ASSESSMENT OF BIGEYE TUNA (*THUNNUS OBESUS*) IN THE EASTERN PACIFIC OCEAN

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SUMMARY

Since the expansion of the floating-object fishery in the early 1990s, the IATTC has directed substantial research toward the assessment of bigeye tuna in the eastern Pacific Ocean. The stock assessment is currently undertaken using A-SCALA, a modeling framework developed by staff of the IATTC, which utilizes fishery, biological, and environmental information to estimate abundance, fishing mortality, and sustainable yields. Historically, bigeye tuna have been caught almost exclusively by longline vessels. Over the 1993-2001 period, longline catches have declined, while estimates of surface catches, based on scientific sampling, have increased, exceeding longline catches since 1996. This has lead to increased catches of juveniles. Total biomass is estimated to be at historically low levels and spawning biomass, while above SBR_{AMSY} *at the start of 2003, is predicted to decline in the future due to weak recruitment in recent years. The current level of fishing mortality is estimated to be too high, and sustainable yields would be increased if fishing mortality on juvenile bigeye tuna were reduced. Accuracy of catch statistics must be improved, for both longline and purse seine fisheries, and better standardization of catch and effort data for the purse seine fishery is necessary to reduce uncertainty in the stock assessment, particularly uncertainty in current conditions.*

RÉSUMÉ

Depuis l'expansion de la pêcherie sous objet flottant, au début des années 1990, la CIATT a consacré d'importants programmes de recherche à l'évaluation du thon obèse dans l'Océan Pacifique Est. L'évaluation du stock est actuellement menée à l'aide de A-SCALA, un cadre de modélisation, développé par un membre du personnel de la CIATT, utilisant des informations halieutiques, biologiques et environnementales afin d'estimer l'abondance, la mortalité par pêche et les productions soutenables. Historiquement, les thons obèses ont été capturés presque exclusivement par les palangriers. Au cours de la période 1993-2001, les prises palangrières ont décliné alors que les estimations des prises de surface, basées sur l'échantillonnage scientifique, se sont accrues, dépassant les prises palangrières depuis 1996. Cela a donné lieu à l'augmentation des prises de juvéniles. La biomasse totale est estimée être à des niveaux historiquement bas et il est prévisible que la biomasse reproductrice, tout en se situant au-delà de SBR_{APME} *au début de l'année 2003, diminue à l'avenir compte tenu d'un faible recrutement ces dernières années. Le niveau actuel de mortalité par pêche est estimé être trop élevé et des productions soutenables augmenteraient si la mortalité par pêche des thons obèses juvéniles était réduite. L'exactitude des statistiques de capture doit être améliorée, à la fois pour la pêcherie palangrière et la pêcherie de senneurs, et une meilleure standardisation des données de prise et d'effort pour la pêcherie de senneurs est nécessaire en vue de réduire les incertitudes dans l'évaluation du stock, et notamment les incertitudes associées à la situation actuelle.*

RESUMEN

Desde la expansión de las pesquerías sobre objetos flotantes a comienzos de los noventa, la IATTC ha realizado importantes trabajos de investigación encaminados a la evaluación del patudo en el océano Pacífico oriental. La evaluación del stock se está realizando actualmente utilizando A-SCALA, una estructura de modelación desarrollada por el personal de la IATTC, que utiliza información sobre pesquerías, biología y medio ambiente para estimar la abundancia, mortalidad por pesca y rendimientos sostenibles. Históricamente, el patudo ha

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sido capturado casi exclusivamente por palangreros. Durante el periodo 1993-2001, las capturas de palangre han descendido, mientras que las estimaciones de capturas de superficie, basadas en muestreos científicos, se han incrementando y superan a las capturas de palangre desde 1996. Esto ha dado lugar a un incremento de las capturas de juveniles. Se estimó que la biomasa total se hallaba en niveles históricamente bajos y se prevé que la biomasa reproductora, aunque se hallaba por encima de SBR_{AMSY} *a comienzos de 2003, descenderá en el futuro debido al débil reclutamiento de los últimos años. Se estima que el nivel actual de mortalidad por pesca es demasiado alto y que los rendimientos sostenibles se incrementarían si se redujera la mortalidad por pesca del patudo juvenil. Debe mejorarse la precisión de las estadísticas de captura, tanto para las pesquerías de palangre como para las de cerco, y es necesario estandarizar mejor los datos de captura y esfuerzo de la pesquería de cerco para reducir la incertidumbre en la evaluación del stock, sobre todo la incertidumbre asociadas con la situación actual.*

KEYWORDS

Abundance, Bigeye tuna, Stock assessment, Tuna fisheries

1 Introduction

The bigeye fishery in the eastern Pacific Ocean is one of the most valuable tuna fisheries in the world. In this paper we provide an overview of the fishery data and stock assessment for the stock. The stock assessment described here was that undertaken in May-June 2003. Other Inter-American Tropical Tuna Commission (IATTC) publications provide more detailed descriptions of these aspects and interested readers are directed to these publications for further details, e.g., a description of the fisheries and the fisheries data (Anonymous 2003), a description of the stock assessment methodology (Maunder and Watters 2003), and a description of the stock assessment itself (Anonymous 2003, Harley and Maunder 2004). As bigeye stock assessments for the EPO are currently undertaken annually, please contact the IATTC to find out what is the most recent assessment to determine the best current evaluation of the status of the stocks and catches etc.

A separate stock assessment is undertaken for bigeye tuna in the western and central Pacific Ocean (WCPO) and a description of this fishery and the assessment is provided by Hampton *et al*. (SCRS/2004/067, this meeting).

2 The fishery

Historically, bigeye tuna had been caught almost exclusively by longline vessels. Between 1980 and 1992, annual longline catches in the eastern Pacific Ocean (EPO) averaged 74,000 t versus only 4,800 t for the surface fisheries. Over the 1993-2001 period, longline catches have declined (average 52,000 t) while surface catches (estimated with scientific sampling) have increased dramatically (average 54,000 t) due to the use of fish aggregating devices (FADs) and have exceeded longline catches since 1996 (**Figure 1** and **Table 1**).

The decline in longline catches since 1994 can be attributed mainly to both reductions in effort and reductions in abundance of large bigeye tuna indicated by declining catch per unit effort (CPUE). However, in the most recent years, there appears to have been substantial increases in longline fishing effort as new fleets have entered the fishery and old fleets have changed their targeting practices. Accurate catch data are not available for some important components of the longline fleet after 2000. The increase in purse seine catches is attributed to the dramatic increase in the use of FADs in offshore areas, and to a lesser extent, increased fishing effort on fish associated with flotsam in inshore areas. Most of the purse seine catch of bigeye comes from sets in the area from 90°-120°W, between 5°N and 10°S. Skipjack is the main target species in this fishery with bigeye representing about 20% of the tuna catch in the FAD fishery.

Length-frequency data provide information on the spatial distribution of bigeye tuna and trends in recruitment over time (**Figures 2a** and **2b**). In 2002, both the northern and southern FAD fisheries caught predominantly small bigeye (40-60 cm), but significant numbers of larger bigeye were also caught in the South producing a bimodal distribution. The Equatorial fishery near the Galápagos Islands caught bigeye of a wide range of sizes. Since 1997 there have been dramatic changes in the overall size-composition of bigeye caught by the purse seine fleet. A series of very strong cohorts was recruited to the fishery from 1995 to 1997, and these fish produced the majority of the bigeye catches until 2001. As these fish grew, the mean size of bigeye in the catch increased. Recruitment appears to have been weak since 1998. The longline fishery catches much larger fish than those caught in the purse seine fishery (**Figure 2b**). There is some evidence of the series of large cohorts in the longline length-frequency data, but the patterns are much less pronounced.

3 Data collection

3.1 Catch and effort data

Estimates of purse seine catch and effort come from two sources: logbooks kept by the fishermen, and data recorded by observers. Raw data in the form of Daily Activity Records kept by observers provide detailed information on the positions of the vessels and times spent searching and setting that could be used for models based on search time or search area. For the assessment we do not use set-by-set information; instead we use monthly 5° area catch and effort data. Purse seine effort data are available only as the number of sets by set type and total days fished for all set types combined. Days fished is considered to be a more appropriate measure of effort than numbers of sets, because days fished incorporates searching time (Maunder and Watters 2003). Therefore we convert total days fished into days fished by set type, using the five-step approach described by Watters and Maunder (2001) and repeated below.

In Step 1, information from the IATTC logbook database is used to compute the catch per day of fishing (CPDF) of the three main tuna species (bigeye, yellowfin, and skipjack) and all set types (floating object, dolphin, and unassociated) combined. This computation is done for each month and IATTC length-frequency sampling area (see **Figure 2b**). In Step 2, the estimates of the CPDF are divided into estimates of the total landings (by month and sampling area for all three tuna species combined) from the IATTC landings data base (hail weights and cannery statistics). This division raises the effort from logbook data to include effort that was not reported in vessel logbooks, providing an estimate of the total days fished for all three set types combined in each month and sampling area. In Step 3, linear regression models (one model for each year) are used to determine the average number of days fishing required to make a single set of each type. In 1990, for example, sets on floating objects, dolphins, and unassociated schools of tuna were estimated to take, respectively, averages of about 1.3, 0.9, and 0.7 days each. In Step 4, the results from the regression analyses are used in conjunction with the number of sets (by set type) recorded in the logbook database to predict the proportion of days fished per set type. Finally, in Step 5, the total days fished from Step 2 are multiplied by the proportions from Step 4 to obtain estimates of the total days fished by set type within each time-area stratum.

This method, while likely better than using number of sets as the unit of effort, does not correct for changes in catchability over time and therefore trends in catch per unit of effort (CPUE) calculated using this effort measure may not reflect trends in relative abundance (see Section 4.4 for further details).

Longline catch and effort data are provided to the IATTC by organizations of nations in which the various fleets are registered. The data are generally at 5° or 1° area spatial resolution by month and effort is measured in the number of hooks fished. For the Japanese fleet we receive information on the typical configuration of the gear (e.g., number of hooks per basket) in each spatial/temporal strata and utilize this information for standardization of CPUE, e.g., Maunder and Harley (2003).

3.2 Catch estimates

Estimates of the purse seine catches and landings of tunas come from several sources, including logbooks kept by the fishermen, data recorded by observers aboard the vessels, unloading data provided by canneries and other processors, and export and import records. For reporting purposes estimates of the total amount of catch that is landed are based principally on data from unloadings.

As small bigeye and yellowfin tuna are difficult to distinguish from one another, there is a serious concern that estimates of landings based on unloading estimates, and other sources, may be biased. This problem has been noted in the Indian and Atlantic Oceans before the 1980s. For this reason, a scientific species-composition sampling scheme has been carried out since 2000 as part of the length-frequency sampling program (Section 2.3). The total catches of all tunas combined are still based on the unloading estimates, but the species composition of the catch is taken from the scientific sampling rather than the estimates provided by the cannery.

In some years, the unloading and species-composition estimates of bigeye tuna catches are very different. Over the 2000-2002 period, the species-composition estimates are, on average, 38% higher than the unloading estimates. For the stock assessment we increase 1993-99 bigeye catches to account for the bias. Currently, we do not know exactly what is the cause of these differences, e.g., a general underestimate across all unloadings or large underestimates in certain areas, and this information will be necessary to determine how best to adjust catch estimates prior to 2000 when species-composition sampling began.

Data on the retained catches for most of the larger longline vessels operating in the EPO, and for an increasing portion of the smaller ones, are obtained from various sources. These vessels, particularly the larger ones, direct their effort primarily at bigeye and yellowfin tuna. The primary source is the raised[2] 5° catch and effort data provided to the IATTC by different fleets. These data are provided in weight, number of fish, or both and are usually received 12-24 months after the end of the fishing year. For some fleets (e.g., Japan) we also receive aggregated estimates of retained catches in weight, but without effort data (except for the number of vessels). These aggregated data are usually received every six months and only two months after the end of the time period. As we do not have detailed effort data associated with these catch estimates, they have previously not been included in the stock assessment. There are also some fleets that we do not have catch estimates for, of particular concern are the small- and medium-sized longline vessels that operate in the EPO targeting bigeye tuna and other pelagic species.

