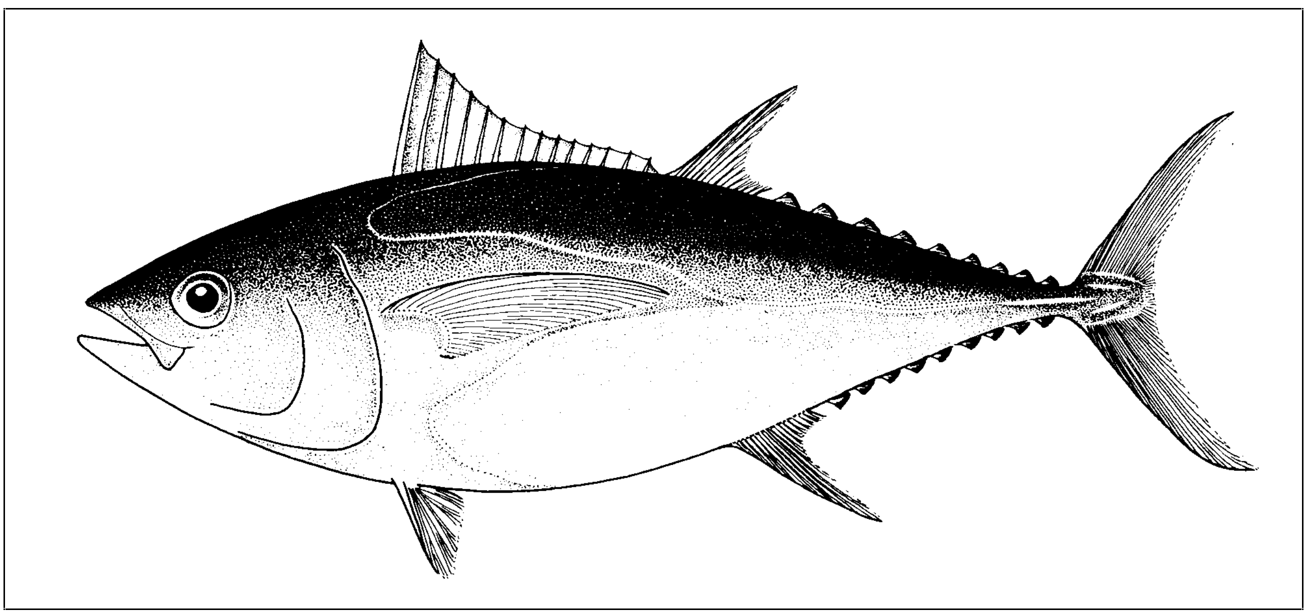
SECRETARIAT OF THE PACIFIC COMMUNITY
NOUMEA, NEW CALEDONIA

A SUMMARY OF CURRENT INFORMATION ON THE BIOLOGY, FISHERIES AND STOCK ASSESSMENT OF BIGEYE TUNA (*Thunnus obesus*) IN THE PACIFIC OCEAN, WITH RECOMMENDATIONS FOR DATA REQUIREMENTS AND FUTURE RESEARCH



Oceanic Fisheries Programme
Technical Report No. 36

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'**Pacific Community**' is the new name of the South Pacific Commission (SPC). The new name became official on 6 February 1998, in commemoration of the 51st anniversary of the 1947 Canberra Agreement which originally established the SPC.

The change of name does not alter the established SPC acronyms, but their meanings are modified.

'**Pacific Community**' applies to the total organisation, i.e. the member governments, the Conference, the CRGA and the Secretariat. '**Secretariat of the Pacific Community (SPC)**' refers to those who provide the service to members of the Community.

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ABSTRACT

Bigeye tuna (*Thunnus obesus*) are an important component of tuna fisheries throughout the Pacific Ocean. They are the principal target species of the large ‘distant-water’ longliners from Japan and Korea 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 therefore fundamental to the economic survival of the longline fishery in the western and central Pacific Ocean, the catch of which had a landed value in 1996 of approximately US$800 million. This report reviews aspects of bigeye tuna biology, catch estimates from pelagic fisheries exploiting bigeye, fisheries data collection systems and data gaps. Analyses are conducted to improve catch-per-unit-effort (CPUE) indices by partly accounting for operational (fishing gear) and environmental effects.

Since 1980, the Pacific-wide longline catch of bigeye has varied between 90,000 and 165,000 metric tonnes (t). Japanese longline vessels contribute over 80% of the catch. Longline catch in the eastern Pacific Ocean (EPO), the area east of 150°W, has varied in the range of about 50,000–115,000 t since 1980, surpassing 90,000 t during four years, whereas the catch was typically 40,000–60,000 t in the western and central Pacific Ocean (WCPO), the area west of 150°W.

Since 1994, a rapid increase in purse-seine catches of juvenile bigeye, first in the EPO and, in the past year in the WCPO, has created further uncertainty regarding the sustainability of the current levels of exploitation. Purse-seine catches in the EPO increased from typical levels of less than 10,000 t per year to approximately 30,000 t in 1994; 37,000 t in 1995; and 52,000 t in 1996 (the preliminary estimate for 1997 is also 52,000 t). These increases have been due to the adoption of new fishing methods involving the use of drifting fish aggregating devices (FADs) to aggregate tuna, and deeper purse-seine nets to catch the tuna, mostly bigeye, located deeper in the water column. In the WCPO, purse-seine catches of bigeye are estimated to have been less than 20,000 tonnes per year up to 1995, but the catch is believed to have increased significantly through the adoption of similar fishing techniques to those used in the EPO.

In Pacific tuna fisheries, SPC data collection systems include: 1) logbook records of catch and effort, 2) independent catch estimates based on at-sea observer records and 3) port sampling of size and weight of the landed catch. Logbook coverage is moderate (~50%) for vessels participating in the longline fishery, because there are incomplete data for distant water longliners (Japan, Korea and Taiwan) fishing in international waters (more complete data are held by the fishing nations concerned). Logbook coverage in the purse-seine fishery is high (>90%), but bigeye catches are not routinely estimated because they are not separated from yellowfin of similar size in the catch. The US Treaty observer programme annually monitors ~20% of the US purse-seine activity, but observer activity is poor (1%) in the other fleets. Over 1,000 longline vessels participate in the WCPO longline fishery; consequently, observer coverage is also low, approximately 1%. At-sea observer sampling is the only method of monitoring the quantities of bigeye (and other species) that are discarded. Observer estimates of the rate of discard of bigeye tuna averaged 5% for the longline fishery and 6% for the purse-seine fishery. Port sampling occurs in 24 regional ports in the WCPO.

CPUE indices are an integral part of stock assessment, but the indices are rarely proportional to stock size because many factors can affect fishing efficiency, such as area of fishing, targeting practices and oceanographic conditions. Trends in standardised longline CPUE were produced from the three major longline fleets by incorporating information on depth of fishing gear, and habitat (temperature and oxygen) preferences and constraints. For the EPO, standardised indices were similar to nominal CPUE trends, which suggested a decline during the 1960s and a period of stability thereafter. In contrast, trends in the WCPO were strongly dependent on assumptions of temperature preference. One hypothesis, based on the best available scientific data, indicated that population density had continuously declined since 1962 and that the mean population density in the 1960s was three times greater than in the 1990s. An alternative temperature preference hypothesis for the WCPO suggested that there had been a period of population stability, similar to that shown by the nominal CPUE trend.

The current status of the bigeye stock remains uncertain mainly because of 1) the difficulty of quantifying the effects of juvenile exploitation by the purse-seine fishery, 2) various hypotheses concerning the interpretation of CPUE trends and 3) data deficiencies which preclude the estimation of key population parameters. Suggestions are provided for future data and monitoring efforts and stock assessment requirements.

RÉSUMÉ

Le thon obèse (*Thunnus obesus*) est une composante importante des ressources thonières pêchées dans tout le Pacifique. Il est la principale espèce-cible des palangriers japonais et taiwanais de gros tonnage qui pratiquent la pêche hauturière, ainsi que des palangriers de plus petit tonnage ayant leurs principaux ports d'attache dans plusieurs États et territoires océaniens et qui ciblent le thon frais de qualité *sashimi*. Les cours des produits congelés et frais du thon obèse sur le marché japonais du *sashimi* sont les plus élevés parmi les thons des tropiques. Le thon obèse est donc fondamental pour la survie économique de la pêche à la palangre dans l'océan Pacifique occidental et central, où, en 1996, la valeur des prises au débarquement a avoisiné 800 millions de dollars É.-U. Ce rapport fait le point sur certains aspects de la biologie du thon obèse, sur les estimations de prises des flottilles de pêche pélagique qui exploitent cette espèce, sur le système de recueil des données halieutiques et sur les données manquantes. Des analyses sont effectuées pour améliorer les données de captures par unité d'effort (CPUE), en tenant partiellement compte des effets opérationnels (engins de pêche) et écologiques.

Depuis 1980, la quantité de thons obèses capturés dans l'ensemble du Pacifique varie entre 90 000 et 165 000 tonnes, dont plus de 80 pour cent sont à mettre à l'actif des palangriers japonais. Dans l'océan Pacifique oriental, c'est-à-dire dans la zone située à l'est de la longitude 150°O, le volume des prises a varié entre 50 000 et 115 000 tonnes environ depuis 1980, dépassant 90 000 tonnes pendant quatre ans, alors que, dans l'océan Pacifique occidental et central, à l'ouest de la longitude 150°O, il a généralement fluctué entre 40 000 et 60 000 tonnes.

Depuis 1994, un accroissement rapide des quantités de juvéniles de thon obèse capturés par les senneurs, tout d'abord dans l'océan Pacifique oriental, puis au cours de l'année dernière dans l'océan Pacifique occidental et central, fait planer de nouvelles incertitudes quant aux possibilités de maintenir à terme les niveaux d'exploitation actuels. Dans l'océan Pacifique oriental, les prises réalisées par les senneurs ont augmenté, passant de niveaux généralement inférieurs à 10 000 tonnes par an à environ 30 000 tonnes en 1994, 37 000 en 1995 et 52 000 tonnes en 1996 (selon les estimations préliminaires pour 1997, ce volume serait aussi de 52 000 tonnes). Ces augmentations ont résulté de l'adoption de nouvelles méthodes de pêche axées sur l'utilisation de dispositifs de concentration du poisson (DCP) dérivants destinés à regrouper les thons et de sennes plus profondes destinées à capturer les thons évoluant à de plus grandes profondeurs dans la colonne d'eau, essentiellement les thons obèses. Dans l'océan Pacifique occidental et central, d'après les estimations, les quantités de thons obèses capturés à la senne ont été inférieures à 20 000 tonnes par an jusqu'en 1995, mais il est très probable que, grâce à l'adoption de techniques de pêche semblables à celles utilisées dans l'océan Pacifique oriental, les prises ont augmenté substantiellement.

Dans les pêcheries de thon du Pacifique, les systèmes de recueil des données de la CPS s'appuient notamment sur : 1) les données de prises et d'effort issues des livres de pêche; 2) les estimations indépendantes de prises reposant sur les relevés des observateurs en mer; et 3) l'échantillonnage au port de la taille et du poids des prises débarquées. L'enregistrement des données dans les livres de pêche des palangriers est moyen (~50%), parce que les données relatives aux palangriers pratiquant la pêche hauturière (Japon, Corée et Taiwan) dans les eaux internationales (des données plus complètes sont en possession des pays concernés) sont incomplètes. Le taux d'enregistrement des données dans les livres de pêche des senneurs est élevé (>90%), mais le volume des prises de thon obèse ne fait pas habituellement l'objet d'estimations parce qu'il est englobé dans le volume des prises de thons jaunes de taille semblable. Le programme d'observation prévu au titre du traité multilatéral

conclu avec les États-Unis d'Amérique permet de surveiller chaque année environ 20 pour cent des opérations conduites par les senneurs américains, mais les activités d'observation des autres flottilles sont faibles (1%). Plus de 1 000 palangriers opèrent dans l'océan Pacifique occidental et central; les données statistiques obtenues auprès des observateurs sont donc également rares, de l'ordre de 1 pour cent. L'échantillonnage réalisé dans le cadre de missions d'observation en mer est la seule méthode qui permet de surveiller les quantités de thons obèses (et d'autres espèces) qui sont rejetés. D'après les estimations des observateurs, le taux de thons obèses non retenus est en moyenne de 5 pour cent pour les palangriers et de 6 pour cent pour les senneurs. Les opérations d'échantillonnage au port se déroulent dans 24 ports de l'océan Pacifique occidental et central.

Les indices de CPUE font partie intégrante de l'évaluation des stocks, mais ils sont rarement représentatifs de l'importance du stock parce que de nombreux facteurs peuvent avoir une incidence sur l'efficacité de la pêche, par exemple la zone de pêche, les pratiques en matière de ciblage et les conditions océanographiques. Des tendances de CPUE à la palangre normalisées ont été établies à partir de données obtenues auprès des trois principales flottilles de palangriers en intégrant les informations relatives à la profondeur de l'engin de pêche, aux préférences et aux contraintes liées à l'habitat des poissons (température et oxygène). Pour l'océan Pacifique oriental, les indices sont semblables aux tendances nominales de CPUE, ce qui donne à penser à un déclin pendant les années 60 et à une période de stabilité ensuite. Au contraire, dans l'océan Pacifique occidental et central, les tendances dépendent fortement des hypothèses de préférences de température. Selon les meilleures données scientifiques disponibles, une hypothèse indique que la densité de population a baissé de façon continue depuis 1962 et que la densité moyenne de population dans les années 60 était trois fois plus importante que dans les années 90. Une autre hypothèse liée à la préférence de température pour l'océan Pacifique occidental et central laisse penser qu'il y a eu une période de stabilité de la population semblable à celle qu'a fait apparaître la tendance de CPUE nominale.

L'état actuel du stock de thons obèses reste incertain, surtout pour les raisons suivantes : 1) la difficulté de quantification des effets de l'exploitation de juvéniles par la flottille de senneurs; 2) les différentes hypothèses concernant l'interprétation des tendances de CPUE; et 3) les lacunes statistiques qui ne tiennent pas compte de l'estimation des paramètres clés concernant la population. Des propositions sont faites concernant les conditions à remplir dans l'avenir pour les données, les efforts de surveillance et l'évaluation des stocks.

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SUMMARY OF BIGEYE TUNA BIOLOGY

FISHERIES FOR BIGEYE TUNA IN THE PACIFIC OCEAN

FISHERY DATA COLLECTION SYSTEMS

BIGEYE CPUE INDICES

LIST OF ACRONYMS

CSIRO	Commonwealth Scientific and Industrial Research Organisation
CPUE	catch per unit of effort
DO	dissolved oxygen
EPO	eastern Pacific Ocean
FAD	fish aggregating device
FFA	South Pacific Forum Fisheries Agency
FSM	Federated States of Micronesia
GAM	General Additive Model
GLM	General Linear Model
HBF	hooks between floats
IATTC	Inter-American Tropical Tuna Commission
LCEM	Landed Catch and Effort Monitoring
MSY	Maximum Sustainable Yield
NMFS	National Marine Fisheries Service
OFP	Oceanic Fisheries Programme
ORSTOM	Institut Français de Recherche Scientifique pour le Development en Coopération
PRC	Peoples Republic of China
PTRP	Philippines Tuna Research Project
RTTP	Regional Tuna Tagging Project
SCTB	Standing Committee on Tuna and Billfish
SPC	Secretariat of the Pacific Community
TDR	time-depth recorder
WCPO	western and central Pacific Ocean

Section 1

INTRODUCTION

Bigeye tuna (*Thunnus obesus*) are an important component of tuna fisheries throughout the Pacific Ocean. They are the principal target species of the large 'distant-water' longliners from Japan and Korea 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 therefore fundamental to the economic survival of the longline fishery in the western and central Pacific Ocean. The catch of bigeye tuna had a landed value in 1996 of approximately US$800 million.

The Pacific-wide longline catch of bigeye tuna has varied between 80,000 and 160,000 metric tonnes (t) since the 1950s. During this time, catch per unit of effort (CPUE) by longliners has declined steadily, particularly in the area east of 160°W where the largest longline catches are taken. Surplus production model analysis based mainly on the longline data have 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 stock of large bigeye caught by longliners is at least fully exploited, and possibly over-exploited.

Since about 1994, a rapid increase in purse-seine catches of juvenile bigeye, first in the eastern Pacific and, in the past year in the western and central Pacific, has created further uncertainty regarding the sustainability of the current levels of exploitation. Purse-seine catches in the eastern Pacific increased from typical levels of less than 10,000 tonnes per year to approximately 30,000 t in 1994, 37,000 t in 1995 and 52,000 t in 1996 (IATTC, 1997). These increases have been due to the adoption of new fishing methods involving the use of drifting fish aggregating devices (FADs) to aggregate tuna and deeper purse-seine nets to catch the tuna, mostly bigeye, located deeper in the water column. In the western and central Pacific (west of 150°W), purse-seine catches of bigeye are estimated to have been less than 20,000 tonnes per year up to 1995 (Hampton et al., 1998). By 1997, this catch is believed to have increased to approximately 30,000 t through the adoption of similar fishing techniques to those used in the eastern Pacific.

In addition to concerns regarding the possible impact of these increases in purse-seine catch on the bigeye tuna stock, there is also a related concern that such catches, which are processed as low-priced product for canning, will ultimately impact the catches of high-priced, sashimi-quality bigeye by longliners. Such adverse impacts, if they occur, have the potential to reduce the profitability of the longline fishery and thus significantly affect the economies of a number of Pacific Island countries.

The uncertainties regarding the impact of the fisheries on the stock, and fishery interaction exist for several reasons. First, in the western and central Pacific, estimates of bigeye catches by purse-seiners and other surface fisheries are less precise than the catches of the other target species, skipjack and yellowfin tuna. Bigeye catches are not specifically recorded in the fishing logs of many vessels because of the difficulty in separating catches of juvenile bigeye and yellowfin (which are of similar appearance) during bulk handling of the catch. Bigeye catches must therefore be estimated from species composition samples taken at sea by scientific observers or in unloading ports by scientific sampling staff. In the western and central Pacific, the coverage of purse-seine trips by observer or port-based sampling is relatively low, which introduces unavoidable sampling errors into the catch estimates. This problem is much less serious in the eastern Pacific, where the purse-seine fleet is subjected to 100% observer coverage. Uncertainty also results because gaps in understanding of various aspects of the biology of bigeye tuna, such as stock structure, east-west population mixing and natural mortality rates, mean that the response of the stock to fishing pressure cannot be accurately predicted.

The purpose of this report is to review the biology, fisheries, data collection and stock assessment of bigeye tuna, with emphasis on recent work undertaken by SPC. While the focus of the report is on the western and central Pacific Ocean (i.e. west of 150°W), information from the eastern Pacific is included where appropriate. In section 2, we review those aspects of the biology of bigeye tuna (distribution, reproduction, movements, stock structure, age and growth, and natural mortality) that have an important bearing on stock assessment. In section 3, we review the fisheries that catch significant quantities of bigeye tuna, and in section 4, the various fishery data collection systems that are in place. In section 5, previous and current stock assessment research is reviewed. Finally, in section 6, the most important information gaps are summarised and suggestions made for future research and data collection to address these shortcomings.

Section 2

SUMMARY OF BIGEYE TUNA BIOLOGY

2.1 Distribution of adults and juveniles

Adult bigeye tuna (>100 cm fork length) inhabit the tropical and temperate waters of the Pacific Ocean between northern Japan (40°N) and the north island of New Zealand (40°S) in the west, and from about 40°N to 30°S in the east, except near coastal waters of Central America between 5° and 20°N (Figure 1). Overall habitat is limited by temperature and dissolved oxygen concentration. Within these limits, food supply is probably the major determinant of distribution.

