SCRS/2004/067 Col. Vol. Sci. Pap. ICCAT, 57(2): 242-270 (2005)

RECENT DEVELOPMENTS IN FISHERIES, DATA COLLECTION AND STOCK ASSESSMENT FOR BIGEYE TUNA (*THUNNUS OBESUS*) IN THE WESTERN AND CENTRAL PACIFIC OCEAN

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SUMMARY

Bigeye tuna has been exploited by industrial fisheries in the western and central Pacific Ocean since at least 1950. Historically, longline has been the main capture method, targeting large fish for the sashimi market. In the mid-1990s, developments in the purse seine fishery resulted in increased catches of juvenile bigeye, mostly caught in association with floating objects (logs and FADs). Also, catches of juvenile bigeye in the domestic fisheries of Indonesia and Philippines are thought to have increased during this period. In recent years, the total bigeye catch in the WCPO has averaged nearly 120,000 t, with 55-65% by the longline fishery. Fishery data on bigeye are collected primarily by logsheet, port sampling and observer programs. The main data problems are insufficient observer and port sampling coverage of the purse seine fleet to accurately estimate total catches, and a lack of information from the domestic fisheries of Philippines and Indonesia regarding bigeye catches. Stock assessment models for bigeye in the WCPO have been developed in recent years using the MULTIFAN-CL modelling framework, an integrated statistical approach that incorporates all available catch, effort, size and tagging data into the assessment. An important input into the model is longline effort pre-standardized to account for the effects of changing vertical and geographical distribution of the gear and the fish. The results of recent assessments indicate that bigeye tuna is at least fully, and perhaps over-exploited in the WCPO, particularly in the equatorial zone. Significant impacts on stock biomass result from all major fishery components. Problems with the current assessment and input data are discussed.

RÉSUMÉ

Le thon obèse est exploité par les pêcheries industrielles dans l'Océan Pacifique Ouest et Centre depuis, au moins, 1950. Historiquement, la palangre a été la principale méthode de capture, ciblant les grands poissons pour le marché du sashimi. Au milieu des années 1990, les avancées dans la pêcherie des senneurs ont engendré une augmentation des prises de thons obèses juvéniles, capturés pour la plupart en association avec des objets flottants (épaves et Dispositifs de Concentration du Poisson). De même, on pense que les prises de thons obèses juvéniles dans les pêcheries nationales de l'Indonésie et des Philippines se sont accrues durant cette période. Ces dernières années, la prise totale de thon obèse dans l'Océan Pacifique Ouest et Centre a avoisiné en moyenne 120.000 t, avec 55-65% réalisée par la pêcherie palangrière. Les données de la pêche sur le thon obèse sont surtout collectées par le biais des carnets de pêche, l'échantillonnage au port et les programmes d'observateurs. Les principaux problèmes relatifs aux données résident dans une couverture insuffisante par les observateurs et par l'échantillonnage au port de la flottille des senneurs pour estimer avec précision les prises totales, ainsi qu'un manque d'information en provenance des pêcheries nationales des Philippines et de l'Indonésie en ce qui concerne les prises de thon obèse. Les modèles d'évaluation du stock pour le thon obèse dans l'Océan Pacifique Ouest et Centre ont été élaborés ces dernières années à l'aide du cadre de modélisation MULTIFAN-CL, une approche statistique intégrée qui inclut toutes les données de prise, d'effort et de taille et de marquage disponibles dans l'évaluation. Une importante valeur d'entrée du modèle est l'effort palangrier pré-standardisé permettant de tenir compte des effets de la distribution verticale et géographique changeante de l'engin et du poisson. Les résultats des dernières évaluations indiquent que le thon obèse est au moins totalement exploité, et peut-être surexploité dans l'Océan Pacifique Ouest et Centre, notamment dans la zone équatoriale. Tous les principaux

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composants de la pêche ont des impacts importants sur la biomasse du stock. Les problèmes concernant l'évaluation actuelle et les données d'entrée sont discutés.

RESUMEN

El patudo ha sido explotado por las pesquerías industriales en el océano Pacifico occidental y central (WCPO) desde al menos 1950. Históricamente, el palangre ha sido el principal método de captura, dirigiéndose a peces grandes para el mercado de sashimi. A mediados de los noventa, los cambios en la pesquería de cerco produjeron un incremento en las capturas de patudo juvenil, capturado sobre todo en asociación con objetos flotantes (troncos y DCP). También se cree que las capturas de patudo juvenil de las pesquerías nacionales de Indonesia y Filipinas se han incrementado durante este periodo. En los últimos años, el promedio de la captura total de patudo en el WCPO se ha situado en casi 120.000 t, atribuyéndose a la pesquería de palangre el 55-65% de esta captura. Los datos de las pesquerías de patudo se recopilan sobre todo mediante cuadernos de pesca, muestreo en puerto y programas de observadores. Los principales problemas relacionados con los datos son la insuficiente cobertura de observadores y de muestreo en puerto de la flota de cerco, para poder estimar con precisión las capturas totales, y la falta de información de las pesquerías nacionales de Filipinas e Indonesia en relación con las capturas de patudo. En los últimos años se han desarrollado modelos de evaluación de stocks para el patudo en el WCPO, utilizando una estructura de modelado MULTIFAN-CL, un enfoque estadístico integrado que incorpora todos los datos disponibles de captura, esfuerzo, talla y marcado en la evaluación. Un importante valor de entrada del modelo es el esfuerzo de palangre pre-estandarizado para incluir los efectos de la distribución geográfica y vertical cambiante de los artes y los peces. Los resultados de evaluaciones recientes indican que el patudo está siendo por lo menos plenamente explotado o quizá sobreexplotado en el WCPO, sobre todo en la zona ecuatorial. Todos los componentes principales de las pesquerías tienen un impacto significativo en la biomasa del stock. Se debaten los problemas de la evaluación actual y de los datos de entrada.

KEYWORDS

Catch/effort, Catchability, Stock assessment, Yield predictions, Population dynamics,
Catch statistics, Size composition, Tagging, Bigeye tuna

1 Introduction

Bigeye tuna (*Thunnus obesus*) are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. They have a maximum fork length of about 200 cm, and are relatively fast growing, reaching sexual maturity at about 3 years of age at a size of about 110 cm. They are the longest-lived species of the tropical tunas, with significant numbers of fish reaching 10 years of age – the longest period at large for a tagged bigeye is currently 12 years, an individual that was approximately 2 years old at the time of tagging (Secretariat of the Pacific Community, unpubl. data).

Bigeye tuna are an important component of tuna fisheries throughout the Pacific Ocean. They are taken by purse seine and pole-and-line (surface) gears, mostly as juveniles, and by longline gear, as valuable adult fish. They are a principal target species of both the large distant-water longliners from Japan, Korea and more recently Chinese Taipei, and of the smaller fresh sashimi longliners based in several Pacific Island countries. Prices paid for both frozen and fresh product on the Japanese sashimi market are the highest of all the tropical tunas. Bigeye tuna are the economic cornerstone of the tropical longline fishery in the western and central Pacific Ocean (WCPO – the Pacific Ocean west of 150°W), the catch of which has an estimated landed value of approximately US$ one billion annually.

Early stock assessments of bigeye tuna were conducted using surplus production model analysis based mainly on longline catch and effort data. These analyses suggested that the maximum sustainable yield (MSY) may be somewhat less than the maximum observed longline catch (Miyabe 1995), leading to the conclusion that the Pacific-wide stock of large bigeye caught by longliners is at least fully exploited, and possibly over-exploited.

Purse seine catches of bigeye tuna in the WCPO and in the eastern Pacific Ocean (EPO) increased rapidly in the 1990s, as did catches in the domestic fisheries of Philippines and Indonesia. These catches were mainly of small to medium sized juvenile bigeye tuna. In order to incorporate this dramatic change in the size composition of the catch into stock assessments, size-based, age-structured assessment methods were developed (Hampton and Fournier 2001; Maunder and Watters 2003), and are now routinely used for bigeye tuna assessments in both the EPO (e.g., Harley and Maunder 2003) and WCPO (e.g., Hampton *et al.* 2003). The most recent assessments in both regions have raised concerns about the impacts of fishing on the stocks. These concerns have resulted in management measures being implemented by the IATTC in the EPO[2] and the consideration by parties involved in the soon-to-be-established Western and Central Pacific Fisheries Commission (WCPFC) of various options for limiting bigeye tuna fishing mortality in the WCPO.

The purpose of this report is to review recent developments in the fisheries, data collection and stock assessment of bigeye tuna in the WCPO. It also identifies important gaps in fisheries and biological data, and discusses areas of particular concern regarding the stock assessment and its management implications.

2 Fishery description

2.1 Longline

The longline fishery has operated over a wide area of the WCPO since the early 1950s and in the EPO since the mid-1950s. Japanese vessels initially participated in the fishery, and were joined later by Chinese Taipei and Korean vessels. Vessels from Pacific Island countries and the Peoples Republic of China (PRC) are more recent entrants to the fishery. Since 1980, the catch of bigeye has steadily increased, due both to more effective targeting and increased fishing effort. The Japanese fleet continued to dominate the catch until around 1990, but catches by other fleets have increased strongly over the past decade while the Japanese catch has declined. The bigeye catch in 2002 was in excess of 80,000 t, the highest ever, with Japan contributing approximately one-third of the total (**Figure 1**).

While the longline fishery is widely distributed across the tropical and sub-tropical Pacific, the bigeye catch is concentrated in equatorial waters between about 15°N and 15°S (**Figure 2**). CPUE generally tends to increase from west to east (**Figure 3**), likely as a result of the shoaling of the thermocline impacting the depth distribution of bigeye and resulting in higher catchability by longline. Lower CPUE in the WCPO at 15°–30°N and at 10°–30°S occurs because the cooler waters inhabited by bigeye tuna during the day are at depths greater than 300 m in these areas, deeper than the typical maximum fishing depth of longline gear. In the far EPO off central America, low CPUE occurs because dissolved oxygen concentration (<1.0 ml O_2 l^{-1}) in waters of the preferred temperature is generally less than the limiting level, and presumably indicates an absence of bigeye in subsurface waters in this region.

2.2 Purse seine

Purse seine bigeye catches increased from historical levels of less than 15,000 t in the WCPO to reach a high of 38,000 t in 1999 (**Figure 4**). Since 1999, catches have declined to an estimated 20,000 t in 2002. Purse seine catches of bigeye occur almost exclusively through sets on floating objects, either naturally occurring logs and other debris (referred hereafter as “logs”), or drifting or anchored fish aggregation devices (referred to hereafter as “FADs”) (**Figure 5**). Unlike yellowfin and skipjack tuna, very little bigeye is caught in unassociated (or school) sets in the WCPO. Much of the late-1990s’ catch increase was due to the increased use of drifting FADs (**Figure 6**), and in general the magnitude of the bigeye catch is dependent on the extent of FAD usage. All of the major purse seine fleets have used FADs, although Korea less so than Japan, Chinese Taipei and USA (**Figure 7**). Recently, the development of the Papua New Guinea fleet, which fishes largely on anchored FADs in the Papua New Guinea EEZ, has contributed to the expansion of the ‘other’ category in **Figure 7**.

The Pacific-wide distribution of purse seine bigeye catches reflects the largely separate fisheries in the WCPO and EPO (**Figure 8**). In the WCPO, catches are concentrated between 5°N and 10°S, while in the EPO the latitudinal range of the fishery is slightly greater. The distribution of catch in the WCPO shows that (anchored) FAD sets provide the majority of the catch in Papua New Guinea and Solomon Islands waters (**Figure 9**). Elsewhere in the western region of the WCPO, log sets are an equally important source of bigeye catch. However, to the east of 165°E, (drifting) FAD sets tend to provide most of the bigeye catch.

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[2] Inter-American Tropical Tuna Commission, Resolution on Bigeye Tuna, 16 June 2000, http://www.iattc.org/PDFFiles/C-00-02%20BET%20resolution%20Jun%2000.pdf

2.3 Philippines and Indonesia

Bigeye tuna are also caught in the domestic fisheries of Philippines and eastern Indonesia, which generally take small tuna in large quantities by a variety of fishing methods – approximately one third of the entire WCPO tuna catch is attributable to these fisheries. Unfortunately, limited information on the species composition is available for these fisheries. Sampling data from the Philippines fishery indicates that approximately 10% of the oceanic 'tuna' catch (i.e., yellowfin and bigeye) is bigeye tuna. This assumption is applied in estimating the bigeye tuna catches of these fisheries. The catch is estimated to have increased rapidly since the mid-1990s, reaching 18,000 t in 2002 (**Figure 10**).

2.4 Other fisheries

The only other significant bigeye tuna catches recorded in the WCPO are by pole-and-line vessels, primarily Japanese coastal and distant-water vessels (Indonesian pole-and-line catches are included catch figures discussed in section 2.3). These catches have varied between 1,000 t and 3,000 t per year. The largest component of the catch occurs in the Japanese coastal fishery, but small catches also occur in equatorial waters.

2.5 Total bigeye tuna catch in the WCPO

The estimated total catch of bigeye tuna in the WCPO is shown in **Figure 11**. The catch is dominated by the longline fishery, although the purse seine fishery and Philippines and Indonesian domestic fisheries have become significant over the past decade. The total catch has exceeded 100,000 t per year since 1997.

2.6 Size composition of the catch

Figure 12 shows the evolution of the size composition of the WCPO bigeye catch both in terms of numbers of fish and weight by length class. Apart from the 1950s when longlining was more concentrated in North Pacific sub-tropical waters (where clear modal structure is characteristic), there has been little obvious change in longline size composition over the history of the fishery. However on closer inspection, we can see some truncation of the size composition for larger-sized bigeye – from the 1990s on, there are relatively few bigeye >170 cm FL in the catch compared with the earlier periods. Large catches of juvenile and some larger bigeye tuna by the purse seine fishery and domestic fisheries of Philippines and Indonesia become significant from the 1980s onwards. These fisheries tend to dominate the size composition when catches are expressed in number of fish; however longline catches are pre-eminent when the catch composition is expressed in weight (**Figure 12**).