3.3 Size composition data

Length-frequency samples are the basic source of data used for estimating the size and age compositions of the various species of fish in the landings. Length-frequency samples of tunas from purse seine, pole-and-line vessels, and recreational catches made in the EPO are collected by IATTC personnel at ports of landing in Ecuador, Mexico, Panama, the USA, and Venezuela. The catches of bigeye were first sampled in 1975.

The methods for sampling the catches of tunas are described by Tomlinson (2002). Briefly, the fish in a well of a purse seiner or pole-and-line vessel are selected for sampling only if all the fish in the well were caught during the same calendar month, in the same type of set (floating-object, unassociated school, or dolphin), and in the same sampling area. These data are then categorized by fishery (**Figure 3** and **Table 2**), based on the definitions used in the assessments.

There are also several specific projects in which weight-at-length data, otoliths, and ovaries are collected from a small number of bigeye for studies of age and growth and reproductive biology.

3.4 Floating-object data

Since 1987, observers aboard purse seine vessels have recorded information on sightings of floating objects (both flotsam and FADs). Much of this information is entered into a data base, but other information, such as drawings of the objects, are not. This data base contains information on multiple sets on the same floating object, and some attributes of the floating objects, e.g., object type, color, depth of attached netting. The IATTC is currently testing observer forms specifically designed to capture detailed information on FADs. Information requested on these forms includes: FAD construction, how vessels locate FADs, what materials they add to FADs found at sea, if electronic equipment is added to a FAD, what information this provides to the vessel, e.g., direction, position, temperature, or presence of fish.

The collection of these types of data will be critical to improving our standardization of the CPUE of purse seine vessels and in ongoing investigations into factors that may increase the catchability of bigeye tuna around FADs.

3.5 Tagging data

Since 2000, the IATTC have conducted four tagging research cruises directed at bigeye tuna to collect information to improve our understanding of bigeye tuna and improve the assessment and management of the stock in the EPO. Details of this work are described by Schaefer and Fuller (2002, 2004). Briefly, data collected to date include recapture information for bigeye tuna tagged with either conventional and archival tags, data on behavior of bigeye tuna associated with and not associated with floating objects, and habitat preference information from archival tags. Some of these data are being included in the stock assessment of bigeye tuna, and it is anticipated that further information will be analyzed and included in the future. Also, these data are

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[2] In May 2004 scientific staff from both Chinese Taipei and the Republic of Korea indicated that the longline data that they had been providing to the IATTC were not raised, and were likely missing about 20% of the catches from their respective fleets.

providing insights into approaches for standardizing the CPUE of purse seine vessels that set on bigeye associated with floating objects.

4 Stock assessment

4.1 Stock structure

There are not enough data available to determine whether there are one or several stocks of bigeye tuna in the Pacific Ocean. The present information, based on tagging data, is briefly described. Up until the end of 2003 over 18,000 bigeye had been tagged in the Pacific Ocean, 8,074 in the WCPO and 10,336 in the EPO. A lower proportion of fish tagged in the WCPO (12.5% or about 1,000 fish) have been recovered compared to the EPO (39.3% or about 4060 fish). In each region about 95% of fish were recaptured within 1000 nm of the release point and could be due to a combination of high fishing mortality and low movement rates. Of the over 5,000 recoveries, only four fish (<0.08%) have been reported recaptured after crossing the 150°W. Thus, the best available data suggest minimal exchange of fish between the WCPO and EPO and no evidence to suggest anything other than "no net movement" between the two areas, but it is possible that this conclusion could change based on results of future tagging programs.

Based on these data, for the purposes of the current stock assessment, it is assumed that there are two stocks, one in the eastern Pacific Ocean (EPO), east of 150°W, and the other in the western and central Pacific, and that there is no net movement between these areas. In the past few years, the IATTC staff has been collaborating with scientists of the Secretariat of the Pacific Community, Oceanic Fisheries Programme, and of the National Research Institute of Far Seas Fisheries of Japan to conduct a Pacific-wide assessment of bigeye. Results of the Pacific-wide assessment of the EPO component are very similar to the EPO assessment undertaken by the IATTC (Hampton et al. 2003). The Pacific-wide assessment estimates very low exchange between the western and eastern Pacific, but there is little direct data to provide information on this. There are still some concerns, in particular, the western limit of the eastern Pacific longline fishery is around 160°W, but the EPO assessment includes only data for fish caught out to 150°W.

4.2 Modeling approaches

While early assessments where undertaken using cohort analysis (IATTC 2000), the last four stock assessments for bigeye tuna in the EPO have been undertaken using A-SCALA, an age-structured, statistical, catch-at-length model developed by staff at the IATTC (Maunder and Watters 2003). A-SCALA is similar to MULTIFAN-CL, which is used for assessing tuna stocks in the western and central Pacific Ocean (Fournier et al. 1998, Hampton and Fournier 2001), and both methods give the same results under the same sets of assumptions (unpublished results). The main differences are that the current version of A-SCALA does not model spatial structure in the population dynamics and cannot accommodate tagging data.

In assessing bigeye tuna with A-SCALA, we consider multiple fisheries separately (e.g., data are disaggregated by fishery), estimate growth inside the model, and allow for environmental effects on both recruitment and catchability.

The following parameters are fixed (though A-SCALA is configured to allow estimation of all except the first two): length-weight relationship, fecundity, natural mortality (age-specific), recruitment variation, and the steepness (defined in Section 4.5.2) of the Beverton Holt (1957) stock-recruitment relationship.

The following parameters are estimated: mean recruitment, recruitment deviates for each time period, age-specific selectivity for each age and fishery (except for the discard fisheries), effort deviates for each time period and fishery, mean catchability for each fishery, and coefficients for relationships with environmental variables.

A-SCALA utilizes catch and effort data and fits to the catches by estimating mean catchability and effort deviates that allow for catchability to vary over time. While the model is data intensive, its statistical nature means that it does not require size-composition data for all time periods, nor does it assume that the size composition of the samples of the catch are exactly the same as the total size composition of the catch.

A-SCALA estimates both mean length at age and variability in length at age based on information from (1) length-frequency data, (2) raw data from ageing studies, and (3) growth equations reported in the literature.

Aside from A-SCALA, presently no other methods are used to assess bigeye tuna in the EPO. Production models are not thought to be appropriate for assessing bigeye in the EPO. The dramatic changes in age-specific fishing mortality patterns bought about by the development of the fishery on bigeye tuna associated with floating objects invalidates the assumption that the catches and CPUE indices come from the same (vulnerable) population. A more simplistic age-structured assessment could be considered where the various fisheries are combined to create a two-fishery assessment, i.e., have a single longline fishery and a single surface fishery.

4.3 Data included

Biological, fishery, and environmental data are utilized in the stock assessment of bigeye tuna in the EPO. The model is started in 1975 assuming that the stock was exploited at that time. Longline vessels were catching bigeye in the EPO in the late 1950s and potentially it would be beneficial to start the model at this time and assume that the population was unexploited. While this has been attempted recently, and provided very similar results to the short-term model, this long-term modeling approach is presently unsatisfactory for several reasons: (1) A-SCALA cannot accommodate the spatial structure necessary to account for the rapid expansion of the fleet, (2) gear configuration data is not available to correct for the well-documented changes in targeting practices that occurred before 1975, and (3) length-frequency data for this period have not been compiled. The long-term model may still be an important future goal, and preparation of data collected before 1975 should be continued.

The most recent assessment utilized data for 1975-2002, and used a quarterly time step, so all biological, fishery, and environmental data were also incorporated on a quarterly time step. We will discuss the sources of biological data in Section 4.5, and here we will discuss the other data sources.

4.3.1 Fisheries data

For the assessment, 13 fisheries are defined, based on method (e.g., longline, purse seine sets on unassociated schools or floating objects), geographical location, and time period, e.g., we separate the early floating-object fishery from that that has operated since the recent expansion (**Table 2** and **Figure 3**). Four types of fishery information are utilized in the assessment: retained catches, effort, size composition of the retained catches, and estimates of discards for the purse seine fisheries that catch juvenile bigeye tuna associated with floating objects.

As was described in Section 3.2, there is considerable uncertainty in estimates of retained catches of bigeye tuna for purse seine vessels in the EPO. Species composition estimates of bigeye catches were considerably higher (average of 38% over the 2000-2002 period) than unloading estimates. The current assessment utilizes the species composition estimates for 2000-2002, and increased the unloading estimates for 1993-1999 by 38% to compensate for potential biases (**Table 1** and **Figure 1**). A sensitivity analysis was conducted using only the unloading estimates.

While purse seine catches are modeled in tons, longline catches are modeled in terms of the number of fish caught. This is because earlier catch data provided by Japan are in this format. Catches for all longline fleets are combined – the longline fishery is split into northern and southern components (**Figure 3**). Unlike purse seine catch data that are available for the most recent year, detailed longline catch and effort data are lagged by at least 1-2 years, so substitutions are made for recent catch and effort based on recent catch rates and effort distributions.

For the surface fisheries, effort is modeled as the number of days fished – no attempt has been made in the current assessment to standardize effort (see Section 4.4 below). For the longline fishery, data for a subset of the fleet (the Japanese fleet) are analyzed to provide a standardized CPUE series (see Section 4.4 below). The total catch of all longline fleets is divided by the standardized CPUE to calculate the estimate of effective effort that is used in the assessment model. Unfortunately, we did not have the data necessary to calculate standardized CPUE for 2001 so some assumptions were made. We assumed that the quarterly CPUEs for 2001 were the same as those for 2000. Effective effort for 2001 was estimated by dividing the reported landings by the assumed CPUE. Effective quarterly effort in 2002 was assumed to be the same as that exerted during the corresponding quarter of 2000. Examination of nominal effort that was available for 2000 and 2001 suggested that this is a reasonable assumption, but recent information on the expansion of fishing effort by the fleets of China and Chinese Taipei indicates that this approach likely underestimated longline effort in 2001 and 2002.

Data on the size composition of the catches are available for both purse seine and longline fleets, and these are included in the stock assessment. There are important statistical questions relating to the relative quality, and thus weighting of different samples, and how this should be considered in the stock assessment. The purse seine samples are attributed a sample size representing the number of wells sampled (generally less than 30 per fishery/time stratum) and the longline data are attributed a sample size based on the number of fish measured (usually in the tens of thousands). To ensure that (1) the length-frequency data do not overly influence the overall objective function, and (2) that length-frequency data for the longline fishery do not have more influence than those for the purse-fishery, the sample sizes for the longline length-frequency data are reduced. First, the average sample size for each purse seine and each longline fishery is calculated. A scalar is calculated by dividing the greatest average sample size for a purse seine fishery by the greatest average sample size for a longline fishery. All sample sizes for longline samples are then multiplied by this scalar so that the average sample size for the most-sampled longline and purse seine gears is the same.

A sensitivity analysis was carried out to determine the influence of the length-frequency sample size (see Maunder and Harley 2003). McAllister and Ianelli (1997) used an analytical method to determine the effective sample size for catch-at-age data based on the observed and predicted proportional catch at age. They used a method of iteratively modifying the sample size based on this calculation until the estimates of sample size converged. Usually this took only three or four iterations. We used this method to determine new sample sizes for each set (fishery and time period) of length-frequency data. The re-weighted sample sizes were much greater than the base case for all fisheries. The analysis indicated that the purse seine effective sample size is still less than the number of fish measured (about 50 per well) and that the longline effective sample size is still substantially less than the number of fish measured, but the longline data sets have much greater effective sample sizes than the length-frequency samples from the surface fisheries.