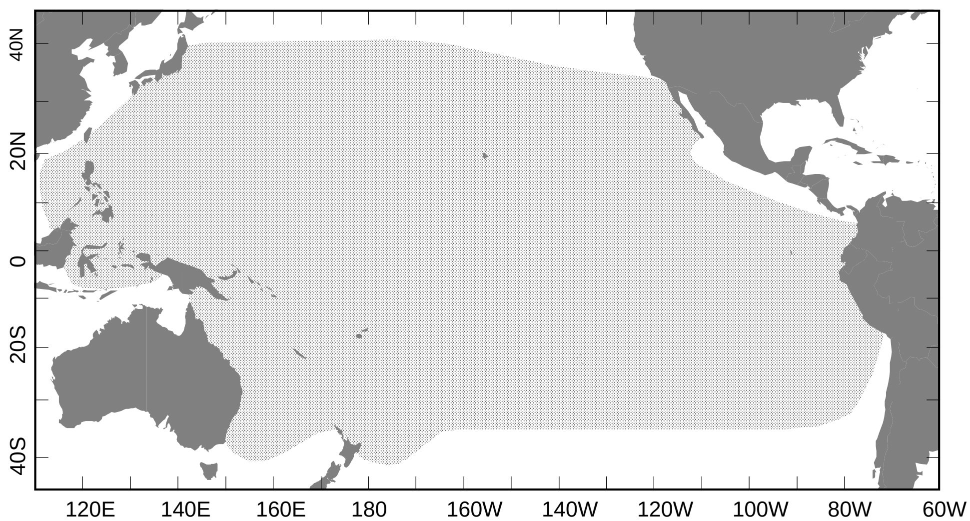


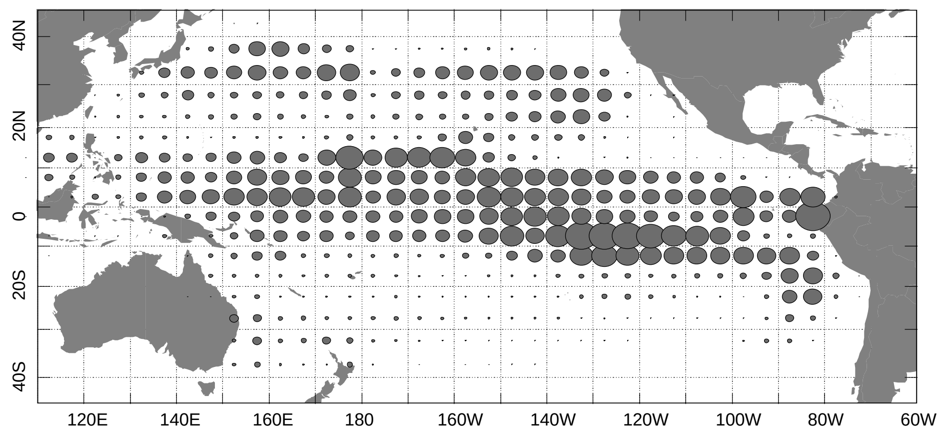
Figure 1. Schematic distribution of bigeye tuna in the Pacific Ocean.

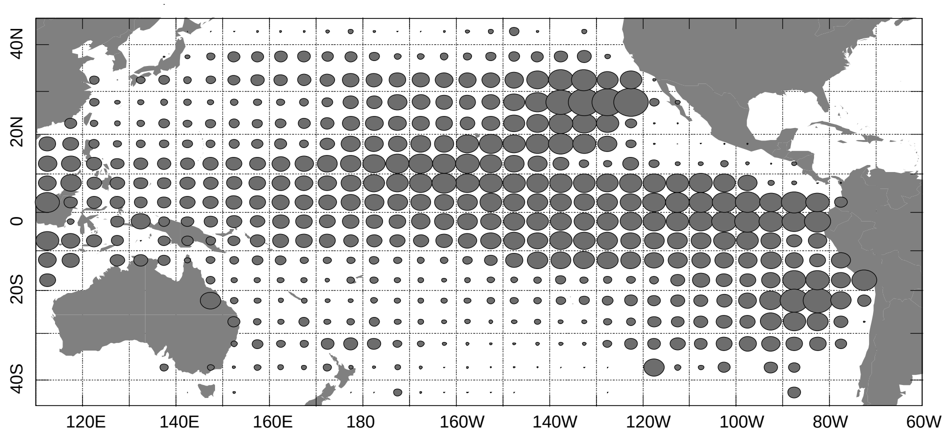
Due to well developed behavioural and physiological thermoconserving mechanisms (Holland et al., 1992; Holland and Sibert, 1994), adult bigeye can inhabit water with ambient temperatures as low as 10°C (Hanamoto, 1987). Oxygen tolerances of bigeye have not been estimated experimentally, but are hypothesised to range between 0.5 and 1.0 ml O_2 l^{-1} (Sharp, 1978; Sund et al., 1980). The distribution of longline catch (Figure 2) and CPUE (Figure 3) reflects these environmental constraints. Low CPUE in the western Pacific at 15°–30°N and in the western and central Pacific at 10°–30°S occurs because the depth of the 15°C isotherm is greater than 300 m in these areas, deeper than the typical maximum fishing depth of longline gear. In the far eastern Pacific off central America, low CPUE occurs because of low dissolved oxygen concentration (<1.0 ml O_2 l^{-1}) in waters of the preferred temperature, and presumably indicates an absence of bigeye in subsurface waters in this region.

Sonic tracking studies and night longlining trials suggest that adult bigeye occur at depths of at least 250 m during the day but move to surface waters at night (Kume and Morita, 1966; Holland et al., 1990). They also appear to make regular, brief excursions up to the bottom of the mixed layer during the day to assist in thermoregulation (Holland et al., 1990).

Less is known of the distribution of juvenile bigeye because, until recently, they have not been targeted by industrial tuna fisheries in the Pacific Ocean. Smaller body size, and therefore smaller thermal inertia, probably results in a preference for warmer waters, and thus some compression of distribution towards the tropics. Juvenile bigeye have been caught in relatively small numbers by purse seiners in both the western and eastern Pacific. Limited sampling indicates that bigeye from 40 to 70 cm in fork length may represent up to

30% of the purse-seine catch reported as yellowfin in the western and central Pacific in some years (SPC, unpublished data). These bigeye are most commonly taken in log and FAD sets, along with similar-sized yellowfin and skipjack. Bigeye taken in the eastern Pacific purse-seine fishery, mostly during October - March, have a wider size range of 60 to 120 cm. Recently, sets on drifting FADs have resulted in large increases in purse-seine catch of bigeye (see section 3). The distribution of recent purse-seine catches of bigeye is shown in Figure 4.





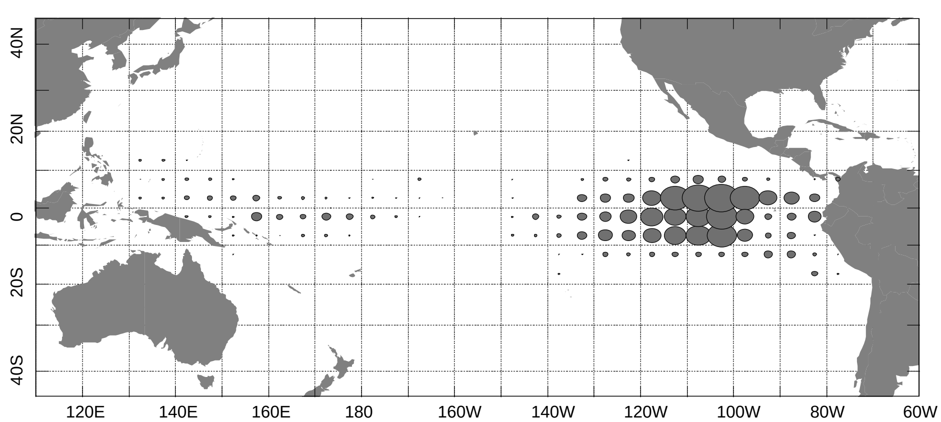


Figure 2. Distribution of bigeye tuna longline catch (in number) 1962 - 1995.

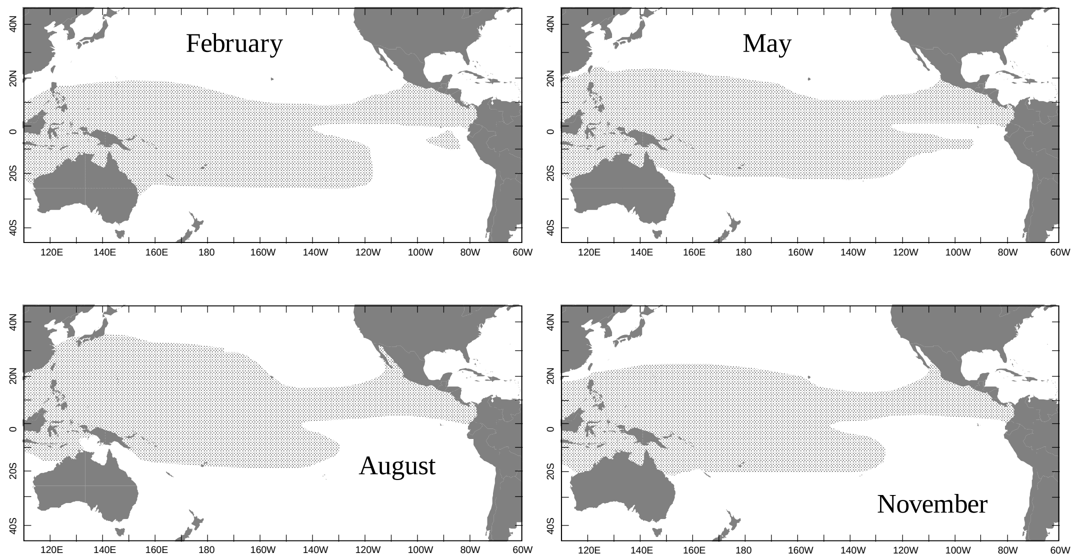
Figure 3. Distribution of bigeye tuna longline CPUE 1962 - 1995.

Figure 4. Distribution of reported purse-seine catches of bigeye tuna 1994 - 1996. Note that bigeye catches in the western Pacific are under-reported in logbooks.

2.2 Reproduction

Adult bigeye spawn in the warm (>26°C), surface waters of the Pacific. The spatial extent of the potential spawning area can therefore be approximated by the 26°C sea-surface-temperature isotherm (Figure 5). Spawning would be expected to occur between about 20°N and 20°S in the western and central Pacific, between the equator and 20°N in the far eastern Pacific and between the equator and about 10°N in the region of 120°W. The observed distribution of bigeye larvae (Nishikawa et al., 1985) largely agrees with the isotherm distributions (Figure 6). In the western Pacific, bigeye caught at 10°N–10°S are often mature between April and September (Kikawa, 1962). In the eastern Pacific, mature bigeye have been reported from two areas: at 0°–10°N during January – September and at 5°–10°S during January - June (Kume and Joseph, 1966). Note that the incidence of mature bigeye in longline catches may underestimate the temporal and spatial distribution of spawning.

Bigeye mature at a size of 100-130 cm probably during their third year of life (Calkins, 1980). Histological



examination indicates bigeye can spawn every 1.00–1.57 days when reproductively active (Nikaido et al., 1991). Batch fecundity in the equatorial central Pacific is thought to be in the order of 2.2 million eggs at

Figure 5. Averag… , August and November.

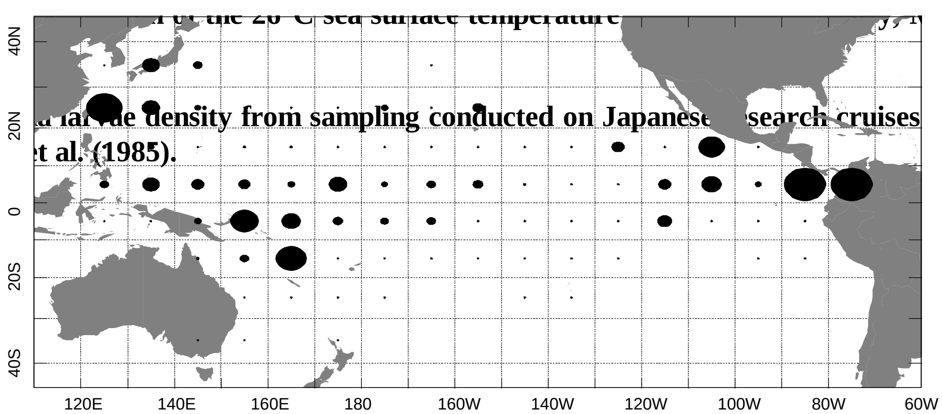


Figure 6. Bigeye … density from sampling conducted on Japanese … cruises …56–1981. Source: Nishikaw… et al. (1985).

150 cm. Of the mature fish examined, 90% were identified to have spawned within 24 h and most spawning probably took place from 19:00hr to 24:00hr. The duration of the spawning season for individual bigeye is not known.

Examination of sex ratio data from the broad area of the equatorial Pacific longline fishery shows a general predominance of male fish over most of the size range studied (Kikawa, 1966; Kume, 1969). The dominance of males becomes more prominent as size increases (Figure 7). This pattern is characteristic of tunas generally, and might result from sex-specific mortality (elevated mortality of adult females) and/or growth.

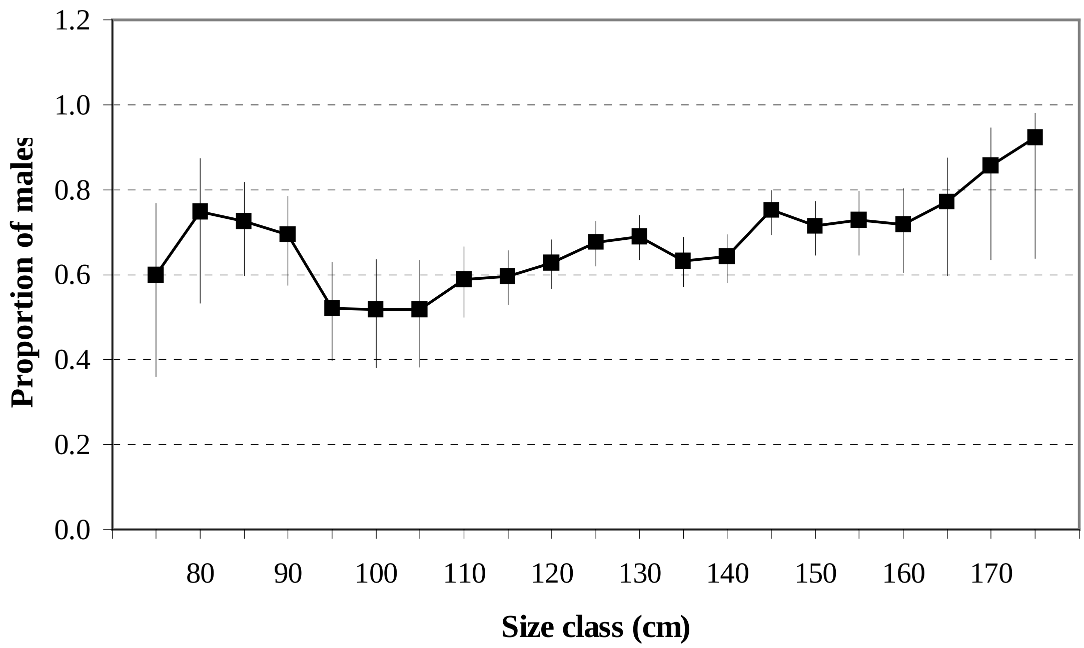


Figure 7. Proportion of male bigeye, by size class, from a sample of 2,977 bigeye collected by scientific observers on longliners in the WCPO. The error bars represent 95% confidence intervals on the proportions.

2.3 Movements

Bigeye movements are the least documented of all the commercially important tunas, largely because of the difficulty of catching fish in suitable condition for tagging. The SPC's Regional Tuna Tagging Project (RTTP) released 6,796 bigeye during 1989-92 with approximately 65% (4,458) being released in the Coral Sea. Many of the tagged bigeye were observed to move extensively throughout the western and central Pacific (Figure 8a). Several bigeye tagged in the Coral Sea off north-eastern Australia were recaptured east of 180°. Two such recoveries occurred in the vicinity of 130°W (displacements of >4,000 nm in 4.0 and 1.8 yrs), in the main bigeye fishing area for Japanese and other longliners. Two recaptures of fish released in Kiribati waters (Gilbert Islands) were recovered in Hawaii by local longliners. Bigeye clearly have the capacity for long-distance movement — 25% of observed tagged bigeye movements were greater than 200 nm, with about 5% greater than 1,000 nm (Figure 8b).

In some locations, notably in the Coral Sea off north-eastern Australia (where most bigeye were tagged during the RTTP), a large fraction (217 out of a total of 260 returns from Coral Sea releases — 83%) of tagged bigeye have now been recaptured in the release area up to six years later. Some bigeye it seems show a high degree of residency in some locations. This is evident in the plot of displacement versus time at liberty (Figure 9).

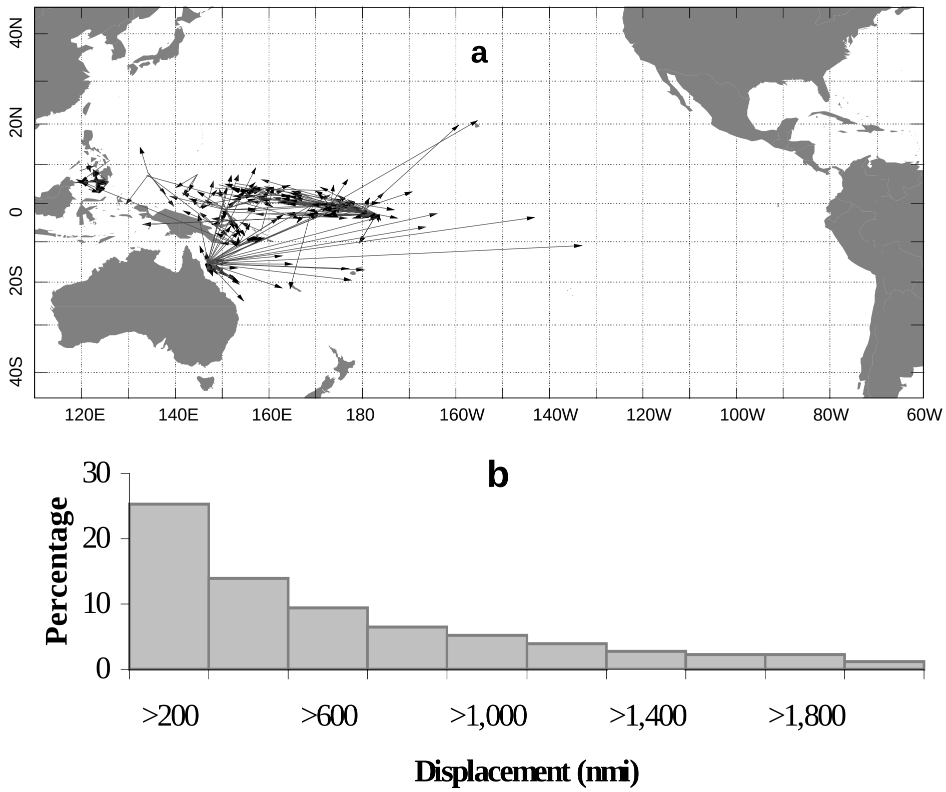


Figure 8 a. Displacements >100 nmi of bigeye tuna tagged by the SPC's Regional Tuna Tagging Project (RTTP). 8b. The cumulative distribution of all RTTP tagged bigeye displacements having accurate location data.