3 Fishery data collection systems

Fishery data for bigeye tuna are collected through several related data collection systems. Here we describe logsheet, observer, and port sampling data collection by SPC in the WCPO. We also outline the current status of data collection systems in Philippines and Indonesia.

3.1 Logsheet data

Catch and effort logsheet data easily provide the highest coverage of any data collected in the WCPO tuna fisheries. Catch and effort logsheet data are available in two basic forms, data provided at the fishing operation level and data aggregated by month and 1°x1° or 5°x5° grid fishing areas. The aggregate data are provided by distant-water fishing nations and generally cover the extent of their fisheries. **Table 1** shows the coverage of catch and effort logsheet data by gear for recent years, excluding the Indonesian and Philippine domestic fisheries. Coverage of purse seine data has been close to, or at 100% in recent years. The aggregate data for the distant-water pole-and-line and longline fleets include high-seas activities, which are generally not provided in the logsheet data at the fishing operation level.

The accuracy of reporting bigeye catch on logsheets varies by gear type. In the longline fishery, bigeye is one of the main target species and therefore catch (in number) is reported for each fishing operation (i.e., longline set). The longline logsheet has provision for recording the catch in weight but this is typically a visual estimate since most vessels do not have weighing devices on board (the actual weight of the catch by species for the entire trip is usually obtained at point of unloading; see port sampling data below).

The logsheet used in the purse seine fishery has the provision for reporting bigeye catch, but it is rarely reported since bigeye are not only difficult to distinguish from juvenile yellowfin, but are commercially equivalent, and therefore reported as one catch in the column for yellowfin. At this stage, there is no reliance made on the catch of bigeye reported on purse seine logsheets. This also tends to be the case in the pole-and-line fishery; while there is provision to record bigeye catch on the pole-and-line logsheet, bigeye are usually grouped with the yellowfin catch.

3.2 Observer data

Scientific observers are trained to collect catch and effort data from longline, pole-and-line and purse seine vessels operating in the region. Unlike logbook data collection, observers collect very detailed information on the components of fishing effort and individual catch from each fishing operation. Unfortunately, observer coverage is currently much lower than logsheet coverage (for 2001: 6.4% for the purse seine fishery; 0.5% for the longline fishery and ~0.1% for the pole-and-line fishery). Observer coverage of the WCPO purse seine fishery is skewed towards effort on-board US purse seine vessels, which is conducted through a regional program targeting 20% coverage each year (**Table 2**). The main constraints to increasing observer coverage at this stage are the lack of resources (human and financial) and the effort required to identify and train suitable candidates to become observers.

Observers on longline vessels record information for each bigeye tuna taken by the gear; information collected includes the fork length, the condition (life status), the fate and sex. Due to the large numbers of fish taken in sets on purse seine and pole-and-line vessels, observers must randomly sample the catch when it is placed onboard the vessel. The sub-component yellowfin/bigeye species composition data collected is then used to estimate the bigeye catch expected in the combined ‘yellowfin plus bigeye’ catch reported on catch logsheets (since bigeye catch is not accurately reported on purse seine and pole-and-line logsheets).

Observers may also be required to collect samples from bigeye for aging (otolith) and stomach-content studies, for example

3.3 Port sampling data

Port samplers are required to collect total weight and size data by species at ports of unloading throughout the region (**Figure 13**). The coverage of port sampling is currently constrained by problems caused by vessels using remote ports and countries not having the resources to undertake the work involved. In 2001, port sampling coverage of the purse seine fishery (based on trips sampled) was 29.4% and coverage for the longline fishery was 10.9% (there was negligible sampling of the pole-and-line fishery during 2001). In the longline fishery, port samplers are required to collect individual length and weight measurements from the entire target catch (i.e., including bigeye) of a vessel unloading. The port sampler is also required to liaise with the fishing company or unloading agent to obtain the total unloaded catch by weight and species for each vessel unloading; this information can then be used to adjust the catch reported on the logsheet (see above).

Port samplers in the purse seine and pole-and-line fisheries must select certain storage wells to ensure their sample can be readily identified to an acceptable time/area/set-type stratum. Once a well has been selected, the port sampler randomly samples the storage well as it is being unloaded. In some ports, more emphasis is placed on obtaining yellowfin/bigeye species composition data since this is critical in estimating the bigeye catch in these fisheries, although the normal random sampling protocol used in port sampling is considered sufficient to estimate the bigeye catch. The importance of port sampling data collection in determining the catch of bigeye in these fisheries has resulted in several reviews being undertaken in recent years, with work in this area expected to continue in the coming year.

3.4 Philippines and Indonesia

Data collection in the Philippines and Indonesian fisheries has been restricted to sampling at ports of unloading and several cruises undertaking tagging experiments. The coverage of sampling over the past decade has generally been hampered by the lack of resources to cover such diverse and widespread fisheries. Indeed, there has been little or no sampling related to bigeye catch in the Indonesian tuna fishery for more than ten years. In the Philippines, the recent port sampling projects of 1993–1994 (the Landed Catch and Effort Monitoring Project) and the 1998–2002 (National Stock Assessment Project) involved government staff collecting random samples from a variety of fisheries (e.g., purse seine, ring-net, handline, longline and troll) at key ports of unloading. The coverage of port sampling undertaken in these projects is considered poor, but has at least allowed some indication of the extent of the bigeye catch in this area of the WCPO. The distinction between very small bigeye and yellowfin has been a key area of work in the latter Philippines port sampling project and the data should therefore be a useful inclusion to stock assessments once available.

4 Stock assessment

Assessments of the status of bigeye tuna populations in the Pacific have, in the past, been hampered to some extent by difficulties in selecting the most appropriate geographical scale on which to conduct assessments. This results because of a lack of information on the extent of spatial mixing of bigeye across this wide area. Analysis of mtDNA and DNA microsatellites in nearly 800 bigeye tuna failed to reveal significant evidence of widespread population subdivision in the Pacific (Grewe and Hampton 1998). While these results are not conclusive regarding mixing rates, they are broadly consistent with the results of SPC's tagging experiments on bigeye tuna. Bigeye tuna tagged in locations throughout the western tropical Pacific have displayed movements of up to 4,000 nautical miles (Hampton and Williams SCRS/2004/058, this meeting) over periods of one to several years, indicating the potential for gene flow over a wide area; however, the large majority of tag returns were recaptured much closer to their release points. Also, recent tagging experiments in the EPO using archival tags have so far not demonstrated long-distance migratory behaviour (Schaefer and Fuller 2002) over relatively short time scales (< 2 years). In view of the ongoing uncertainty regarding basin-scale mixing rates over generational time scales, stock assessments of bigeye tuna have been conducted recently for the WCPO and EPO separately; however, a Pacific-wide model, incorporating spatial structure into the analysis to allow for the possibility of restricted movement between some areas, is also being developed for comparative purposes (Hampton *et al.* 2003).

The bigeye tuna assessment presented in this section is based on the MULTIFAN-CL[3] assessment of WCPO bigeye tuna presented at the 2003 meeting of the Standing Committee on Tuna and Billfish (SCTB 16) (Hampton *et al.* 2003). The assessment will soon be updated to incorporate additional Japanese longline size composition data from the 1950s and 1960s and other data. This new assessment will be presented to SCTB 17 in August 2004.

4.1 Stock assessment data compilation

The data used in the bigeye tuna assessment consist of catch, effort, length-frequency and weight-frequency data for the fisheries defined in the analysis, and tag release-recapture data. The details of these data and their stratification are described below.

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–40°S, 120°E–150°W. Within this overall area, a five-region spatial stratification was adopted for the assessment (**Figure 2**). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally.

The time period covered by the assessment has been extended back to 1950, to cover most significant post-war tuna fishing in the WCPO. The primary time period covered by the assessment is 1950–2002. An additional two years (i.e., to the end of 2004) are added as a projection period. Within this period, data were compiled into quarters (Jan-Mar, Apr-Jun, Jul-Sep, Oct-Dec).

MULTIFAN-CL requires the definition of 'fisheries' that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). Seventeen fisheries have been defined for this analysis on the basis of region, gear type and, in the case of purse seine, set type (**Table 3**).

4.1.1 Catch and effort data

Catch and effort data were compiled according to the fisheries in **Table 3**. Catches by the longline fisheries were expressed in numbers of fish, and catches for all other fisheries expressed in weight. This is consistent with the form in which the catch data are recorded for these fisheries. Purse seine catches of bigeye are not reliably

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[3] MULTIFAN-CL is a length-based, age-structured statistical model that is typically fit to catch, effort, size and tagging data. The software and its documentation are available on the MULTIFAN-CL web site www.multifan-cl.org.

recorded on logsheets for most fleets, and must be estimated from sampling data. The methods used to derive such estimates for the purse seine fishery are described in Lawson (2002).

Effort data for the Philippines and Indonesian fisheries were unavailable and the relative catch was used as a proxy for effort. Alternatively, we could have defined effort for these fisheries to be missing, in which case the relative effort over time would have been determined only by the effort deviations, which have a lognormal probability distribution with constant mean and variance. We felt that it was better to have a “null hypothesis” of effort proportional to catch, rather than constant over time. In practice, this assumption has not been found to influence the results overly, as the variance of the effort deviations for these fisheries is set at a high level to give the model flexibility to fit the total catch.

Effort data units for purse seine fisheries are defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (log, FAD or school sets) in logbook data. For the longline fisheries, we typically use several estimates of effective (or standardised) effort derived in separate studies (Bigelow *et al.* 2003; Langley 2003) for SCTB assessment reports. Separate analyses are then undertaken for each longline effort series and the assessment results compared. The various standardised longline CPUE series from which the standardized effort series were derived for the SCTB 16 bigeye assessment are shown in **Figure 14**. The results presented here are restricted to those of the base-case analysis, i.e., those based on the general linear model estimates of standardized longline effort. The assessment results based on the other standardization methods can be found in Hampton *et al*. (2003); however, the overall stock assessment conclusions were not found to be overly sensitive to the choice of standardization method.

Within the model, effort for each fishery was normalised to an average of 1.0 to assist numerical stability. Some longline fisheries were grouped to share common catchability parameters in the various analyses. For such grouped fisheries, the normalisation occurred over the group rather than for the individual fisheries so as to preserve the relative levels of effort between the fisheries. Also, effort for these fisheries was divided by the relative size of the respective region, assuming that the bigeye stock occupies the entire region for the modelled time period. The application of these procedures allowed longline CPUE to index exploitable abundance in each region (rather than density), which in turn allowed the simplifying assumption that catchability for the longline fisheries is the same among regions.

4.1.2 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 120 2-cm size classes (10–12 cm to 228–230 cm). Each length-frequency observation consisted of the actual number of bigeye tuna measured. A graphical representation of the availability of length (and weight) samples is provided in **Figure 15**. The data were collected from a variety of sampling programs, which can be summarized as follows:

- Philippines: Size composition data for the Philippines domestic fisheries derived from a sampling program conducted in the Philippines in 1993–94 were augmented with data from the 1980s and for 1995 for the 2002 assessment. No additional size data were available for this assessment, although additional data are expected to be available next year.
- Indonesia: Limited size data were obtained for the Indonesian domestic fisheries from the former IPTP database. Under the assumption that most of the catch is by pole-and-line gear, catches by the SPC tagging vessels operating in Indonesia in 1980 and 1991–93 have also been used to represent the size composition of domestic fishery catches. Therefore, the size data available for this assessment are the same as those used in previous years.
- Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling programs since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling program for U.S. purse seiners in Pago Pago, American Samoa and an observer program conducted for the same fleet. Since the early 1990s, port sampling and observer programs on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set. For each purse seine fishery, size samples were aggregated without weighting within temporal strata.
- Longline: The majority of the historical data were collected by port sampling programs for Japanese longliners unloading in Japan and from sampling aboard Japanese research and training vessels. It is assumed that these data are representative of the sizes of longline-caught bigeye in the various model regions. In recent years, data have also been collected by OFP and national port sampling and observer

programs in the WCPO. Note that in previous years, Japanese length-frequency data had consisted of a combination of actual length measurements and weight measurements converted to length. These data have now been separated and the Japanese length data now consist of length-measured fish only.

4.1.3 Weight-frequency data

Individual weight data for the Japanese longline fisheries previously converted to lengths and aggregated with length measurement data were available and included in this assessment in their original form. For many other longline fleets, 'packing list' data are available from export documentation, and these data are progressively being processed and incorporated into the assessment database. For this assessment, the available weight data (apart from those provided by Japan) originated from vessels unloading in various ports around the region from where tuna are exported, including Guam, Palau, Federated States of Micronesia (FSM), Marshall Islands, Fiji and eastern Australian ports. Data were compiled by 1 kg weight intervals over a range of 1−150 kg. As the weights were generally gilled-and-gutted weights, the frequency intervals were adjusted by a gilled-and-gutted to whole weight conversion factor for bigeye tuna (1.1018). The time-series distribution of available weight samples is shown in **Figure 15**.

4.1.4 Tagging data

A large amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of bigeye tuna tag releases and returns from the OFP's Regional Tuna Tagging Project conducted during 1989–1992, and more recent releases and returns from tagging conducted in the Coral Sea by CSIRO. Tags were released using standard tuna tagging equipment and techniques by trained scientists and technicians. The tag release effort was spread throughout the tropical western Pacific, between approximately 120°E and 170°W (see Kaltongga 1998 for further details).