For the purposes of stock assessment, it is assumed that bigeye tuna are discarded from the catches made by purse seine vessels for one of two reasons: inefficiencies in the fishing process (e.g., when the catch from a set exceeds the remaining storage capacity of the fishing vessel), or because the fishermen sort the catch to select fish that are larger than a certain size. In both cases, the amount of discarded bigeye is estimated with information collected by IATTC or national observers, applying methods described by Maunder and Watters (2003). Estimates of discards resulting from inefficiencies in the fishing process are added to the catches made by purse seine vessels. Discards that result from the process of sorting the catch are treated separately, and the catches taken by these fisheries are assumed to be composed only of fish 2-4 quarters old. Estimates of the amounts of fish discarded during sorting are made only for fisheries that take bigeye associated with floating objects, and no discarding is assumed to have occurred prior to the expansion of the floating-object fishery in 1993. It is assumed that all discarded fish die.

4.3.2 Environmental data

Two sources of environmental data have been utilized in the stock assessment of bigeye tuna in the EPO–one thought to be related to recruitment and the other thought to be related to the catchability of bigeye tuna to vessels setting on floating objects (Watters and Maunder 2002).

Zonal-velocity anomalies (velocity anomalies in the east-west direction) at 240 m depth and in an area from 8°N-15°S and 100°-150°W are used as the candidate environmental variable affecting recruitment (Watters and Maunder 2002). The zonal-velocity anomalies were calculated as the quarterly averages of anomalies from the long-term (January 1980-December 2002) monthly climatology. These data were included in the stock assessment model after they had been offset by two quarters because it was assumed that recruitment of bigeye in any quarter of the year might be dependent on environmental conditions in the quarter during which the fish were hatched. Recently, a modification was made to A-SCALA to allow for missing values in the environmental index thought to be related to recruitment. This allows us to start the population model in 1975, five years before the start of the time series for the environmental index (Maunder and Harley 2003).

The zonal-velocity anomalies were estimated from the hindcast results of a general circulation model and are posted on the Internet by the U.S. National Oceanic and Atmospheric Administration, National Centers for Environmental Prediction.

No influence of environmental conditions on catchability was included in the most recent assessment because the current method to include these data cannot handle missing data (unlike the method for including environmental data for estimating recruitment). In previous assessments, fishery-specific indices of vertical shear were considered as candidate environmental variables affecting catchability. These shear indices were calculated by taking the absolute difference of hindcast velocities at 25 and 240 m. The differences were based on zonal velocities or meridional velocities (velocities in the north-south direction) depending on the fishery. The vertical shear indices were calculated, for each quarter, as fishery-specific spatial averages over the geographical extent of each fishery strata. The data that were used to develop the vertical shear indices were obtained from the same source as those used for modeling an environmental effect on recruitment. Future assessments will again consider environmental influences, once A-SCALA has been adapted to account for missing values in the time series.

4.4 Abundance indices and catchability

In the bigeye tuna assessments in the EPO, the treatment of CPUE abundance indices and catchability differs for purse seine and longline fisheries. Fishery-specific CPUE series are presented in **Figure 4**.

For purse seine fisheries, CPUE is calculated as catch for a trip divided by the numbers of days fished. As noted before, the purse seine effort is separated by set type (floating object versus unassociated) and geographical location, and CPUE series are provided for each. Presently, there is no attempt to further standardize the aggregated effort data for factors relating to catchability, aside from early analyses that incorporated environmental data (see Section 4.3.2 above). Because the data are essentially unstandardized, we do not assume that trends in CPUE necessarily reflect trends in abundance. A-SCALA estimates a mean catchability for a gear and quarterly "effort deviates" which represent variation in catchability. Earlier versions of A-SCALA allowed for a random walk in catchability, in addition to the effort deviates. This added several hundred parameters and considerable computational time without resulting in estimates in catchability that were different to those based solely on mean catchability plus the effort deviates. Effort deviates are constrained by an assumed standard deviation reflecting our opinion as to how much catchability could vary for each fishery. The current assessment estimates significant trends in these effort deviates for some fisheries, indicating that the model assigns much of the trends in CPUE to increases in the efficiency of the fleet, rather than to trends in abundance (**Figure 5**). Future research will be directed at deriving a more reliable CPUE series for at least a subset of the purse seine fleet. If an index is obtained for which changes in catchability can be assumed to be minimal, it will provide valuable information on the abundance of juvenile bigeye tuna.

Estimated trends in both total and spawning biomass are very sensitive to the CPUE series for the longline fishery and assumptions about catchability. At least three methods have been used to estimate CPUE series since A-SCALA has been used to assess bigeye tuna. CPUE series have been estimated using regression trees and simulated annealing (Watters and Deriso 2000), deterministic habitat-based standardization (Bigelow et al. 2002), and neural networks (Maunder and Harley 2003). The current assessment used neural network-standardized CPUE after cross-validation testing indicated that this method outperformed the deterministic and statistical habitat-based methods (Maunder and Harley 2003). All analyses have used data for only a subset of the longline fleet (the Japanese fleet), and were based on aggregate data (e.g., 5° areas by month). In cases where the trends in CPUE differ between analyses, estimated biomass trajectories and stock status also differ, and can sometimes lead to alternative recommendations for management.

As the longline CPUE is standardized, we assume that the variation in catchability that can occur is much less than for the purse seine fisheries. Thus, trends in CPUE effort for the longline fisheries are assumed to reflect trends in the abundance of the ages of fish caught by the longline fleet. There is a great need for a thorough review of methods for standardizing longline CPUE; in particular there is a need to consider how the spatial distribution of the fishery might affect any measures of CPUE (Walters 2003).

4.5 Biological inputs

A-SCALA requires detailed biological data, but, as the IATTC has only recently begun assessing bigeye tuna in the EPO, we have only recently begun to update our biological input parameters based on recent scientific studies. A summary of the values of the biological parameters assumed or estimated in the bigeye assessment is provided in **Table 3**.

4.5.1 Growth

While growth is estimated within the assessment model, the sizes of individuals greater than three years of age is strongly constrained to follow the von Bertalanffy growth curve of Suda and Kume (1967). The estimated growth curve (**Figure 6**) indicates that growth during the first three years departs significantly from the pattern of the von Bertalanffy curve. The IATTC is currently undertaking an age and growth study of bigeye tuna, based on the analysis of daily growth rings of otoliths, which will be incorporated into future assessments.

The length-weight relationship represents a weakness in our knowledge. Currently we use the relationship of Nakamura and Uchiyama (1964) which is based upon over 9,000 individuals, ranging in length from 80 to 190 cm. Recently collected data for 360 bigeye tuna ranging in size from 30-150 cm (Schaefer and Fuller, unpublished data) indicate that the relationship of Nakamura and Uchiyama (1964) may overestimate the weights of small and medium (50-100 cm) bigeye by 10-15%. This is because small fish were not included in the study of Nakamura and Uchiyama and thus predictions of the weights of smaller individuals is outside the range of the observed data. This has implications for both the stock assessment and the estimation of purse seine catches from the species-composition sampling. Obtaining a new length-weight relationship may require sampling many thousands of individuals to allow consideration of spatial and seasonal patterns.

4.5.2 Reproductive biology

Recent data and re-analysis of previous data necessitated changes in the assumptions regarding reproductive biology of bigeye tuna in the EPO. Previously it was assumed that there was knife-edge maturity at 3.5 years, but recent estimates indicate that 50 percent of females are not mature at 5 years of age (IATTC Quarterly Report for October-December 2002). It is assumed that fecundity of females is proportional to their weight. Previous assessments (Watters and Maunder 2002, Maunder and Harley 2002) undertaken using A-SCALA included incorrect fecundity data because weight at age had been estimated incorrectly.

As A-SCALA is not sex-structured, we input the proportion of females at age to allow estimation of female spawning biomass. We make the assumption that sex ratios observed in the catch reflect sex ratios in the entire population. Presently, we use estimates based on a data set comprising historical estimates from Kume and Joseph (1966) and recent estimates collected from purse seine catches (IATTC Quarterly Report for October-December 2002). These estimates are similar to those based on samples from the Japanese longline fleet for the EPO (Dr. N. Miyabe, unpublished data).

It is believed that bigeye recruitment may occur continuously throughout the year because individual fish can spawn almost every day if the water temperatures are in the appropriate range (Kume 1967). Therefore, in the population modeling, it is assumed that bigeye tuna can be recruited to the fishable population during every quarter of the year. Confirmation of this assumption based on more recent samples will be important, as will determining the appropriate range of environmental conditions required for spawning.

The stock-recruitment relationship is critical for determining many important biological reference points (discussed in detail in Section 4.7), in particular those related to achieving the average maximum sustainable yield (AMSY). Presently it is assumed that the stock-recruitment relationship follows a Beverton-Holt (1957) relationship with lognormal deviations from the curve. The critical shape parameter of the stock-recruitment curve, which is called steepness, controls how quickly recruitment decreases when the spawning biomass is reduced. It is defined as the fraction of virgin recruitment that is produced if the spawning biomass is reduced to 20% of its unexploited level (Mace and Doonan 1988). 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). The base case assessment for bigeye tuna assumes that steepness = 1. A sensitivity analysis where steepness = 0.75 provides a very similar fit to the observed data, but provides a far more pessimistic outlook on the current stock status.

The estimates of spawner biomass and recruitment provide very little information of likely values of steepness, particularly because estimates of recruitment are uncertain except for the years since the development of the floating-object fishery, and because the estimated range in spawning biomass levels is small. Simulation studies indicate that recruitment variation hinders our ability to estimate steepness, so it is unlikely that we will confidently estimate this critical quantity in the foreseeable future (Harley et al. in prep). In Section 4.6 we discuss how a recent simulation study might influence the values that we assume for future stock assessments.

In addition to the assumptions required for the stock-recruitment relationship, we make further assumptions about the variability in recruitment. It is assumed that the standard deviation on the logarithm of the recruitment deviates of about 0.6.

4.5.3 Natural mortality

Natural mortality is a critical parameter for stock assessment, but, unfortunately it is very difficult to estimate. The assessment is further complicated by the likelihood that natural mortality varies with age (Hampton 2000). Age-specific vectors of natural mortality (M) used in the previous assessment of bigeye tuna (Watters and

Maunder 2001, 2002, Maunder and Harley 2002) were based on fitting to age-specific proportions of females, maturity at age, and natural mortality estimates of Hampton (2000). As the first two of these quantities have been revised for the current assessment, new age-specific vectors of natural mortality were estimated outside of the assessment model (S. J. Harley and M. N. Maunder, unpublished analysis). The new estimates are slightly lower than previous estimates, and increase at greater ages due to the later maturity assumed.

In the model we do not explicitly assume an age representing the longevity of bigeye. The model has a "plus-group" which accumulates all fish ages 10 years and older. Based on the assumed values of natural mortality, about 10% of an unexploited population would be in the plus group.

4.6 Reference points

Maintaining tuna stocks at levels capable of producing the AMSY is the current management objective specified by the IATTC Convention. Estimation of AMSY-related reference points requires age-specific information on natural and fishing mortality, fecundity, size, and the steepness of the stock-recruitment relationship (Maunder 2002). In Section 4.5 we indicated that there was uncertainty in many of these quantities, in particular the steepness of the stock-recruitment relationship, to which AMSY-related quantities are very sensitive. We will discuss two of the important inputs below, steepness and fishing mortality.

Recent simulation studies have indicated that the bigeye stock-recruitment data do not provide sufficient information to allow for reliable estimation of steepness, particularly because of the high recruitment variation observed (Harley et al. in prep). Presently it is assumed that steepness = 1, and steepness = 0.75 is provided as a sensitivity analysis. Harley et al. (in prep) showed that if it is assumed that steepness = 1, but it was, in fact, less than 1 (but all other parameters were unchanged), overfishing would occur and suboptimal yields would be attained. They investigated which assumed values of steepness would lead to the best outcomes, in terms of sustainable yields and conservation of spawning biomass, given the uncertainty in the true value of steepness. It was found that for both yellowfin and bigeye tuna AMSY-strategies based on values of steepness ranging from 0.6 to 0.7 performed well if the true value of steepness was between 0.5 and 1.0 (Harley et al. in prep). Further investigations are being undertaken to determine how this information should guide future assumptions about steepness, given that it is unlikely that reliable estimates of steepness can be obtained from available data.