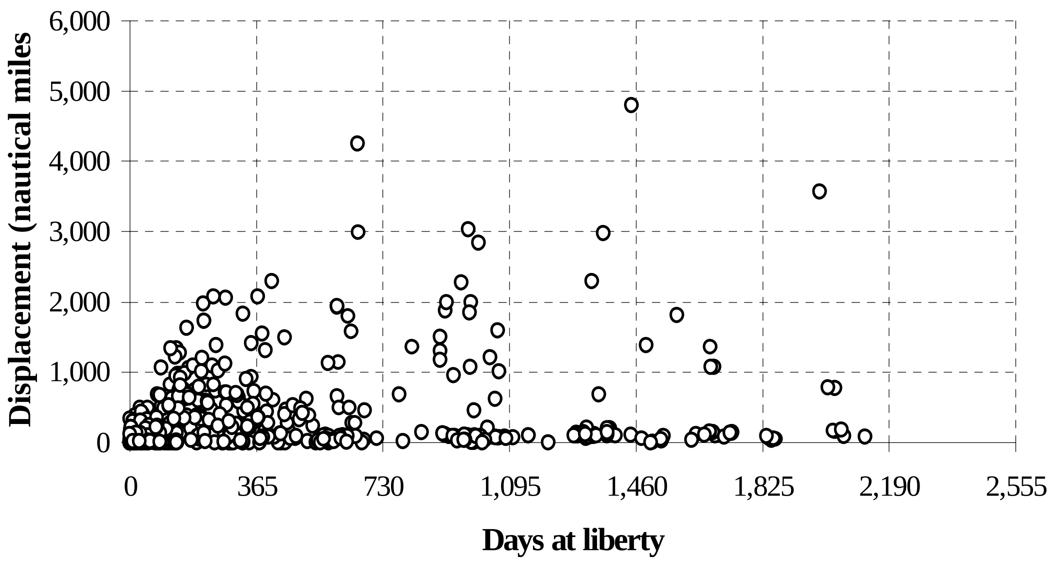


Figure 9. Plot of displacement of tagged bigeye versus time (days) at liberty.

2.4 Stock structure

Bigeye stock assessments generally assume a Pacific-wide stock structure, however other stock structure hypotheses, such as separate eastern and western stocks have also been considered. The contraction of bigeye spawning habitat and apparent scarcity of larvae in the central Pacific may be more consistent with separate western and eastern populations than with a single Pacific-wide population. Also, the tagging data suggest that movement of bigeye from the western Pacific to the eastern Pacific is not extensive. On the other hand, there is no strong discontinuity in longline CPUE for bigeye across the Pacific that would indicate stock separation.

The genetic structure of Pacific bigeye has recently been investigated in a study carried out by SPC and the CSIRO in Hobart, Australia (Grewe and Hampton, 1998). Bigeye muscle-tissue samples were collected from various locations across the Pacific in the second half of 1995 (Table 1). Genetic analysis of the samples involved the assessment of mitochondrial DNA (mtDNA) and nuclear DNA microsatellite variation. Variation in microsatellite and mtDNA allele frequencies among samples was assessed using standard Monte Carlo chi-square approaches. Significant differences in frequencies would indicate that collection localities represent areas that contain genetically distinct groups.

Table 1. Sampling locations, size range and numbers of fish comprising the bigeye tissue samples for genetic analysis.

Sample	Sampling location	Size range (cm)	Number of fish
1. Philippines	5°N, 125°E	20 - 30	96
2. FSM	3-5°N, 141°E	27 - 57	72
3. Coral Sea	16°S, 147°E	100 - 150	96
4. Marshall Islands	7°N, 170°E	130 - 150	72
5. Hawaii	20°N, 160°W (approx.)	80 - 150	96
6. French Polynesia	6 - 12°S, 142 - 150°W	60 - 130	72
7. Eastern Pacific	5°S, 115°W	40 - 50	96
8. Peru	8 - 18°S, 90 - 125°W	68 - 180	72
9. Ecuador	0°, 85°W	100 - 220	96
TOTAL			768

Eight loci were used to first examine a sub-sample of 36 fish from each of two sites (Philippines and Ecuador) that represented the extreme ends of the sampling locations of this study. With rare exception, most alleles at each locus were found in both populations. Statistical comparisons indicated that allele frequencies at each locus were not significantly different between these two populations.

Four loci were then chosen to analyse the entire sample from each sample location. For three loci, differences among the samples were not significant (P = 0.425, 0.325 and 0.388). For one locus, the differences were marginally significant (P = 0.038). Variation of mtDNA haplotypes among samples was also marginally significant (P=0.046). Overall, the results of the genetics study do not provide convincing evidence of genetic differentiation of bigeye tuna in the Pacific.

2.5 Age and growth

Growth of bigeye has previously been inferred from scale readings (Suda and Kume, 1967) and modal progression of length frequencies (Kume and Joseph, 1966). The reliability of these estimates is questionable because of the restricted size range of the samples (in particular the lack of small fish) and possible errors in the age estimates obtained from scale readings and length-frequency modes.

Recent data on bigeye growth has been obtained from RTTP tag returns and from counts of presumed daily growth increments on bigeye otoliths. As further work is required to validate the otolith increment counts the following account of results of work in progress should be considered as preliminary. The tagging data set (311 returns with reliable dates and lengths at release and recapture) is an excellent data set for estimating growth as it covers a wide range of release lengths (29 - 126 cm), recapture lengths (29 - 175 cm) and times at liberty (1 - 2,298 days). The otolith-increment counts consist of 124 samples in the length range 25 - 151 cm. These samples were taken from a total collection of 161 fish (34 collected during the RTTP, 127 provided by the ORSTOM Centre in Tahiti). Only specimens considered to be either 'excellent' or 'good' in terms of readability were analysed.

A von Bertalanffy growth curve jointly fitted to both data sets (Kirkwood, 1983) yielded parameter estimates (standard errors in parentheses) of L_∞ = 165.3 cm (0.014), K = 0.3732 yr^{-1} (0.027) and t_0 = - 0.342 years. The age-length relation using both sets of data is shown in Figure 10. In order to display the tagging data on the same figure as the otolith data, the ages at release of tagged fish at liberty > 1 year were estimated from the inverse growth function (composite model), and the time at liberty added. This represents an approximate estimate of age at recapture, which is plotted against length at recapture in Figure 10. Note that we have only displayed tagging data for times at liberty > 1 year because the assumed age at release is responsible for a large component of the age at recapture for short times at liberty. However, all tagging data were used for the estimation of parameters.

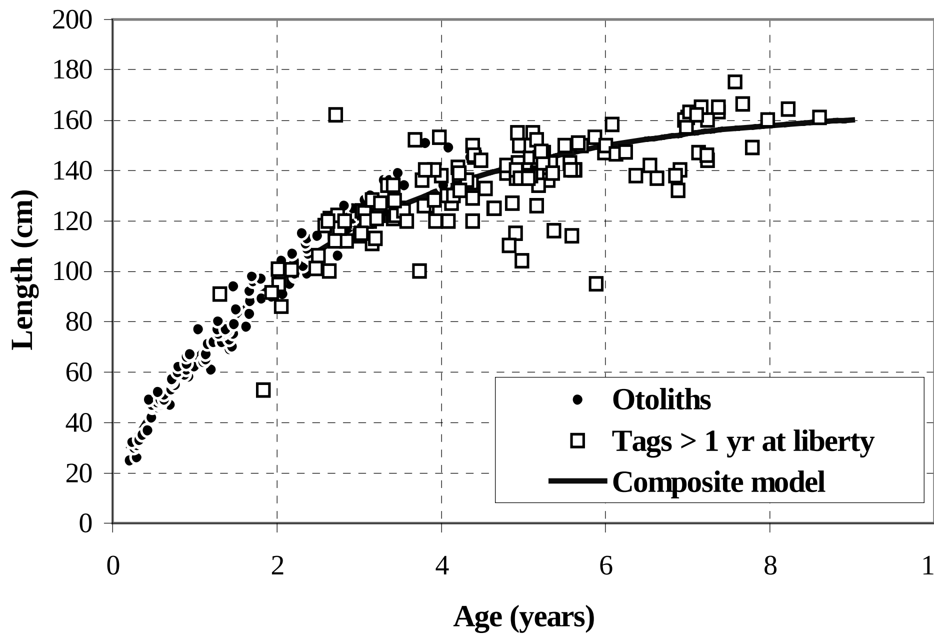


Figure 10. Bigeye length versus age. The small solid circles represent preliminary length and age observations inferred from presumed daily otolith increments. The open squares represent assumed age and length at recapture for tagged bigeye at liberty > 1 year. The age at recapture was calculated from the age at release (estimated from length using the inverse growth function of the composite model) plus the time at liberty.

The composite growth model provides a reasonable fit to the tagging data, with length-increment residuals showing a fairly even scatter about zero (Figure 11). The model also fits the otolith data for lengths < 110 cm, but for larger fish the estimated ages are substantially less than predicted by the model (Figure 12). This suggests that estimated ages for bigeye > 110 cm are probably underestimated. A refit of the composite model excluding otolith samples from fish > 110 cm yielded slightly different parameter estimates:
L_∞ = 166.3 cm (0.015), K = 0.3494 yr^{-1} (0.027) and t_0 = -0.3888 years (0.017).

Validation of the periodicity of otolith increment formation is currently being investigated at the Inter-American Tropical Tuna Commission (IATTC) and CSIRO (Hobart). It is hoped that this work will further assist the interpretation of otolith-increment counts.

Bigeye are believed to be significantly longer lived than yellowfin tuna. Several tagged bigeye have been recaptured in excess of six years at liberty (the longest period at liberty is currently 6.7 years). These fish were aged between two and three years at release, which suggests that significant numbers of fish survive at least until eight years of age.

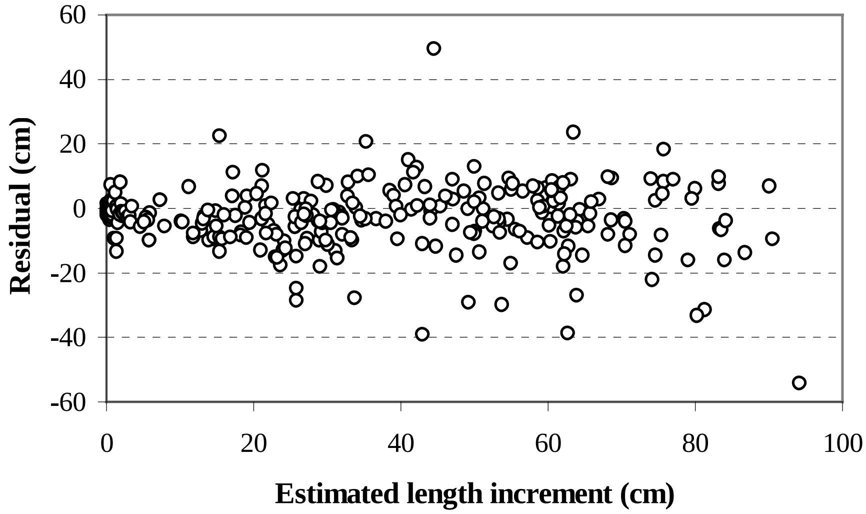


Figure 11. Length-increment residuals (observed-estimated) plotted by the estimated length increment. Disregarding obvious outliers (likely due to extreme measurement error), there is no obvious trend and the distribution is fairly even about zero.

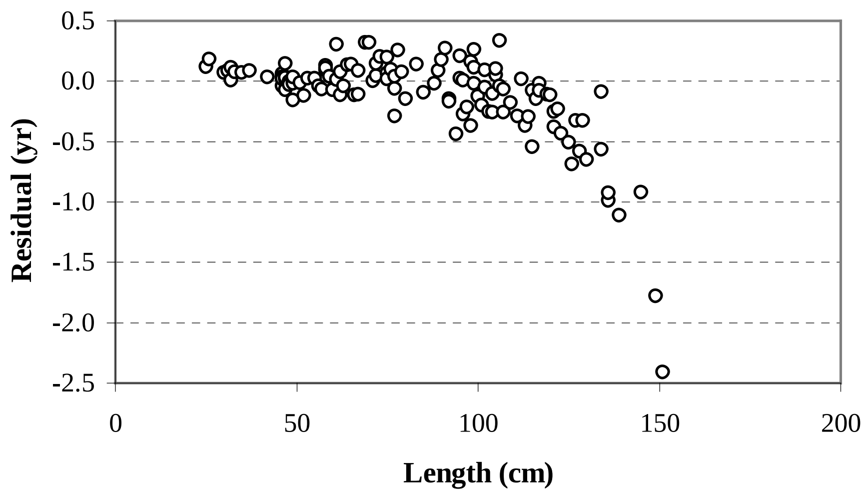


Figure 12. Age residuals (observed-expected) from the otolith data plotted against length. Estimated ages correspond well with the joint parameter estimates up to a length of 100 cm. For bigeye larger than 100 cm the estimated ages are generally younger than expected.

2.6 Natural mortality

The natural mortality rate of bigeye was estimated by analysis of catch-at-age data for the longline fishery during 1957–1964 to be 0.361 yr^{-1} with total mortality ranging from 0.6 to 1.4 yr^{-1} (Suda and Kume, 1967). Several estimates of natural mortality rate have also been obtained from analyses of RTTP tagging data (Hampton et al., 1998). Estimates have been obtained for small fish (<40 cm) tagged in the Philippines, for small - medium (45 - 65 cm) fish tagged in the western equatorial Pacific and for medium - large fish (>60 cm) tagged in the Coral Sea (Table 2). The estimates vary greatly, possibly in relation to the size of the tagged fish. Note also that an unknown amount of movement away from the tag release area may be incorporated into these estimates. This may be particularly significant in the case of the Coral Sea releases.

Table 2. Estimates of natural mortality rate for tagged bigeye tuna of different sizes released in different locations in the western Pacific during 1990-1992. Note that for each estimate, a component of the stated rate may be due to movement away from the release location.

Location	Size range of releases (cm)	Estimated natural mortality rate (yr^{-1})
Philippines	20-40	4.08-6.72
Western equatorial Pacific	45-65	1.05-1.39
North-western Coral Sea	60-110	0.52-0.59

Section 3

FISHERIES FOR BIGEYE TUNA IN THE PACIFIC OCEAN

Bigeye tuna in the Pacific Ocean are primarily taken by longline gear, for which they are a major target species. Smaller but still substantial amounts are taken by the purse-seine fishery, particularly in sets on logs or other floating objects. Such catches, typically of juvenile bigeye, are not normally recorded as such, but are usually combined with the yellowfin catch in logsheet records and landing statistics.

This section provides catch and effort statistics for fisheries exploiting bigeye in the western and central and eastern Pacific Ocean. The summary is largely based on studies conducted by the Oceanic Fisheries Programme (OFP), SPC and the Inter-American Tropical Tuna Commission (IATTC). Annual bigeye catch data by gear type for the western and central Pacific (WCPO), the area west of 150°W, and including eastern Indonesia and the Philippines (Figure 13) were compiled for the years 1988-95 (Hampton et al., 1998) and recently extended to cover all years since 1980. Statistics for the eastern Pacific Ocean (EPO), the area east of 150°W were compiled for the years 1971-96 (IATTC, 1997).

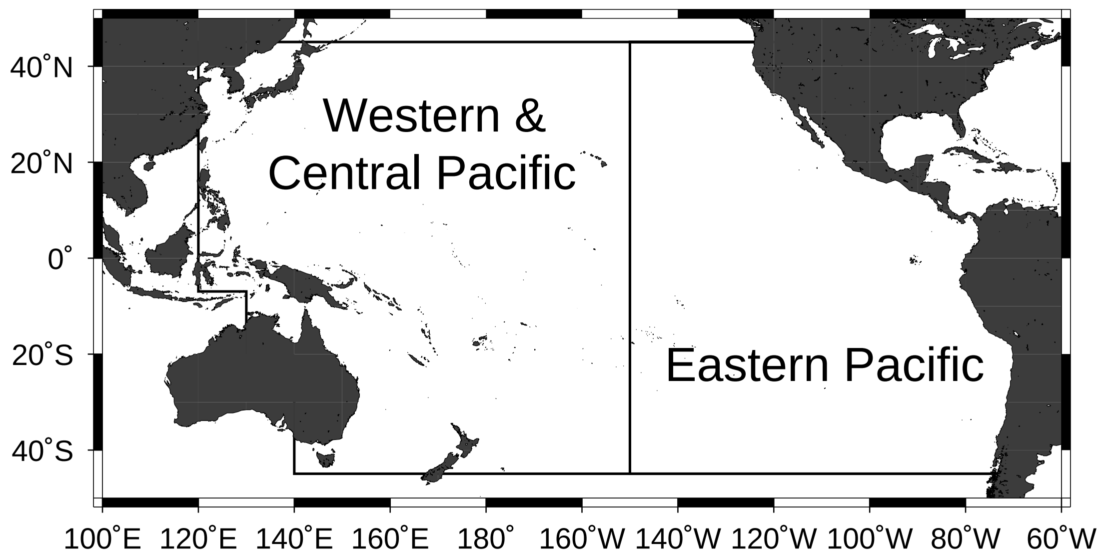


Figure 8. Areas used in estimation of bigeye tuna catch.

3.1 Longline fishery

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, then progressively Taiwanese and Korean vessels. Vessels from Pacific Island countries and the Peoples Republic of China (PRC) are more recent entrants to the WCPO. Bigeye have always been a significant component of the catch, but increased targeting of the species occurred when deep longlining began in the late 1970s.

Longline fishery estimates for the WCPO were based on the best information available, including Lawson (1997) and aggregated data made available to the OFP by the Fisheries Agency of Japan, the National Fisheries Research and Development Institute of Korea, the National Taiwan University and the Council of Agriculture (Executive Yuan) of Taiwan. WCPO catches listed under the 'Other' category in Table 3 are mainly from the Hawaiian longline fleet (Boggs and Ito, 1993; Curran et al., 1996) and fleets based in various Pacific Island countries. The WCPO estimates exclude catches in the Philippines and Indonesia, which are provided in section 3.3.

Table 1. Estimated bigeye catch (metric tonnes) from longline vessels operating in the western-central and eastern Pacific Ocean tuna fisheries (excluding Indonesia and the Philippines). Values in parentheses are estimates used from a previous year. Source: Published 5° square data or logsheet data at the SPC OFP. Korean statistics are for the SPC area (Lee et al., 1997). EPO statistics are from the IATTC (1997). Entire details of data sources are included in OFP (1998).

Western Central Pacific Ocean (WCPO)						EPO	Pacific Ocean
Year	Japan	Korea	Taiwan	Other	Sub-Total	Sub-Total	Total
1980	36,943	13,106	2,339	398	52,786	59,180	111,966
1981	30,911	7,838	2,093	405	41,247	52,531	93,778
1982	35,614	6,988	1,245	462	44,309	46,431	90,740
1983	33,188	5,923	1,171	542	40,824	79,807	120,631
1984	36,674	7,086	1,509	694	45,963	67,265	113,228
1985	37,955	10,022	2,035	776	50,788	73,761	124,549
1986	34,295	10,156	904	831	46,186	115,348	161,534
1987	42,439	15,119	1,023	928	59,509	105,400	164,909
1988	34,338	11,928	1,460	1,314	49,040	65,007	114,047
1989	38,285	9,774	721	1,605	50,385	66,690	117,075
1990	44,169	15,898	1,220	1,727	63,014	92,733	155,747
1991	32,524	12,103	1,929	2,263	48,819	95,582	144,401
1992	38,154	14,860	2,976	3,171	59,161	71,416	130,577
1993	30,108	12,580	1,534	6,078	50,300	64,820	115,120
1994	29,049	19,603	2,308	9,570	60,530	67,831	128,361
1995	25,394	15,389	1,803	7,662	50,248	52,514	102,762
1996	(25,394)	13,846	1,369	7,659	(48,268)	48,099	(96,367)

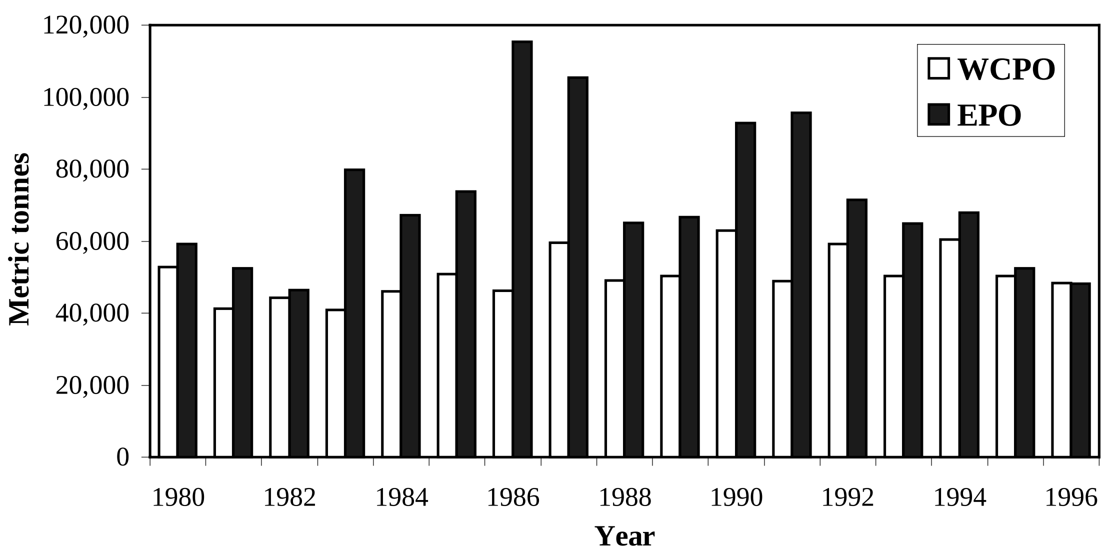


Figure 9. Bigeye catch by longline fishing in the western-central (WCPO) and eastern Pacific Ocean (EPO).