For incorporation into the MULTIFAN-CL analyses, tag releases were stratified by release region (all bigeye tuna releases occurred in regions 2, 3 and 4), time period of release (quarter) and the same length classes used to stratify the length-frequency data. A total of 8,322 releases were classified into 18 tag release groups in this way. Of the 1,082 tag returns in total, 949 could be assigned to the fisheries included in the model. Tag returns that could not be so assigned were included in the non-reported category and appropriate adjustments made to the tag-reporting rate priors and bounds. The returns from each size class of each tag release group were then classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

4.1.5 Model description

The model can be considered to consist of several components, (i) the dynamics of the fish population; (ii) the fishery dynamics; (iii) the dynamics of tagged fish; (iv) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i)-(iv) are given in Hampton and Fournier (2001) and Hampton *et al.* (2003) and are summarized in **Table 4**. In addition, we describe the procedures followed for estimating the parameters of the model and the way in which stock assessment conclusions are drawn using a series of reference points.

4.1.5.1 Population characteristics

The model partitions the population into 5 spatial regions (**Figure 2**) and 40 quarterly age-classes. The first age-class has a mean fork length of around 25 cm and is approximately three months of age according to analysis of daily structures on otoliths (Lehodey *et al.* 1999). The last age-class comprises a "plus group" in which mortality and other characteristics are assumed to be constant. For the purpose of computing the spawning biomass, we assume that bigeye tuna in age-classes 1-10 are immature, 50% of bigeye in age-classes 11-12 are mature, and 100% of fish in age-classes 13-40 are mature. The relationship between length and weight is specified (based on length-weight data held by SPC) and held fixed in the model. The population is "monitored" in the model at quarterly time steps, extending through a time window of 1950–2004, with the final two years constituting a projection period. The main parameters estimated are quarterly recruitment in each region, age-specific selectivity for each fishery, effort deviations (which are parameters describing the random variability in the relationship between fishing effort and fishing mortality and which are constrained by distributional assumptions, or priors, specific to each fishery), average catchability and, for fisheries in which catchability is allowed to vary over time, catchability deviations (also constrained by fishery-specific distributional assumptions), movement parameters, age-specific natural mortality and growth parameters. The parameterization and constraints for these population dynamics processes are described in **Table 4**.

4.1.5.2 Parameter estimation

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. Some parameters were assigned specified starting values consistent with available biological information.

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

4.1.5.3 Stock assessment interpretation methods

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

− Fishery impact

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

We approach this problem by computing "unexploited" biomass time series (at the sub-region level) using the estimated model parameters, and assuming that fishing mortality was zero. Because both the *real* biomass B_t and the *unexploited* biomass B_{0t} incorporate recruitment variability, their ratio at each time step of the analysis, B_t / B_{0t} can be interpreted as an index of fishery depletion.

− Yield analysis

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

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 1999–2001. We do not include 2002 in the average because catch and effort data for several fisheries are available only until 2001.

− Fishery interaction

Estimates of fishery interaction are frequently of interest in a management context. In the case of bigeye tuna, it is of particular interest to estimate the impact of small fish catches – by the purse seine, Philippines and Indonesian fisheries – on the catch rates of the longline fishery. We undertake this analysis in a similar fashion to determining the impact of fisheries on stock biomass. But in this case, we set fishing mortality in the "small fish" fisheries to zero and observe the resulting increase in predicted longline catch. This increased catch is a measure of the impact of the "small fish" fisheries on the longline fishery.

4.1.6 Stock assessment results

For the full details of bigeye tuna parameter estimates, the reader is referred to Hampton *et al*. (2003). In this report, we report selected results of interest in the context of stock assessment interpretation.

4.1.6.1 Growth

The estimated growth curve is shown in **Figure 16**. The non-von Bertalanffy growth of juvenile bigeye tuna is evident, with near-linear growth in the 50–100 cm size range. This growth pattern is similar to that observed in both otolith and tagging length-increment data (Lehodey *et al*. 1999).

4.1.6.2 Natural mortality

Natural mortality (M) shows characteristic variation with size and age-class (**Figure 17**). There is an initial decline in M with age-class, reaching a minimum of 0.06 qtr^{-1}, after which the rate increases to about 0.17 qtr^{-1} before declining again to around 0.1 qtr^{-1} for the oldest age classes. The increase in M for the middle age-classes begins at about the size at first maturity. It is therefore possible that the increase is due to higher female mortality associated with spawning, and the subsequent decrease to lower natural mortality in an increasingly male-dominated population. It is also possible that the estimated variability in M-at-age is to some extent an artifact of other assumptions of the model, e.g., catchability and selectivity for the longline fisheries in the different regions being assumed to be constant over time and common among fisheries. If such assumptions are incorrect, it is possible that bias in M-at-age could be introduced. This possibility will be investigated by simulation analysis in the near future.

4.1.6.3 Recruitment

The recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in **Figure 18**. The regional estimates display large interannual variability and variation on longer time scales. For the aggregated estimates, there is an overall increasing trend over time. This is caused mainly by very low recruitment prior to about 1980, followed by much higher levels in regions 2 and 3.

Approximate 95% confidence intervals are provided for the aggregate WCPO recruitment estimates. Note the rapid expansion of the confidence region towards the end of the time series, and in particular as the model enters the projection phase. This is expected, as the model receives no data-based information on recruitment in this phase – the point estimates and confidence region largely reflect the priors on the recruitment deviations. Confidence intervals are also very wide prior to about 1965. There were no significant surface fisheries at this time, and size composition data for the longline fisheries pre-1965 are not currently available. Therefore, there is little information on quarterly recruitment levels during the early period of the fishery. This makes the interpretation of the estimated increasing trend in recruitment somewhat problematic. On the one hand, it may be viewed as suspicious that the model estimates sharply increased recruitment in the areas and at the times when the catches of small bigeye expanded. This poses the question of whether the model is simply increasing recruitment to accommodate the increased catches, rather than increasing fishing mortality. On the other hand, the poor resolution of recruitment pre-1965 could easily have created a misleading trend in the recruitment point estimates. This question might be resolved (i) when pre-1965 longline size composition data are available and (ii) by further analysis to investigate the effects of various catchability assumptions on the recruitment estimates.

4.1.6.4 Biomass

Estimated biomass time-series for each region and for the WCPO are shown in **Figure 19**. Biomass declines during the 1950s and 1960s in all regions except region 5. In regions 2 and 3, biomass recovers during the 1970s and 1980s before entering a sharp decline in the 1990s. Region 5 is marked by a strong increase in biomass from the mid-1990s. Overall, biomass declines during the 1950s and early 1960s, and is essentially stable thereafter.

4.1.6.5 Fishery impact

We measure fishery impact at each time step by comparing the estimated biomass to the biomass that would have occurred in the historical absence of fishing. The two trajectories are plotted in **Figure 20**. Impacts are significant in all regions, with the exception of region 5. Impacts are particularly strong in regions 2 and 3, where most of the catch is taken.

It is possible to ascribe the fishery impact, $1-B_t/B_{0t}$, to specific fishery components in order to see which types of fishing activity have the largest impact on population biomass (**Figure 21**). The longline fishery has a significant impact on the bigeye tuna population in all model regions; it is the most significant component of overall fishery impact in all regions with the exception of region 2 and is responsible for around half of the WCPO impact in recent years. In regions 2 and 3, the purse seine fisheries and the Indonesian and Philippines domestic fisheries also have high impact.

4.1.6.6 Effect of 'small fish' catches on the longline fishery

In the WCPO, the effect of the purse seine, Philippines and Indonesian fisheries on longline catch rates is of particular interest, because of the potential of such small fish catches to have a "downstream", negative impact on catches of larger more valuable bigeye. **Figure 22** shows the comparison of observed longline catches and the longline catches that are estimated would have occurred in the absence of the small-fish fisheries. As expected, the interaction effects are highest for the fisheries in regions 2 and 3, where the small-fish catches occur. However, there is also some effect in region 1, reflecting the movement of fish from regions 2 and 3 to region 1.

4.1.6.7 Yield analysis

The main results of the yield analysis are the estimates of the commonly used reference points $B_{current}/B_{MSY}$ and $F_{current}/F_{MSY}$. These ratios and their approximate 95% confidence intervals are plotted as a time series in **Figure 23**. Both total biomass and adult biomass have remained above their MSY-based reference points throughout the time series[4], but fishing mortality has exceeded the fishing mortality at MSY in recent years. The yield analysis therefore predicts that, under average recruitment conditions, biomass would soon decline below the MSY-based reference point.

We investigated the precision of the estimates of $F_{current}/F_{MSY}$ by comparing the normal approximation of the probability distribution obtained from the Hessian-Delta method with a probability distribution obtained by likelihood profile. The latter was derived by undertaking a series of fits strongly penalising the objective function for deviation from a series of target $F_{current}/F_{MSY}$ values. The exponentiated value of the posterior density at each of these points is proportional to the probability distribution of $F_{current}/F_{MSY}$. The distribution based on likelihood profile is quite different to the normal approximation (**Figure 24**). The modes are the same, but the likelihood profile distribution is skewed, indicating higher probability of higher $F_{current}/F_{MSY}$ than that predicted by the normal approximation. This suggests that a more cautionary interpretation of the yield analysis results is warranted.

5 Discussion

The assessment method used for bigeye tuna in the WCPO, like any assessment method, has strengths and weaknesses. A major strength of MULTIFAN-CL and similar methods is its ability to integrate information from many data and other information sources. The other major strength is that the specification of model structure is very flexible and thus model complexity can be easily tailored to data richness. The ability to model various biological processes, such as growth, movement and natural mortality, provides a means of evaluating the biological consistency of model results with other data. Of course, the price that we pay for complex, realistic models is that they are computationally intensive and parameter estimation is time consuming. One outcome of this is that, with the current generation of computers, the implementation of a fully-Bayesian approach to estimating uncertainty, for example by the use of the Markov Chain Monte Carlo approach, is not yet feasible for complex models. However, other approximations, such as likelihood profile, for estimating the posterior distributions of key management quantities such as $F_{current}/F_{MSY}$ are currently being developed and show considerable promise.

The 2003 bigeye tuna assessment strongly suggests that current level of bigeye exploitation is not sustainable in the long term, particularly if the apparent recent increase in productivity (elevated recruitment) is not permanent. This result is consistent across the various WCPO analyses conducted, is consistent with the results of a Pacific-wide bigeye assessment (Appendix A in Hampton *et al.* 2003) and is also consistent with the current status of bigeye tuna in the eastern Pacific Ocean determined by independent assessments (Appendix A in Hampton *et al.* 2003). A similar result was also obtained for a spatially aggregated analysis for the WCPO (Appendix B in Hampton et al. 2003). Largely as a result of the assessment, options for reducing fishing mortality on bigeye tuna are now being considered[5].

The 2003 bigeye assessment summarized in this report gave considerably different results to the 2002 assessment, apparently as a result of various changes to the bigeye tuna assessment database. We expect the

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[4] Note that plotting these ratios in a time series assumes that the average age-specific selectivity used in the yield analysis to calculate the MSY quantities was the same throughout the time series. We know that this is not the case because of the recent increase in surface fishery catches.

[5] A working paper discussing management options for bigeye tuna is currently being prepared by the Interim Secretariat of the Western and Central Pacific Fisheries Commission Preparatory Conference and will be presented at PrepCon 6 in Bali, Indonesia in April 2004.

database to continue to evolve, not only through the addition of new data, but through the acquisition of historical data from the early longline fishery. Until the compilation of historical data is complete, some instability in the assessment results may continue. In the following sections, we discuss some of the main gaps in fishery data and biological information, and the assessment problems that result from these gaps

Bigeye tuna assessments in the WCPO continue to be hampered by gaps in fishery data and a lack of information on some key biological processes. In terms of fishery data, the main data gaps recognized are (in order of importance from a stock assessment perspective):

1. There is a need for better information on bigeye catches from the domestic fisheries of Philippines and Indonesia. As noted earlier, the current information is rudimentary at best, and current estimates of catch and size composition are supported by very little data. There is a need to establish (in the case of Indonesia) new sampling programs in the major landing ports to adequately estimate the species composition of the catch by various gear types and to collect information on the total catch and effort by major gear categories. Such sampling programs now exist in the Philippines, but they need to be assessed and enhanced if necessary. Once such sampling data are available, it may be possible to reconstruct the historical data for the major gear types. A proposal addressing these problems has been developed and is currently under consideration by countries participating in the WCPFC Preparatory Conference.
2. Currently, there is very limited size composition data available for the longline fishery prior to 1965. The lack of such data creates large uncertainty regarding bigeye stock conditions in the early years of exploitation, i.e., the 1950s and early 1960s. One of the impacts of this on the current assessment appears to be an underestimation of recruitment variability during this period. It also creates additional uncertainty in the estimation of initial fishing mortality rates. Some size composition data for the Japanese longline fishery is known to exist for this period, but have had to be re-processed from original records. It is hoped that this data processing will be completed in time for these data to be included in the 2004 assessment.
3. Other data of potential value for the early longline fishery operating out of Hawaii are also known to exist and may provide additional information on stock conditions in the 1950s and earlier. These data are currently being assembled in cooperation with the National Marine Fisheries Service in Honolulu.
4. Estimates of bigeye catches and size composition by purse seiners are based on at-sea observer and in-port sampling programs. Coverage of the purse seine fleet by these programs is currently dominated by the U.S. purse seine fleet operating out of American Samoa. The contribution of the U.S. fleet to the total catch has declined in recent years, and observer and port-sampling coverage of other fleets needs to be increased.

