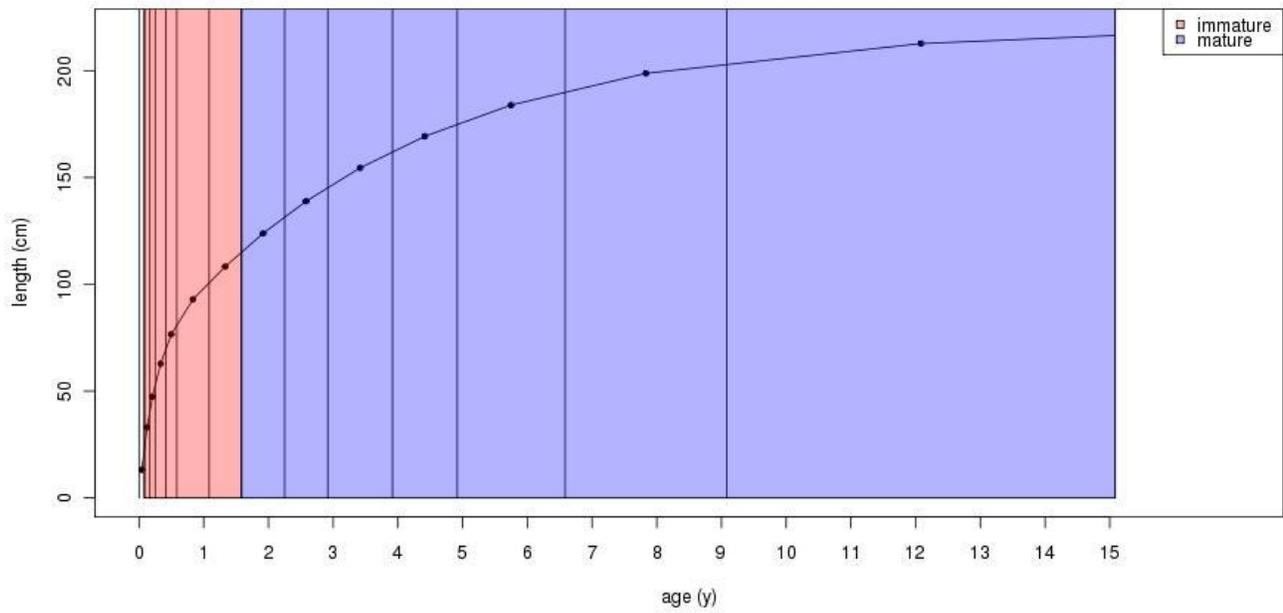


Figure 1. Age cohorts used in the swordfish configuration.

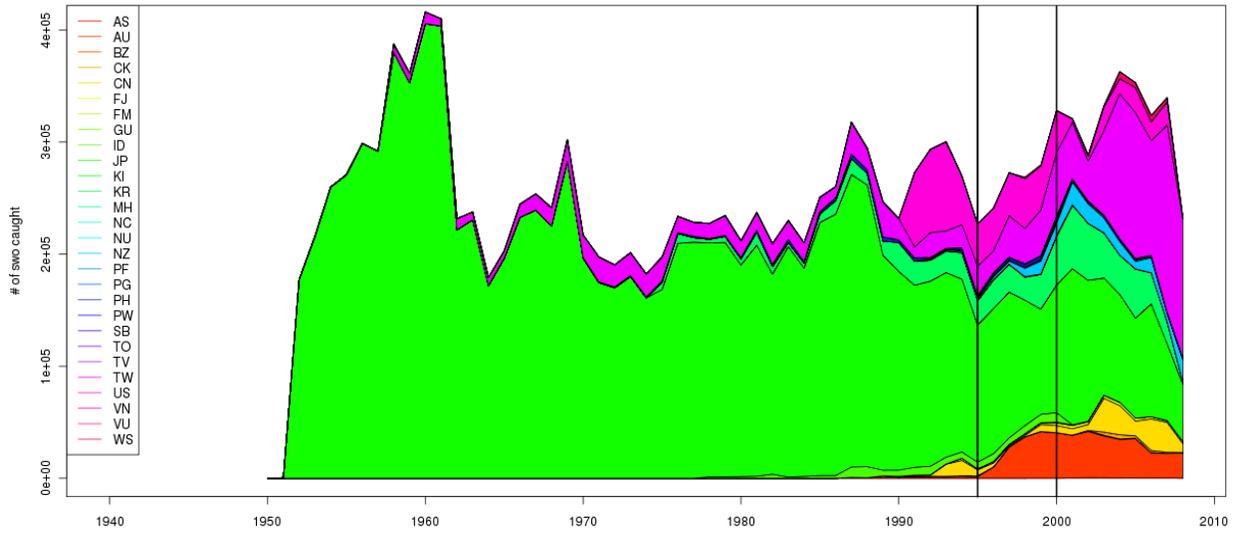


Figure 2a. Data provided by the SPC for the whole Pacific Ocean, composition of catch (# of fish caught) by flag. Vertical lines highlight the period used for parameter optimization.

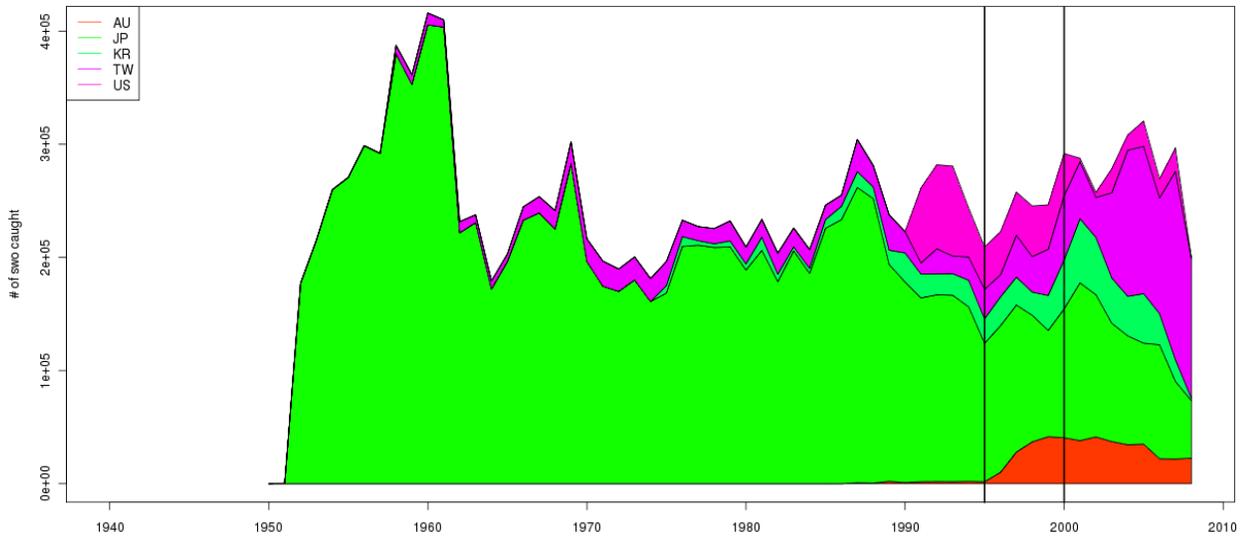


Figure 2b. Same, for the main contributors during the optimization period: 1995-2000. Australia (10%), Japan (50%), Korea (10%), Taiwan (13%), USA (17%).