Japanese longline vessels contribute over 80% of the longline bigeye catch from the Pacific Ocean (Table 3). Catches are greater in the EPO than in the WCPO (Figure 14). Since 1980, annual catch in the EPO surpassed 85,000 metric tonnes (mt) during four years, while WCPO catch was typically <50,000 mt. Longline bigeye catch in the Pacific Ocean was highest in 1986 and 1987 at 161,000 and 165,000 mt respectively (Table 3). In the 1980s, Japanese vessels expended more longline effort in the WCPO (Table 4), though some of the effort targeted yellowfin tuna.

The average seasonal distribution of Japanese longline effort and bigeye CPUE was calculated for a 10-year period (1986 - 1995). Effort in the WCPO was high during the initial seven months of each year, but declined below 12 million hooks per month from August to December (Figure 15). In contrast, effort was high in EPO from October to February and below 12 million hooks per month from March to September. Throughout the year, CPUE was fairly stable in the EPO at ~0.8 bigeye per 100 hooks. Bigeye CPUE in the WCPO was less than in the EPO and more variable, but absolute CPUE between regions cannot be compared at this level of stratification because some effort in the WCPO targets yellowfin.

Table 4. Japanese longline effort (hooks) in the western-central (WCPO) and eastern Pacific Ocean (EPO). EPO statistics are from the IATTC (1997).

	Japanese longline effort (hooks)		
Year	**WCPO**	**EPO**	**Total**
1980	222,381,200	138,140,800	360,522,000
1981	241,908,400	131,275,104	373,183,504
1982	224,574,300	116,199,848	340,774,148
1983	197,720,200	127,176,160	324,896,360
1984	202,896,900	119,635,456	322,532,356
1985	211,479,200	106,757,808	318,237,008
1986	183,896,700	160,552,528	344,449,228
1987	193,584,100	188,392,544	381,976,644
1988	213,026,100	182,694,224	395,720,324
1989	197,725,900	170,373,088	368,098,988
1990	182,776,300	178,419,456	361,195,756
1991	174,895,000	200,364,704	375,259,704
1992	156,768,800	191,283,709	348,052,509
1993	170,586,400	159,955,430	330,541,830
1994	163,249,300	163,976,027	327,225,327
1995	150,761,600	125,145,630	275,907,230
1996	144,444,800	125,000,000	269,444,800

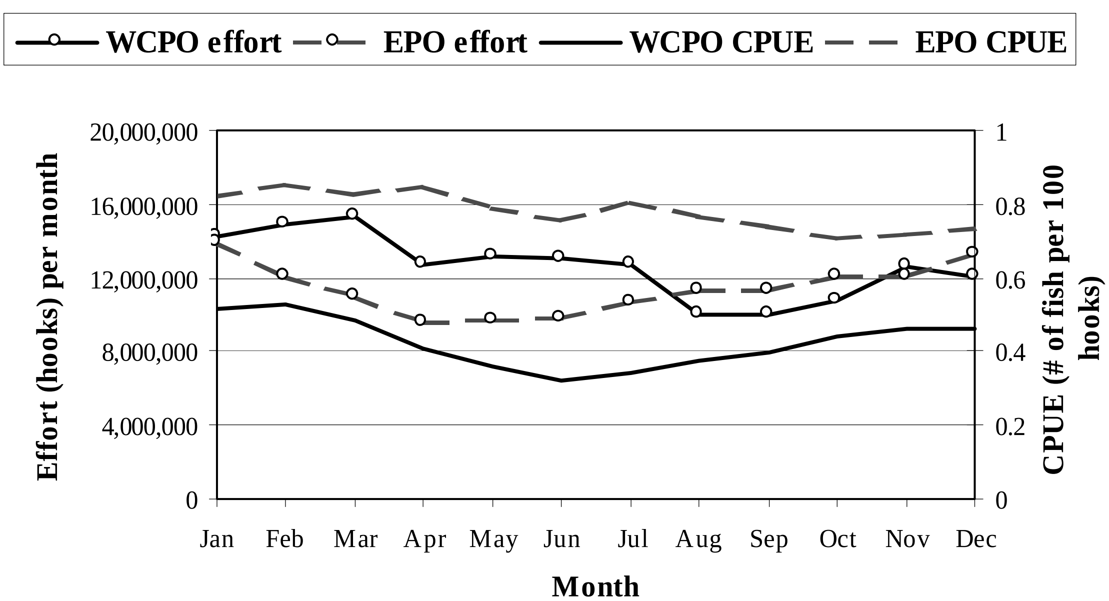


Figure 10. Average monthly effort and bigeye catch rate (CPUE) in the western-central (WCPO) and eastern Pacific Ocean (EPO) for the Japanese longline fleet (1986 - 95).

3.2 Purse-seine fishery

For the WCPO, few catch estimates of mainly juvenile bigeye by purse seine have been available; the species are not separated from yellowfin of similar size in the catch, and are not readily distinguishable to the untrained eye. Tanaka (1989), in Miyabe (1994), suggests that, based on sampling of Japanese purse-seine unloadings at Yaizu port for the period 1976 to 1985, between 1% and 4% of the total catch weight was bigeye. More recently, sampling of the catches of US purse seiners fishing in WCPO and unloading at Pago Pago since June 1988 by National Marine Fisheries Service (NMFS) has allowed species and size composition for this fleet to be obtained. Based on NMFS port-sampling, the percentage of bigeye in school (unassociated) and log (associated) sets averaged 1.0 and 12.7%, respectively (Table 5). No comprehensive data exist for fleets other than those of the United States and Japan. The OFP produced bigeye catch estimates for all fleets operating in the WCPO (Table 6) by extrapolating the bigeye composition of the US catches (stratified by set type) to the other fleets using the method of Hampton et al. (1998). Though the estimation was based on a variety of assumptions, the catch estimates represent the best information currently available for the WCPO.

Table 5. Percentage of bigeye (by weight) expected in the purse-seine logsheet-reported catch of yellowfin, based on NMFS port sampling data (A. Coan, pers. comm.).

	Percentage Bigeye	
Year	SCHOOL	LOG
1988	3.04	8.88
1989	0.48	16.02
1990	0.34	11.62
1991	1.01	10.12
1992	0.66	13.92
1993	0.91	12.94
1994	0.44	11.59
1995	0.98	16.3

Table 6. Estimated purse-seine catch (tonnes) of bigeye in the western-central and eastern Pacific Ocean (EPO). Source: For the WCPO, bigeye catch was estimated from expected percentage of bigeye in the catch for all fleets (Lawson, pers. comm.). EPO statistics are from the IATTC (1997).

Western Central Pacific Ocean (WCPO)							EPO	Pacific Ocean
Year	Japan	Korea	Taiwan	US	Other	Sub-Total	Sub-Total	Total
1980	1,472	6	-	77	58	1,613	15,421	17,034
1981	2,506	53	-	1,135	174	3,868	10,091	13,959
1982	3,475	222	-	1,600	249	5,546	4,102	9,648
1983	1,979	100	276	4,950	328	7,633	3,260	10,893
1984	1,305	54	427	4,442	415	6,643	5,936	12,579
1985	2,533	162	508	1,769	813	5,785	4,532	10,317
1986	2,282	172	724	2,591	657	6,426	1,939	8,365
1987	2,431	1,508	955	4,212	1,299	10,405	776	11,181
1988	1,298	1,077	780	1,948	853	5,956	1,053	7,009
1989	2,465	2,060	2,268	2,421	2,259	11,473	1,470	12,943
1990	2,931	2,091	2,546	1,762	1,373	10,703	4,712	15,415
1991	3,360	2,604	3,175	1,550	1,414	12,103	3,740	15,843
1992	4,949	4,622	4,331	3,480	2,811	20,193	5,497	25,690
1993	4,630	2,586	2,733	3,731	2,312	15,992	8,069	24,061
1994	1,604	2,277	1,758	1,711	1,558	8,908	29,375	38,283
1995	1,637	2,174	1,389	3,190	3,331	11,721	36,941	48,662
1996	1,941	1,149	1,017	9,860	2,718	16,685	52,132	68,817

Bigeye catch estimates in the EPO have less uncertainty, because most purse-seine activity is monitored by IATTC or Mexican national observers. Purse-seine catch of bigeye in the eastern Pacific has increased from <10,000 t per year prior to 1994 to ~30,000 t in 1994, ~37,000 t in 1995 and ~52,000 t in 1996 (Table 6, IATTC 1997). Vessels in the EPO are targeting small-to medium-sized bigeye (average weight of 11 kg) aggregated under floating logs and drifting FADs using special techniques such as deeper nets, lights and bait to chum the fish closer to the surface. Bigeye catch in the EPO has increased rapidly in the 1990s, while the WCPO catch has remained relatively stable at ~15,000 t (Figure 16).

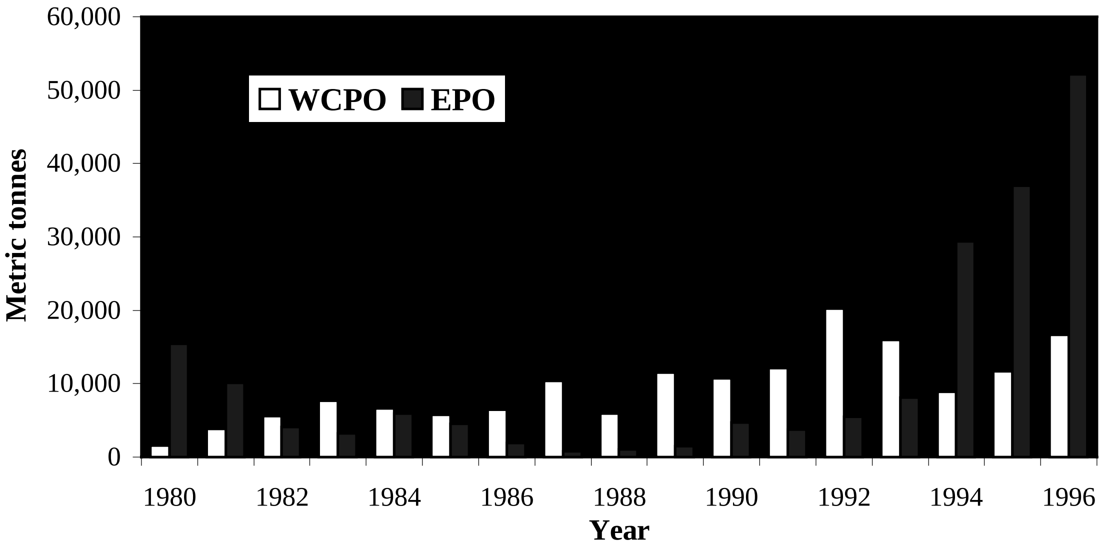


Figure 11. Bigeye catch by purse-seine fishing in the western-central (WCPO) and eastern Pacific Ocean (EPO). Data are preliminary for 1996.

The proportion of bigeye in purse-seine sets often depends on whether a set was made on an unassociated (i.e. free-swimming school) or an associated (i.e. log or FAD) set. Since 1988, 78% of the US purse-seine sets were unassociated and 22% associated. Based on NMFS port-sampling, catch composition data was applied to estimate the CPUE between set types for the US fleet (Figure 17). The CPUE trends are stable for both set types. As expected, associated sets have a greater bigeye CPUE (annual range = 0.72 - 1.7 t per set) than unassociated sets (annual range = 0.02 - 0.06 t per set).

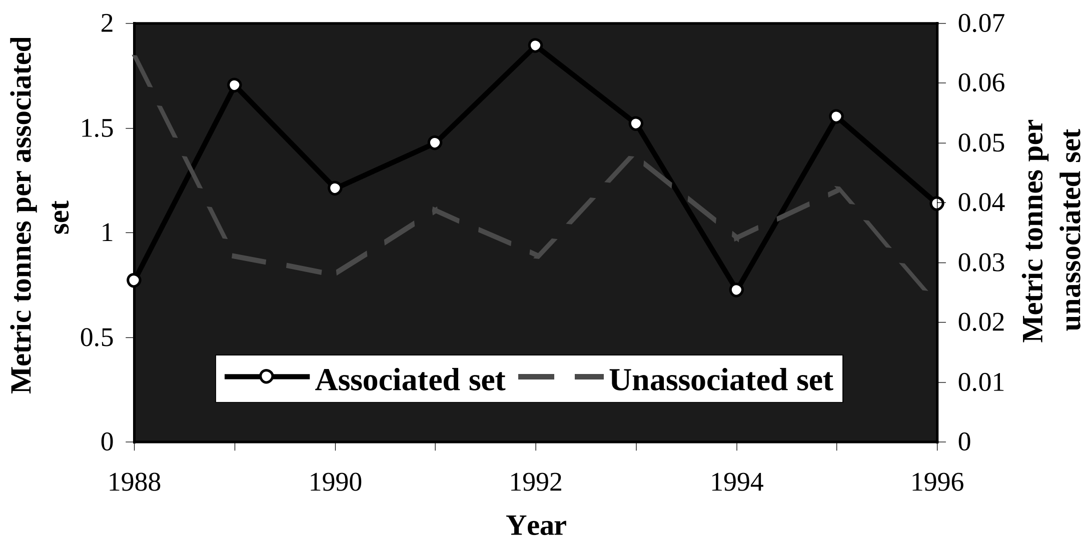


Figure 12. Comparison of bigeye CPUE (tonnes per set) from associated and non-associated sets in the US purse-seine fleet operating in the western and central Pacific Ocean (WCPO).

3.3 Domestic fisheries of the Philippines and Indonesia

Significant quantities of bigeye are known to be taken in the multi-gear Philippines tuna fishery, but again bigeye are not routinely separated from small yellowfin in the catch and are not reported separately in published FAO statistics. Fisheries which exploit bigeye in the Philippines include: bagnet, gillnet, handline, longline, purse-seine, ring net and seine net. Estimated bigeye catches in Philippine waters were determined by adjusting catches of yellowfin (Lawson & Williams, 1998) based on species compositions sampled during the Landed Catch and Effort Monitoring (LCEM) Programme of the Philippines Tuna Research Project (PTRP). The proportion of bigeye in yellowfin-plus-bigeye catches is similar for all gears at around 10%. Raised annual bigeye catch ranges from 3,434 t to 8,706 t for the period 1980 to 1996 (Table 7).

Table 7. Estimated catch (tonnes) of bigeye in waters of Indonesia and the Philippines from a variety of gear types. Values in parentheses are estimates used from a previous year. Source: Indonesia: Lawson (pers. comm.); Philippines: Lawson & Williams (1998).

Year	Indonesia	Philippines	Total
1980	1,735	4,202	5,937
1981	2,164	5,140	7,304
1982	2,381	4,756	7,137
1983	2,005	5,642	7,647
1984	2,591	5,436	8,027
1985	2,888	5,900	8,788
1986	3,361	5,405	8,766
1987	3,909	4,756	8,665
1988	4,144	5,208	9,352
1989	4,417	5,673	10,090
1990	4,688	7,385	12,073
1991	5,094	8,706	13,800
1992	5,378	4,146	9,524
1993	5,850	3,434	9,284
1994	5,763	5,855	11,618
1995	(5,763)	5,573	(11,336)
1996	(5,763)	5,603	(11,366)

Few tuna catch data, apart from estimated landings, are available from Indonesia. Fisheries which exploit bigeye in Indonesia include: pole and line, handline and purse-seine. It has therefore been necessary to extrapolate from data for adjacent Philippines waters, by gear (Hampton et al., 1998; OFP, 1997). Estimated bigeye catches in Indonesian waters were determined by adjusting yellowfin catch estimates (Lawson, 1996) using species compositions sampled during the Philippines LCEM Programme. For Indonesia, raised annual catch of bigeye ranges from 1,735 t to 5,850 t for the period 1980 to 1996 (Table 7).

In the last 10 years the estimated catch of mostly juvenile bigeye from eastern Indonesia and the Philippines exceeded 9,000 tonnes and was similar in magnitude to the entire surface catch of the purse-seine fleets in the WCPO.

3.4 Other fisheries

Minimal amounts of bigeye are caught in other fisheries, such as pole and line, trolling and handlining (Table 8). Bigeye are a small bycatch component in the Japanese pole and line fishery as catches averaged 2,700 mt per year since 1980. Several countries (Japan, Taiwan and the United States) also report a total annual catch of bigeye in the range of 100 to 700 mt from unclassified gear types.

3.5 Total bigeye catch in the Pacific Ocean

Total bigeye catch in the Pacific Ocean has fluctuated between 110,000 and 187,000 t per year since 1980 (Table 9, Figure 18). The international longline fleet provides approximately 80% of the total catch by weight during the 1980s, but its contribution has fallen in recent years with the increase in purse-seine catches.

Table 8. Estimated bigeye catch (tonnes) in the Pacific Ocean tuna fisheries from pole and line and other gear types. Values in parentheses are estimates used from a previous year. Source: tables compiled by the Western Pacific Yellowfin Research Group.

	Japanese pole and line			
Year	**Coastal**	**Offshore**	**Unclassified**	**Total**
1980	22	1,994	127	2,143
1981	56	2,337	163	2,556
1982	109	3,807	176	4,092
1983	93	3,762	176	4,031
1984	26	3,192	150	3,368
1985	111	3,981	303	4,395
1986	118	2,519	279	2,916
1987	86	2,810	228	3,124
1988	221	1,449	455	2,125
1989	373	3,544	389	4,306
1990	144	3,276	221	3,641
1991	130	1,230	418	1,778
1992	75	1,033	676	1,784
1993	31	1,749	278	2,058
1994	323	1,878	337	2,538
1995	(323)	2,520	240	(3,083)
1996	(323)	(2,520)	334	(3,177)

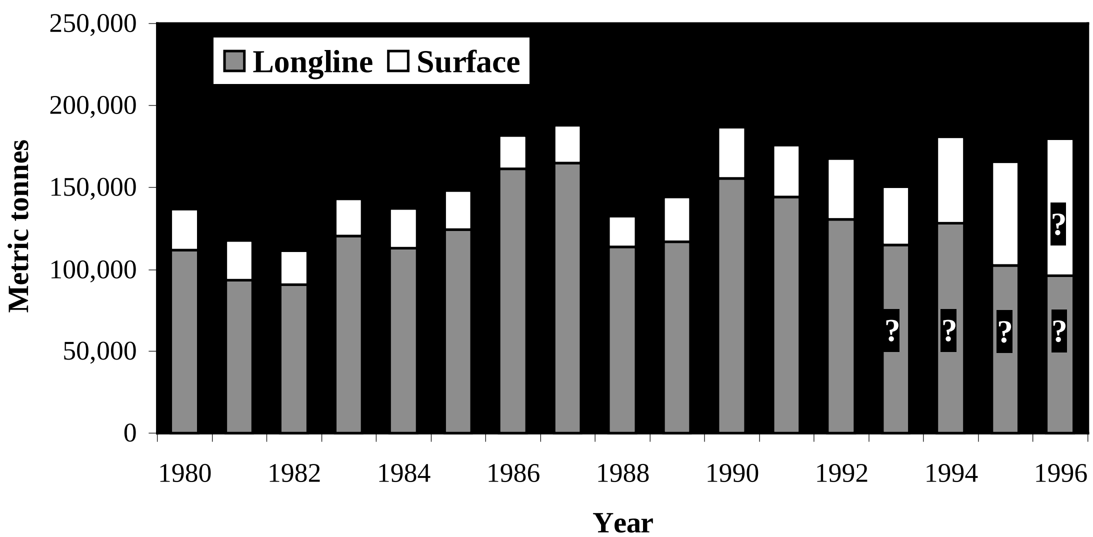


Figure 13. Annual longline and surface catch of bigeye tuna in the Pacific Ocean. Question marks indicate preliminary data.