While there has been much recent progress in understanding several aspects of bigeye tuna biology, a number of important issues remain to be resolved. Those that have a direct impact on bigeye tuna stock assessments include the following:

1. New information is gradually coming to hand regarding the movement of bigeye tuna on a variety of spatial scales, largely through archival tagging studies (e.g., Schaefer and Fuller 2002). To date, the available information indicates a degree of regional fidelity at least at the EPO/WCPO scale, and perhaps at smaller scales. At the same time, conventional tagging experiments have documented movements of bigeye over distances as great as 4,000 km (Hampton and Williams SCRS/2004/058). Further tagging is required to establish the large-scale movement characteristics of bigeye tuna over generational time scales. A priority area for such tagging to occur would be in the tropical Pacific at 160°W–130°W, a particularly important longline fishing area that straddles the current definition of EPO/WCPO.
2. As noted above, recent archival tagging as well as conventional tagging have indicated that, at least in some areas, bigeye tuna display a degree of local residence over possibly many years. For example, conventional tagging experiments in the Coral Sea off northern Australia have resulted in a protracted time series of tag returns in the release area. Several such returns have now been recorded after more than 10 years at liberty (Hampton and Williams SCRS/2004/058, this meeting). Recently, a bigeye tuna tagged at the Cross Seamount in Hawaii was recaptured in the same location after 7 years at liberty (David Itano, pers. Comm.). If some bigeye tuna show a high degree of persistence associated with geographical features, such as seamounts, islands and larger land masses, the dynamics of such ‘resident populations’ (in particular, rates of emigration and replenishment) have clear implications for how local-scale fishing activities might be managed. It could also be important from a regional stock assessment perspective because of how we interpret and analyze longline catch and effort data to

estimate standardized CPUE and effort. For example, could some of the early declines in longline CPUE reflect local depletion of such ‘resident populations’ by fishing effort concentrated in the vicinity of such aggregations? Geographically fine-scale analyses of historical longline data may be able to shed light on this question. Further archival and conventional tagging of geographically associated and open-ocean bigeye tuna are also required to assess possible differences in movement behavior by these groups.

3. The increase in the use of both drifting and anchored FADS over the past decade raises related questions regarding bigeye tuna movement. Archival tagging in the EPO in the vicinity of FADs and oceanographic moorings is providing new information on bigeye tuna movement in relation to these objects. Given the large increase of both anchored and drifting FADs in the WCPO, we need to ask how the meso-scale or even large-scale movement characteristics of bigeye tuna have been altered by FADs. This has implications for our stock assessment models, which currently assume temporal stability in movement characteristics.
4. Recent archival tagging is also providing a wealth of new information regarding the vertical distribution of bigeye tuna. Such information can potentially be used in habitat models to produce estimates of longline CPUE and effort that are standardized for the effects of changing depth distribution of the fishing gear and bigeye tuna habitat. However, the deployment of archival tags on bigeye tuna has been limited to just a few locations in the Pacific, and it is not possible to extrapolate the observed depth distributions directly to other parts of the Pacific because of the likely impacts of different vertical temperature profiles and other oceanographic variability on the depth distribution of bigeye. Attempts have been made to use temperature distributions obtained from archival tag records to estimate depth distributions in other locations; however, the geographical stability of temperature-related vertical distribution is currently untested. We need to better understand the nature of the variability in bigeye tuna depth distribution, ideally in terms of environmental parameters that can be readily obtained through observation systems or oceanographic models. This will require more effort in deploying archival tags across a range of oceanographic environments in the Pacific.
5. Current bigeye tuna assessments in both the WCPO and the EPO rely on size composition data to provide information on bigeye tuna growth. In both assessments, there is assumed to be no spatial or temporal variation in growth rates. Such variability, if it occurs, could affect the assessments. For example, it has long been observed that the average size of longline-caught bigeye tuna increases from west to east across the equatorial Pacific. Yellowfin tuna share the same characteristic. Researchers in the 1950s (e.g., Murphy and Shomura 1955) attributed the changes in average size to differential growth rates resulting from west-to-east increases in productivity related to the equatorial upwelling. An alternative hypothesis, which is implicit in current stock assessments, is that the differences in average size reflect differences in the age composition of the catches. To our knowledge, this important issue remains unresolved, and might be addressed by analyzing length-at-age determined from otolith ring counts for bigeye tuna sampled at different longitudes along the equatorial area.
6. It has long been observed that bigeye tuna, in common with other tuna species, show size- and/or age-related changes in sex ratio, with females becoming increasingly rare with increasing fish size. The most likely explanation is that females and males have differential natural mortality, with females possibly having higher natural mortality rates following reproductive maturity because of the high energetic demands of female spawning. Another possibility is sexually dimorphic growth. It could be important to account for such differential mortality (or growth) in stock assessments. For example, should female and male spawning biomass be separately monitored for the purpose of determining stock status? Currently, the stock assessment models are not sex structured, and sex composition data are not routinely collected from the fisheries. Sex structure is currently being developed in the MULTIFAN-CL model, but historical data on sex-specific size composition are required to parameterize a sex structured model.

The availability of fisheries data and biological information to address the above gaps will be critical for improving the quality of the bigeye tuna stock assessment in the years to come. For the assessment model structure itself, the next major advance is likely to be the incorporation of multiple species in the one assessment. All of the fisheries that catch bigeye also catch other species of tuna, often during the same fishing operation. The purse seine, Philippines and Indonesian fisheries also catch skipjack and yellowfin tuna, while the longline fisheries also catch yellowfin and albacore tuna as well as a range of billfish species.

The following example provides an indication of the potential advantage of a multi-species assessment model. Currently, bigeye and yellowfin tuna assessments are carried out independently, and estimates of population biomass and other parameters are obtained. The species composition of the bigeye plus yellowfin group in purse seine log and FAD sets in the WCPO is approximately 25% bigeye (Lawson 2002, 2003). However, the estimates of bigeye and yellowfin exploitable biomass for floating object purse seine sets from the respective independent assessments generally indicate that bigeye comprise a somewhat lower proportion of the composite exploitable population (**Figure 25**), particularly in region 2. A similar proportion of bigeye to that observed in species composition samples would be expected if bigeye and yellowfin catchability by floating object purse seine sets is similar. Modeling both species simultaneously would allow common catchability constraints and observations such as species composition data to impact the estimates of relative population size of the two species, thus potentially providing additional information to the analysis. During 2004, we will be attempting to develop a multi-species version of MULTIFAN-CL, and a two-species model of bigeye and yellowfin tuna will likely be the first application.

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Table 1. Coverage (%) of catch and effort data by gear, 1995–2002. 'Logsheet' refers to coverage by operational level data only; 'Log + aggr' refers to coverage of operational level data and aggregate data (5°x5° spatial grids for months in the case of longline data and 1°x1° spatial grids for months in the case of pole-and-line and purse seine data). Aggregate data have not yet been provided for some fleets in 2002. These statistics exclude the Philippines and Indonesian domestic fisheries.

	Gear type					
	Longline		*Pole-and-line*		*Purse seine*	
Year	*Logsheet*	*Log + aggr*	*Logsheet*	*Log + aggr*	*Logsheet*	*Log + aggr*
1995	40.3	93.9	35.3	94.9	83.1	94.3
1996	30.0	82.8	23.6	92.8	86.7	95.8
1997	28.6	76.1	19.1	94.7	81.8	99.3
1998	25.6	72.7	27.5	96.1	83.0	98.4
1999	30.9	74.9	20.3	94.0	89.1	100.0
2000	31.5	74.4	9.7	94.9	83.8	98.7
2001	30.1	72.4	16.3	90.0	84.1	100.0
2002	22.2	(38.6)	14.6	(14.6)	90.8	100.0

Table 2. Coverage of observer data in the WCPO purse seine fishery for the main fishing fleets during 2001.

Vessel Nation	*Coverage (%)*
Main DWFN fleets	
Japan	1.8
Korea	1.9
Chinese Taipei	4.0
USA	28.5
Main Pacific-islands fleets	
FSM	14.6
Papua New Guinea	3.4
Philippines	11.3
Solomon Islands	12.4

Table 3. Definition of fisheries for the MULTIFAN-CL analysis of bigeye tuna.

Fishery	*Nationality*	*Gear*	*Region*
LL 1	All	Longline	1
LL 2	All excl. Chinese Taipei & China	Longline	2
CH/TW LL 2	Chinese Taipei and China	Longline	2
LL 3	All excl. Chinese Taipei & China	Longline	3
CH/TW LL 3	Chinese Taipei and China	Longline	3
LL 4	All excl. Australia	Longline	4
AU LL	Australia	Longline	4
LL 5	All	Longline	5
PS/LOG 2	All	Purse seine, log sets	2
PS/FAD 2	All	Purse seine, FAD sets	2
PS/SCH 2	All	Purse seine, school sets	2
PS/LOG 3	All	Purse seine, log sets	3
PS/FAD 3	All	Purse seine, FAD sets	3
PS/SCH 3	All	Purse seine, school sets	3
PH RN	Philippines	Ringnet	2
PH HL	Philippines	Handline	2
ID	Indonesia	Various	2

Table 4. Main structural assumptions of the bigeye tuna analysis, and details of estimated parameters, priors and bounds.

Category	*Assumptions*	*Estimated parameters (ln = log transformed parameter)*	*No.*	*Prior*		*Bounds*	
				μ	σ	*Low*	*High*
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.04 times actual sample size for non-longline fisheries and 0.1 times for longline fisheries with a maximum effective sample size of 100.	None	na	na	na	na	na
Observation model for weight-frequency data	Normal probability distribution of frequencies, variance determined by effective sample size and observed frequency. Effective sample size assumed to be equal to the actual sample size for the Australian longline fishery, and 0.1 times the actual sample size for other longline fisheries with a maximum effective sample size of 100.	None	na	na	na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	5	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal. PH RN and PH HL rates constrained to be equal. All reporting rates constant over time.	LL 1–LL5, CH/TW LL fisheries	7	0.5	0.7	0.001	0.9
		AU LL fishery	1	0.8	0.7	0.001	0.9
		PS fisheries	1	0.42	0.05	0.001	0.9
		PH, ID fisheries	2	0.8	0.05	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level from the quarter following the quarter of release.	None	na	na	na	na	na
Recruitment	Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (beta prior for steepness with mode at 0.9 and SD of 0.10) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	220	SRR	0.7	-20	20
		Average spatial distribution of recruitment	4	-	-	0	1
		Time series deviations from average spatial distribution (ln)	875	0	1	-3	3
Initial population	A function of the initial recruitment and equilibrium age structure in each region, which is in turn assumed to arise from the natural mortality and movement rates.	Initial recruitment scaling (ln)	1	-	-	-8	8
Age and growth	40 quarterly age-classes, with the last representing a plus group. Juvenile age-classes 1-8 have independent mean lengths constrained by a small penalty for deviation from the von Bertalanffy growth curve; adult age-class mean lengths constrained by VB curve. SD of length-at-age are log-linearly related to the mean length-at-age. Mean weights (W_j) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (a=0.0000210132, b=3.0 independently estimated from available length-weight data).	Mean length age class 1	1	-	-	20	40
		Mean length age class 40	1	-	-	140	200
		von Bertalanffy *K*	1	-	-	0	0.3
		Independent mean lengths	7	0	0.7		
		Length-at-age SD	1	-	-	3	8
		Dependency on mean length (ln)	1	-	-	-0.69	0.69

Category	*Assumptions*	*Estimated parameters (ln = log transformed parameter)*	*No.*	*Prior*		*Bounds*	
				μ	σ	*Low*	*High*
Selectivity	Constant over time. Various smoothing penalties applied. Coefficients for the last 4 age-classes are constrained to be equal. Longline selectivities are non-decreasing with increasing age. Longline fisheries L2-L5 share selectivity parameters.	Selectivity coefficients	518	-	-	0	1
Catchability	Constant over years and among regions for longline fisheries (effort data are scaled to reflect different region sizes). Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries. Non-longline fisheries and the Australian and Chinese Taipei/Chinese longline fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years.	Average catchability coefficients (ln)	13	-	-	-15	1
		Seasonality amplitude (ln)	14	0	2.2	-	-
		Seasonality phase	14	-	-	-	-
		Catchability deviations PH/ID (ln)	45	0	0.1	-0.8	0.8
		Catchability deviations other (ln)	76	0	0.7	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distributions. SD inversely proportional to the square root of normalized effort.	Effort deviations LL 1–LL5 (ln)	1005	0	0.16	-15	15
		Effort deviations PH, ID (ln)	380	0	0.22	-15	15
		Effort deviations other (ln)	889	0	0.7	-15	15
Natural mortality	Age-dependent but constant over time and among regions. Smoothing penalties constrain the age-dependency.	Average natural mortality (ln)	1	-	-	-	-
		Age-specific deviations (ln)	39	0	0.22	-5	5
Movement	Age-dependent and varies by quarter but constant among years. Age-dependency for each coefficient (2 per region boundary) is log-linear.	Movement coefficients	48	0	0.32	0	3
		Age-dependent component (ln)	48	0	0.32	-4	4

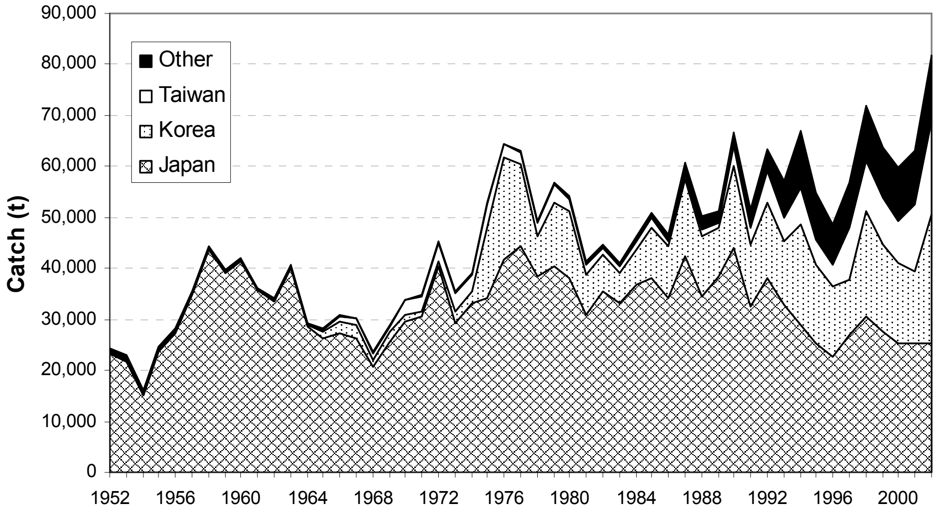

Figure 1. Catch of bigeye tuna by the major longline fleets in the WCPO.