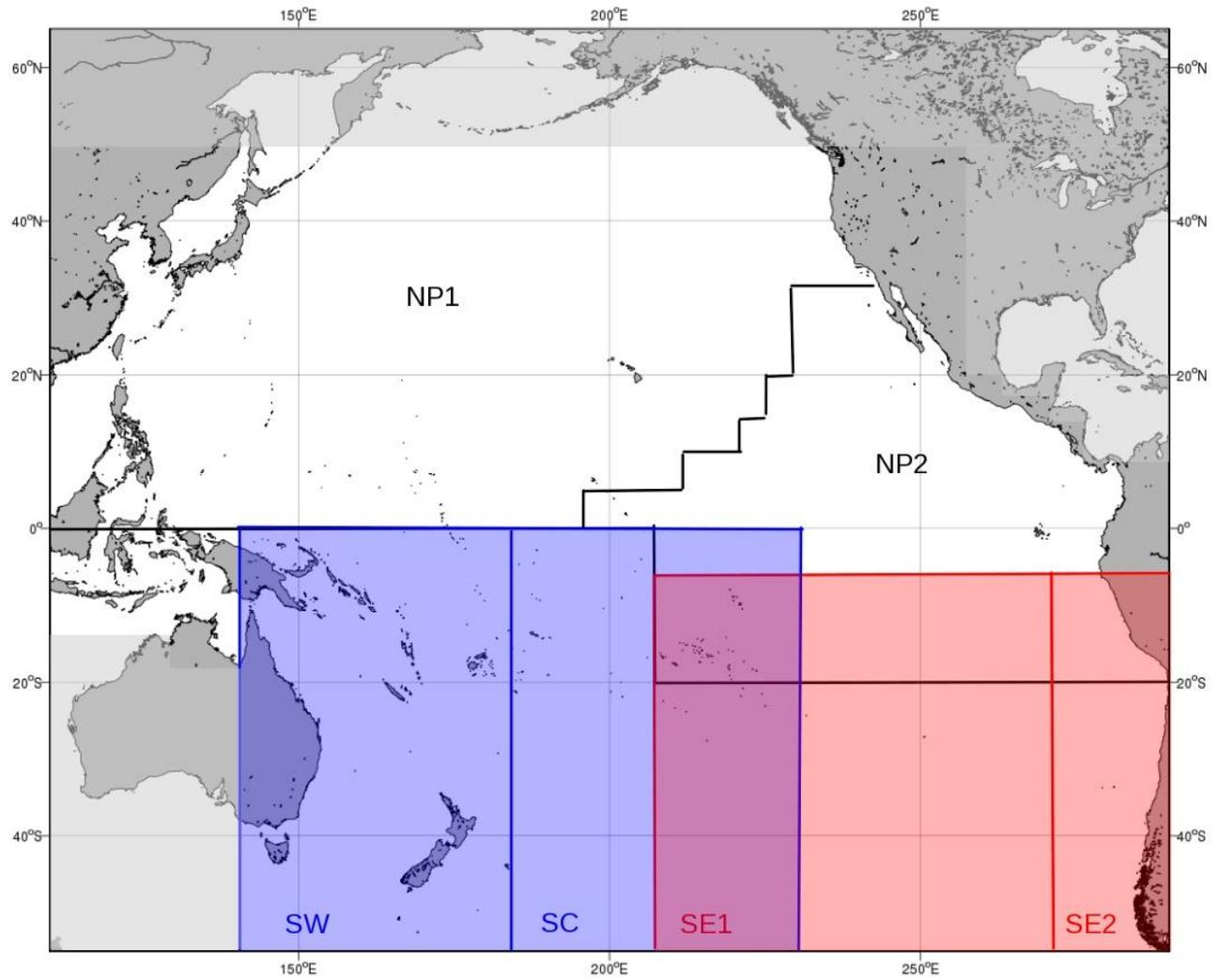


Figure 3. Areas used in the various stock assessments. blue: WCPFC (Kolody et al. 2008), red : IATTC (Hinton & Maunder 2011, draft), white delineated by black lines : ISC (Courtney & Piner 2010)

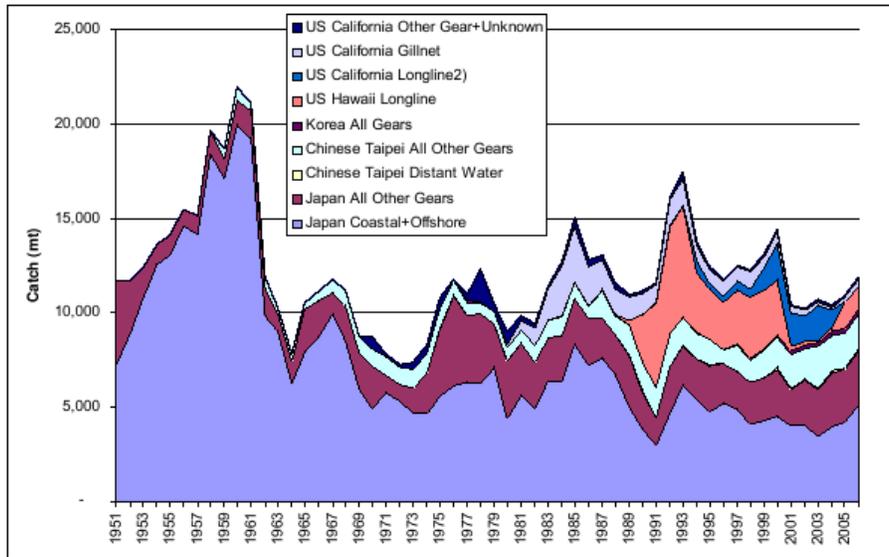


Figure 3.1. Sub-Area 1 annual catch of swordfish (mt) by fleet (Courtney and Wagatsuma 2009).

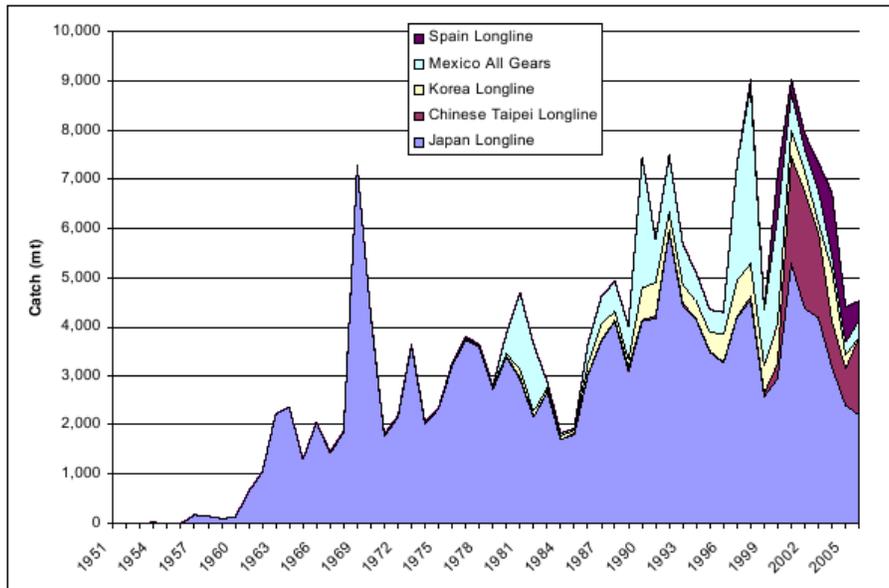


Figure 3.2. Sub-Area 2 annual catch of swordfish (mt) by fleet (BILL-WG 2009c; Appendix A).