Table 9. Estimated bigeye catch (tonnes) in the Pacific Ocean tuna fisheries. Values in parentheses are estimates used from a previous year.

	Western Central Pacific Ocean (WCPO)						Eastern Pacific Ocean (EPO)			Pacific Ocean
Year	Longline	Purse seine	Other	Indonesia	Philippines	Total	Longline	Surface	Total	Total
1980	52,786	1,613	2,143	1,735	4,202	62,479	59,180	15,421	74,601	137,080
1981	41,247	3,868	2,556	2,164	5,140	54,975	52,531	10,091	62,622	117,597
1982	44,309	5,546	4,092	2,381	4,756	61,084	46,431	4,102	50,533	111,617
1983	40,824	7,633	4,031	2,005	5,642	60,135	79,807	3,260	83,067	143,202
1984	45,963	6,643	3,368	2,591	5,436	64,001	67,265	5,936	73,201	137,202
1985	50,788	5,785	4,395	2,888	5,900	69,756	73,761	4,532	78,293	148,049
1986	46,186	6,426	2,916	3,361	5,405	64,294	115,348	1,939	117,287	181,581
1987	59,509	10,405	3,124	3,909	4,756	81,703	105,400	776	106,176	187,879
1988	49,040	5,956	2,125	4,144	5,208	66,473	65,007	1,053	66,060	132,533
1989	50,385	11,473	4,306	4,417	5,673	76,254	66,690	1,470	68,160	144,414
1990	63,014	10,703	3,641	4,688	7,385	89,431	92,733	4,712	97,445	186,876
1991	48,819	12,103	1,778	5,094	8,706	76,500	95,582	3,740	99,322	175,822
1992	59,161	20,193	1,784	5,378	4,146	90,662	71,416	5,497	76,913	167,575
1993	50,300	15,992	2,058	5,850	3,434	77,634	64,820	8,069	72,889	150,523
1994	60,530	8,908	2,538	5,763	5,855	83,594	67,831	29,375	97,206	180,800
1995	50,248	11,721	3,083	(5,763)	5,573	76,388	52,514	36,941	89,455	(165,843)
1996	48,268	16,685	3,177	(5,763)	5,603	79,496	48,099	52,132	100,231	(179,727)

Section 4

FISHERY DATA COLLECTION SYSTEMS

The objective of data collection systems is to provide estimates of total catch including discards, fishing effort and size composition of the catch. In the Pacific tuna fisheries, bigeye data collection systems include: 1) logbook estimates of catch and effort, 2) independent catch estimates by at-sea observer sampling, and 3) port sampling of size and weight of the landed catch. Data collection systems for each fishery that exploits bigeye in the western and central Pacific are described below.

4.1 Logbook data

Since its inception in 1981, the OFP has maintained a database on industrial tuna fisheries in the WCPO. The main sources of the data have been daily catch and effort logsheets provided to SPC by member countries. Logsheets have been obtained either from distant-water fishing vessels under access agreements, or from domestic vessels. Coverage of longline and purse-seine catches in the SPC statistical area is summarised in Table 2. Statistics for 1996 and 1997 are considered preliminary. Coverage of the longline fishery has increased since 1992 to a high of 57% in 1995. Longline coverage remains moderate because logbook coverage is not extended to international waters. Coverage of the purse-seine fishery has increased considerably in the 1990s due in large part to the 1993 ban on transshipment at sea which enabled verification of catches at regional landing ports. Annual coverage rate has been greater than 80% since 1993 and reached 94% in 1996.

Table 2. Coverage of retained catches of target species (skipjack, yellowfin, bigeye and albacore) in the SPC statistical area by logsheet data held at SPC on 31 December 1997. The number of vessels covered (Vessels), the number of days at sea covered (Days), the catch in metric tonnes covered by the logsheet data (Logsheet catch), the total catch in metric tonnes (Total catch), and the coverage of the total catch by logsheet data (Coverage), are presented. Statistics for 1996 and 1997 are preliminary.

Gear Type	1992	1993	1994	1995	*1996**	*1997**
Longline						
Vessels	939	1,126	1,263	1,254	*1,030*	*693*
Days	55,014	81,107	101,997	112,512	*71,878*	*39,037*
Logsheet catch	42,405	42,145	63,589	64,452	*42,692*	*24,162*
Total catch	105,914	115,794	136,683	113,518	*108,102*	...
Coverage	40	36	47	57	*39*	...
Purse seine						
Vessels	190	194	192	188	*183*	*173*
Days	25,679	31,573	29,862	28,297	*31,980*	*22,827*
Logsheet catch	479,250	578,221	694,149	628,233	*646,811*	*462,261*
Total catch	855,996	718,322	822,579	757,642	*690,178*	...
Coverage	56	80	84	83	*94*	...

4.2 Observer data

Several national and international organisations (e.g. SPC, Forum Fisheries Agency (FFA), Marshall Islands Marine Resources Authority and the Micronesian Maritime Authority) operate fishery observer programmes in the WCPO. Observers gather baseline data from most of the major industrial fleets of the region including: catch, fishing strategies, set information and vessel/crew characteristics. Observer coverage is low for the purse-seine fishery in the WCPO compared to the EPO. The US Treaty observer programme annually monitors ~20% of the sea days (~30 trips) within the US purse-seine fleet in the WCPO (FFA, 1997). While observer coverage is moderate for the US fleet, coverage is poor for the other fleets (FSM, Japan, Taiwan, Korea and the Philippines) operating in the WCPO as only 80 trips (2,362 sets) or 0.5% of the total effort (479,245 sets) was monitored from 1993 to 1996 (OFP, 1997b). The overall purse-seine observer coverage is ~4%. Ninety-one longline trips (863 sets) were monitored in the WCPO from 1992 to 1996. Observer coverage rate in the longline fishery is poor (1%) as approximately 1,000 vessels participate in the WCPO longline fishery.

Fishery observers collect important information on discarding practices and length composition of the catch. In particular, observer sampling is the only method to estimate the magnitude of bigeye discarding, as logbook data provide an estimate of the retained catch only. From observer data held at the SPC, bigeye discard rate averaged 5.0% for the longline fishery (247 fish discarded of 4,940 caught) and 6.4% for the purse-seine fishery (136 tonnes of the 2,130 caught). In the longline fishery, bigeye are usually discarded due to shark damage, while in the purse-seine fishery, bigeye are discarded because they are small, or in poor condition.

Size-composition data are vital for inclusion into size- or age-structured population-dynamics models. Observer sampling provides some data, but most bigeye size-composition data comes from port-sampling. Since 1992, observers have taken 3,800 bigeye length measurements in the longline fishery and 11,600 in the purse-seine fishery (Table 11). Of the four distant-water longline fleets, the majority of length data has been taken aboard Japanese and Taiwanese vessels. Length sampling has been poor for Chinese and Korean vessels. In the purse-seine fishery, observer sampling mainly occurs on US vessels due to higher coverage (Table 10). Observer coverage is low for the other fleets, consequently less than 400 bigeye are typically measured per year in these fleets.

4.3 Port-sampling data

The implementation of port-sampling programmes and the ban on high-seas transshipments for purse-seine vessels operating in the EEZs of SPC member countries have provided the opportunity to collect unloading data at ports in the region. Port sampling consists of monitoring the size and species composition of landed catches. Also, landing weight can be used to verify logsheet data. The OFP coordinates or supports sampling in 23 regional ports in the western and central Pacific (Figure 19). In addition, the NMFS conducts port sampling in Pago Pago, American Samoa.

In the OFP database, port-samplers have taken 268,000 bigeye length measurements in the longline fishery and 42,000 in the purse-seine fishery since 1992 (Table 11). Bigeye measurements from the Chinese and Taiwanese longline fleet comprise the majority of the length information. Sampling of the Japanese fleet has significantly increased since 1992 with almost 20,000 fish being sampled in 1996. No bigeye length data have been taken from the Korean longline fleet since 1993.

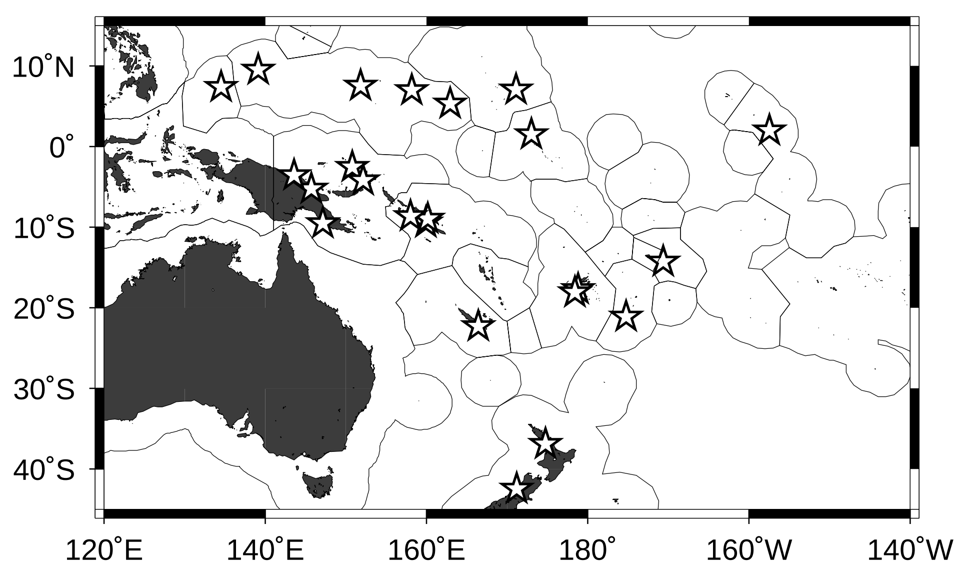


Figure 14. Port-sampling locations (stars) within the SPC's statistical area where data are collected on the longline and purse-seine fleets.

Table 11. Number of bigeye size measurements taken from the various fleets and fisheries operating in the WCPO.

Observer Sampling								
Gear	**Fleet**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**Total**
Longline	China		100	97	247			444
	Fiji			34	224			258
	FSM			3	2	7		12
	Japan		353	423	456	47		1,279
	Korea	38	49					87
	Marshall Is.							
	New Caledonia	11				68		79
	Taiwan		207	629	229	88	34	1,187
	USA				223			223
	Other		2		197	11		210
	Total	49	711	1,186	1,578	221	34	3,779
Purse seine	FSM		35	200	27			262
	Japan		291	250	250			791
	Korea		3	426	109	282		820
	Philippines					80		80
	Taiwan		111	352	324	354		1,141
	USA	928	1,069	857	919	4,730		8,503
	Other						20	40
	Total	928	1,509	2,085	1,629	5,446	20	11,637

Port Sampling								
Gear	**Fleet**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**Total**
Longline	China	2,635	23,104	52,058	38,029	21,638	500	137,964
	Fiji	1,621						1,621
	FSM	221	403	630	791	1,142		3,187
	Japan	959	1,218	6,757	10,114	19,871	422	39,341
	Korea	6,138	436					6,574
	Marshall Is.	138	514	410	244			1,306
	New Caledonia	2	158	351	885	595	77	2,068
	Taiwan	12,789	20,018	18,239	9,226	11,119	1,314	72,705
	USA	1,325	557	174	194	732		2,982
	Other					306	21	327
	Total	25,828	46,408	78,619	59,483	55,403	2,334	268,075
Purse seine	FSM		99	9				108
	Japan							
	Korea		384	1,378	66	15		1,843
	Philippines		1,525	2,464		545		4,534
	Taiwan		121	243	287			651
	USA	7,338	4,934	3,782	5,690	13,390		35,134
	Other	7	13	3				23
	Total	7,345	7,076	7,879	6,043	13,950		42,293
Handline	Philippines	70	8,768	8,931				17,769
Multiple gear	Philippines		125	12				137
Ring net	Philippines		868	444				1,312
	Total	70	9,761	9,387				19,218

Over 80% of the bigeye length data from purse-seiners comes from the US fleet (Table 11). Port-sampling of the US fleet primarily occurs in American Samoa, where the fleet prefers to land its catch (Coan and Prescott, 1996). For the US fleet, port sampling provides roughly four times more length measurements than the US Treaty observer programme. There are few bigeye length data for the Taiwanese and Korean purse-seine fleets in the WCPO and no data for the Japanese fleet. In recent years there has been sampling of the Japanese purse-seine fleet at Yaizu port (Miyabe, 1997), but the OFP does not presently have access to the data.

4.4 Domestic fisheries of the Philippines and Indonesia

The LCEM (Landed Catch and Effort Monitoring) Programme carried out during 1993 and 1994, as part of the Philippines Tuna Research Project (PTRP), at 18 landing sites throughout the Philippines, provided the opportunity to estimate bigeye catches. The LCEM programme produced raised catch estimates at the landing sites, chosen to provide maximum coverage of the landings of oceanic species (skipjack, yellowfin and bigeye). While in operation, the LCEM programme measured over 19,000 bigeye from various fisheries: handline, multiple gears and ring net (Table 11). Over 17,000 length samples were from the handline fishery. No bigeye size data are available from Indonesia.

4.5 Size composition of bigeye catch by gear types

The OFP has access to bigeye size-composition data collected by SPC observers and port samplers (longline and purse-seine), NMFS port samplers (purse-seine) and Philippines port samplers over the past several years. The longline size data are unimodal, with the mode at approximately 140 cm (Figure 20). The size composition of purse-seine-caught bigeye is similar for unassociated and associated sets, with most sampled fish being in the range 40 - 90 cm (Figure 21). However, unassociated sets have some incidences of larger bigeye (110 - 140 cm), which have not been recorded in samples from associated sets. Bigeye catches in the Philippines by the purse-seine, ringnet and handline gears are predominantly of small fish (20 - 50 cm), although larger fish to 170 cm are also caught in smaller numbers by handline (Figure 22).

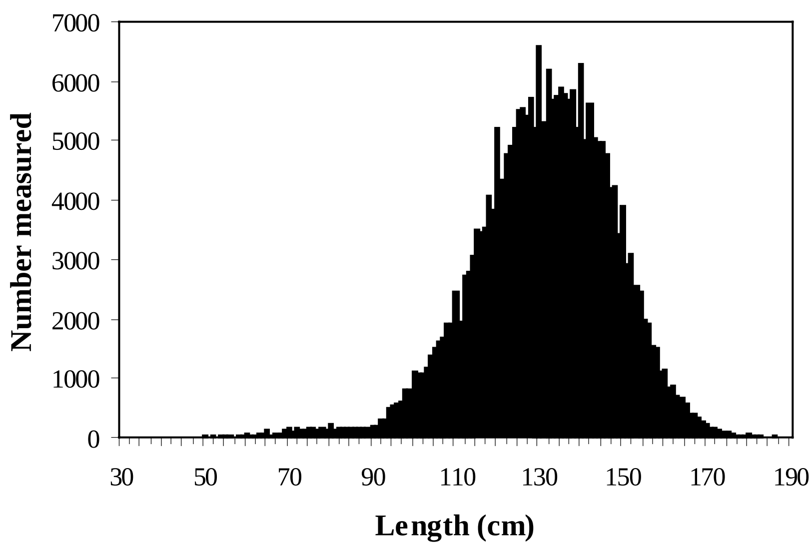


Figure 15. Size composition of bigeye in the WCPO longline catch. Source: SPC port-sampling data (1992 - 1996).

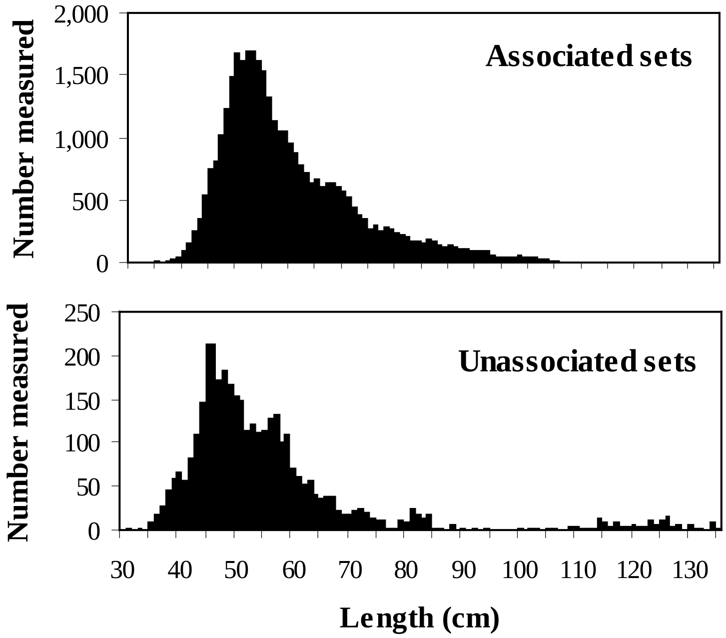


Figure 21. Size composition of bigeye in the US purse seine catch. Source: NMFS port-sampling data (1988 - 1996).

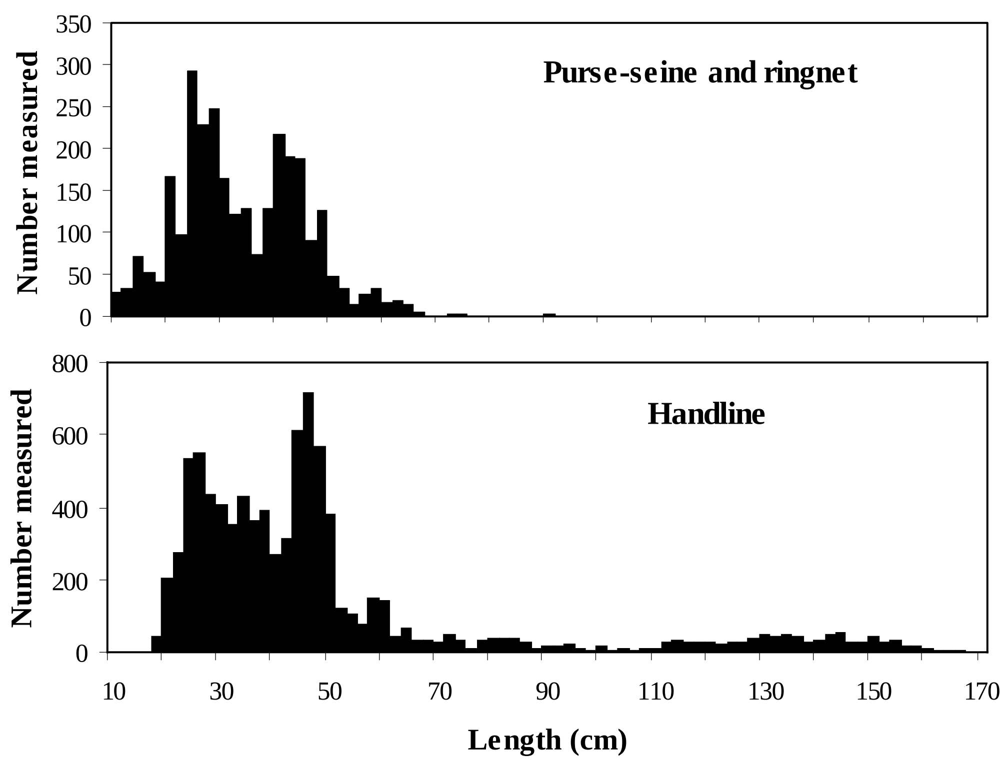


Figure 22. Size composition of purse-seine, ringnet and handline-caught bigeye, sampled in the Philippines Landed Catch & Effort Monitoring Programme.