When calculating AMSY-based reference points, the period over which to take estimates of fishing mortality must be chosen. Estimates for the most recent year are extremely uncertain, and highly correlated with estimates of recent recruitment, i.e., the alternative scenarios of weak recruitment and high fishing mortality versus strong recruitment and low fishing mortality provide very similar fits to the observed data. This is partly caused by our lack of a reliable abundance index for the purse seine fisheries. To overcome this problem, estimates of the average fishing mortality over the two years previous to the most recent year are used, rather than the estimate for the most recent year. Unfortunately, in a recent bigeye assessment (Maunder and Harley 2002), the recommended management advice was very sensitive to which years fishing mortality was taken for. Maunder and Harley (2003) showed, using retrospective analysis, that the historical estimates are more reliably estimated, but using these may introduce bias if there are temporal trends in fishing mortality patterns. The same approach was necessary to determine which values of catchability should be used for future projections. Further simulation studies should be considered to determine the best approach for determining which estimates of fishing mortality to use.

Three important quantities that are considered in management advice associated with AMSY: S_{AMSY}, the spawning biomass when the stock is at the AMSY level; SBR_{AMSY}, the ratio of the spawning biomass when the stock is at the AMSY level to the spawning biomass in an unexploited population ratio; and F-multiplier, the change in current fishing mortality required to produce AMSY.

The F-multiplier is used as a critical piece of management advice. When this value is estimated close to 1 it suggests that current fishing mortality levels are sustainable, provided that spawning biomass is not below S_{AMSY}. When this value is estimated to be less than 1 it indicates that fishing mortality levels are too high and should be reduced. Presently a single F-multiplier for the fishing mortality pattern for all gears combined is estimated: we do not estimate separate F-multipliers for purse seine and longline fisheries, i.e., we do not attempt to maximize AMSY through changes in the division of catches among gear types. However, several reference points that are related to optimal yields are calculated and presented, but these are not formally used in management advice. For example, yield-per-recruit reference points (e.g., critical weight), reference points related to strategies for increasing spawning potential, and indications of likely levels of AMSY that could be achieved based on alternative age-specific harvest strategies (Maunder 2002) are used.

The new IATTC convention (which has not yet come into force) includes provisions that recommend incorporation of precautionary approaches to fisheries management (IATTC 2003). Research into reference points that are consistent with the precautionary approach is currently being undertaken (e.g., Harley et al. in prep) and will continue in the future.

4.7 Current estimated status of the stock

Uncertainty in the estimates of stock status obtained from the model, are based on the covariance matrix of the estimated model parameters. The model estimates of uncertainty most likely underestimate the true uncertainty for several reasons including: (1) the model structure may not be appropriate, (2) historical catch estimates may be revised in the future, and (3) assumed biological parameters may be revised upon collection of more samples. Nevertheless, the analysis represents the best available scientific interpretation of the status of the stock based on the data and knowledge available at the time of the assessment. Historical views of the trends in abundance can be expected the change as more (and better) data becomes available and our knowledge improves.

Recruitment of bigeye tuna to the fisheries in the EPO is variable. Over the range of spawning biomasses estimated by the base case assessment, the abundance of bigeye recruits appears to be unrelated to the spawning biomass of adult females at the time of hatching. There are two important features in the estimated time series of bigeye recruitment. First, greater-than-average recruitments were estimated in 1977, 1979, 1982-1983, 1992, 1994, and 1995-1997 (**Figure 7** and **Table 4**). However, the lower confidence bounds of these estimates were greater than the estimate of average virgin recruitment for only two years, 1994 and 1997, so it is not certain that these recruitments were greater than the average virgin recruitment. Above average recruitment is estimated for the first quarter of 2001, but this estimate is uncertain. Second, recruitment has been estimated to be much less than average for most of the recent period from the second quarter of 1998 to the end of 2000, and the upper confidence bounds of a few of these recruitment estimates are below the average virgin recruitment (**Figure 7**). Evidence for these low recruitments comes from the decreased CPUEs achieved by some of the floating-object fisheries, discard records from observers, length-frequency data, and poor environmental conditions for recruitment. The extended sequence of low recruitments is important because it is likely to produce a sequence of years in which the spawning biomass ratio will be below the level that would support the AMSY.

The total biomass of bigeye (1+ year-olds) estimated in the EPO increased during 1980-1984, and reached its peak level of about 630,000 t in 1986 (**Figure 8** and **Table 4**). After reaching this peak, the total biomass of 1+ year olds decreased to an historic low of about 228,000 t at the start of 2003. Spawning biomass has generally followed a trend similar to that for total biomass, but lagged by 1-3 years. Fishing has reduced the total biomass of bigeye present in the EPO (**Figure 9**); both total and spawning biomass were predicted to be at their lowest levels by the end of 2003. There has been an accelerated decline in biomass since the small peak in 2000, with both poor recruitment and fishing responsible.

There have been important changes in the amount of fishing mortality caused by the fisheries that catch bigeye tuna in the EPO. The fishing mortality on bigeye less than about 20 quarters old has increased substantially since 1993, while that on fish more than about 24 quarters old has remained relatively constant even though longline effort has been reduced. The increase in average fishing mortality on the younger fish was caused by the expansion of the fisheries that catch bigeye in association with floating objects. Accordingly prior to 1993 the majority of the catch consists of larger fish that could have had opportunities to reproduce, but since the development of this fishery the majority of the bigeye caught are substantially smaller than the size at which they can reproduce. Estimates of catchability from the base case assessment suggests that (1) the use of FADs has substantially increased the catchability of bigeye by fisheries that catch tunas associated with floating objects, and (2) that bigeye are substantially more catchable when they are associated with floating objects in offshore areas.

At the beginning of January 2003, the estimated spawning biomass of bigeye tuna in the EPO was beginning to decline from a recent high level (**Figure 10**). At that time the estimated spawning biomass ratio (SBR) was about 0.30, about 62% greater than the level that would be expected to produce the AMSY (**Table 5**), with lower and upper confidence limits (±2 standard deviations) of about 0.19 and 0.40. The estimate of the lower confidence bound is above the estimate of SBR_{AMSY} (0.18), suggesting that, at the start of January 2003, the spawning biomass of bigeye in the EPO was greater than the level required to produce the AMSY. However, vulnerable biomass is estimated to be less than B_{AMSY} due to recent below average recruitment and current catches are above the AMSY level (**Table 5**). For this reason, the F-multiplier indicates that fishing mortality should be reduced at least 16% from the levels estimated in 2000 and 2001 if, however, recent fishing mortality is greater than the 2000-2001 levels even greater reductions are necessary.

The most plausible sensitivity analysis is that for which steepness = 0.75. This produces considerably more pessimistic results than the base case (**Table 5**). It estimates that SBR_{AMSY} is much greater (0.29), that the stock is below this level at the beginning of 2003, and vulnerable biomass is 40% below the B_{AMSY} level. The F-multiplier indicates that fishing mortality should be reduced 46% from recent levels to achieve AMSY.

4.8 Projected status of the stock

Projections are undertaken, assuming that future fishing effort will remain at levels equal to the average for the most recent two years, and that future catchability will remain at levels equal to the average of two and three years ago. This is done because recent estimates of catchability are extremely uncertain. Currently two approaches are used to project recruitment and abundance into the future and evaluate the potential impacts of alternative management strategies.

The first method is based on point-based projections, in which we assume that current stock status is known exactly and we project the population forward 5 to 10 years 500 times, each with an alternative randomly-sampled recruitment series. We them summarize the results by the quartiles of important quantities (e.g., the 10^{th} and 90^{th} quartiles of spawning biomass five years into the future). The second method uses confidence intervals based on normal approximations and the delta method (Maunder and Harley 2003). The model is extended and future recruitments are estimated as free parameters, but without data to estimate them. This method allows us to incorporate both future recruitment variation and uncertainty in current conditions and the parameters of the population model. We compared the performance of each approach using a simulation study testing the proportion of times that the true future biomass was contained within the estimated confidence bounds. It was found that the normal approximation greatly outperformed the point-based method for short-term projections (1 to 3 years), but that both methods perform similarly for medium- and long-term projections (Maunder et al. in prep). However, there are biases in the normal approximation method currently used that should be corrected, but there will always be additional bias when a spawner-recruitment relationship is present (Maunder et al. in prep).

Projections for both methods yield similar conclusions. The weak recruitment during 1998-2000 should cause the SBR to decrease throughout 2003 and to be substantially less than SBR_{AMSY}. The spawning biomass of bigeye in the EPO should decline to historically low levels and then further (**Figure 10**). This decline is predicted regardless of the amount of fishing effort and environmental conditions that occur in the near future. The SBR is projected to further decrease during 2004-2006. A significant decrease in longline catches is also predicted, based on the available estimates of effort (**Figure 11**). However, given that recent data not previously available for the assessment indicate significant increases in longline fishing effort, catches may not decrease as soon as predicted. For the base case model where steepness = 1, purse seine catches are expected to decline less than longline catches. If recruitment is related to spawner biomass, purse seine catches will decline as recruitment is reduced due to reduced spawner abundance, and subsequently any stock recovery will also be delayed.

When undertaking projections, we also consider the potential impacts of possible changes to the way the fisheries presently operate. Preventing the discards of small bigeye tuna from catches taken around floating objects (or ensuring that discarded fish survive) would increase the SBR, the yield-per-recruit, the catch taken by the surface fleet, and the catch taken by the longline fleet. Thus, any measure that effectively reduces the kill of bigeye that are about 2-5 quarters old may help to achieve a variety of management objectives, e.g., increase spawner biomass and reduce fishing mortality on juvenile bigeye. Reducing future purse seine effort by 25% is predicted to increase spawning biomass, mean weight of the catch, and longline catches, while only slightly reducing purse seine catches. Conversely, increasing purse seine effort by 25% will further decrease spawning biomass, mean weight of the catch, and longline catches. Reducing future longline effort by 25% is projected to have greater short term (less than three years) benefits in increases in spawning biomass than reducing purse seine effort, but after five years the benefits of reducing purse seine effort are three times those of reducing longline effort.

5 Problems faced in the assessment

Here we describe some of the problems encountered in the assessment of bigeye tuna in the EPO and challenges that should be faced in managing the resource from a stock assessment perspective.

5.1 Stock assessment

There are several important issues facing the assessment of bigeye tuna. These issues arise because (1) there are concerns regarding the status of the resources, and (2) the assessment is very young, i.e., the IATTC has not been undertaking assessments for bigeye tuna as long as it has for yellowfin.

Presently, the bigeye population in the EPO is modeled as a single closed stock – or at least with no net loss or gains from sources outside the EPO. For the assessment, the western boundary of the EPO is 150°W. While this boundary easily covers all the EPO purse seine fishery, the eastern component of the longline fishery extends westward to around 160°W, and data west of 150°W are not included in the assessment. There are concerns that this leads to inappropriately modeling of the stock. However, results from the Pacific-wide assessment show that biomass trends for the EPO are very similar when movement from east to west (and west to east) is allowed and presently available tagging data indicates no evidence of any significant exchange. Future tagging studies could address questions regarding stock structure.

The basic information required for a stock assessment is catch data, and for bigeye tuna in the EPO these data are uncertain. The IATTC is entering its fourth year of scientific sampling of purse seine catches to determine the species composition of the catch. As the total retained catch estimates based on scientific sampling have been considerably different to the traditional unloading estimates, it is critical to (1) carefully examine the catch estimates for the biases that are present, and (2) determine how best to adjust historical catch estimates based on the study of these biases.