Figure 4. North Pacific catches, corresponding to areas NP1 and NP2 on Fig. 3 (from Courtney & Piner 2010).

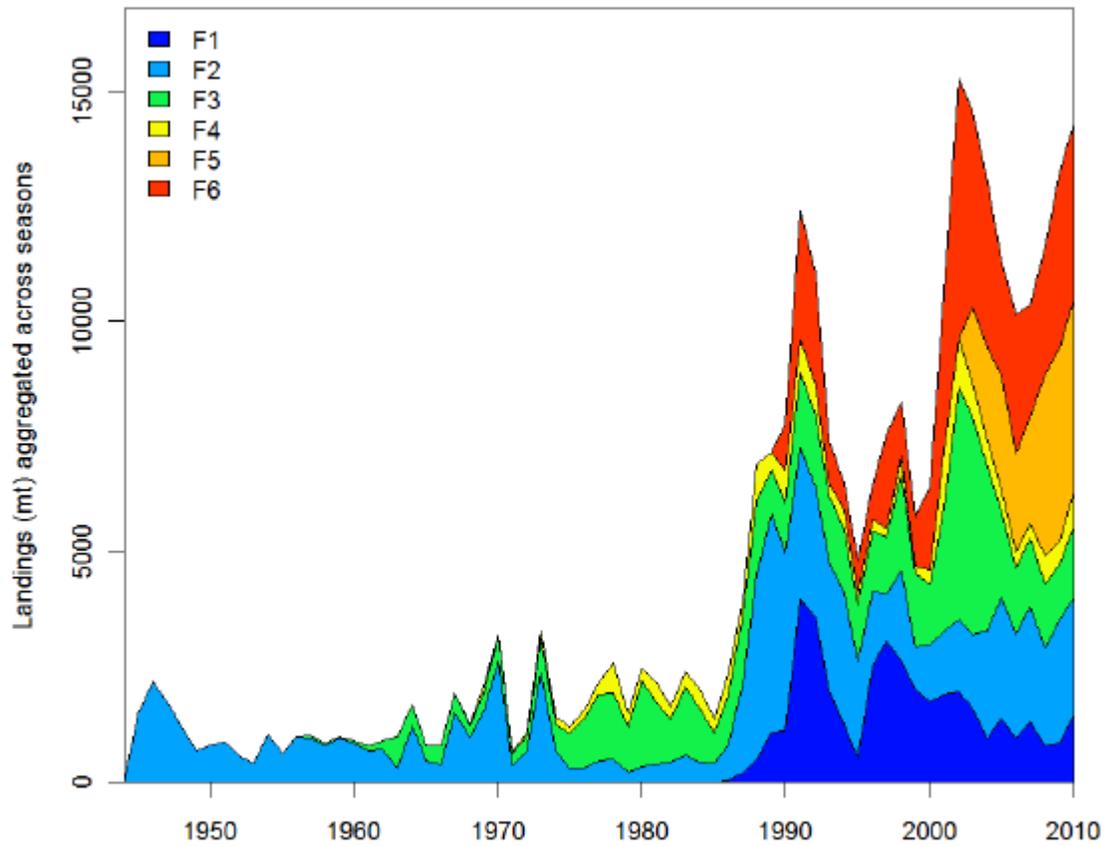


Figure 5. South-east Pacific catches. F1: Chile industrial longline, offshore, F2: Chile artisanal and Peru, coastal, F3: Japan and Japan-like longline, offshore, F4 : Japan and Japan-like tuna longline, coastal, F5 : Spain longline, offshore, F6 : Spain longline, coastal. (From Hinton & Maunder 2011, draft). The offshore and coastal areas are denominated SE1 and SE2 respectively in Fig. 3.

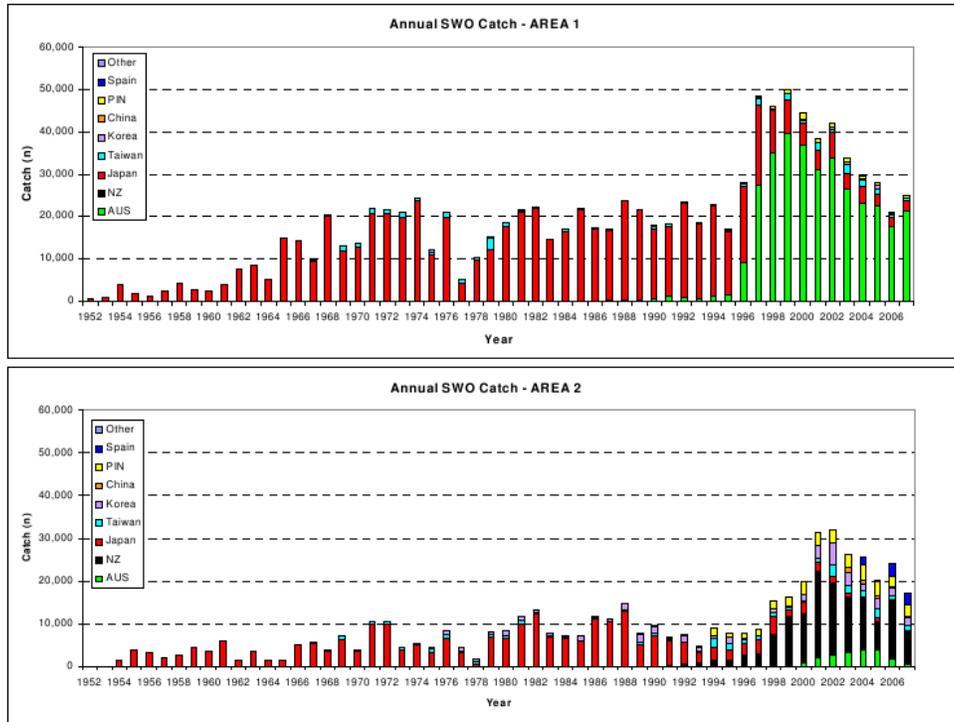


Fig. 6a. South-west Pacific catches, corresponding to areas SW and SC in Fig. 3. (from Kolody et al. 2008)