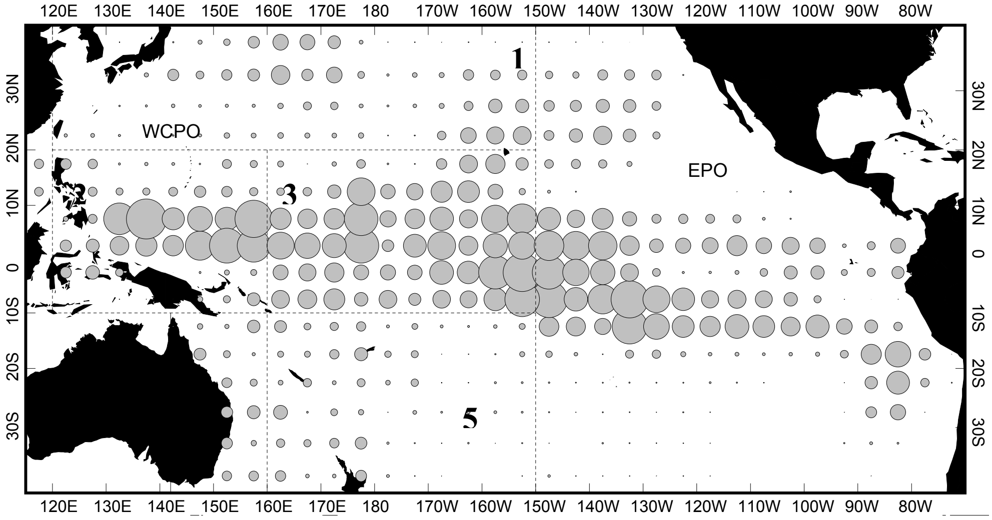

Figure 2. Geographical distribution of longline catch of bigeye tuna in the Pacific Ocean, 1998–2002. The dashed lines show the spatial stratification used for bigeye stock assessment in the WCPO.

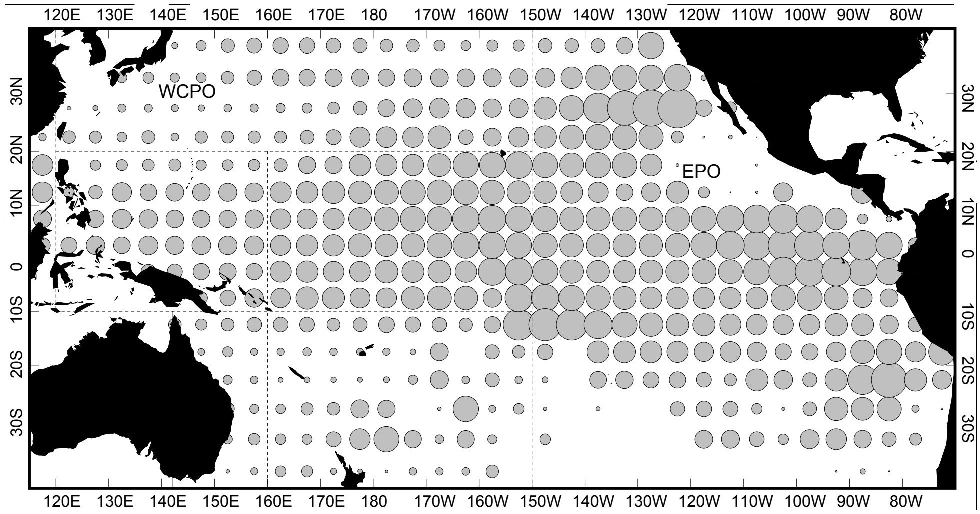

Figure 3. Longline CPUE by the Japanese longline fleet 1952–2002.

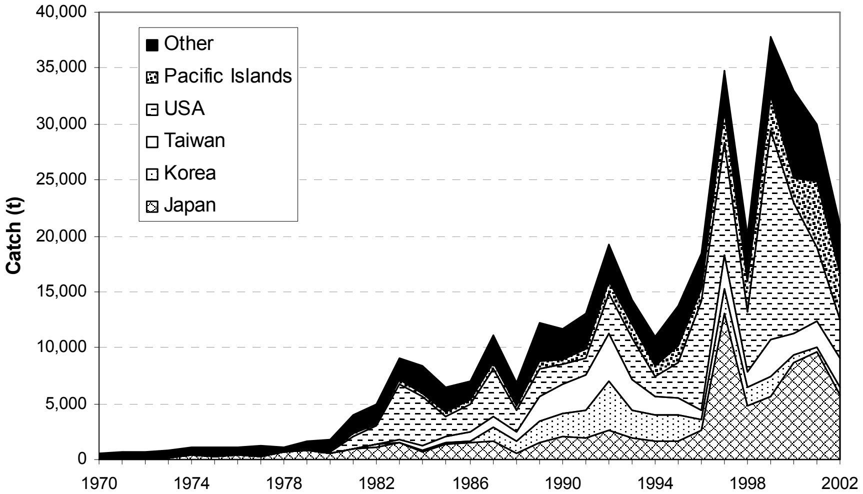

Figure 4. Catch of bigeye tuna by major purse seine fleets in the WCPO.

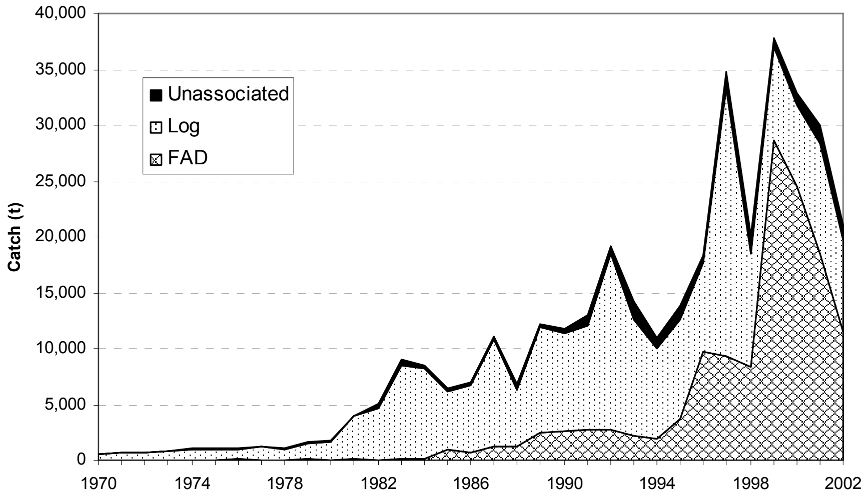

Figure 5. Purse seine catch of bigeye tuna in the WCPO, by set type.

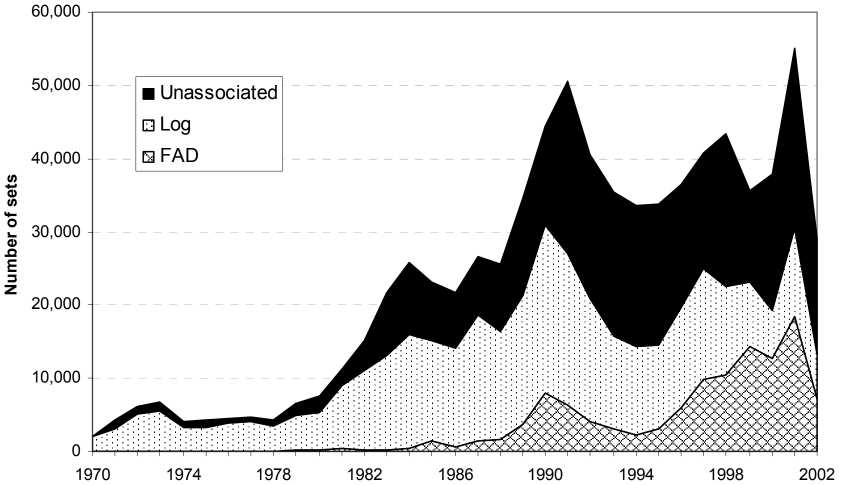

Figure 6. Annual number of purse seine sets, by set type, in the WCPO.

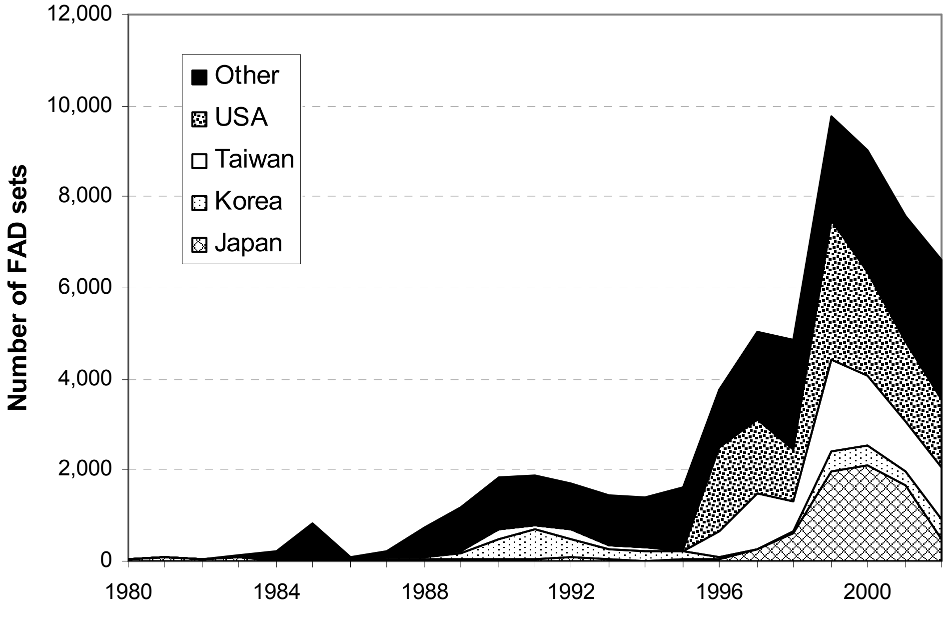

Figure 7. Number of FAD sets in the WCPO purse seine fishery, by nationality.

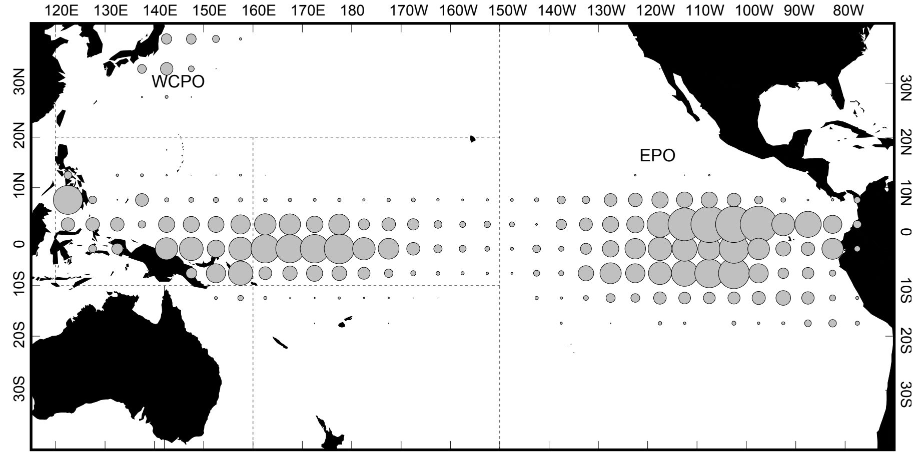

Figure 8. Geographical distribution of purse seine catches of bigeye tuna in the Pacific Ocean, 1994–1999.

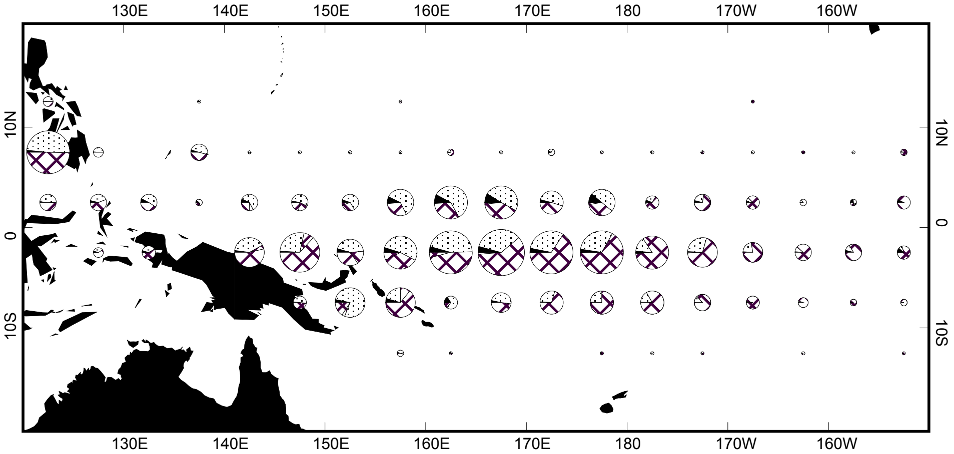

Figure 9. Distribution of bigeye tuna catch 1996–2002, by set type. Hatched: FAD sets; stippled: log sets; black: unassociated sets.