Because bigeye tuna is a target species for many of the longline fleets operating in the EPO, we are less concerned about species mis-identification, but there are three problems. The first is that we have very little information on catches for the small artisinal vessels or catches for other fleets that are not reporting their catches to the IATTC; this can introduce bias into the assessment if there are trends in unreported catches over time, but the problems will be much less if there are no trends. The second problem relates to the estimates of the size composition of the longline catch. Presently we receive size composition data only for those fish caught by the Japanese fleet. Historically, catches by the Japanese represented the majority of the entire longline fishery, so the size composition of longline catches for other nations were not as important. Now these other nations combine to catch a significant proportion of the overall longline catch. If the sizes of bigeye caught by these fleets are different to those caught by the Japanese fleet, bias could be introduced into the assessment. A final problem relating to longline catch data is the delay in receiving data to include in the assessment. With our current deadline of March in a given year, we do not receive catch and effort data or size composition data for the most recent year, only the year before that. This causes two major problems. First we must assume levels of effort in the most recent year and predict catches based on this assumed effort, in recent years there have been large increases in effort which we have not predicted, so the estimates of current conditions can be biased. Second, we rely heavily on patterns in the longline fishery (both CPUE and size-composition data) to validate predictions (e.g., that we had a series of weak recruitments during 1998-2000). The delay means that we are unable to confirm our model predictions immediately and it also increases the number of years required to accurately estimate strength of incoming cohorts because of the correlation between catchability and year class strength discussed below. Overall, this delay undermines the assessment.

As mentioned above, it is difficult to estimate year class strength until a cohort has passed through to the longline fishery. This is in part due to our inability to standardize the CPUE for purse seine vessels that catch juvenile bigeye tuna associated with floating objects. In the most recent 1 to 2 years, the assessment model has difficulty separating catchability from year class strength, i.e., it cannot determine if a cohort is strong or if the fleet has simply increased its efficiency. To at least partly overcome this, we must attempt to standardize purse seine CPUE data. This will be difficult, and will likely require information on the density of floating objects and information on the fishing strategies employed by skippers. Information of the behavior of bigeye tuna while at floating objects will also be critical. For the last four years the IATTC has been undertaking field work to describe the behavior of tuna in association with floating objects (Schaeffer and Fuller 2002, 2004), and hopefully this work will continue into the future.

Until we have a reliable CPUE index for the purse seine fishery, the correlation between recruitment and catchability will make it difficult to provide accurate short-term predictions and reliably estimate current fishing mortality. Further examination of factors related to year class strength could help reduce uncertainty in the recent estimates of recruitment, but our time series is still relatively short.

While we have great uncertainty in interpreting CPUE from purse seine fisheries, we generally assume that we can standardize longline fishing effort so as to provide an accurate index of abundance for the larger individuals captured by longline gear. For the assessments of bigeye in the EPO, we have considered at least three different CPUE series in recent years, with each series leading to a slightly different view of the status of the stock. Furthermore, as the Japanese fleet has reduced its effort in the EPO, its effort has concentrated into a smaller geographic area. This pattern is often associated with hyperstability (CPUE declining more slowly than abundance of the population being fished). There is a clear need for research on the development of the best and most reliable index of abundance based on longline catch and effort data, in particular on indices that consider spatial factors.

Historically, many of the biological parameters used in the assessment were taken from published reports–often up to 50 years old. Even the most basic information–the length-weight relationship comes from a very old study that did not include small fish that make up almost all the purse seine catch. In recent years the IATTC has been undertaking biological studies of age, growth, and reproductive biology. As revised estimates have become available they are often considerably different to those previously assumed. These parameters are important for calculating AMSY-based reference points. It is also hoped that analysis of tagging data will provide important information on natural and fishing mortality.

In addition to these concerns, the standard problems of uncertainty in natural mortality and spawner recruitment dynamics also exist.

5.2 Management

From a scientific/assessment viewpoint, there are three important issues that must be addressed to ensure sound management of the bigeye tuna stock in the EPO.

The greatest problem facing the bigeye tuna stock is the large catches of juvenile bigeye that are caught in association with FADs. The high purse seine catches have allowed total catches to remain high, even though longline effort has been reduced. Bigeye tuna represent only a small part of the total purse seine catch on FADs, which is predominantly skipjack tuna. Given the value of the skipjack catch, it is of critical importance to determine means by which bigeye catches can be reduced without causing large losses in catches of skipjack.

Second, there appears to have been large increases in longline effort directed at bigeye tuna in recent years. Based on the current assessment, annual longline catches must not exceed 37,000 t; this level has been greatly exceeded in recent years. Catches about this level were likely possible based on the capacity of the fishing fleets prior to 2000, but the dramatic increases in effort since 2000 must be reversed – this problem has the potential to overtake the juvenile catches as the greatest threat to the stock.

Finally, the deficiencies in the stock assessment must be addressed to ensure the credibility of the results and the management recommendations based upon it. Present uncertainties in the assessment could potentially undermine its recommendations.

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References

ANONYMOUS. 2003. Tunas and billfishes in the eastern Pacific Ocean in 2002. Inter-Amer. Trop. Tuna Comm., Fishery Status Report, 1: 96 pp.

BEVERTON, R.J.H. and S.J. Holt, 1957. On the dynamics of exploited fish populations. Minis. Agri. Fish. Food Inves., Ser. 2, 19: 533 p.

BIGELOW, K., J. Hampton, 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. Ocean. 11: 143-155.

FOURNIER, D.A., J Hampton, 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.

HAMPTON, J. 2000. Natural mortality rates in tropical tunas: size really does matter. Can. J. Fish. Aquat. Sci. 57: 1002-1010.

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

HAMPTON, J., P. Kleiber, Y. Takeuchi, H. Kurota, M. Maunder. 2003. Stock assessment of bigeye tuna in the western and central Pacific Ocean, with comparisons to the entire Pacific Ocean. Sixteenth Meeting of the STANDING COMMITTEE ON TUNA AND BILLFISH Mooloolaba, Queensland, Australia 9–16 July 2003. SCTB16 BET-1.

HARLEY, S.J., S. Hoyle, M.N. Maunder. In prep. Choosing MSY-related harvest strategies in the face of uncertainty in spawner-recruitment dynamics.

HARLEY, S.J., M.N. Maunder. 2003. Recommended diagnostics for large statistical stock assessment models. Sixteenth Meeting of the STANDING COMMITTEE ON TUNA AND BILLFISH Mooloolaba, Queensland, Australia 9–16 July 2003. SCTB16 MWG-3.

HARLEY, S.J. and M.N. Maunder. 2004. Status of bigeye tuna in the eastern Pacific Ocean in 2002 and outlook for 2003. Inter-Amer. Trop. Tuna Comm., Stock Asses. Rep. 4:.

HINTON, M.G., H Nakano. 1996. Standardizing catch and effort statistics using physiological, ecological, or behavioral constraints and environmental data, with an application to blue marlin (*Makaira nigricans*) catch and effort data from Japanese longline fisheries in the Pacific. Inter-Amer. Trop. Tuna Comm., Bull. 21: 169-200.

IATTC. 2000. Annual report of the Inter-American Tropical Tuna Commission, 1998.

IATTC. 2003. Convention for the strengthening of the Inter-American Tropical Tuna Commission established by the 1949 convention between the United States of America and the Republic of Costa Rica ("Antigua Convention"). Available at http://www.iattc.org/PDFFiles2/Antigua%20Convention%20Jun%202003.pdf

KUME, S. 1967. Distribution and migration of bigeye tuna in the Pacific Ocean. Rep. Nankai Reg. Fish. Res. Lab. 25: 75-80.

KUME, S., J. Joseph. 1966. Size composition, growth and sexual maturity of bigeye tuna, *Thunnus obesus* (Lowe), from the Japanese long-line fishery in the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm. Bull., 11: 45-99.

MACE, P.M., I.J. Doonan. 1988. A generalized bioeconomic simulation model for fish populations. N.Z. Fish. Assess. Res. Doc. 88/4.

MAUNDER, M.N. 2002. The relationship between fishing methods, fisheries management and the estimation of MSY. Fish and Fisheries 3: 251-260.

MAUNDER, M.N., S.J. Harley. 2002. Status of bigeye tuna in the eastern Pacific Ocean in 2001 and outlook for 2002. Inter-Amer. Trop. Tuna Comm., Stock Asses. Rep. 3: 201-311.

MAUNDER, M.N., S.J. Harley. 2003. Methodological improvements to the EPO tuna stock assessments. Sixteenth Meeting of the STANDING COMMITTEE ON TUNA AND BILLFISH Mooloolaba, Queensland, Australia 9–16 July 2003. SCTB16 MWG-2.

MAUNDER, M.N., S.J. Harley, J. Hampton. In prep. Including parameter uncertainty in forward projections of computationally intensive statistical population dynamic models.

MAUNDER, M.N., G.M. Watters. 2003. A-SCALA: an age-structured statistical catch-at-length analysis for assessing tuna stocks in the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Bull., 22 (5):

MCALLISTER, M. K. and J. N. Ianelli. 1997. Bayesian stock assessment using catch-age data and the Sampling/ Importance Resampling Algorithm. Can. J. Fish. Aquat. Sci. 54, 284-300.

NAKAMURA, E.L., J.H. Uchiyama. 1966. Length-weight relations of Pacific tunas. Proc., Governor's [Hawaii] Conf. Cent. Pacif. Fish. Resources, edited by T.A. Manar, Hawaii: 197-201.

OKAMOTO, H., W.H. Bayliff. 2003. A review of the Japanese longline fishery for tunas and billfishes in the eastern Pacific Ocean, 1993-1997. Inter-Amer. Trop. Tuna Comm., Bull., 22: 219-431.

SCHAEFER, K.M., D.W. Fuller. 2002. Movements, behavior, and habitat selection of bigeye tuna (*Thunnus obesus*) in the eastern equatorial Pacific, ascertained through archival tags. U.S. Fish. Bull. 100:765-788.

SCHAEFER, K.M., D.W. Fuller. 2004. Conventional and archival tagging of bigeye tuna (*Thunnus obsesus*) in the eastern equatorial Pacific. Col. Vol. Sci. Pap. ICCAT.

SUDA, A., S. Kume. 1967. Survival and recruitment of bigeye tuna in the Pacific Ocean, estimated by the data of tuna longline catch. Nankai Reg. Fish. Res. Lab. Rep. 25: 91-104.

TOMLINSON, P. 2002. Progress on sampling the eastern Pacific Ocean tuna catch for species composition and length-frequency distributions. Inter-Amer. Trop. Tuna Comm., Stock Assess. Rep, 2: 339-365.

WATTERS, G.M., R. Deriso. 2000. Catch per unit of effort of bigeye tuna: a new analysis with regression trees and simulated annealing. Inter-Amer. Trop. Tuna Comm., Bull. 21: 527-571.

WATTERS, G.M., M.N. Maunder. 2001. Status of bigeye tuna in the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Stock Asses. Rep. 1: 109-210.

WATTERS, G.M., M.N. Maunder. 2002. Status of bigeye tuna in the eastern Pacific Ocean. Inter-Amer. Trop. Tuna Comm., Stock Asses. Rep. 2: 147-246.

WALTERS, C. 2003. Folly and fantasy in the analysis of spatial catch rate data. Can. J. Fish. Aquat. Sci. 60: 1433-1436.

Table 1. Annual retained catches of bigeye tuna, in metric tons, used for the assessment of bigeye tuna undertaken in April 2003. In some cases the data were converted from numbers of fish to weight in metric tons with average weight data estimated by the IATTC staff. "Other" includes China, Costa Rica, Ecuador, El Salvador, French Polynesia, Guatemala, Mexico, and the USA. Data for 2000-2002 were preliminary and an * denotes no data. NOTE: Since the April 2003 assessment these data have been updated for several fleets and no longer represent the best available catch estimates.