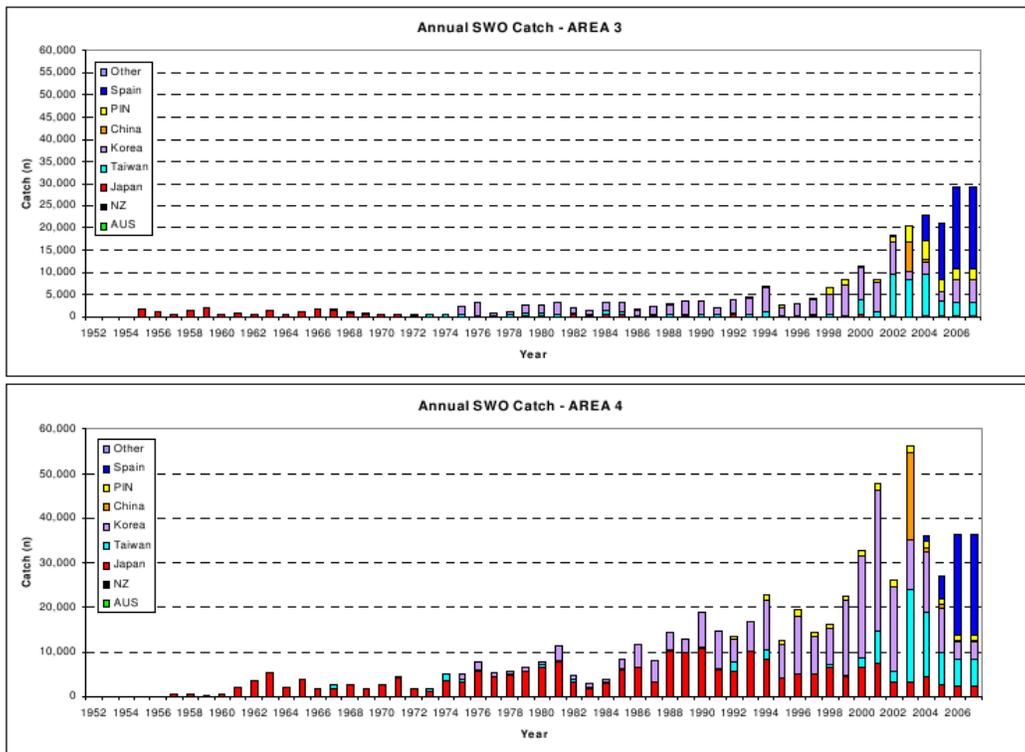


Fig. 6b. Swordfish catch history (numbers) in the South-West (areas 1-2) and South-Central (areas 3-4) Pacific by fishing nation (from Kolody et al. 2008)

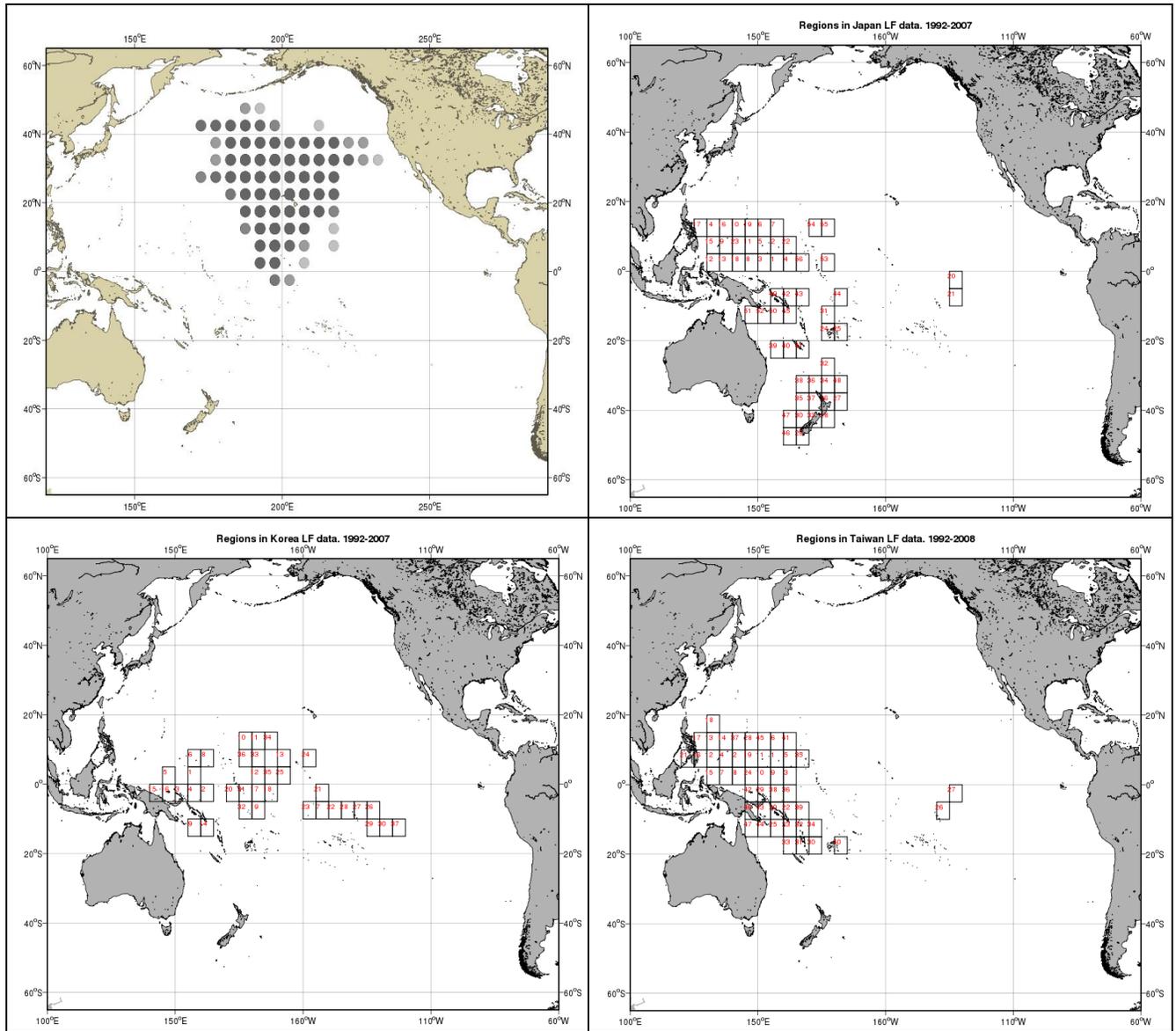


Fig. 7. Regions included in the length-frequency data provided for Hawaii, Japan, Korea, and Taiwan.