Section 5

BIGEYE CPUE INDICES

Fishery indicators, such as trends in catch per unit of effort (CPUE) are often used to infer changes in stock size. While CPUE indices are an integral part of stock assessments, the indices are rarely proportional to stock size because many factors can affect fishing efficiency (e.g. area of fishing, targeting practices and oceanographic conditions). In this section, we review nominal CPUE indices and develop standardised indices which at least partly account for operational (gear) and environmental affects. These standardised CPUE indices should provide a better indication of stock abundance than nominal CPUE.

5.1 Factors affecting nominal CPUE

Bigeye tuna CPUE is known to be affected by several factors other than abundance. The fishing depth of longline gear has been shown to be an important source of CPUE variation in several studies (e.g. Hanamoto, 1987; Boggs, 1992). Generally, gear fishing deeper in the water column is more effective in targeting bigeye tuna. This is thought to be due to a preference of bigeye tuna for 10–15°C water (Hanamoto, 1987; Holland et al., 1990; Boggs, 1992; Brill, 1994). Since the mid-1970s, longliners began to change their setting methods from mainly ‘conventional’ sets (4–6 hooks between floats) fishing a depth range of approximately 90–150 m, to ‘deep’ sets (>10 hooks between floats) fishing a depth range of approximately 100–250 m (Suzuki et al., 1977; Hanamoto, 1987). This is likely to have increased the effectiveness of longline gear in targeting bigeye tuna, with possibly greater efficiency gains in the WCPO, where the optimum temperature range of bigeye tuna is deeper than in the EPO. Also, the concentration of dissolved oxygen (DO) that limits bigeye tuna distribution may be sufficiently shallow in some areas to impact the effectiveness of longline fishing. The average depths of the 15°C isotherm and the 2.0 ml l^{-1} DO isopleth are plotted in Figures 23 and 24 respectively, overlaid with average Japanese longline bigeye tuna CPUE for 1986–1995. High CPUE generally occurs when the 15°C isotherm is within 200 m of the surface. CPUE is poor in tropical and subtropical latitudes of the western Pacific where the 15°C isotherm is below 300 m (Figure 23). The depth of the 2 ml l^{-1} DO isopleth follows a similar pattern to the 15°C isotherm (Figure 24). High CPUE occurs when the depth of low DO is relatively shallow. In the tropical and subtropical South Pacific (15°–30°S), the high DO in deep water coupled with a deep 15°C isotherm corresponds to an area of poor CPUE. There is also high CPUE between 10° and 30°N in the central and eastern Pacific. These waters have high DO at depths of 300 m and greater, but the 15°C isotherm is relatively shallow.

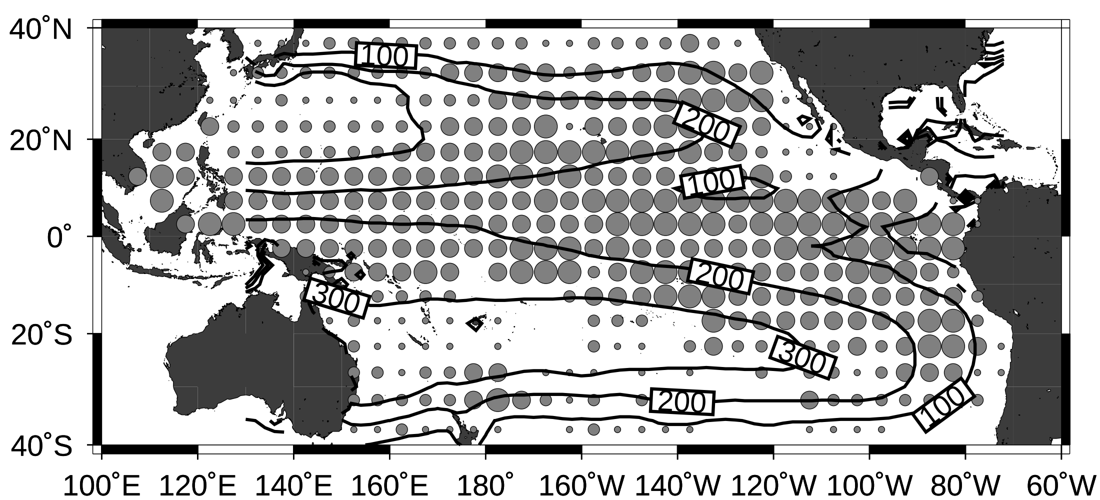


Figure 23. Relationship between the annual depth distribution of 15°C isotherm and nominal bigeye CPUE for the Japanese longline fleet (1986‑95).

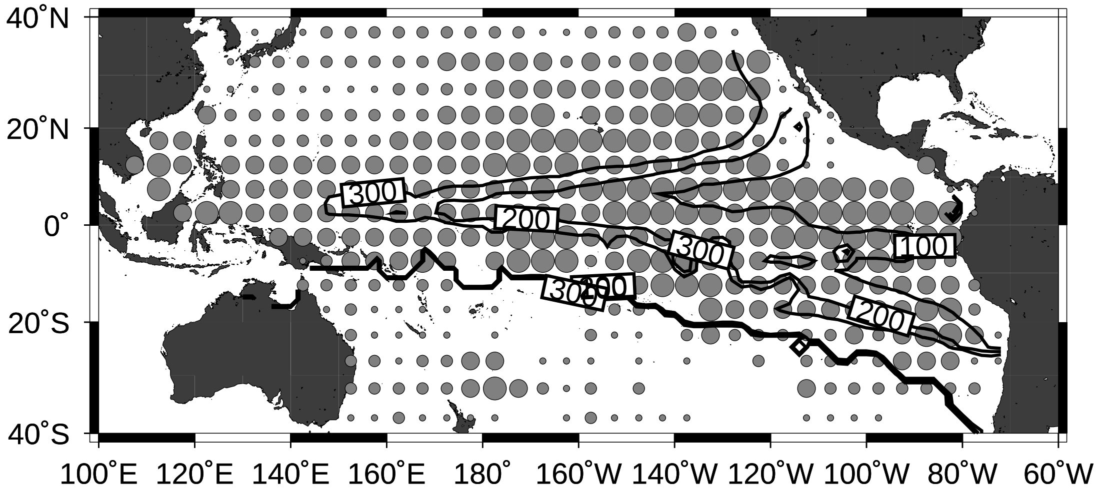


Figure 24. Relationship between the annual depth distribution of the 2 ml l^{-1} DO isopleth and nominal bigeye CPUE for the Japanese longline fleet (1986-95). Only the 100 to 300 m depths are illustrated.

For longline CPUE to be a reliable estimator of relative abundance, it is clear that variation in the fishing depth of longlines and variation in the depth of preferred bigeye tuna habitat need to be accounted for. General Linear Models (GLMs) can potentially be used to remove the variation in nominal CPUE attributable to operational and environmental factors. Miyabe (1995) used a GLM to compensate for seasonal, area and hook-depth effects, showing that, unlike nominal CPUE, standardised CPUE for the Japanese fleet has declined in the EPO in particular (Figure 25). However, GLMs or General Additive Models (GAMs) are ill-suited to using independent information (e.g. from tracking, TDR and physiological experiments) on tuna habitat preferences to standardise CPUE.

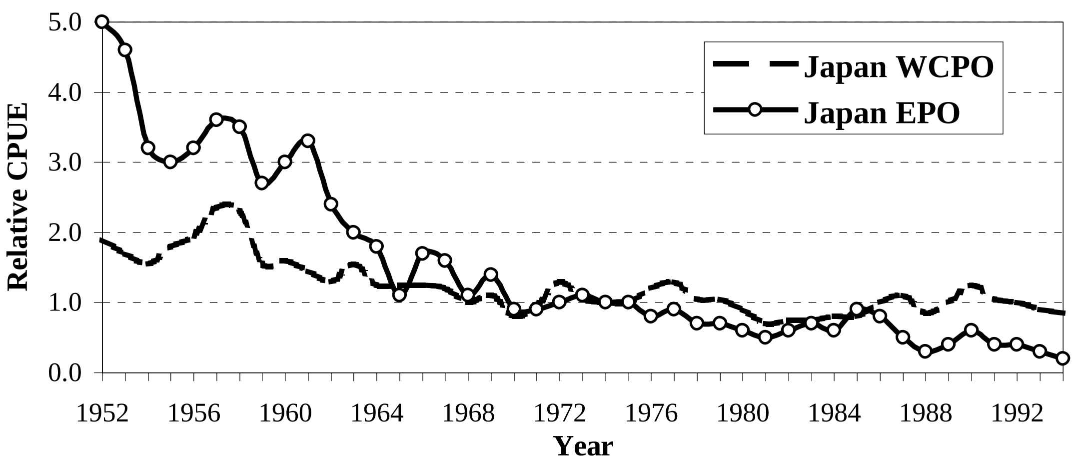


Figure 25. Standardised Japanese longline CPUE for the western and central (WCPO) and eastern Pacific Ocean (EPO) after Miyabe (1995).

5.2 Standardising longline effort and CPUE for operational and environmental effects

Hinton and Nakano (1996) presented a method of standardising longline CPUE using information on habitat preferences and constraints, in combination with environmental data. We apply this method to Pacific bigeye tuna, but our aim is not so much to derive a definitive standardised index of abundance, but rather to highlight the different interpretations of CPUE that can emerge when reasonable assumptions regarding longline fishing depth and bigeye tuna habitat are made.

5.2.1 Description of effort standardisation

The relationship between the mean population density and CPUE can be written as:

(1)
$$\overline{N}_t = \frac{\sum_{i=1}^{a_t} \frac{C_{ti}}{E_{ti} q_{ti}}}{a_t}$$

where $\overline{N}_t$ is the mean population abundance in the area of interest during time period t,

a_t is the number of equally-sized sub-areas comprising the area of interest,

C_{ti} is the catch in sub-area i during time period t,

E_{ti} is the nominal fishing effort in sub-area i during time period t, and

q_{ti} is the catchability coefficient in sub-area i during time period t.

In practice, q_{ti} is not normally known and is assumed to be constant over time and across strata. If this assumption holds, equation (1) can be rewritten as:

(2)
$$\overline{N}_t q = \frac{\sum_{i=1}^{a_t} \frac{C_{ti}}{E_{ti}}}{a_t}$$

with $\overline{N}_t q$ being a relative measure (or index) of mean abundance. Where the assumption of constant q is violated, e.g. where q is affected by an environmental parameter that varies among area strata or over time, the right hand side of equation (2) may not be a reliable index of abundance. A second problem concerns strata for which fishing effort may be zero in a particular time period. Clearly, such strata cannot be included in the summation in equations (1) and (2). This forces an assumption to be made regarding the abundance in strata where effort does not occur. If a_t represents the number of strata with non-zero effort, it is implicit in equation (2) that strata with zero effort are assumed to contain the average abundance across all strata with non-zero effort. This assumption may result in biased abundance indices if the geographical range of the effort distribution contracts or expands over time. For the purpose of this analysis, we will assume average abundance in empty strata, noting that, if the assumption is wrong, this may cause an underestimate in any decline in abundance that may have occurred.

The data used for computing bigeye tuna abundance indices are Japanese, Korean and Taiwanese longline data for the period 1962–1996. These fleets were selected because they constitute the bulk of longline fishing effort in the Pacific and have used standard longline gear (rope mainline, with gear soaking mainly during the day) over a long period of time. Data from recently established longline fleets using monofilament gear and sometimes soaking the gear at night were not included as this may add an additional source of unexplained variation in CPUE.

For the period under consideration, the catch (in number) and effort (in hundreds of hooks) data were stratified by quarterly time periods (t), and by 5° square areas (i). Depth zones (j) of 100 m in the range 0–600 m were also defined. Let k denote a 5° square per quarter observations in year y and assume that all such observations comprise random samples of bigeye density throughout the range of the stock. The index of average annual abundance, I_y is then:

$$I_y = \overline{N}_y q = \frac{\sum_{k=1}^{a_y} \frac{C_{ky}}{E_{ky} \sum_j h_{jky} p_{jky}}}{a_y} \quad (3)$$

where h_{jky} is the proportion of effort in area-time stratum k in year y that fishes in depth zone j,

p_{jky} is the proportion of the fish population in area-time stratum k in year y that occurs in depth zone j, and

a_y is the number of area-time strata sampled by longline gear in year y.

The key elements in the standardisation are the specification of the depth distribution of the longline gear (h_{jky}) and the depth distribution of bigeye tuna (p_{jky}).

5.2.2 Depth distribution of longline gear

The depth at which longline gear fishes is known to be influenced by the set configuration, primarily the length of main line between floats (a 'basket') and the sagging rate (Suzuki et al., 1977; Boggs, 1992). As well, fishing depth will also be influenced by a variety of environmental factors, particularly wind and currents (Boggs, 1992). Such data are not normally available from commercial longline fisheries, but the number of hooks between floats (HBF), which often is available, has been found to be a useful proxy for the targeted fishing depth of longline gear.

For the WCPO, about 21,000 longline trips since 1979 specified the HBF on logsheets provided to the SPC. Most of the HBF data pertained to the Japanese fleet operating in the WCPO. This allowed stratification of the Japanese data by time (3 year segments) and by five areas: (1) north of the equator and west of 150°E, (2) north of the equator and 150°E–150°W, (3) 0°–25°S and west of 150°E, (4) 0°–25°S and 150°E–150°W and (5) south of 25°S. This stratification was desirable because of time and area variation in HBF configurations. There were few logsheet data available for the Japanese fleet operating in the EPO, thus HBF data were taken from published gear configuration histograms (Miyabe and Bayliff, 1987; Nakano and Bayliff, 1992). The EPO HBF data were stratified by year since 1975, but there was no further area stratification within the EPO. Prior to 1975, a figure of five HBF was assumed for the Japanese fleet in both the WCPO and EPO.

For both the WCPO and EPO, HBF data for the Taiwanese fleet from 1967 to 1980 were composed of equal amounts of 7–9 and 10–11 HBF (Table 12). After 1980, HBF data from 1981 to 1996 were stratified by four spatial areas: 0°–40°N, 150°E–180° for the fresh sashimi longliners operating mainly in Micronesia, and three remaining areas (0°–40°N; 70°W–180°; 0°–25°S and 25°–40°S) for the albacore fleet. For both the WCPO and EPO, HBF data for the Korean fleet from 1975 to 1980 were composed of 90% of 4–6 HBF and 10% of 7–9 HBF. After 1980, HBF data were stratified by three areas (0°–40°N, 0°–25°S and 25°–40°S) and several time strata according to data density.

Histograms of HBF were computed (or examined from published material) for each fleet/area/time stratum, as described above, and frequency distributions calculated based on six HBF configurations: regular (4–6), intermediate (7–9), deep1 (10–11), deep2 (12–15), deep3 (16–20) and deep4 (>20). These distributions are shown in Table 12.

Approximate depth distributions are calculated from the HBF distributions. Suzuki et al. (1977) predicted hook depths of 95, 145 and 170 m for Japanese longline baskets of 6 hooks; and 100, 145, 190, 230, 265, 290 and 300 m for baskets of 13 hooks. Uozumi and Okamoto (1997) monitored the hook depth of Japanese longline sets with time-depth recorders (TDR). The deepest hook depths of baskets with 5, 7, 9, 11, 13 and 15 hooks were at 90, 120, 150, 180, 210 and 240 m respectively. The deepest hook depth of the basket with 13 hooks was shallower than that predicted by Suzuki et al. (1977). Uozumi and Okamoto (1997) observed small differences (<30m) in depth among the deepest hooks of baskets from the same set, with sets reaching ≥200 m showing the greatest variation. The authors noted larger differences (70–300 m) between the depths of corresponding hooks from different sets, due to variation in boat and shooter speeds, the effects of winds and currents, and the inter-basket distances.

In studies with TDRs, Boggs (1992) observed that hook depths were usually shallower (55–68%) than those predicted from catenary geometry. Boggs also observed variation in the deepest hook depth during a set, with deep hooks (>300 m) showing the greatest variation (30%). Wendling (1994) used TDRs to determine longline hook depths for sets of 20–50 HBF, and proposed a modified von Bertalanffy model to predict hook depth without data on line angles. He noted substantial variation in the depth of the deepest hook during the same set. At vessel speeds of 5–7 knots, sets of 30–35 HBF were observed to reach 350 m, and those with 40–50 hooks reached 420–550 m.

In light of the above, it is doubtful that hook depth can be predicted with certainty without TDRs. However, crude depth-distribution profiles, providing plausible hook distributions for various fleets under standard (or average) conditions, were generated based on the observations described above (Table 12). One can see that, except for sets with the largest HBF, only a small fraction of the hooks deployed reach 300 m or more.

Table 12. Proportion of hooks by depth (m) and depth zones (j) for different longline gear types. Gear type is defined according to the number of hooks between floats (HBF). Proportion of gear types is stratified by fleet, time and area over the period 1962–1996. Effective effort by depth zone can be calculated by multiplying the two vectors (hooks by depth zones per gear type by the proportion of each gear type).

Gear type	Hooks between floats (range)	Proportion of hooks by depth (metres) zone			
		0-100	100-200	200-300	300-400
Regular	4-6	0.30	0.70		
Intermediate	7-9	0.15	0.80	0.05	
Deep1	10-11	0.10	0.70	0.20	
Deep2	12-15	0.10	0.60	0.30	
Deep3	16-20	0.10	0.45	0.40	0.05
Deep4	>20	0.10	0.30	0.50	0.10

Korean Fleet		Proportion of effort by gear type (hooks between floats)					
Area	Year	4-6	7-9	10-11	12-15	16-20	>20
WCPO and EPO	1975-80	0.90	0.10				
0°-40°N	1981-87	0.67	0.05	0.21	0.07		
	1988-90	0.16	0.07	0.50	0.26	0.01	
	1991-96	0.01	0.08	0.47	0.42	0.00	0.02
0°-25°S	1981-83	0.88	0.09	0.02	0.01		
	1984-87	0.67	0.08	0.20	0.05		
	1988-90	0.19	0.07	0.50	0.23	0.01	
	1991-96	0.00	0.07	0.45	0.46	0.01	0.01
25°-40°S	1981-96	0.90	0.10				
Taiwanese Fleet		**Proportion of effort by gear type (hooks between floats)**					
Area	**Year**	**4-6**	**7-9**	**10-11**	**12-15**	**16-20**	**>20**
WCPO and EPO	1967-80		0.50	0.50			
0°-40°N, 150°E-180°	1981-96	0.10	0.05	0.02	0.06	0.21	0.56
0°-40°N, 70°W-180°	1981-96	0.05	0.59	0.31	0.04	0.01	
0°-25°S	1981-96	0.05	0.59	0.31	0.04	0.01	
25°-40°S	1981-96		0.46	0.49	0.05		

Table 12. (continued)

Japanese Fleet		Proportion of effort by gear type (hooks between floats)					
Area	**Year**	**4-6**	**7-9**	**10-11**	**12-15**	**16-20**	**>20**
WCPO and EPO	1962-74	1.00					
0°-40°N, 120°E-150°E	1975-81	0.49	0.06	0.39	0.06		
	1982-84	0.27	0.09	0.43	0.21		
	1985-87	0.03	0.04	0.30	0.46	0.17	
	1988-90		0.02	0.23	0.44	0.30	0.01
	1991-93		0.01	0.12	0.25	0.58	0.04
	1994-96			0.06	0.12	0.73	0.09
0°-40°N, 150°E-150°W	1975-81	0.37	0.07	0.38	0.18		
	1982-84	0.07	0.04	0.54	0.35		
	1985-87	0.01	0.02	0.34	0.45	0.18	
	1988-90	0.01	0.01	0.22	0.37	0.37	0.02
	1991-93			0.12	0.27	0.58	0.03
	1994-96			0.05	0.15	0.75	0.05
0°-25°S, 120°-150°E	1975-81	0.65	0.02	0.20	0.13		
	1982-84	0.59	0.01	0.10	0.28	0.02	
	1985-90		0.01	0.02	0.60	0.37	
	1991-93			0.04	0.31	0.58	0.07
	1994-96		0.05			0.54	0.41
0°-25°S, 150°E-150°W	1975-81	0.23	0.05	0.29	0.43		
	1982-84	0.33	0.01	0.16	0.49	0.01	
	1985-87	0.07	0.03	0.06	0.56	0.28	
	1988-90	0.01	0.19	0.02	0.25	0.50	0.03
	1991-93		0.07	0.03	0.24	0.64	0.02
	1994-96		0.04	0.03	0.31	0.61	0.01
25°-40°S	1975-81	1.00					
	1982-84	0.98	0.02				
	1985-87	0.95	0.05				
	1988-90	0.91	0.09				
40°S-40°N, 70°-150°W	1975	0.84	0.08	0.06	0.02		
(EPO)	1976	0.69	0.17	0.12	0.02		
	1977	0.34	0.31	0.33	0.02		
	1978	0.25	0.24	0.45	0.06		
	1979	0.25	0.19	0.50	0.06		
	1980	0.20	0.18	0.53	0.09		
	1981	0.20	0.18	0.53	0.09		
	1982	0.16	0.13	0.55	0.16		
	1983	0.10	0.17	0.40	0.33		
	1984	0.06	0.24	0.30	0.40		
	1985	0.02	0.18	0.27	0.53		
	1986	0.02	0.18	0.19	0.61		
	1987-96	0.03	0.14	0.16	0.67		

Using the depth distributions of hooks in various HBF categories (upper part of Table 12) and the HBF distributions for various fleet/area/time strata, approximate depth distributions of the gear, h_{jky}, can be calculated.