	Surface		*Longline[1]*					*Grand total*	
Year	*Scientific*	*Standard*	*Japan*	*Korea*	*Chinese Taipei*	*Other*	*Total*	*Scientific*	*Standard*
1970	1,332	1,332	32,521	*	392	*	32,913	34,245	34,245
1971	2,566	2,566	28,871	*	329	*	29,199	31,765	31,765
1972	2,238	2,238	35,113	*	831	*	35,944	38,182	38,182
1973	1,979	1,979	49,731	*	1,312	*	51,043	53,022	53,022
1974	890	890	36,013	*	576	*	36,589	37,479	37,479
1975	3,723	3,723	40,726	432	432	*	41,590	45,313	45,313
1976	10,243	10,243	52,827	807	217	*	53,852	64,095	64,095
1977	7,055	7,055	70,024	2,352	211	*	72,587	79,642	79,642
1978	11,759	11,759	67,214	2,090	156	*	69,460	81,219	81,219
1979	7,532	7,532	54,377	694	141	*	55,212	62,744	62,744
1980	15,421	15,421	61,951	1,453	555	*	63,959	79,380	79,380
1981	10,091	10,091	49,970	2,135	431	*	52,535	62,626	62,626
1982	4,102	4,102	50,199	2,300	103	*	52,601	56,703	56,703
1983	3,260	3,260	57,185	2,000	68	*	59,253	62,513	62,513
1984	5,936	5,936	44,587	1,362	45	*	45,994	51,930	51,930
1985	4,532	4,532	61,627	3,696	38	*	65,362	69,894	69,894
1986	1,939	1,939	91,981	7,570	77	0	99,628	101,567	101,567
1987	776	776	87,913	9,099	388	1	97,400	98,176	98,176
1988	1,053	1,053	66,015	5,625	436	1	72,076	73,129	73,129
1989	1,470	1,470	67,514	3,581	504	*	71,599	73,069	73,069
1990	4,712	4,712	86,148	9,651	327	*	96,126	100,838	100,838
1991	3,740	3,740	85,011	16,365	249	7	101,632	105,372	105,372
1992	5,497	5,497	74,466	7,837	54	114	82,470	87,967	87,967
1993	11,132	8,069	63,190	8,194	248	196	71,829	82,961	79,898
1994	40,525	29,375	61,471	10,444	261	128	72,303	112,828	101,678
1995	51,495	37,328	49,016	8,196	148	246	57,606	109,101	94,934
1996	70,848	51,353	36,685	8,034	91	170	44,980	115,828	96,333
1997	71,209	51,627	40,571	8,218	114	352	49,255	120,464	100,882
1998	48,500	35,154	35,752	8,233	149	1,064	45,198	93,698	80,352
1999	56,026	40,610	22,224	9,706	90	902	32,922	88,948	73,532
2000	86,755	70,153	27,865	9,854	*	989	38,708	125,463	108,861
2001	58,040	42,846	36,959	13,272	*	3,478	53,709	111,749	96,555
2002	62,396	35,201	29,843	*	*	568	30,411	92,807	65,612

[1] Sources: published and unpublished data from the National Research Institute of Far Seas Fisheries (NRIFSF), Shimizu, Japan, Institute of Oceanography, National Taiwan University, Taipei, Taiwan, Ministry of Agriculture, People's Republic of China, and National Fisheries Research and Development Agency, Republic of Korea.

Table 2. Fishery definitions used for the stock assessment of bigeye tuna in the EPO. PS=purse seine; PL=pole and line; LL=longline; FLT=sets on floating objects; UNA=sets on unassociated fish; DOL=sets on dolphins.

Fishery	*Gear*	*Set type*	*Years*	*Sampling areas*	*Catch data*
1	PS	FLT	1980-1992	1-13	retained catch only
2	PS	FLT	1993-2001	11-12	retained catch + discards from inefficiencies in fishing process
3	PS	FLT	1993-2001	7, 9	
4	PS	FLT	1993-2001	5-6, 13	
5	PS	FLT	1993-2001	1-4, 8, 10	
6	PS PL	UNA DOL	1980-1989	1-13	retained catch only
7	PS PL	UNA DOL	1990-2001	1-13	retained catch + discards from inefficiencies in fishing process
8	LL		1980-2001	N of–de 15°N	retained catch only
9	LL		1980-2001	S of–de 15°N	
10	PS	FLT	1993-2001	11-12	discards of small fish from size-sorting the catch by Fishery 2
11	PS	FLT	1993-2001	7, 9	discards of small fish from size-sorting the catch by Fishery 3
12	PS	FLT	1993-2001	5-6, 13	discards of small fish from size-sorting the catch by Fishery 4
13	PS	FLT	1993-2001	1-4, 8, 10	discards of small fish from size-sorting the catch by Fishery 5

Table 3. Important biological parameters for bigeye tuna in the eastern Pacific Ocean. Sources are described in the text.

Age	*Length*	*Weight*	*Proportion Mature*	*Fecundity*	*Proportion females*	*M*
2	30.0	0.7	0.000	0.0	0.445	0.188
3	35.2	1.2	0.000	0.0	0.445	0.176
4	40.4	1.7	0.000	0.0	0.445	0.164
5	45.6	2.4	0.000	0.0	0.445	0.153
6	50.8	3.3	0.000	0.0	0.445	0.141
7	58.7	5.0	0.000	0.0	0.445	0.129
8	67.3	7.5	0.000	0.0	0.445	0.117
9	75.0	10.2	0.000	0.0	0.445	0.106
10	83.8	14.1	0.000	0.0	0.445	0.094
11	90.3	17.5	0.000	0.0	0.445	0.094
12	99.3	23.0	0.001	0.0	0.445	0.094
13	110.1	31.0	0.004	0.1	0.445	0.094
14	115.4	35.5	0.011	0.4	0.445	0.094
15	120.4	40.2	0.025	1.0	0.445	0.094
16	125.1	44.9	0.054	2.4	0.445	0.094
17	129.6	49.8	0.108	5.4	0.445	0.094
18	133.9	54.7	0.201	11.0	0.444	0.094
19	138.0	59.7	0.334	19.9	0.444	0.094
20	141.9	64.7	0.491	31.7	0.443	0.094
21	145.5	69.6	0.642	44.7	0.442	0.095
22	149.0	74.6	0.764	57.0	0.440	0.097
23	152.3	79.5	0.850	67.6	0.437	0.100
24	155.5	84.3	0.906	76.4	0.432	0.105
25	158.5	89.1	0.941	83.9	0.426	0.112
26	161.3	93.8	0.963	90.3	0.418	0.120
27	164.0	98.4	0.976	96.0	0.407	0.126
28	166.6	102.9	0.984	101.3	0.393	0.131
29	169.0	107.3	0.990	106.2	0.376	0.132
30	171.3	111.6	0.993	110.8	0.356	0.132
31	173.5	115.8	0.995	115.2	0.333	0.131
32	175.6	119.9	0.997	119.5	0.307	0.129
33	177.5	123.8	0.998	123.5	0.281	0.126
34	179.4	127.6	0.998	127.4	0.253	0.124
35	181.2	131.4	0.999	131.2	0.227	0.121
36	182.9	134.9	0.999	134.8	0.201	0.119
37	184.5	138.4	0.999	138.3	0.177	0.117
38	186.0	141.8	0.999	141.7	0.156	0.114
39	187.5	145.0	1.000	144.9	0.136	0.112
40	188.8	148.1	1.000	148.0	0.119	0.111
41	190.1	151.1	1.000	151.0	0.105	0.101

Table 4. Estimated total annual recruitment of bigeye tuna (thousands of fish), initial biomass (metric tons present at the beginning of the year), and spawning biomass (metric tons) in the EPO.

Year	*Recruitment*	*Biomass of Age 1+ fish*	*Spawning biomass*
1975	13,511	488,080	71,104
1976	22,571	516,098	72,818
1977	14,245	514,038	74,077
1978	14,827	505,325	73,756
1979	19,038	498,678	71,029
1980	15,997	501,483	68,539
1981	17,611	489,775	71,334
1982	29,496	493,752	74,914
1983	18,959	521,409	71,236
1984	14,309	559,928	71,481
1985	14,408	618,399	78,844
1986	18,143	630,387	83,619
1987	22,566	570,080	90,814
1988	15,779	524,260	88,056
1989	14,517	529,688	77,364
1990	14,454	541,286	69,237
1991	14,563	511,572	66,481
1992	18,975	460,665	67,434
1993	19,059	443,634	65,178
1994	27,222	440,688	59,385
1995	31,150	428,390	53,723
1996	36,093	409,065	49,552
1997	57,112	396,886	48,117
1998	15,091	395,782	44,154
1999	10,431	454,335	41,213
2000	10,094	494,708	45,052
2001	17,910	422,380	54,713
2002	18,463	313,041	59,638
2003		227,970	52,309

Table 5. Estimates of the AMSY and its associated quantities for the base case and the steepness sensitivity analyses. Both analyses are based on average fishing mortality for 2000 and 2001. B_{recent} and B_{AMSY} are defined as the biomass of bigeye 1+ years old at the start of 2003 and at AMSY, respectively, S_{AMSY} is in terms of the biomass of spawning females, and *SBR* is the spawning biomass compared to the average spawning biomass in the unfished population. C_{recent} is the estimated total catch in 2002.

	Base case	*Steepness = 0.75*
AMSY (T)	77,199	72,928
B_{AMSY} (T)	278,386	444,107
S_{AMSY}	32,338	63,606
B_{AMSY}/B_0	0.28	0.37
SBR_{AMSY}	0.18	0.29
C_{recent}/AMSY	1.35	1.43
$B_{\text{recent}}/B_{\text{AMSY}}$	0.82	0.59
$SBR_{\text{recent}}/SBR_{\text{AMSY}}$	1.62	0.90
F-multiplier	0.84	0.54

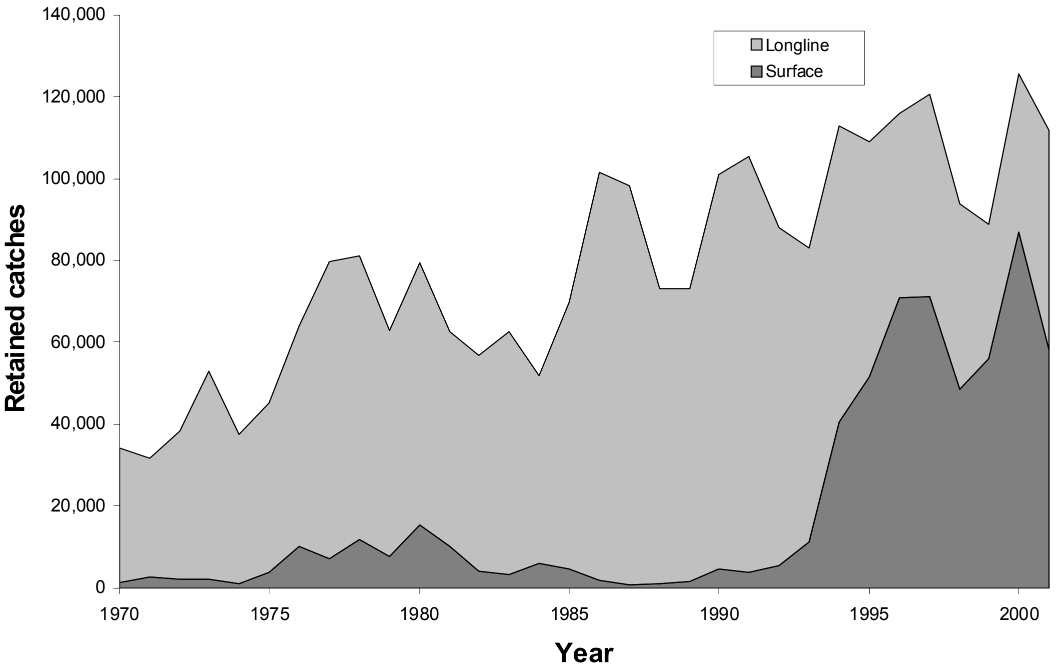

Figure 1. Annual retained catches of bigeye tuna in metric tons used in the April 2003 stock assessment. NOTE: Since the April 2003 assessment these data have been updated for several fleets and no longer represent the best available catch estimates.