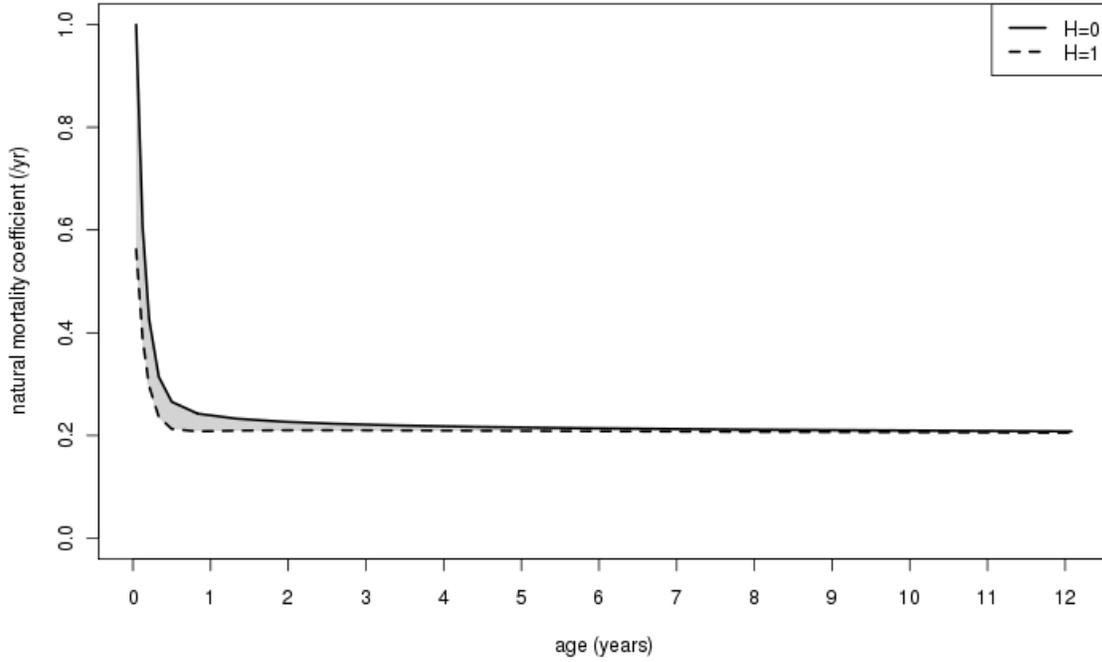


Figure 8. Natural mortality at age (year^{-1}) with range of variability (shaded area) linked to habitat (H) values, between 0 and 1.

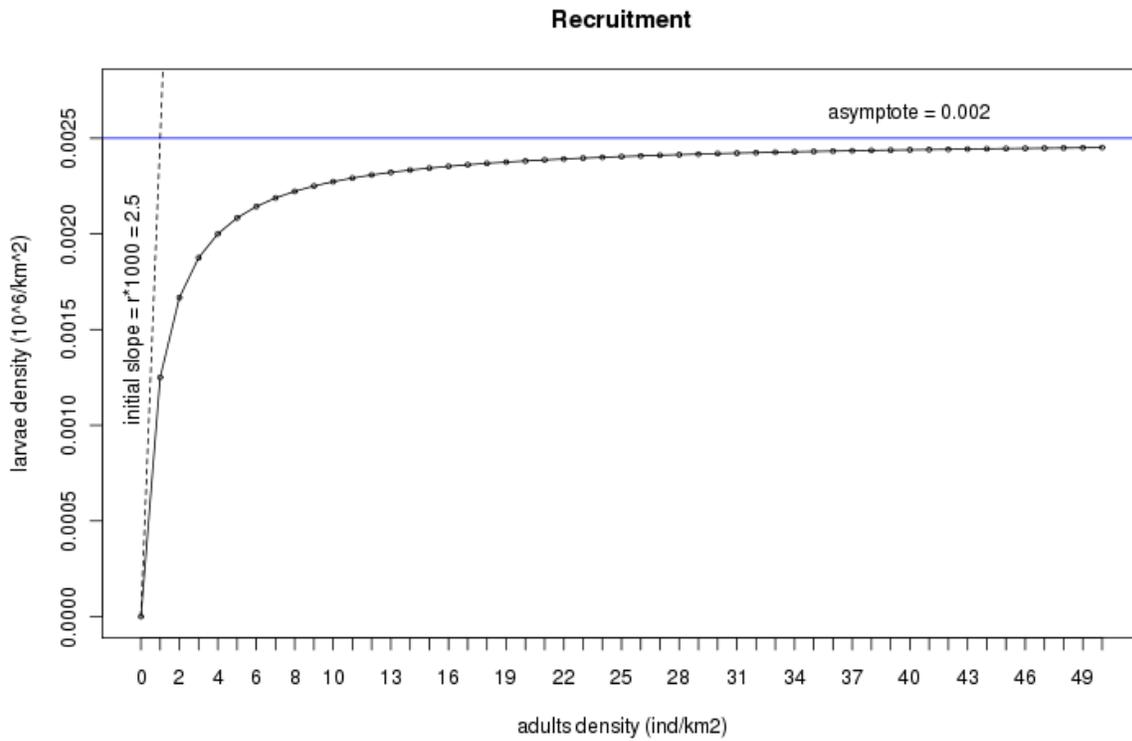


Figure 9. Beverton-Holt stock recruitment relationship used at local (grid cell) scale.

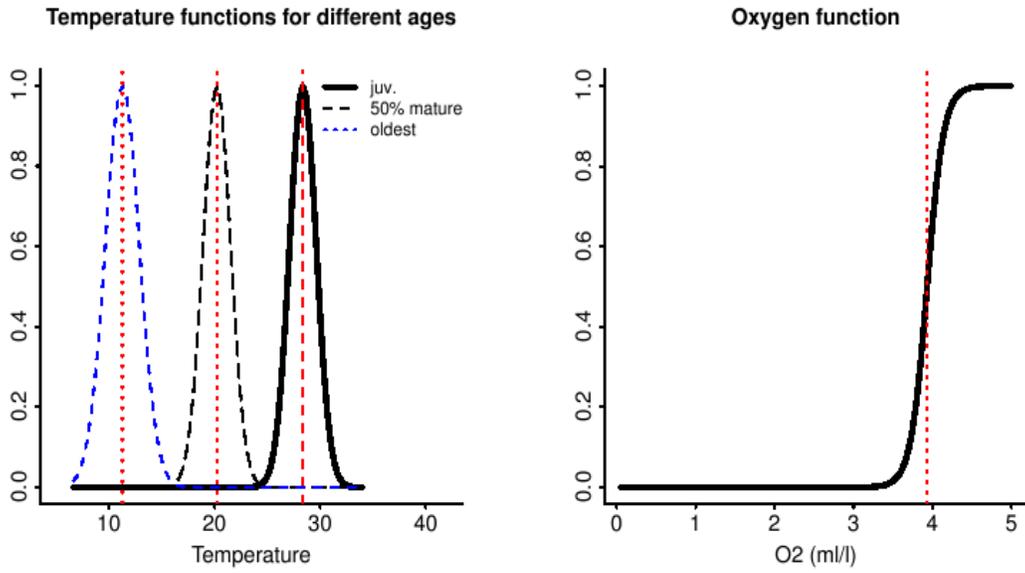


Fig. 10. Estimated temperature and oxygen indexes.