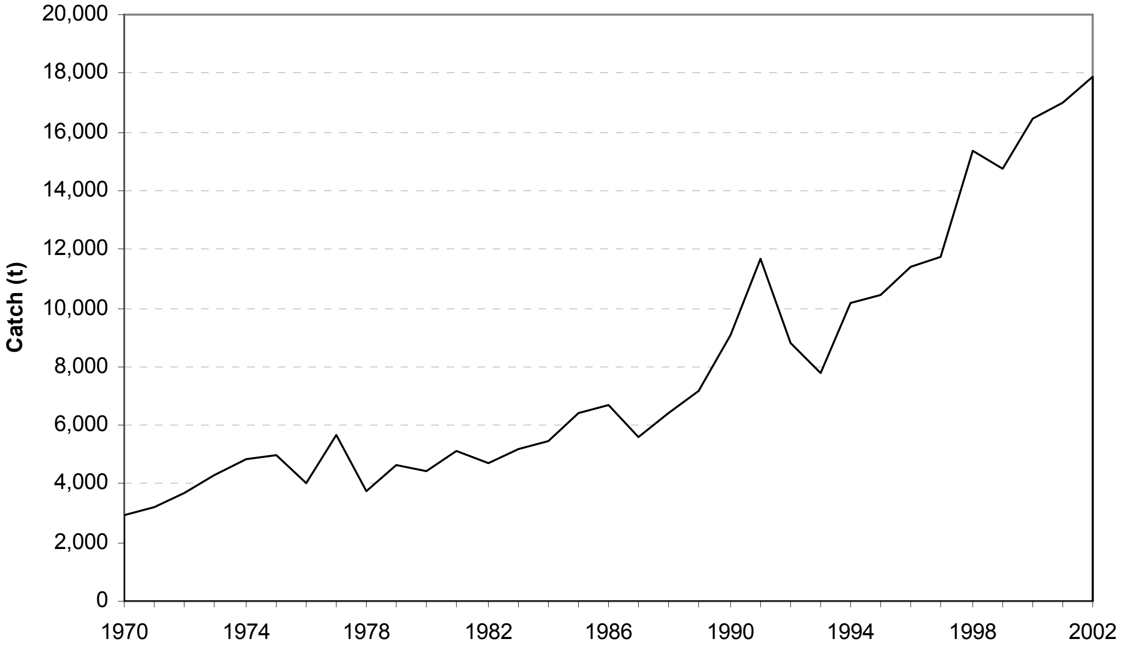

Figure 10. Catch of bigeye tuna by the domestic fisheries of Philippines and eastern Indonesia.

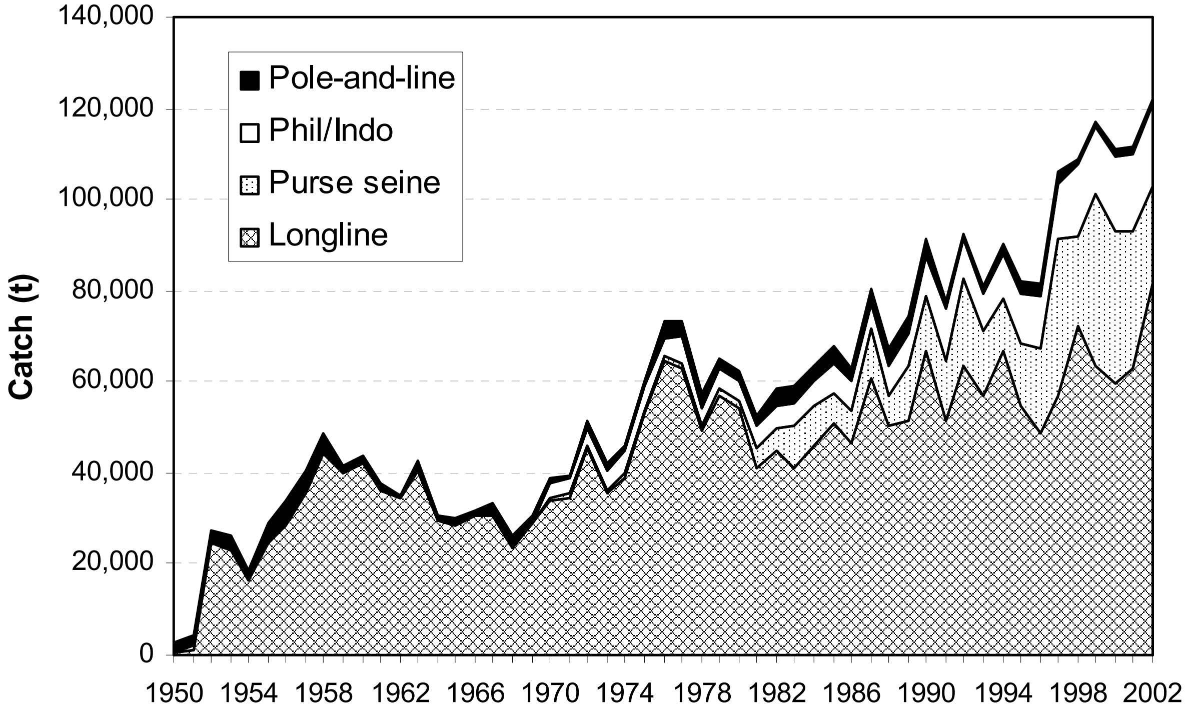

Figure 11. Catch of bigeye tuna in the WCPO, by gear type.

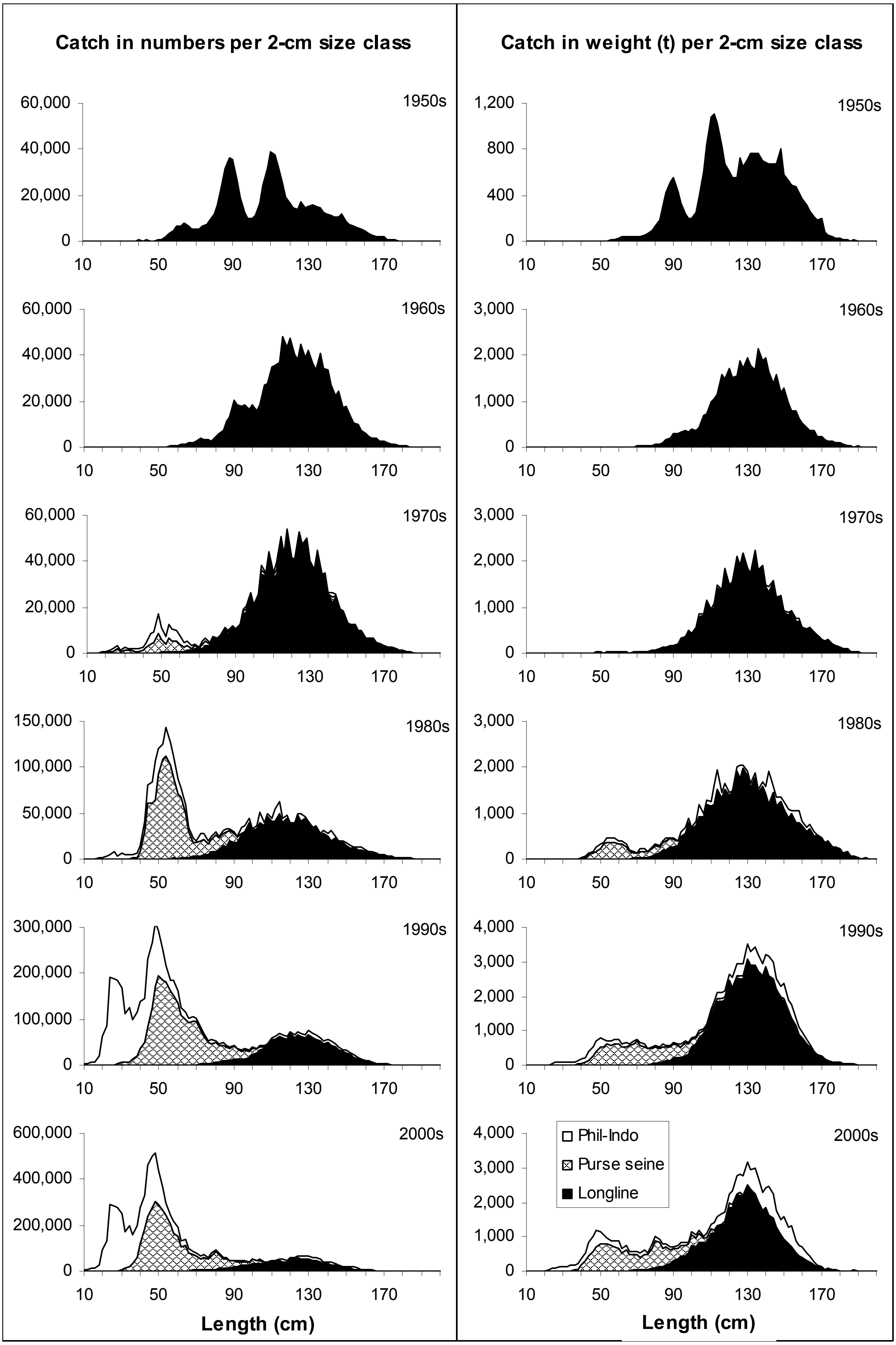

Figure 12. Average annual catches of bigeye tuna in the WCPO by size and gear type during decadal periods.

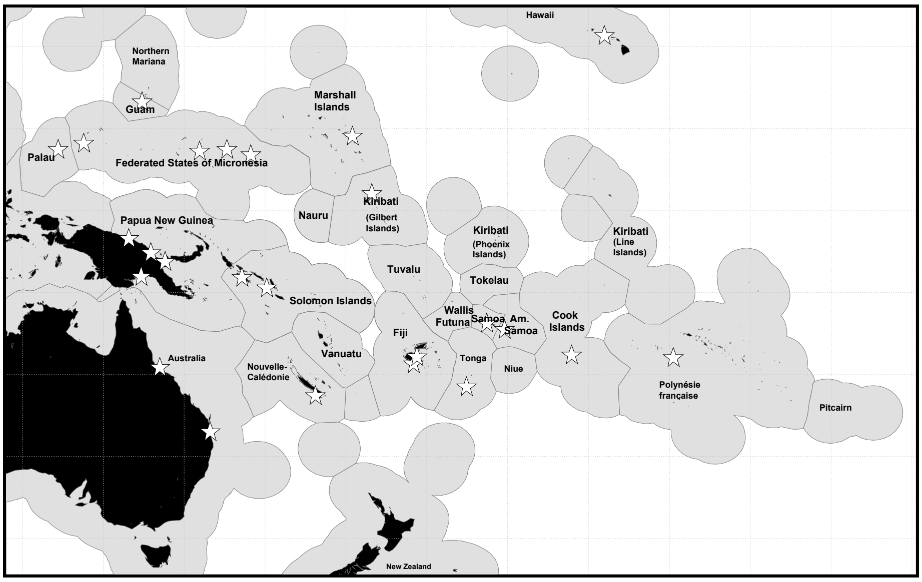

Figure 13. Port sampling locations in the WCPO tuna fishery.

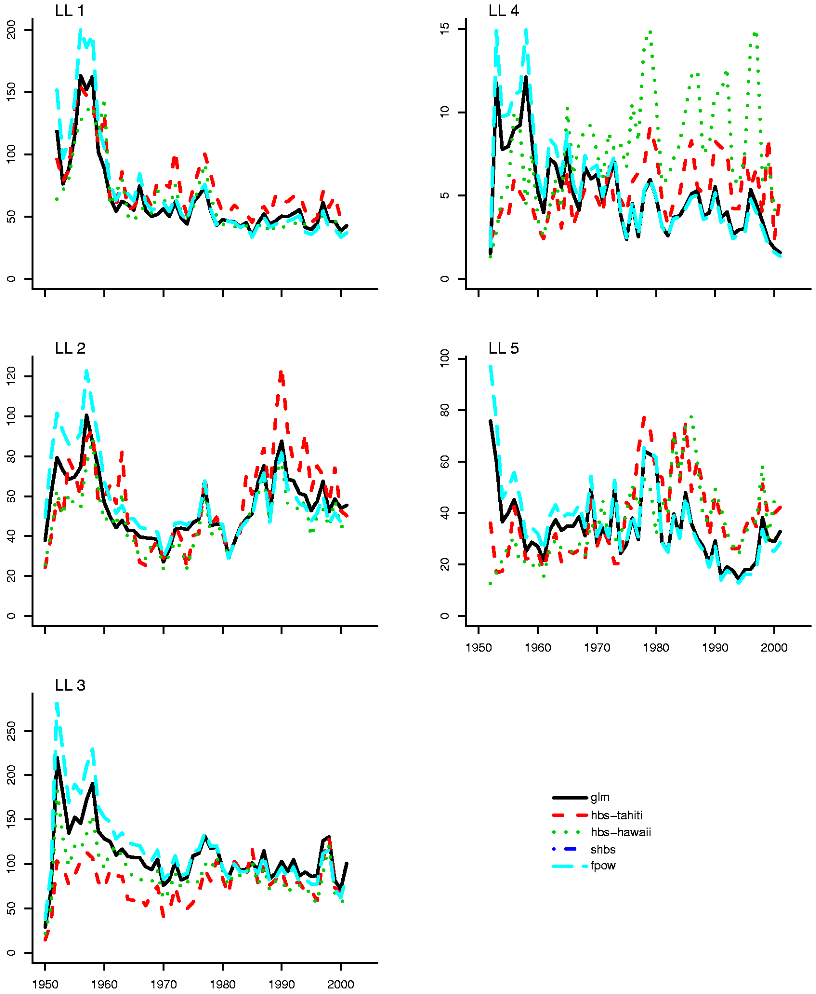

Figure 14. Catch-per-unit-effort (CPUE) for the longline fisheries LL1–LL5 standardised using four different methodologies. glm = general linear model; hbs-tahiti = habitat-based standardisation using a temperature preference hypothesis based on data from Tahihi; hbs-hawaii = habitat-based standardisation using a temperature preference hypothesis based on data from Hawaii; shbs = statistical habitat-based standardisation; fpow = glm standardised effort incorporating expansion for assumed fishing power increase of 1% per year.