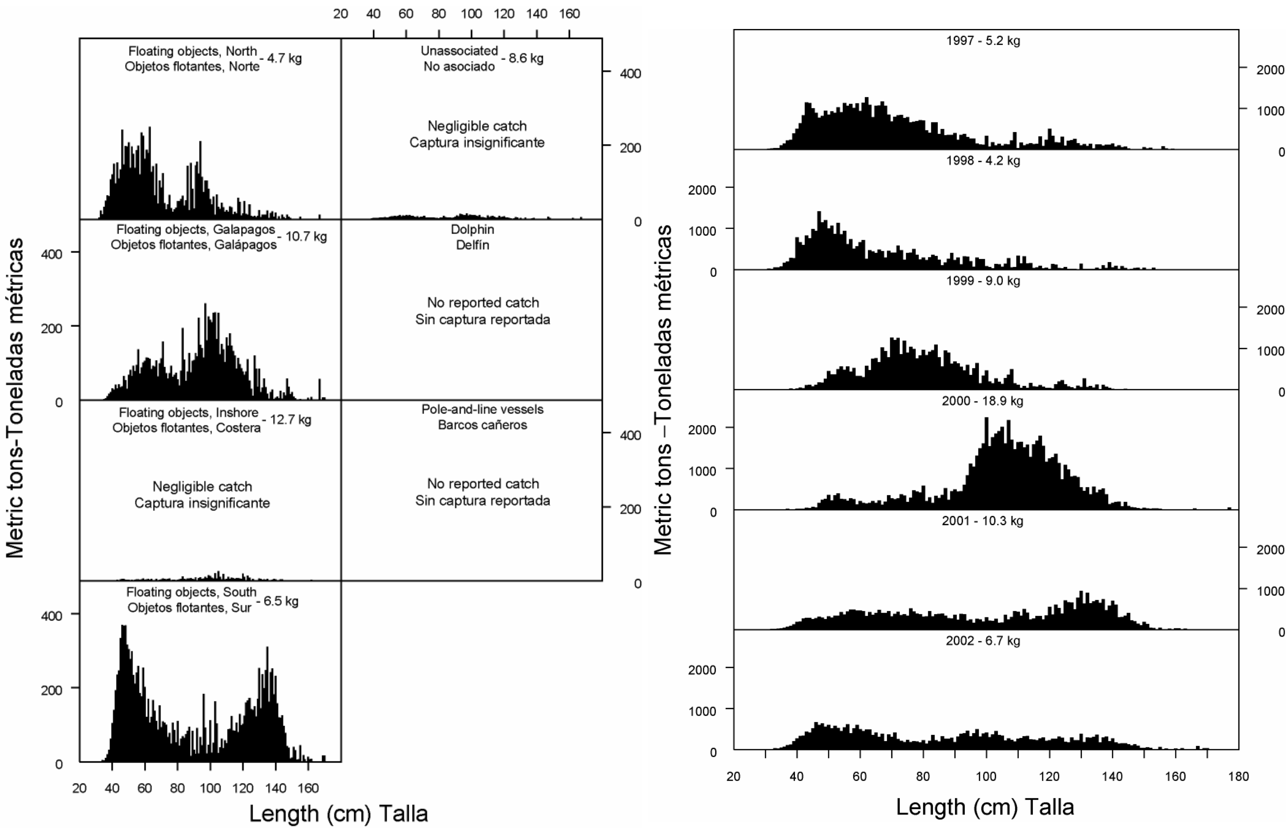

Figure 2a. Estimated size compositions and average weights of the bigeye caught in each surface fishery of the EPO in 2002 (left) and in all surface fisheries combined in 1997-2002 (right).

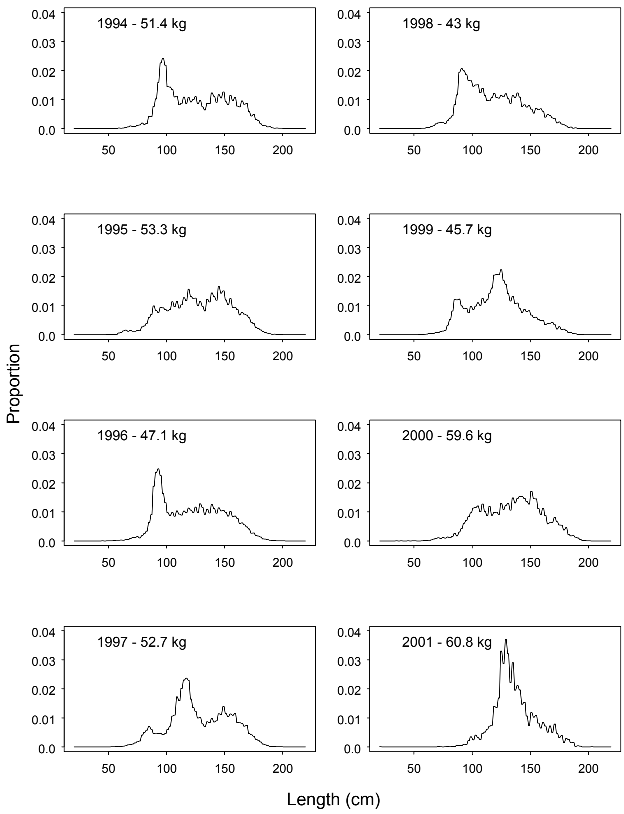

Figure 2b. Estimated size compositions and average weights of the bigeye caught in the longline fisheries in 1994-2001.

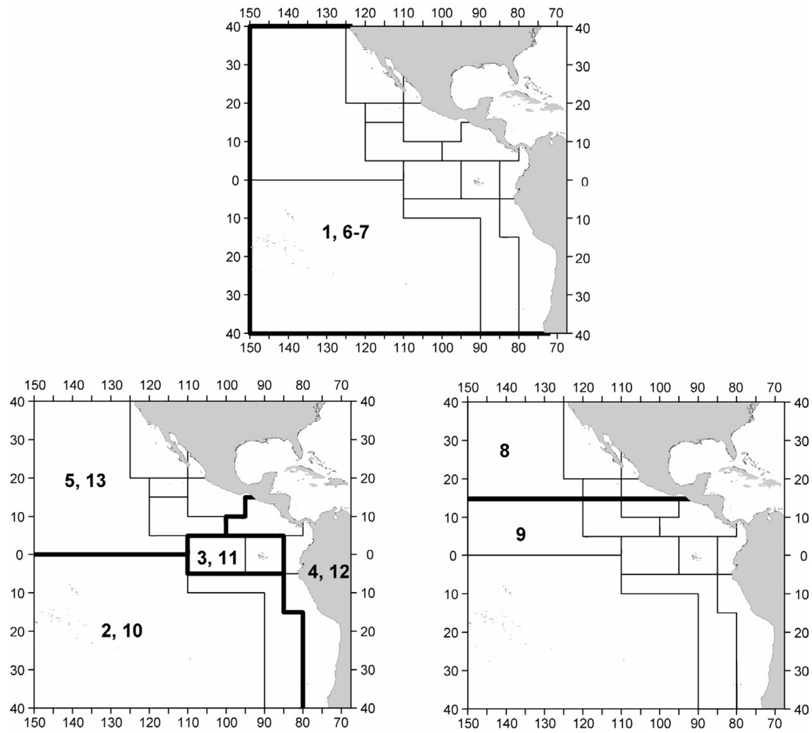

Figure 3. Spatial extents of the fisheries defined for the stock assessment of bigeye tuna in the EPO. The thin lines indicate the boundaries of 13 length-frequency sampling areas, the bold lines the boundaries of each fishery defined for the stock assessment and the numbers the fisheries to which the latter boundaries apply. The fisheries are described in Table 2.

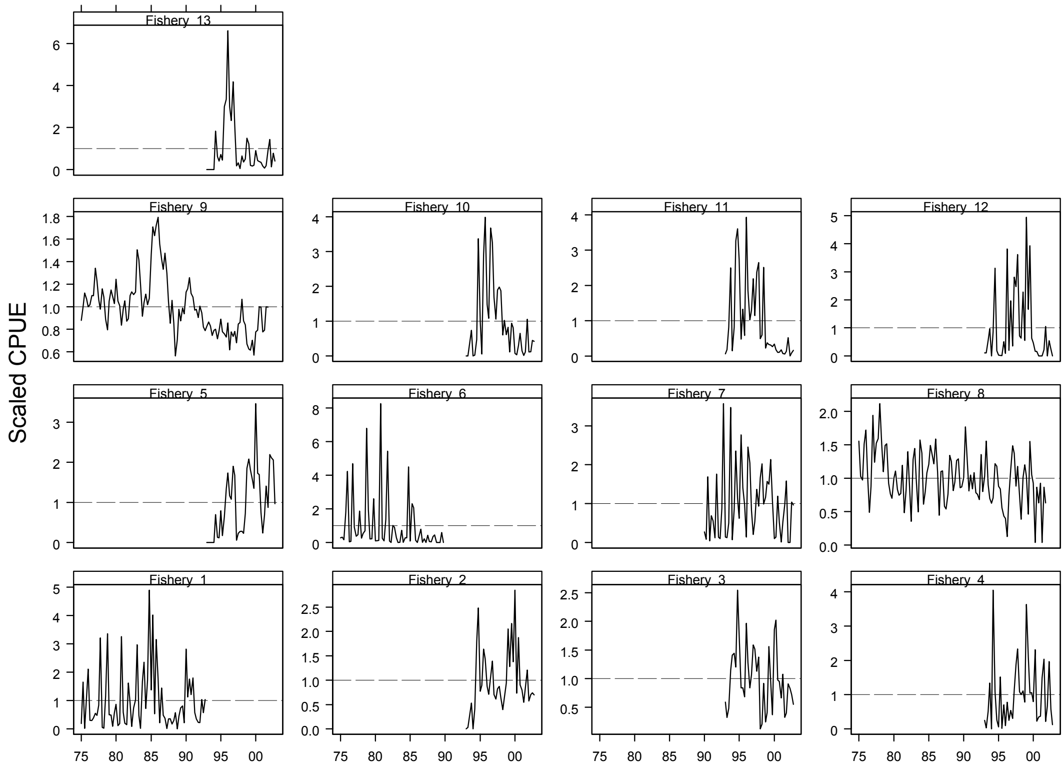

Figure 4. CPUEs of the fisheries defined for the stock assessment of bigeye tuna in the EPO (Table 2). Since the data were summarized on a quarterly basis, there are four observations of CPUE for each year. The data are adjusted so that the mean of each time series is equal to 1.0. Note that the vertical scales of the panels are different.