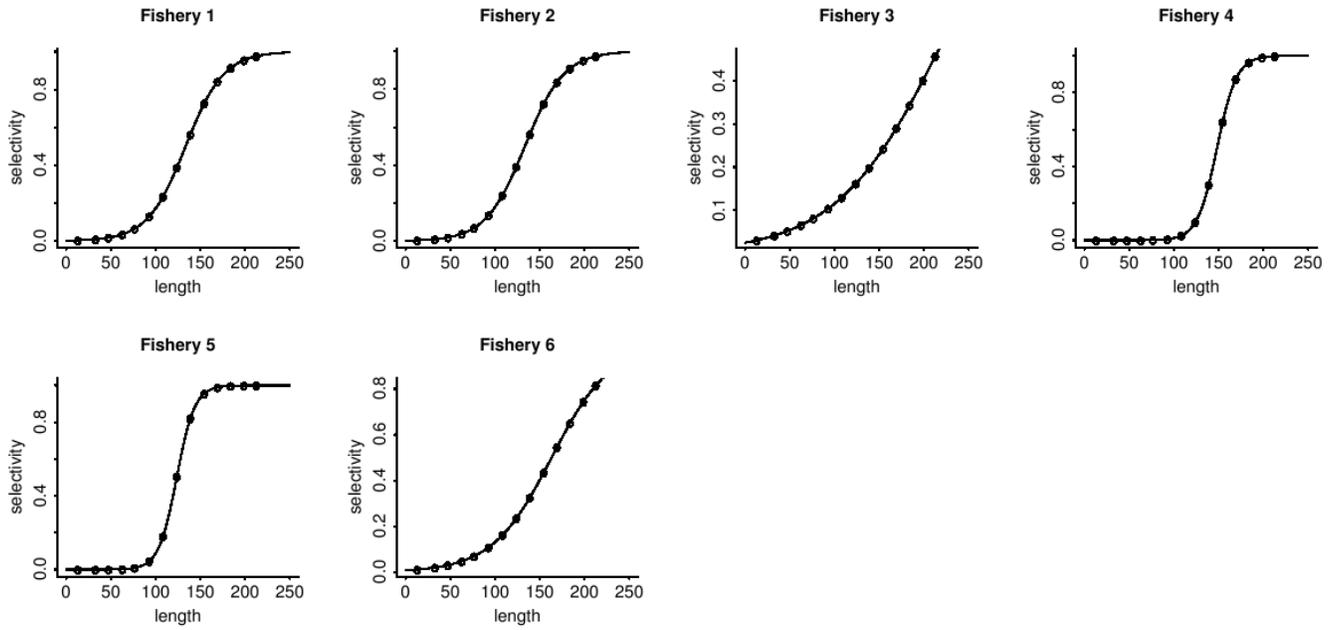


Fig. 11. Estimated selectivity functions for fisheries 1 to 6.

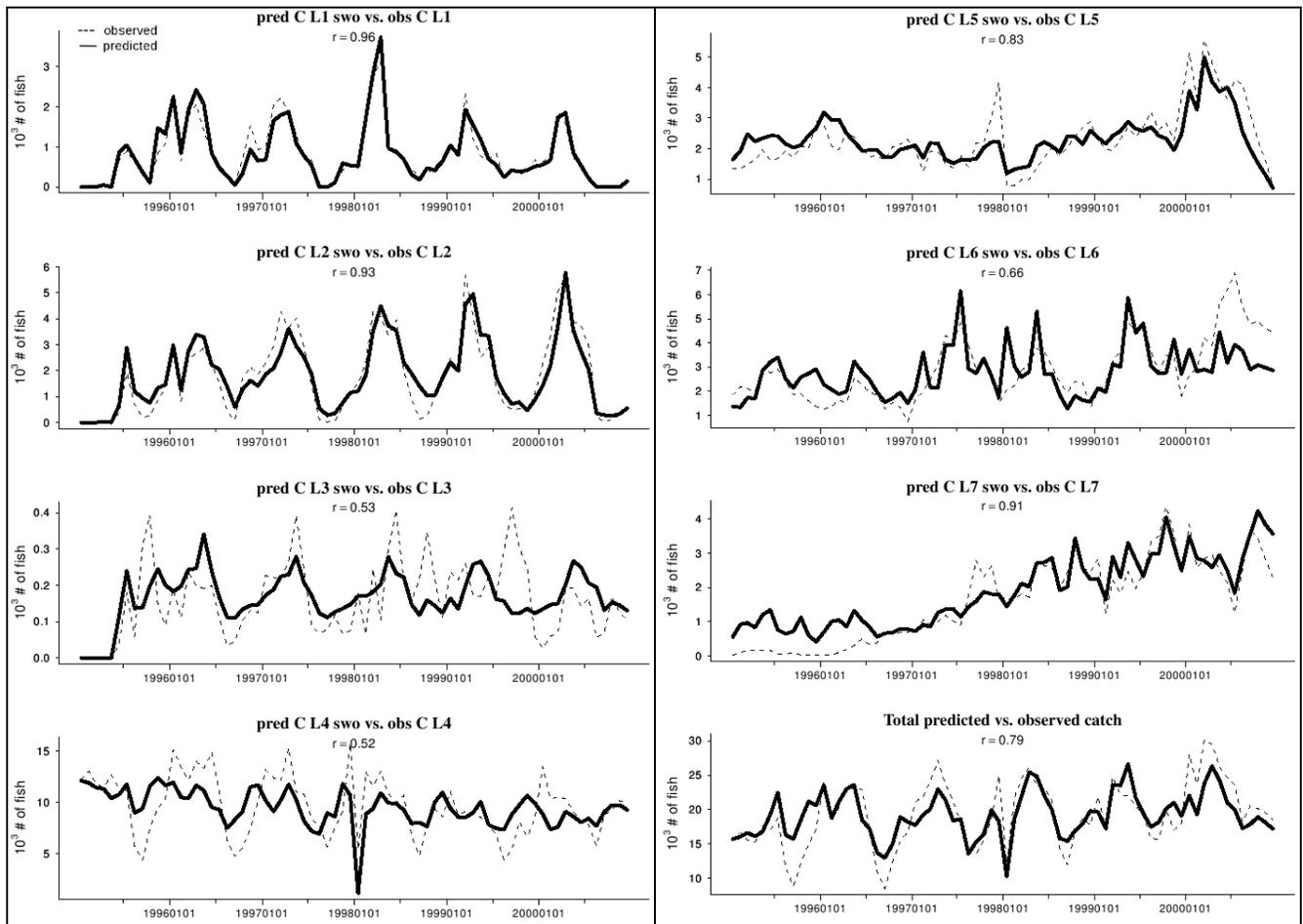


Fig. 12. Fit to catch data (dashed line: observations, solid line: model predictions), with correlation coefficient.