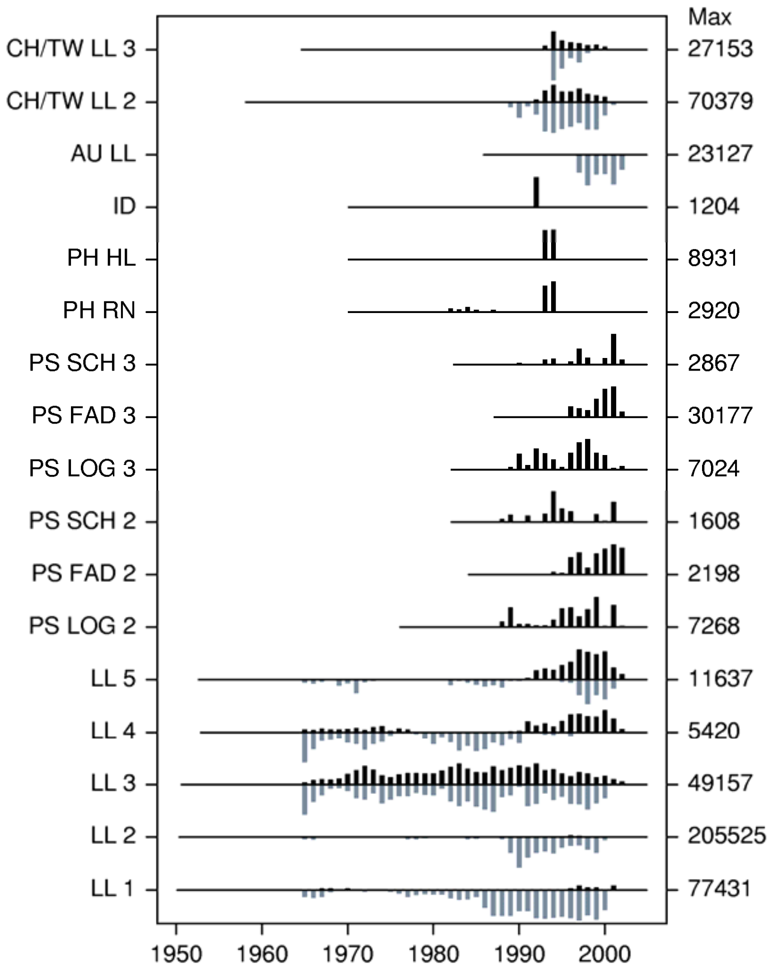

Figure 15. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The sample size corresponding to the maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

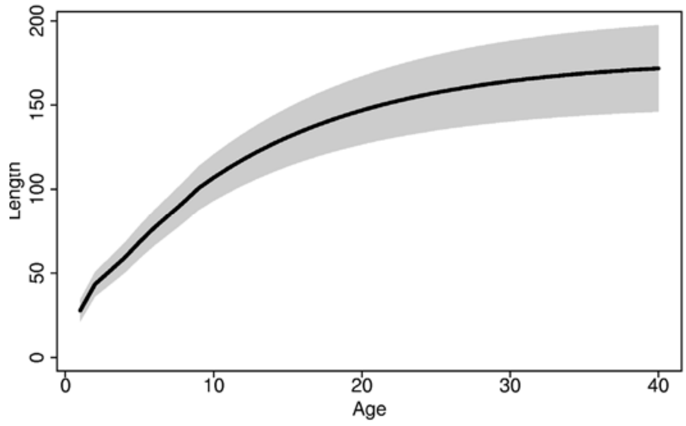

Figure 16. Estimated natural mortality rate by age class. The shaded area represents ± 2 SD.

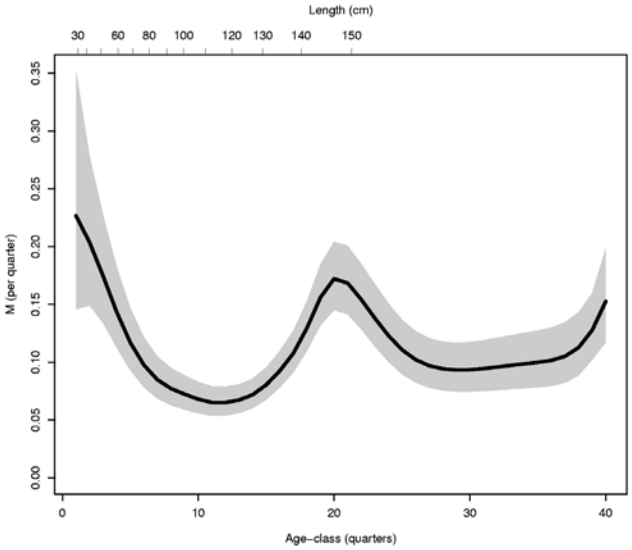

Figure 17. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm.

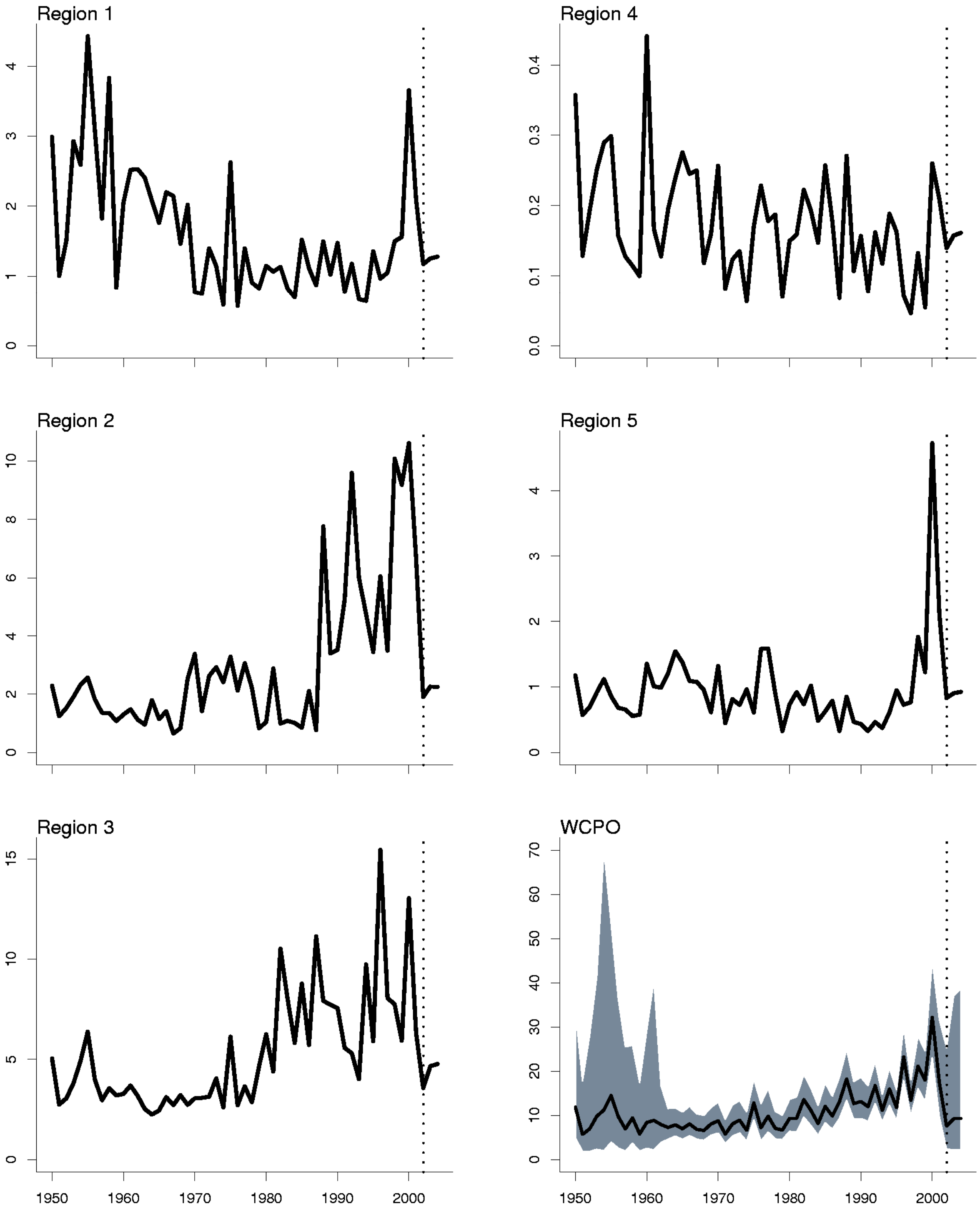

Figure 18. Estimated annual recruitment (millions) by region and for the WCPO. The shaded area for the WCPO indicates the approximate 95% confidence intervals. The dotted vertical line delineates data-supported model estimates from projections. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort.

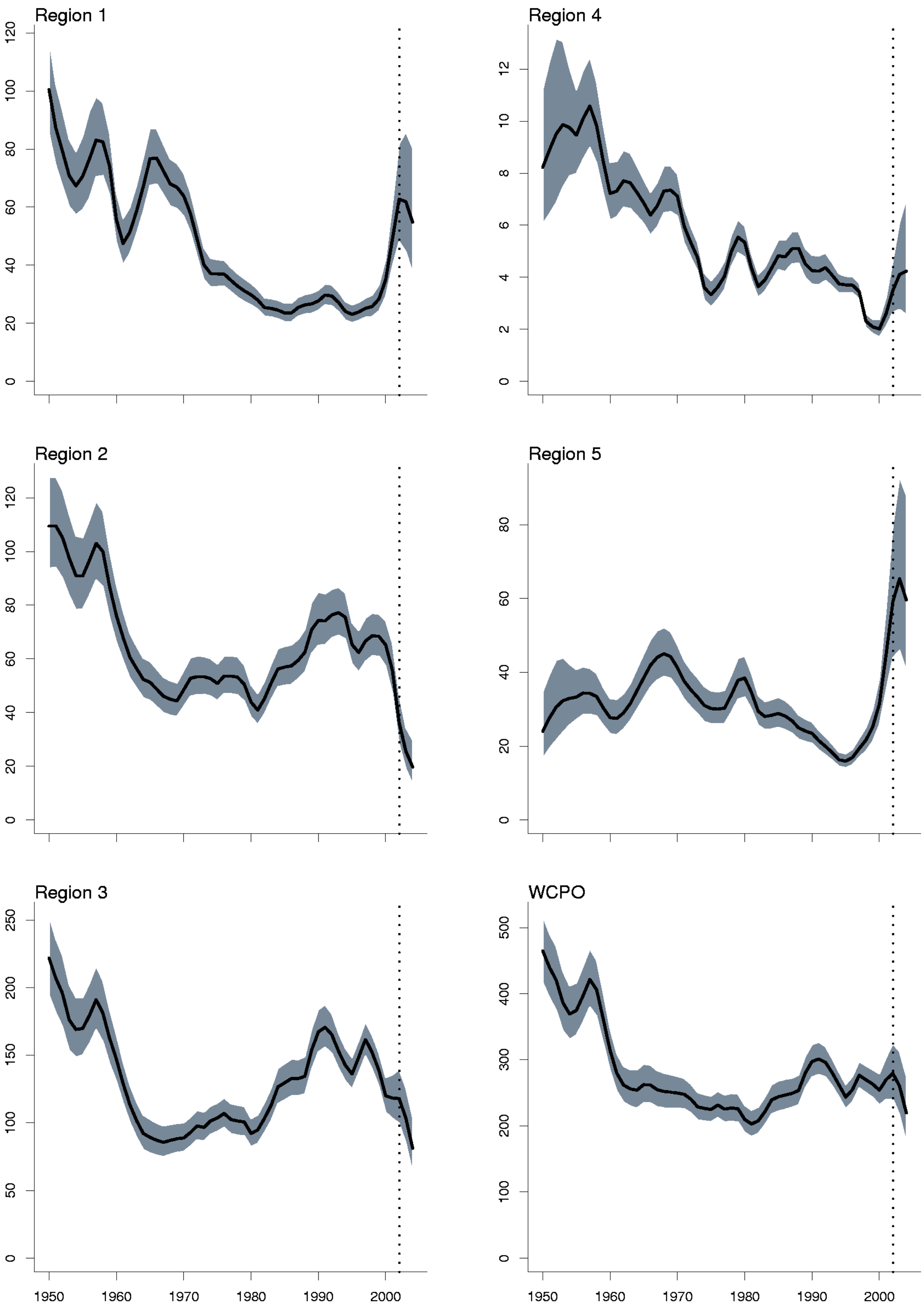

Figure 19. Estimated annual average total biomass (thousand t) by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort.