5.2.3 Depth distribution of bigeye tuna

We assume that the depth distribution of bigeye, as defined by the p_{jky} values, is a simple function of temperature preference and minimum DO requirements. Holland et al. (1990) tracked several juvenile bigeye (72–74 cm FL, or ~10–12 kg) in Hawaii and estimated the daytime, off-FAD distribution of occurrence in relation to temperature. This distribution peaked at 14–17°C. Boggs (1992) obtained the highest daytime CPUE of large bigeye (>30 kg) near Hawaii at 200–400 m (recorded with TDRs), with significantly lower CPUE at <200 m depth. The 200–400 m layer corresponded to temperatures in the approximate range 8–16°C. The apparently colder lower temperature preference of bigeye observed by Boggs (1992) and in previous studies of longline CPUE (Hanamoto, 1987), compared to bigeye tracked by Holland et al. (1990), is possibly related to the larger average size of the fish in the former studies – larger bigeye would have greater thermal inertia, thus allowing more time to be spent in colder water between the regular upward excursions into warmer water for thermoregulatory purposes. As the bigeye caught by commercial longline fisheries are generally >30 kg, we have assumed that the distribution of bigeye relative to ambient temperature, or temperature preference indices (on a scale of 0–1), follows the results of Holland et al. (1990) for temperatures >14°C, remains constant with decreasing temperature to 10°C, and declines to zero at temperatures ≤8°C, consistent with the results of Boggs (1992). This pattern is shown in Figure 26a. A second set of temperature preference indices (Figure 26b), in which the optimum temperature is assumed to be 10–20°C, was also tested to see the effect of the optimum-temperature assumption on the results.

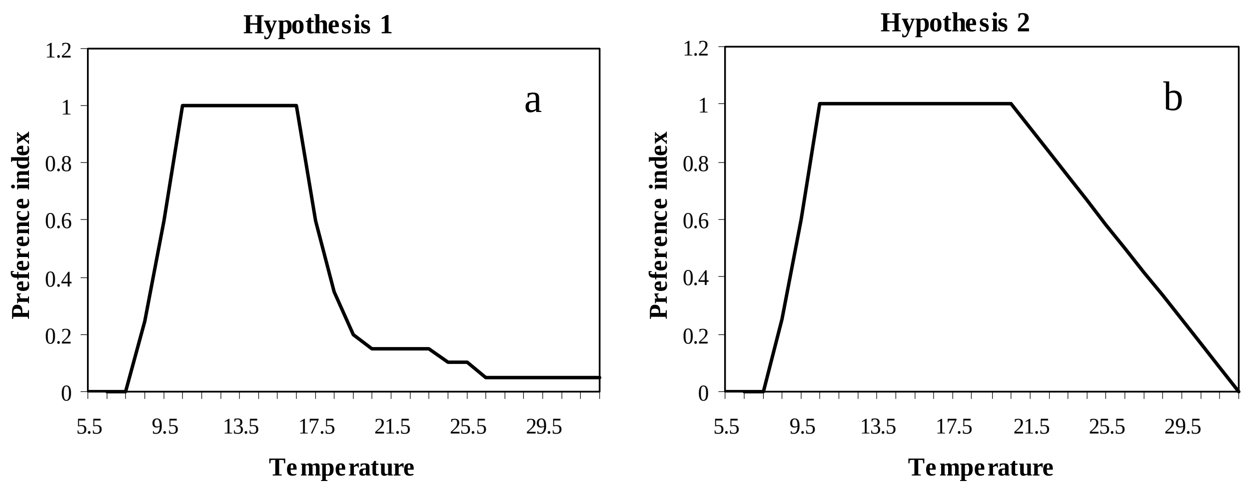


Figure 26. Alternative hypotheses regarding temperature preferences of bigeye tuna: (a) based on sonic tracking (Holland et al., 1990) and longline TDR observations (Boggs, 1992) and (b) assuming a stronger preference for water temperatures > 17°C.

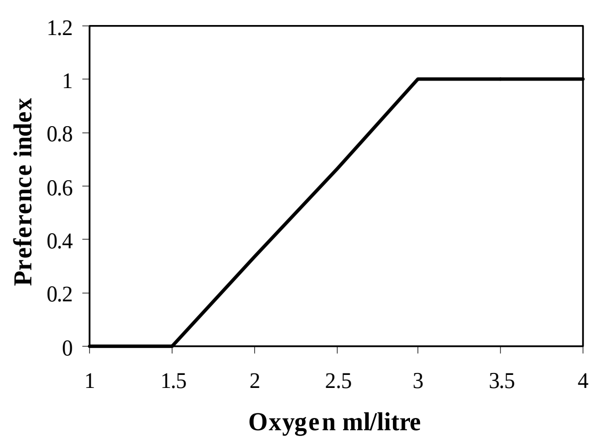


Figure 27. Dissolved oxygen preference of bigeye tuna, based on various physiological observations.

Boggs (1992) concluded that bigeye are rarely caught in waters with DO <1.4 ml l^{-1}, consistent with physiological observations of reduced bigeye cardiac performance at <2.1 ml l^{-1} (Bushnell et al., 1990). We therefore assumed that DO preference indices (again on a 0–1 scale) decline sharply at DO < 3.0 ml l^{-1} and are zero at DO < 1.5 ml l^{-1} (Figure 27).

For each area-time stratum k, a p_{jky} value was assigned for each 100 m depth layer (j) over the range 0–600 m. The p_{jky} value consisted of the product of the bigeye temperature and DO preference indices (as given in Figures 28 and 29) at the particular values of temperature and DO for that depth layer, 5° square and quarter, normalised such that $\sum_j p_{jky} = 1$. Normalised in this way, the p_{jky} values describe the relative depth distribution of bigeye in an area-time stratum. Differences in potential habitat quality, as defined by the temperature and DO preferences, among area-time strata are indicated by the non-normalised products. Temperature and DO profile data were obtained from the World Ocean Atlas climatological databases (Levitus and Boyer, 1994a, b). These data summarise the spatial and seasonal variability in temperature and DO at depth averaged over a long period of time (1934–1994). Ultimately, it would be preferable to use year-specific data to account for inter-annual variability in temperature and DO profiles, but such data are not currently available at the spatial and temporal coverage required for this analysis.

Meridional (north to south) depth profiles of temperature habitat quality, DO habitat quality, combined temperature-DO habitat quality and p_{jky} at 160°E, 150°W and 110°W, are shown in Figure 28 (for the Boggs/Holland temperature indices – hypothesis 1) and Figure 29 (for the alternative temperature indices – hypothesis 2). In Figure 28, the optimum temperature is at >300 m in the western Pacific (160°E section) mid-latitudes. Near the equator, optimum temperatures are found at 200–300 m. Optimum temperature is shallower in the central Pacific (150°W section) and reaches to 100 m depth in the eastern Pacific (110°W section) north of the equator. In the western and central Pacific, DO is limiting at depths >200 m from 5°N to 20°S. Along 110°W, DO is limiting at >100 m depth north of the equator. The combination of temperature and DO preferences suggests that good habitat is generally >300 m in the western Pacific, except around the equator where it is 200–300 m. In the central Pacific, good habitat is found at >300 m south of the equator and somewhat shallower north of the equator. In the eastern Pacific, good habitat occurs at 100–200 m just south of the equator, and at increasing depths to the south. North of about 5°N, the temperature-DO habitat is poor at all depths because the temperature is too warm in the top 100 m and too DO-deficient deeper than 100 m.

A zonal (east to west) section (Figure 30) suggests that, along 10°N latitude, the best bigeye tuna habitat occurs at 200–300 m in the region 150°E–180°. Moving east, good habitat is progressively confined to the upper layers because of shallower DO-deficient water. These patterns are similar under both temperature preference hypotheses. The major difference is that moderate to good habitat is predicted to extend closer to the surface in all areas in hypothesis 2, with less concentration of bigeye predicted at specific depths.

5.2.4 Results of standardised CPUE

The application of equation (3) to the Japanese, Korean and Taiwanese longline data yielded the density indices shown in Figure 31. For the WCPO (Figure 31a), the density index trend is strongly dependent upon which temperature-preference hypothesis is selected. Using the Boggs/Holland temperature preference hypothesis (1), average density is estimated to have declined continuously in the WCPO since 1962. In contrast, there is no apparent trend since 1970 in either nominal (∑Catch/∑Effort) CPUE or in the density index calculated under the alternative temperature preference hypothesis (2). Our interpretation of these differences is that, under hypothesis 1, the progressive changes in setting behavior of the fleets have resulted in longline effort becoming more efficient in the WCPO because of better targeting of optimal bigeye habitat. Under these circumstances, nominal CPUE is over-optimistic if used as an index of abundance. Under hypothesis 2, little or no change in the effectiveness of longline effort is predicted because of the less specific temperature preference assumed for bigeye tuna. Therefore, the density index computed under hypothesis 2 agrees well with the nominal CPUE.

For the EPO (Figure 31b), both density indices and nominal CPUE show similar trends – a decline during the 1960s and an absence of a significant trend thereafter. This probably reflects the dominance of DO in determining the effectiveness of longline effort in the EPO. Also, the shallower optimal temperature layer in the EPO would mean that the change from conventional to deep longline sets would have had a smaller relative impact on effort efficiency in the EPO compared to the WCPO.

For the total Pacific Ocean (Figure 31c), the estimated density indices follow the same pattern as in the WCPO – a continuous decline under temperature preference hypothesis 1, and flat time series for hypothesis 2 and for nominal CPUE.

The changes in estimated bigeye tuna stock distribution over time under both temperature-preference hypotheses are shown in Figure 32. Under hypothesis 1, the distribution of high density extended from about 10°N to 35°N in the 1960s. By the 1990s, high density was restricted to a narrow band across the WCPO to about 120°W at 0–10°S. Under hypothesis 2, there is some contraction of high-density areas in the North Pacific, but the extent of the change is not as great as under hypothesis 1. It is interesting to note that a reduction in the abundance of pelagic fish stocks is often accompanied by a geographical compression of their range (Hilborn and Walters, 1992).

The results of this analysis show that consideration of the fishing depth of longlines in relation to bigeye habitat preference is essential for the interpretation of CPUE. Specifically, we have demonstrated that alternative plausible assumptions regarding bigeye tuna depth distribution in relation to temperature result in vastly different interpretations of CPUE time series for the WCPO and the entire Pacific Ocean. This means that quite precise information on temperature preference will be required in order to have any confidence in bigeye tuna stock assessments in which effort or CPUE are used. We have not yet tested alternative hypotheses regarding DO constraints to depth distribution, or different assumptions regarding longline fishing depth. Further testing of these assumptions, as well as additional standardisation research is outlined in Section 6.3.

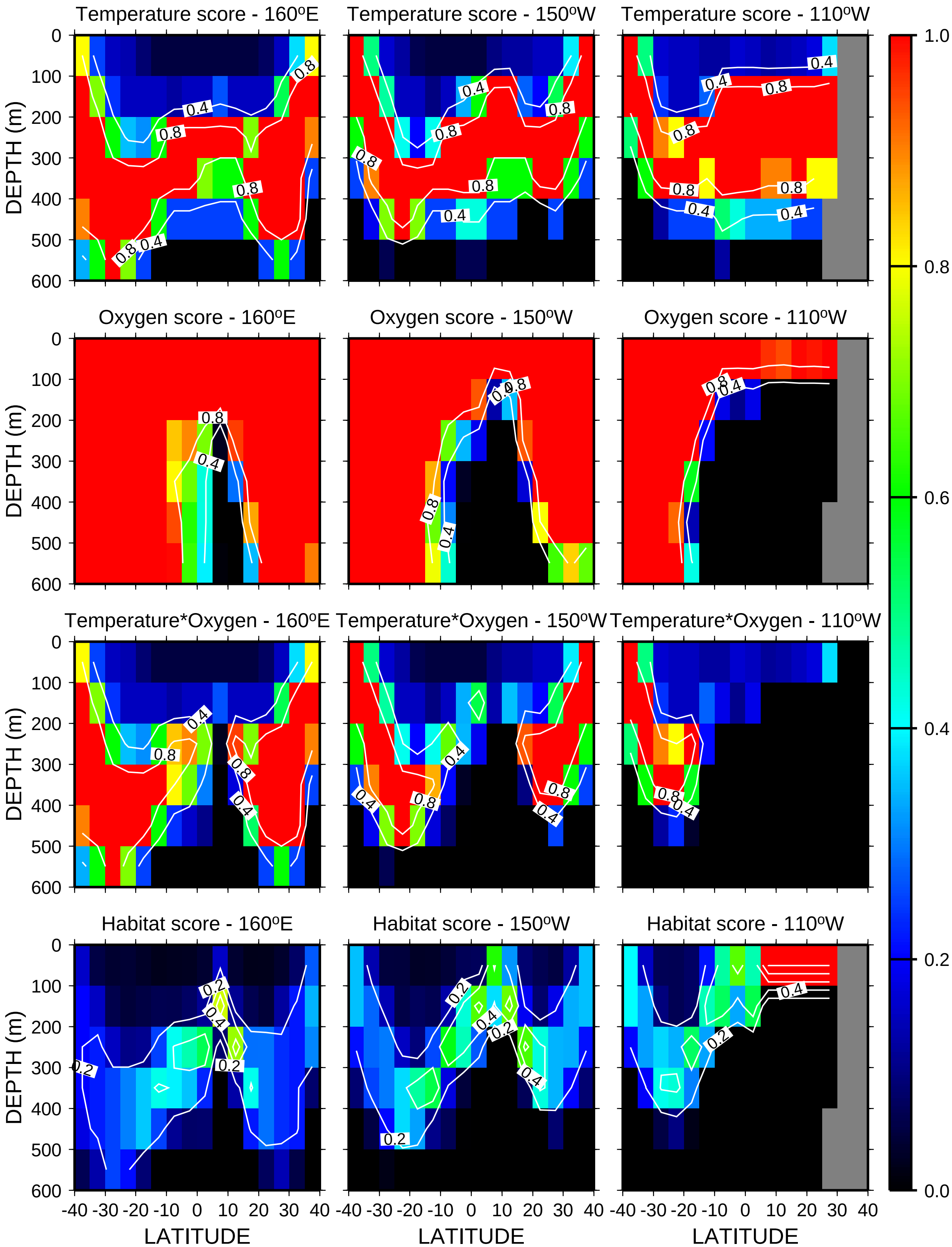


Figure 28. Meridional sections (160°E, 150°W and 110°W) of climatological bigeye tuna habitat indices for temperature, oxygen, combined temperature and oxygen and normalised habitat quality (p_{jky}). Habitat indices follow hypothesis 1.

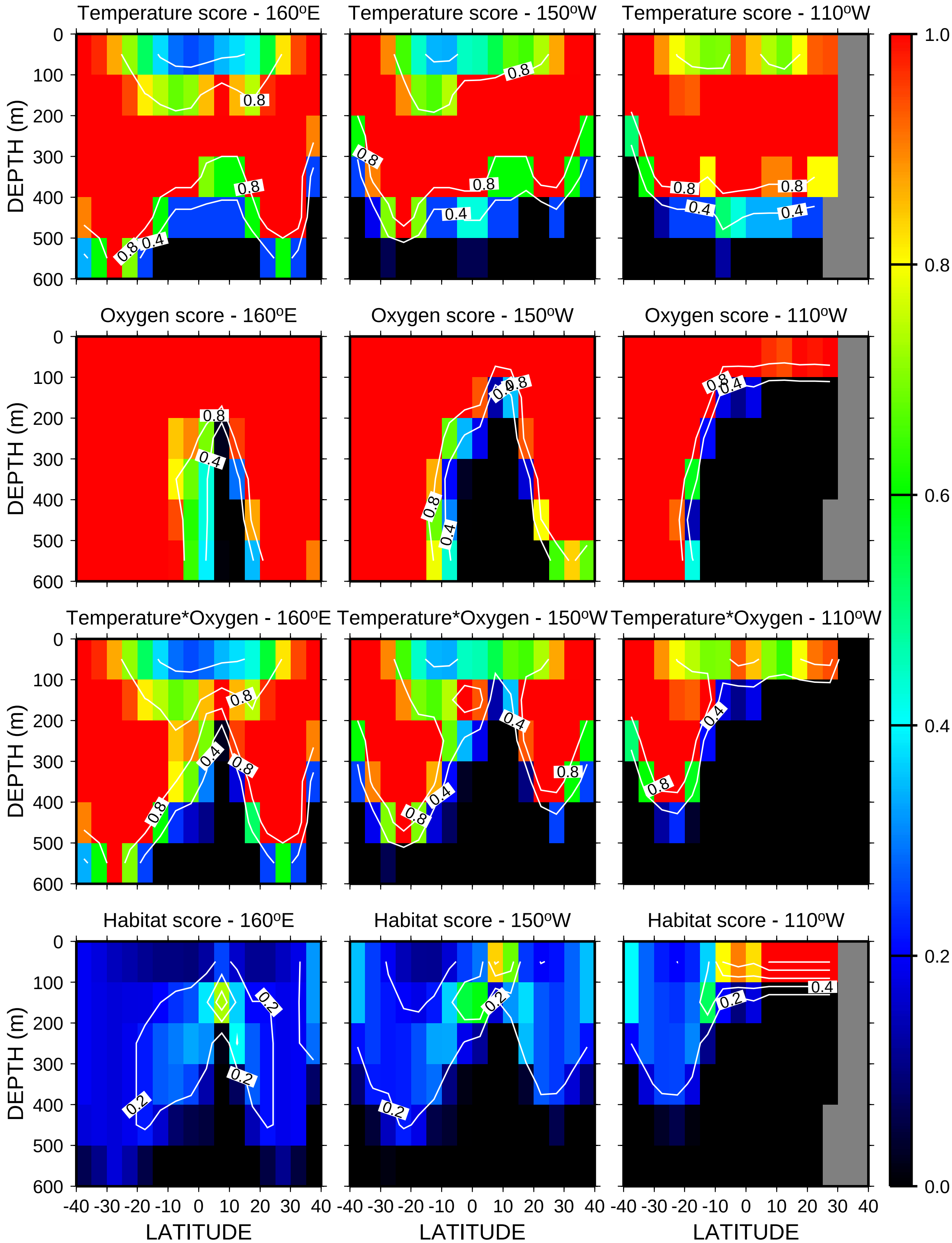


Figure 29. Meridional sections (160°E, 150°W and 110°W) of climatological bigeye tuna habitat indices for temperature, oxygen, combined temperature and oxygen and normalised habitat quality (p_{jky}). Habitat indices follow hypothesis 2.