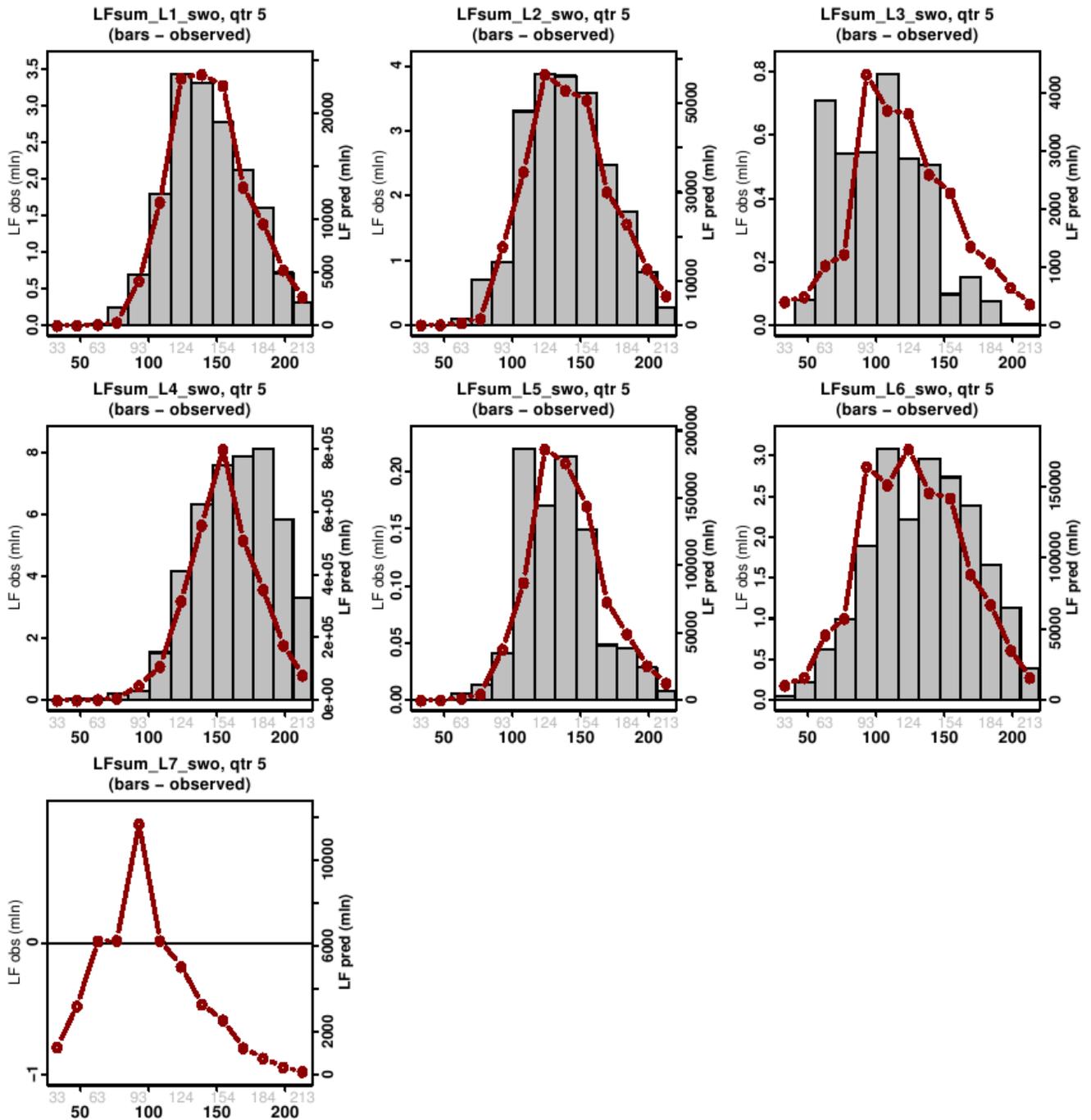


Fig. 13. Fit to length frequency data. (bars: observations, red line : model predictions)

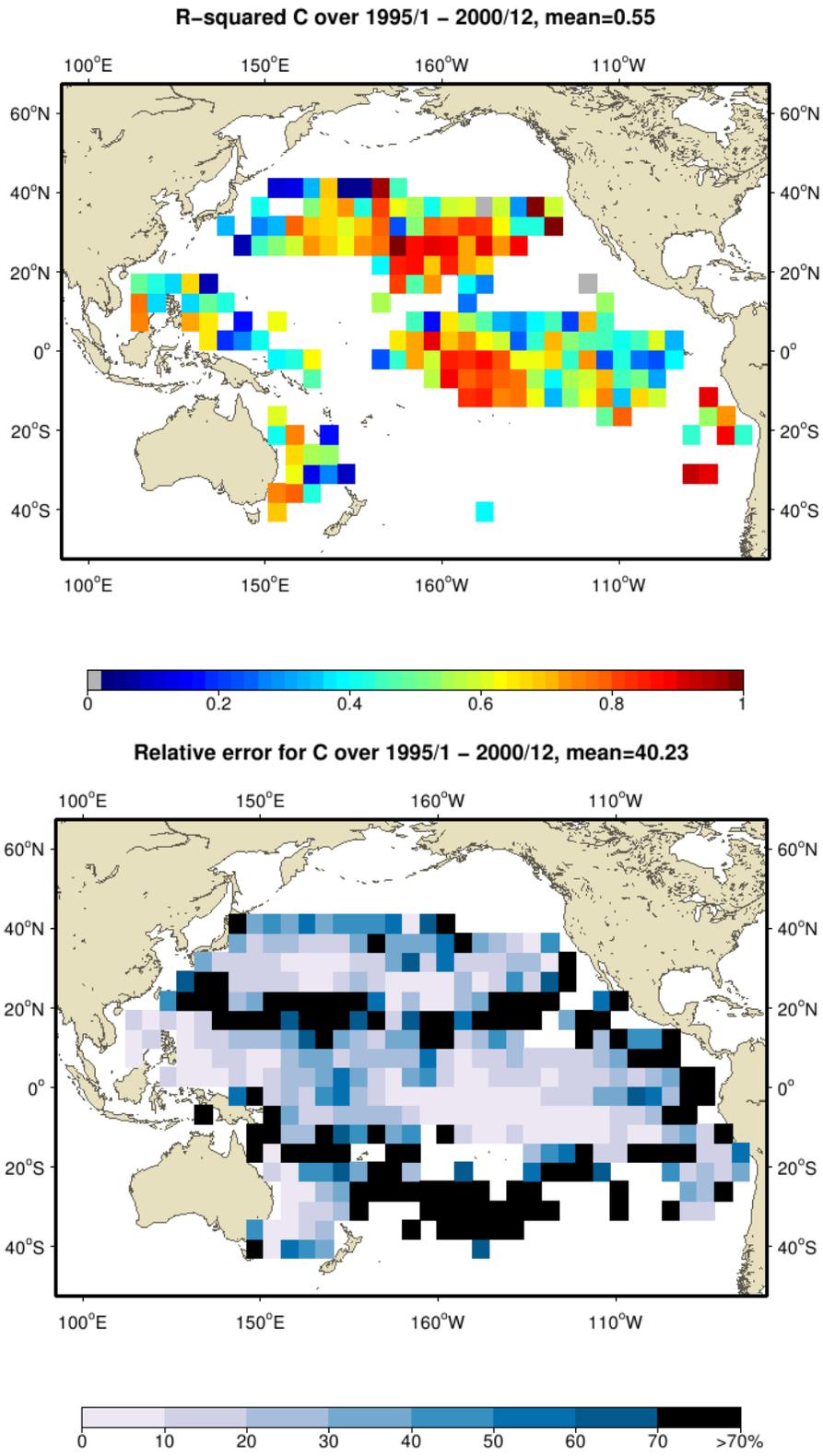


Figure 14. R-squared goodness of fit and relative error for the fit to catch over the optimization period.