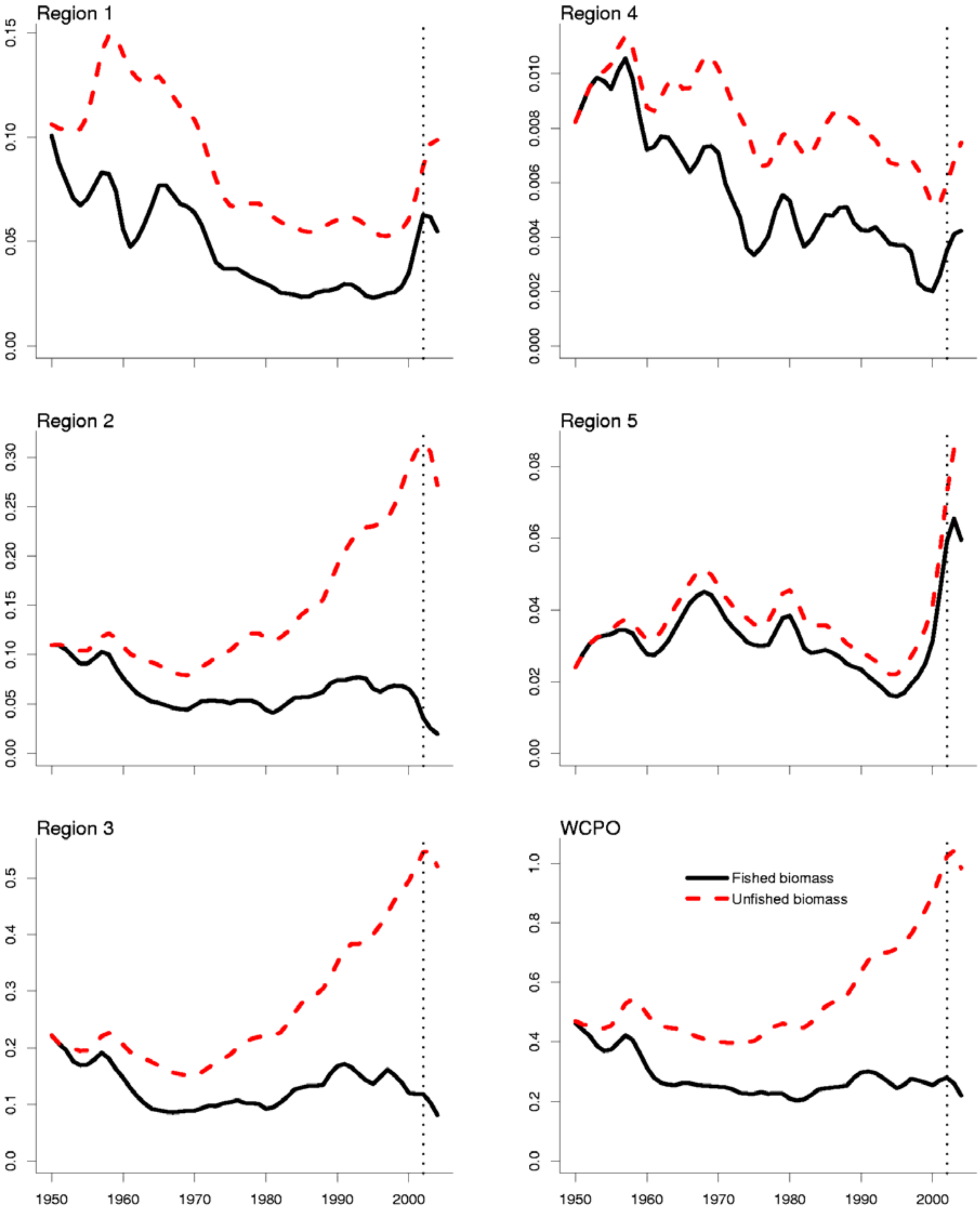

Figure 20. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for each region and for the WCPO. Y-axis units are million t.

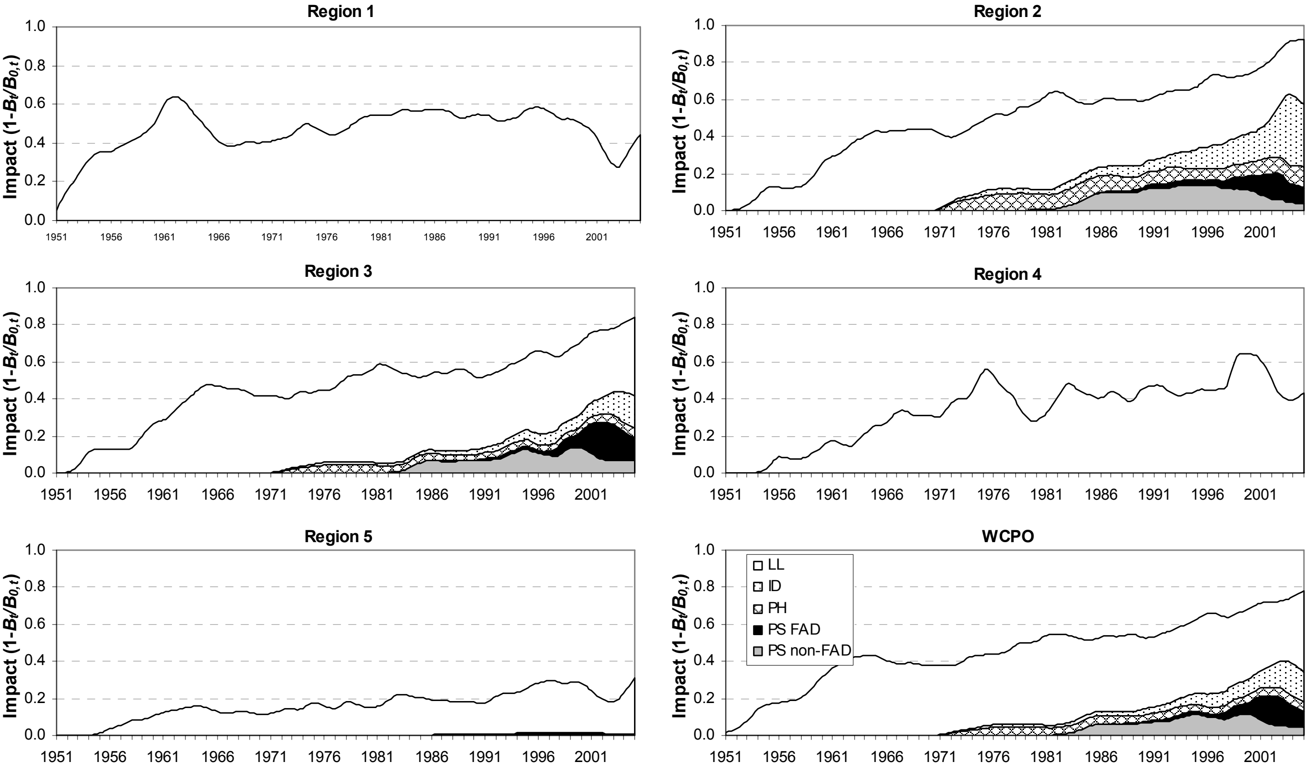

Figure 21. Estimates of reduction in total biomass due to fishing (fishery impact = 1-Bt/B0,t) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; ID = Indonesian domestic fishery; PH = Philippines domestic fisheries; PS FAD = purse seine FAD sets; PS non-FAD = purse seine log and school sets.

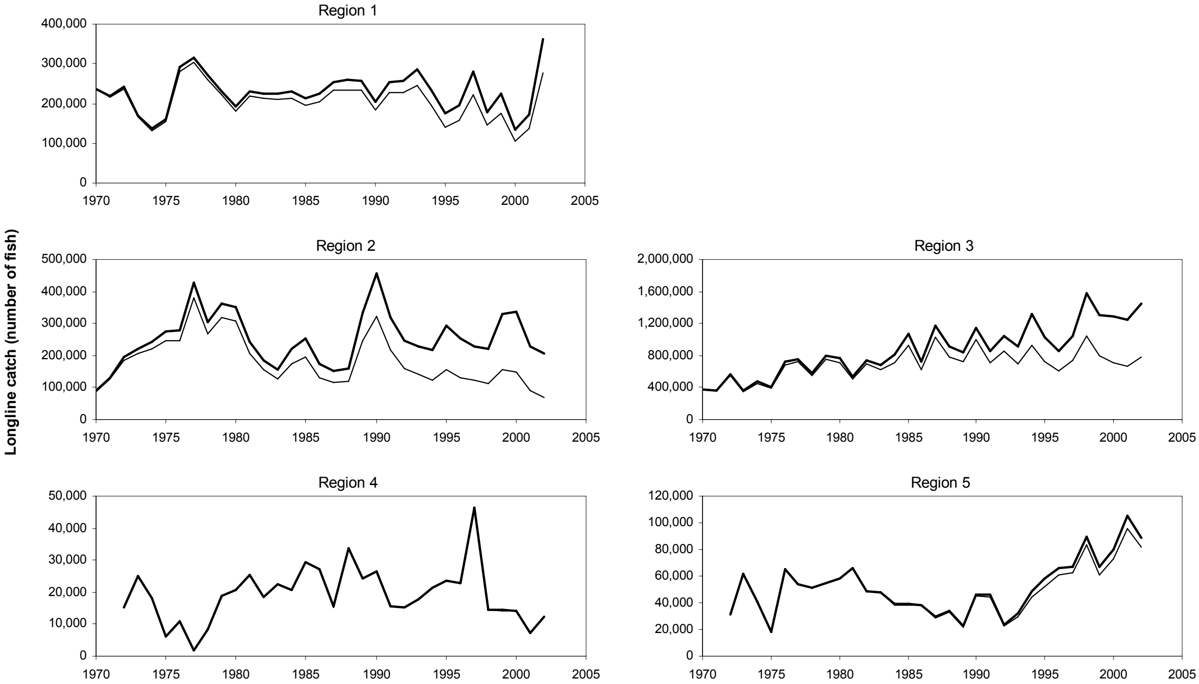

Figure 22. Combined impact of the purse seine, Philippines domestic and Indonesian domestic fisheries on longline catch. The upper thick lines represent estimated longline catches in the absence of these fisheries; the lower lines are the actual longline catches. The difference between the two lines is therefore a measure of interaction between the longline and "small fish" fisheries.

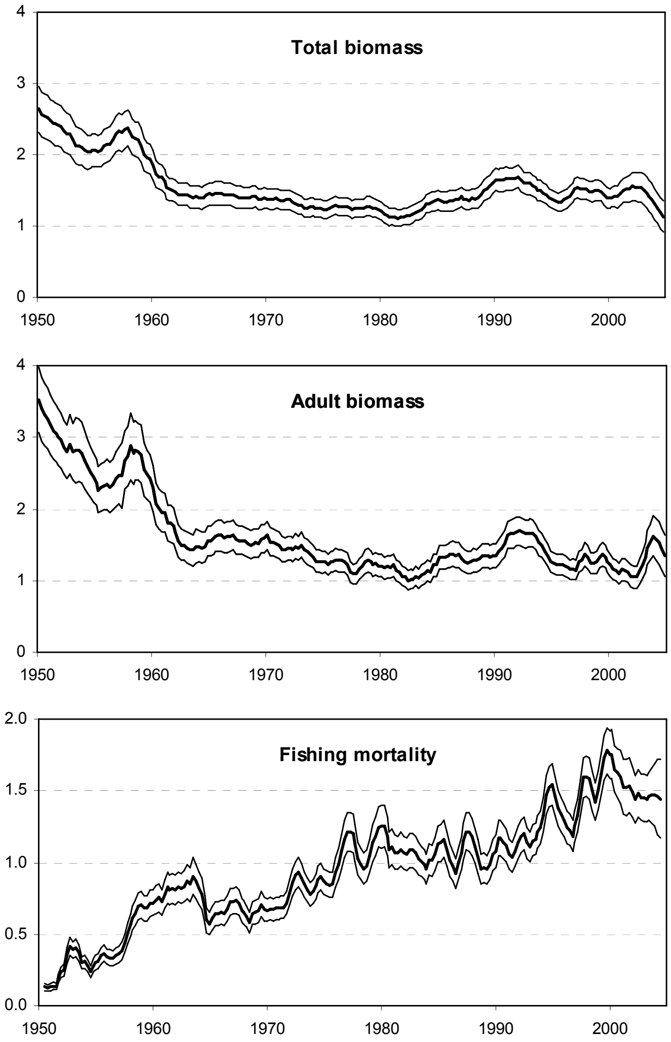

Figure 23. The ratios of total biomass, adult biomass and fishing mortality to their respective MSY quantities. Note that the estimates of biomass and fishing mortality at MSY are based on the average age-specific selectivity occurring in 1999–2001.

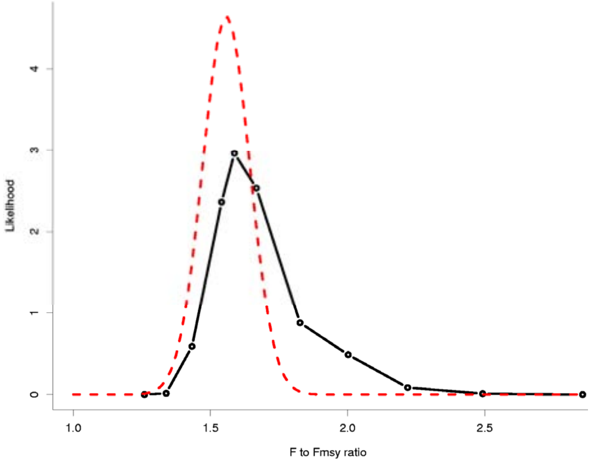

Figure 25. Probability distribution of $F_{current}$ / F_{MSY} based on the likelihood profile method (solid line) and the normal approximation using the Hessian-Delta method (dashed line).

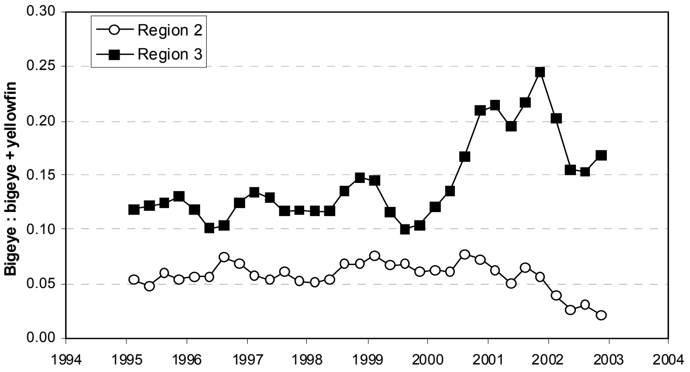

Figure 24. The ratio of purse seine floating objects sets exploitable biomass of bigeye to the sum of bigeye and yellowfin, as estimated from the 2003 assessments.