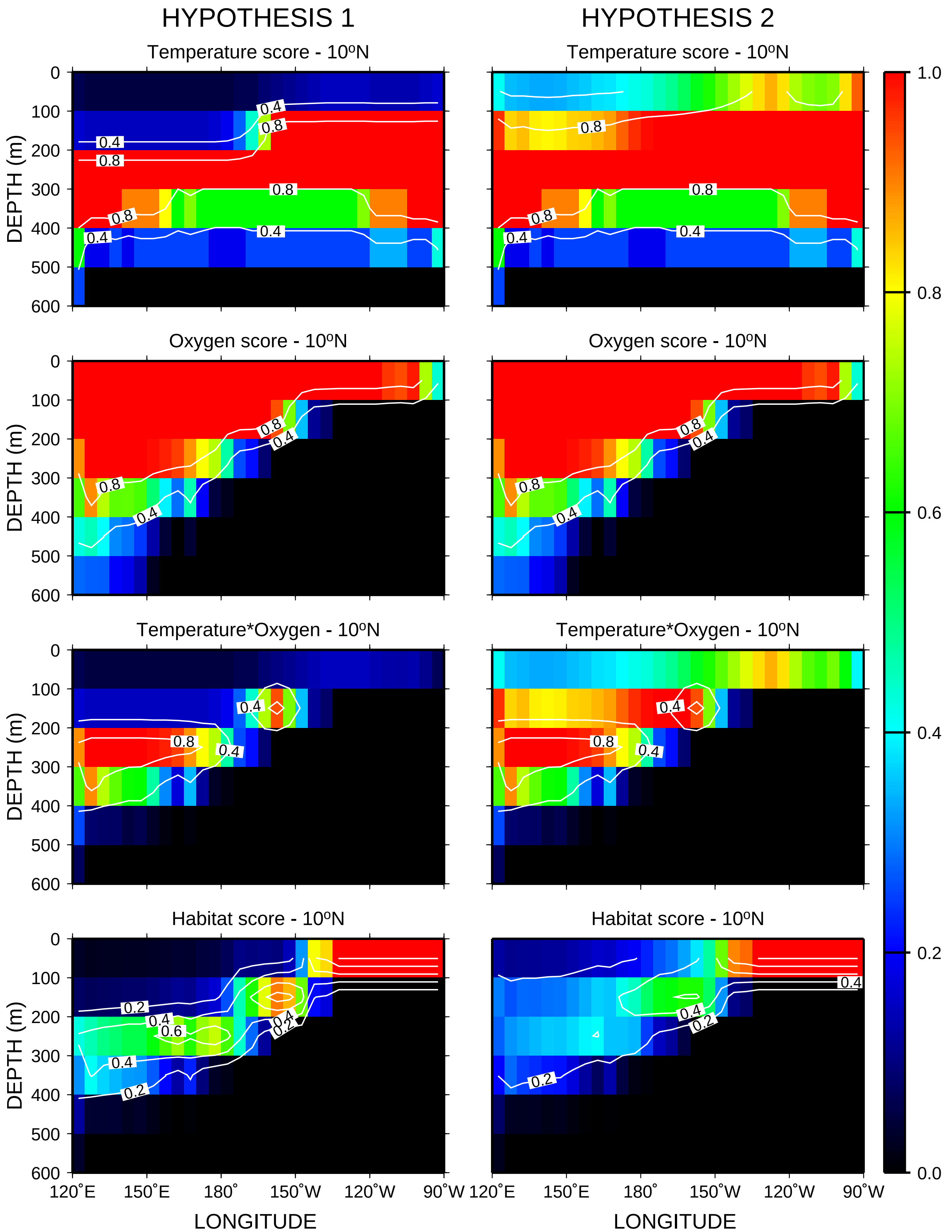


Figure 30. Zonal section at 10°N of climatological bigeye tuna habitat indices for temperature, oxygen, combined temperature and oxygen and normalised habitat quality (p_{jky}). Habitat indices follow hypothesis 1 (left) or hypothesis 2 (right).

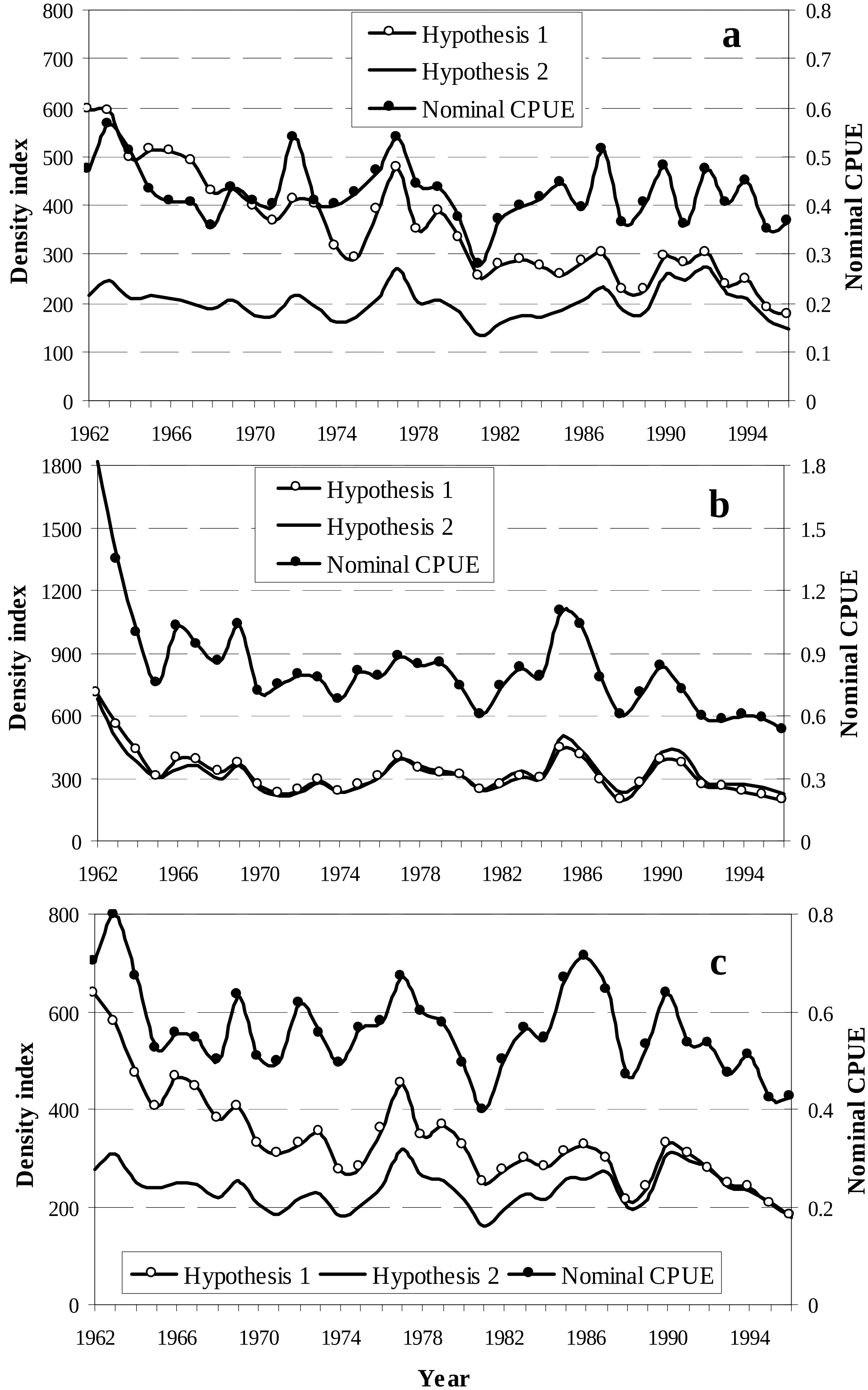


Figure 31. Standardised CPUE obtained for the two temperature preference hypotheses and nominal (∑Catch/∑Effort) CPUE for a. the western and central Pacific, b. the eastern Pacific and c. the entire Pacific Ocean.

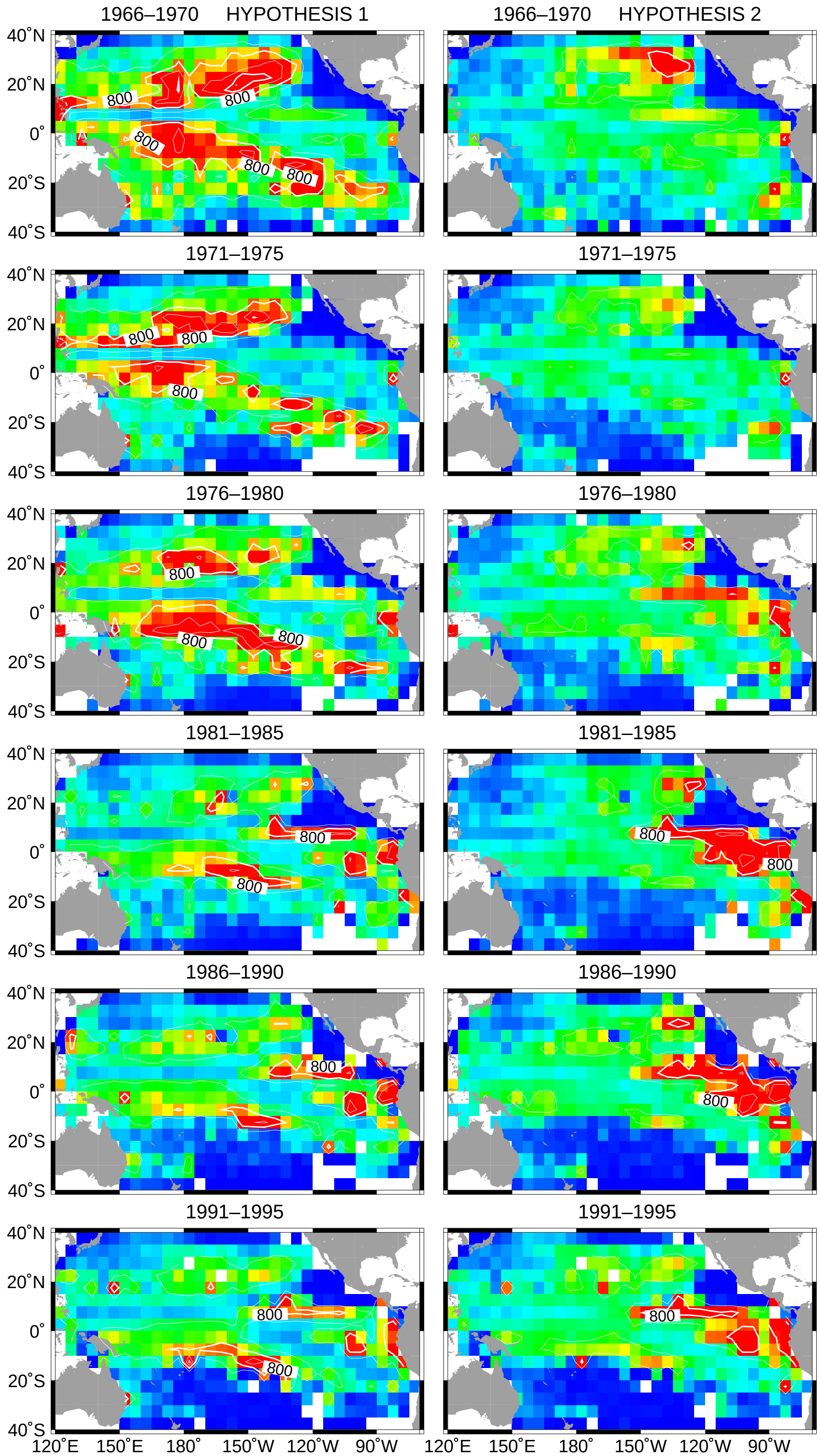


Figure 32. Comparison of bigeye tuna standardised CPUE under hypothesis 1 (left) and hypothesis 2 (right).

Section 6

DATA REQUIREMENTS AND FUTURE RESEARCH

6.1 Stock assessment

Several attempts have been made to assess the status of the Pacific bigeye stock through the use of surplus production models and virtual-population or cohort analysis (reviewed by Miyabe, 1994). Production models, assuming a Pacific-wide stock, estimated the current biomass to be approximately equal to the biomass at the Maximum Sustainable Yield (MSY), which indicates full exploitation. Though production models are simple to fit, the previous estimates of MSY may not be appropriate because the analysis used data sets in which the surface catch of bigeye was underestimated. The surface catch of bigeye has increased drastically since 1993, and thus the age structure of the catch has changed considerably, making further application of production models to Pacific bigeye problematic.

Preliminary cohort analyses have been applied to Pacific bigeye by several researchers. In a recent Pacific-wide analysis, the stock status was found to depend on the assumed values of natural mortality and terminal fishing mortality rate (Miyabe and Takeuchi, 1998). For cohort analyses of bigeye in the eastern Pacific Ocean, the assumed level of natural mortality has a major impact on estimates of surface-fishery impacts on the longline fishery and on estimates of yield per recruit (IATTC, 1998).

Because of these and other uncertainties, it is not possible to confidently estimate the current status of Pacific bigeye tuna. The 11th Standing Committee on Tuna and Billfish (SCTB) recently summarised the situation as follows:

> *The 11th SCTB noted with concern the large and continuing increase in the catch of small-medium sized bigeye in both the eastern Pacific and the western and central Pacific, and the steady decline in longline catches in some areas. However, because of the varying interpretation of observed CPUE trends and the present inability of stock assessments to produce unequivocal results due to poor estimates of some key parameters, the Group considered that the present condition of the Pacific bigeye stock was uncertain.*
>
> *It recommended that directed research efforts to reduce this uncertainty be urgently undertaken, and noted in particular the need for better estimates of the bigeye tuna catch by surface fleets, mixing rates and movements of fish across the range of the stock, and estimates of biological parameters such as size-specific natural mortality rates.*

There has been some recent progress in better defining bigeye population and fishery parameters; however, important gaps in biological and fishery data remain, as outlined in the following section.

6.2 Gaps in biological and fishery data

6.2.1 Biological data

1) A validated age-at-length model facilitates decomposition of fish lengths into age classes. Current research is deriving bigeye age estimates from otolith microstructural analysis, but the periodicity of increment deposition requires validation.

2) Available genetic information cannot refute the hypothesis of a single bigeye stock in the Pacific Ocean (Grewe and Hampton, 1998). Although there may be only one genetic stock, there is a need for better information on mixing rates and movements of fish throughout their range. Conventional and archival tagging data would greatly facilitate the estimation of movement and mixing rates. Archival tagging offers

an advantage over conventional tagging by providing information on habitat preferences, which can be used to better define large-scale distribution.

3) As noted above, stock assessment results are particularly sensitive to assumed levels of natural mortality rate. Available conventional tagging data have provided some information, but more data from a wider range of locations is required.

6.2.2 Logbook data

High-resolution logbook data are frequently required for effort or CPUE standardisation. Deficiencies in data currently available to SPC include:

1) Bigeye and yellowfin tuna catches are not routinely separated in purse-seine logbooks, therefore additional information is required to estimate bigeye tuna catches.

2) Spatial coverage of logbook data is incomplete – the major gaps are for fleets fishing in international waters, including distant-water longliners of Korea and Taiwan, and Japanese longline and purse-seine vessels.

3) Coverage of certain domestic longline fleets of SPC member countries has been poor. SPC member countries and territories that currently do not collect logbook data from domestic fleets at a high coverage rate include Kiribati, Marshall Islands, New Caledonia, Papua New Guinea, Tonga and Vanuatu.

4) An estimate of retained bigeye catch is sufficiently recorded on logbooks for the longline fishery, but estimates of bigeye discards (small or damaged fish) are inadequate with the low observer coverage.

6.2.3 Observer and port-sampling data

6.2.3.1 Purse-seine fishery

1) In the purse-seine fishery, logbook estimates of bigeye catch are not accurate for any fleet. Observer and port-sampling effort is considered low. Therefore, in contrast to the EPO fishery, the magnitude of bigeye catch in the WCPO purse-seine fishery is uncertain.

2) In recent years, the problem of under-reporting of bigeye in the purse-seine fishery has increased as several fleets have developed a preference for setting on associated objects (e.g. FADs, logs) in conjunction with gear modifications which results in a higher percentage of bigeye in the catch. Fleet-specific estimates of bigeye catch are presently calculated using sampling data to partition the logsheet-reported yellowfin/bigeye catch for year, fleet and school type (associated or unassociated). For the Japanese, Korean and Taiwanese fleets, observer and port-sampling coverage is insufficient or unavailable, thus catch composition by year and school type is assumed to be similar to that for the US fleet. The overall estimates of bigeye catch are therefore conditional on this assumption being correct.

3) Bigeye length sampling is inadequate for many longline and purse-seine fleets. Since 1993, sufficient length sampling has occurred only on the US purse-seine fleet. There is a paucity of information for the Korean and Taiwanese fleets. Port-sampling of the Japanese purse-seine fleet occurs in Japan, but data from this sampling are not yet available to other scientists.

6.2.3.2 Longline fishery

1) Size sampling of bigeye occurs more frequently in the longline fishery than in the purse-seine fishery. Size composition data may be adequate for assessment purposes for the Chinese, Japanese, Taiwanese and domestic Pacific Island longline fleets, but data from the Korean fleet are lacking.

6.2.4 The Philippines and Indonesian fisheries

1) No direct bigeye catch estimates are available for the Philippines or Indonesian domestic fisheries. The current estimation procedure for these countries is based on assuming an expected percentage of bigeye in the declared landings of yellowfin. Estimated bigeye catch depends on the accuracy of the estimate of yellowfin landings, which is only approximately known.

2) A major programme during 1993 and 1994 produced bigeye size information for the Philippines fisheries, but current size sampling is limited to infrequent sampling of the purse-seine fishery. Bigeye are widely exploited in Indonesia, but the lack of catch and size information remains a problem.

6.3 Refining CPUE trends

CPUE trends are a critical input to both production and age-structured stock assessment models. In section 5, we provided preliminary standardised CPUE indices by accounting for differences in longline hook depth and bigeye habitat preferences. The results of the study stress the importance of future research in two key areas:

1) archival tagging of bigeye to collect further information on depth distribution and its environmental correlates, and

2) longline TDR deployment to collect further information on longline fishing depth and its variability. It is clear that the development of a more accurate model of longline fishing depth would considerably assist such studies.

If this standardisation approach is used for assessment purposes, the model could also be improved by:

1) testing alternative hypotheses regarding dissolved oxygen (DO) constraints to bigeye depth distribution, or different assumptions regarding longline fishing depth.

2) the use of area and season strata, possibly based on the distribution of temperature–DO habitat, in the calculation of annual density indices;

3) the use of year-specific temperature and DO data for the period 1980–1995 (LODYC model output) to examine the impact of interannual variability in temperature and DO depth distributions.

4) the use of finer-scale depth strata (possibly 50 m rather than 100 m) to specify fishing depth and bigeye depth distribution;

5) the use of finer-scale longline catch and effort data (possibly at 1° rather than 5° spatial resolution) would allow more precise association of bigeye tuna depth distribution with catch-effort observations.

6) examination of patterns of effort concentration over time, and the potential application of interpolation methods, such as krieging, to estimate densities for strata with zero effort.

6.4 Development of stock assessment models

Previous stock assessment approaches applied to Pacific bigeye have been inadequate for a number of reasons, including:

- Production models have not accounted for changes in the age composition of the catch resulting from the expansion of purse-seine fishing for bigeye;

- Standard cohort analysis is unable to fully incorporate information other than catch at age (usually derived separately from length data). In particular, effort data and tagging data are potentially valuable sources of information on the dynamics of the stock.

- Analyses to date have not been structured so as to allow the effects of different stock-mixing hypotheses to be investigated.

The development and application of an integrated, length-based, age- and spatially-structured model capable of incorporating a variety of auxiliary data is required to address these difficulties. This will be the subject of a new research initiative by SPC and other collaborating agencies in the near future.

Section 7

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