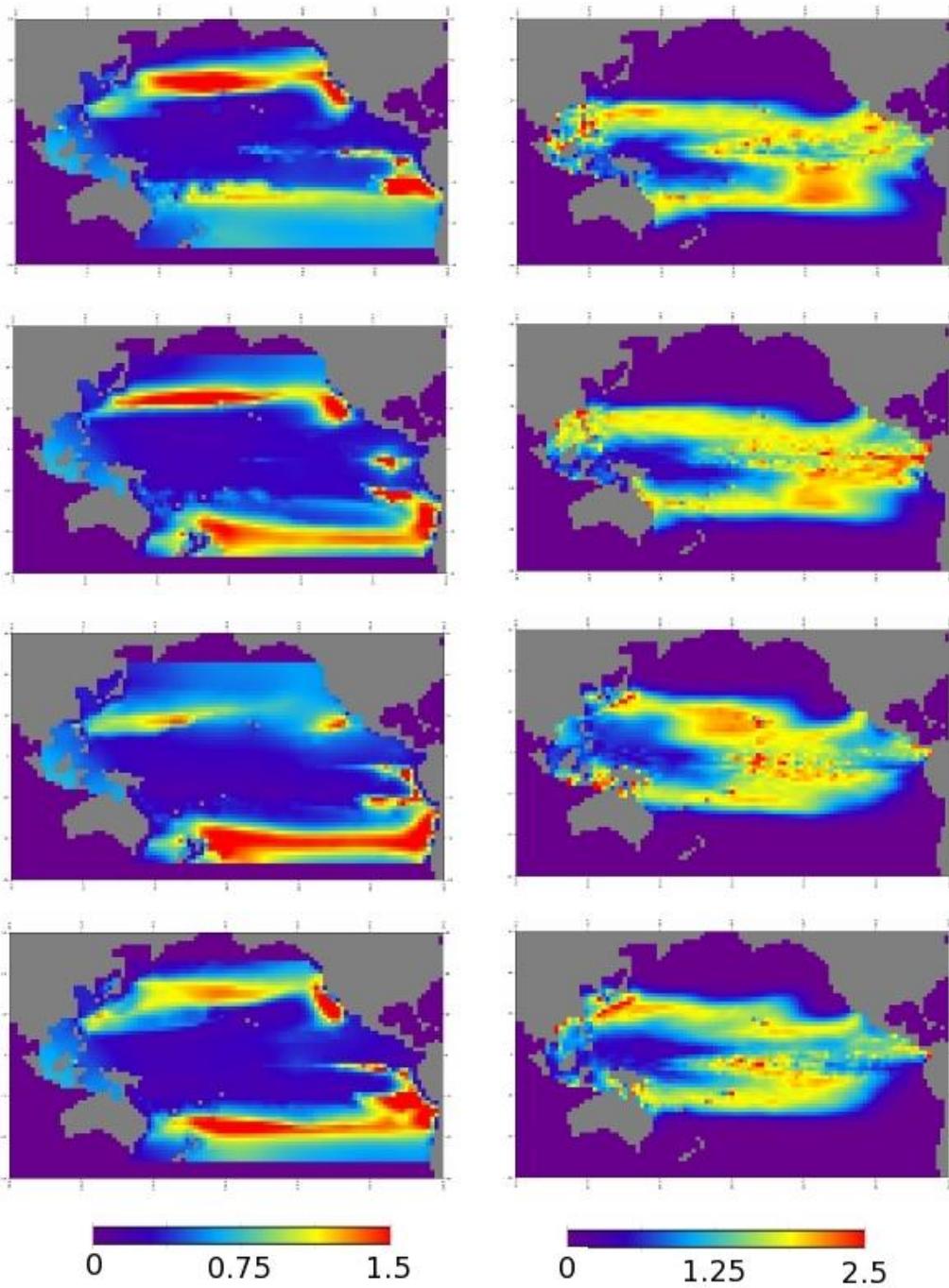


Figure 15. Distribution of adults (left) and juveniles (right) in February, May, August and November (from top to bottom) 1996. Biomasses are in g m^{-2} .

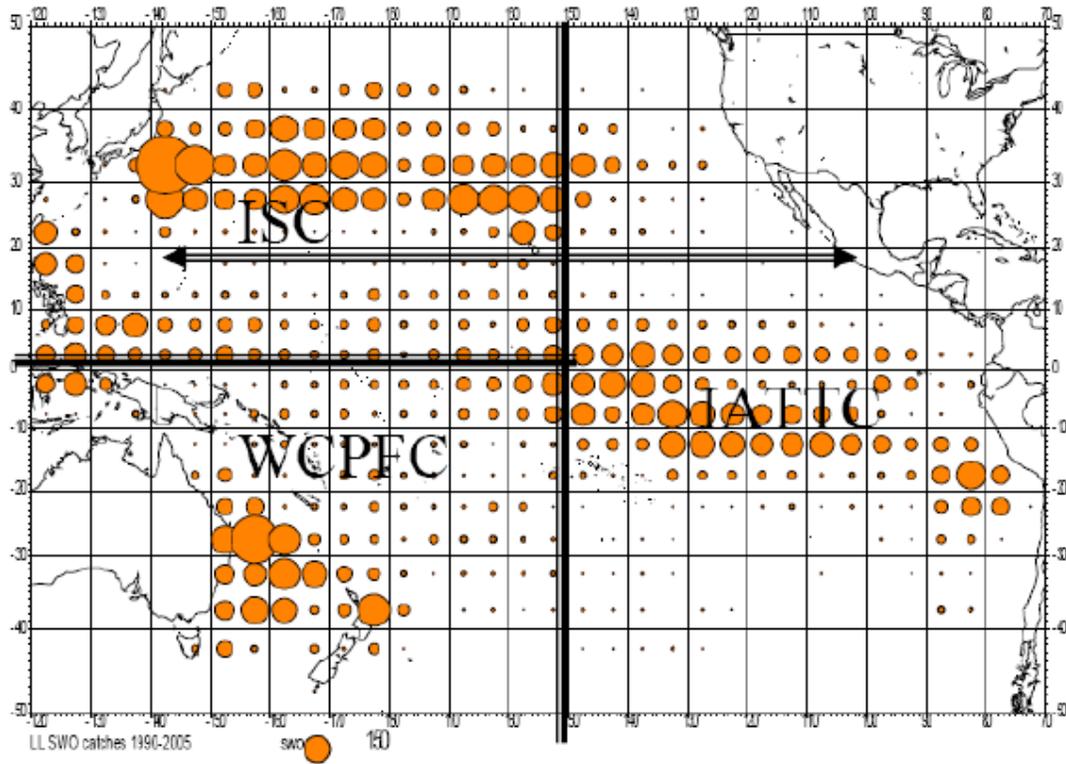


Figure 16. Summary of swordfish longline catch from 1990-2005. (Fonteneau 2005)