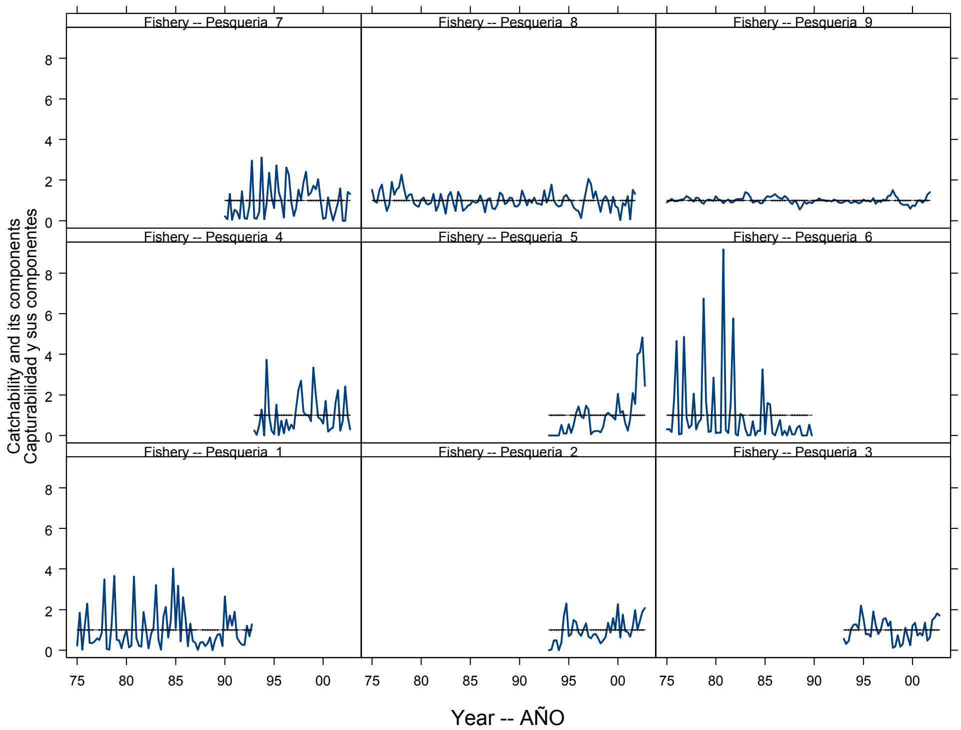

Figure 5. Trends in catchability for the nine fisheries (discard fisheries excluded) that take bigeye tuna in the EPO. The estimates are scaled to the first estimate of q for each fishery (dashed line).

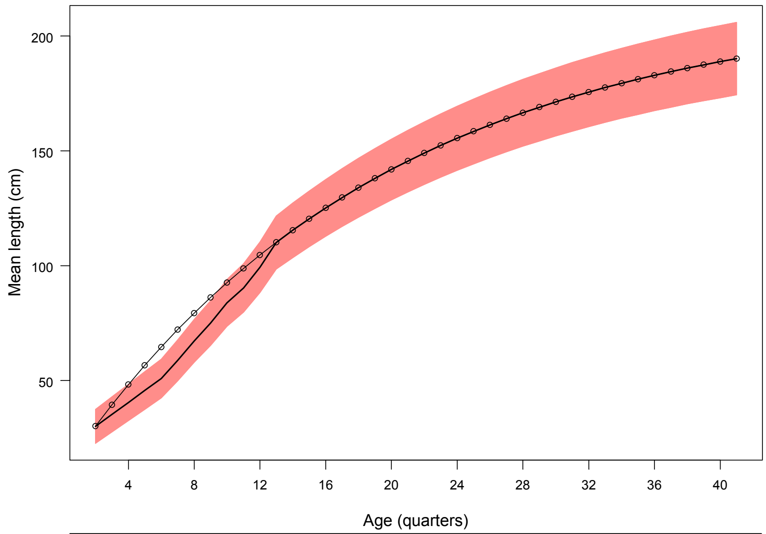

Figure 6. Estimated average lengths at age for bigeye tuna in the EPO. The shaded area indicates the range of lengths estimated to be covered by two standard deviations of the length at age. The line with circles represents the growth curve from Suda and Kume (1967), which is used as a prior.

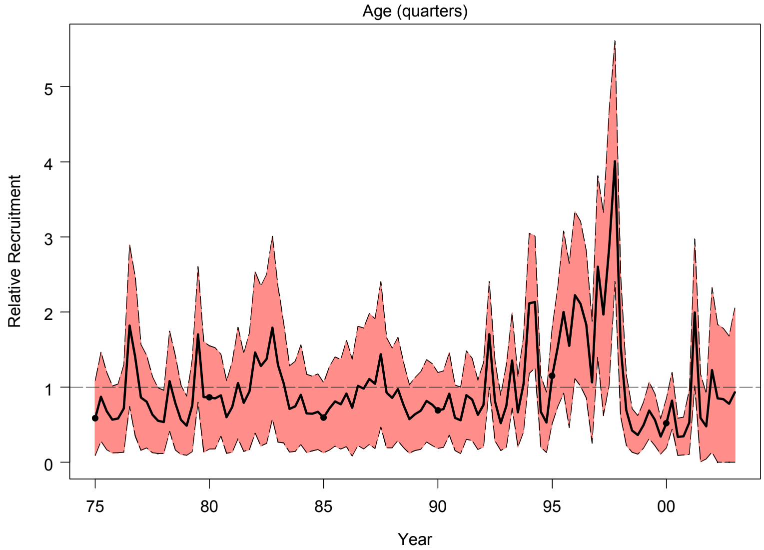

Figure 7. Estimated recruitment of bigeye tuna to the fisheries of the EPO. The estimates are scaled so that the estimate of virgin recruitment is equal to 1.0. The bold line illustrates the maximum likelihood estimates of recruitment, and the shaded area represents the confidence intervals (±2 standard deviations) around those estimates.

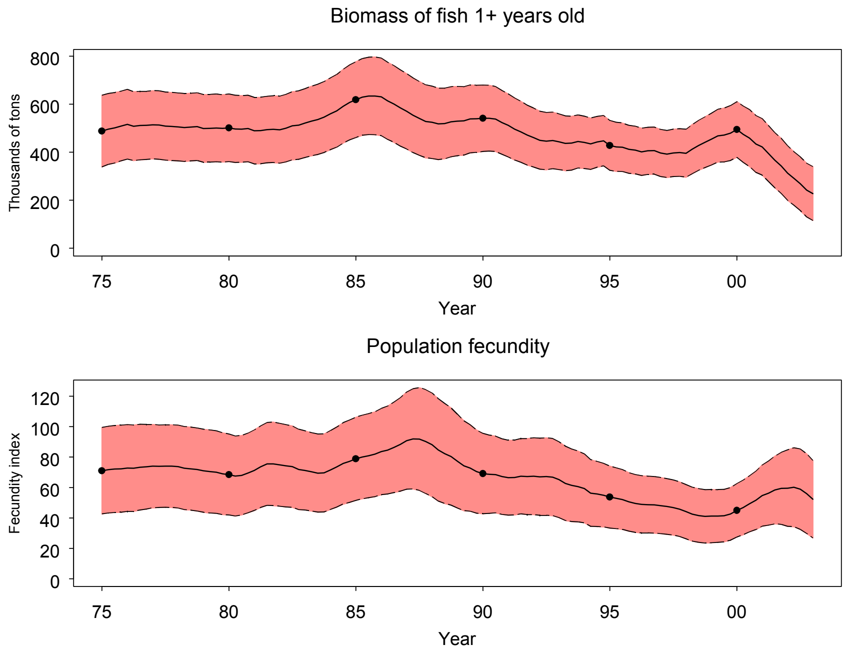

Figure 8. Estimated total biomass (ages 1+) and spawning biomass of bigeye tuna in the EPO. The bold lines illustrate the maximum likelihood estimates of the biomass, and the shaded area represents the confidence intervals (±2 standard deviations) around those estimates.

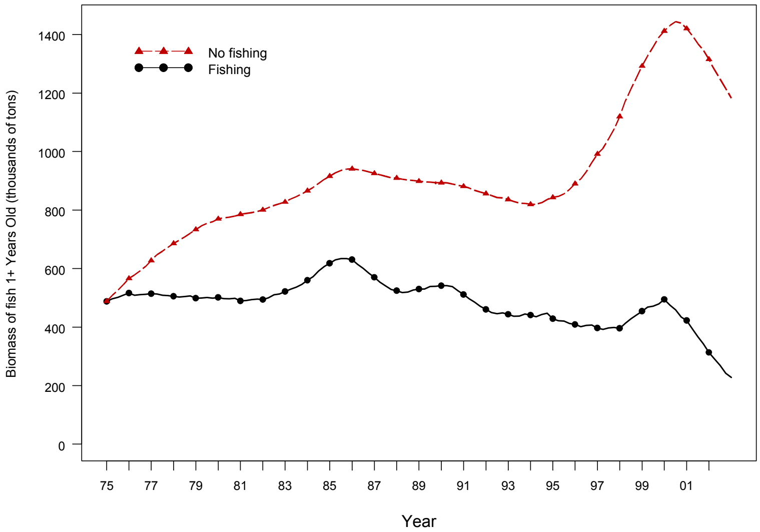

Figure 9. Biomass trajectory of a simulated population of bigeye tuna that was not exploited during January 1975 through December 2002 ("no fishing") and that predicted by the stock assessment model ("fishing").

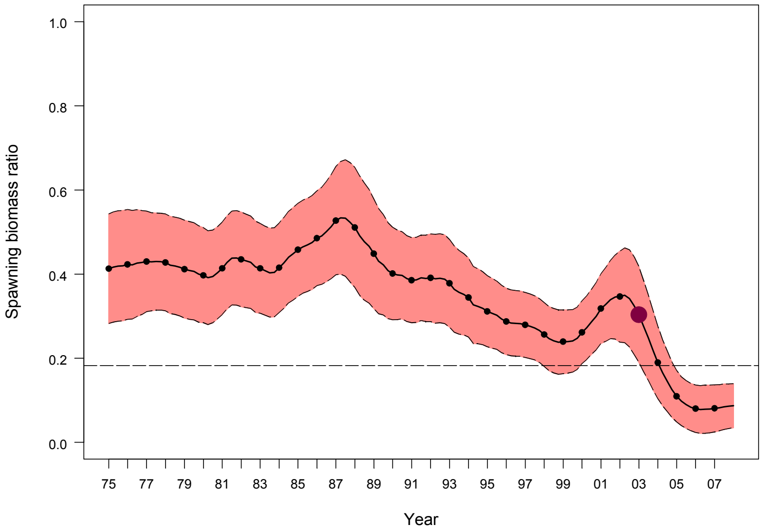

Figure 10. Estimated SBR, including projections for 2003-2007 under average effort for 2001 and 2002 and average catchability for 2000 and 2001 for bigeye tuna in the EPO. The shaded areas indicate the 95% confidence intervals and the large dot indicates the estimate for the first quarter of 2003. The dashed horizontal line indicates the SBR_{AMSY} (0.18).

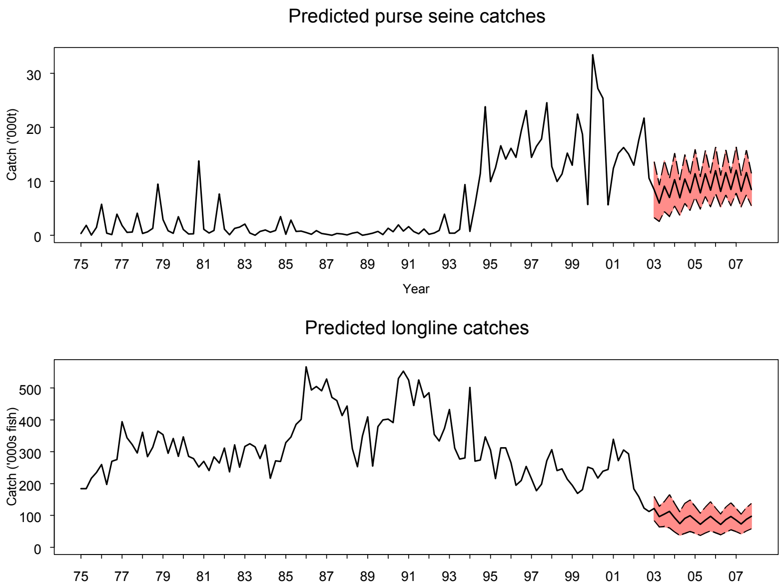

Figure 11. Predicted catches for the surface (Fisheries 2, 3, 4, 5, and 7) and longline (Fisheries 8 and 9) fisheries based on average effort for 2002 and 2001 and average catchability for 2000 and 2001. The shaded areas represent 95% confidence intervals for the predictions.