WPYRG5/ 11

Noumea, New Caledonia
August 21 - 23, 1995

A REVIEW OF THE BIOLOGY AND FISHERIES FOR BIGEYE TUNA, *THUNNUS OBESUS*, IN THE PACIFIC OCEAN

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Working paper for the 5th Meeting of the Western Pacific Yellowfin Tuna Research Group, Noumea, New Caledonia, August 21-23, 1995.

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1. INTRODUCTION

This paper is prepared for the Expert Consultation on Interaction of Pacific Ocean Tuna Fisheries. Thus the contents included here are limited to those related to Pacific bigeye tuna. In compiling this paper, the "Synopsis of biological data on the bigeye tuna, *Thunnus obesus* (Lowe, 1839), in the Pacific Ocean" by Calkins (1980) and "Fishery biology of the bigeye tuna resource in the Pacific Ocean" by Kume (1979a) are major sources of reference.

2. CLASSIFICATION

According to Nelson (1976), Genus *Thunnus* is classified as follows:

Phylum Chordata
- Superclass Gnathostomata
  - Class Osteichthyes
    - Division Euteleostei
      - Superorder Acanthopterygii
        - Order Perciformes
          - Superfamily Scombroidae
            - Family Scombridae
              - Subfamily Scombrinae
                - Tribe Thunnini
                  - Genus *Thunnus*

Bigeye tuna was first described by Lowe (1839) based on the specimen caught in the area of Madeira, Portugal (cited in Iwai *et al.*, 1965). The scientific name given to this species varied considerably among the taxonomists until mid-1960s, since then *Thunnus obesus* has been generally accepted by the scientific community.

The classification of bigeye tuna and other tunas in Genus *Thunnus* is discussed by Iwai *et al.* (1965), Gibbs and Collette (1967), Sharp and Pirages (1978) and Collette and Nauen (1983).

3. EARLY LIFE HISTORY

Currently the egg of this species cannot be differentiated from other tuna eggs. The fertilized egg is known to be pelagic and non-adhesive. Kikawa (1953) reported that the egg had an oil globule and the diameter of running ripe eggs was about 1 mm. In Yuen (1955) and Nikaido *et al.* (1991), the diameter of the most advanced eggs ranges between 0.8 to 1.2 mm. Yasutake *et al.* (1973) described larval development from hatching to 86 hours after hatching of bigeye tuna eggs artificially fertilized on board a research vessel. It is reported that it took 24 to 30 hours before the first hatching at 25.5-29.0°C. The size of larvae when hatched was 2.5 mm and after 26 hours the larvae reached 2.76-3.12 mm in total length. By 86 hours after hatching the early post-larval stage was attained. The development of the larvae in these stages is shown in Figure 1.

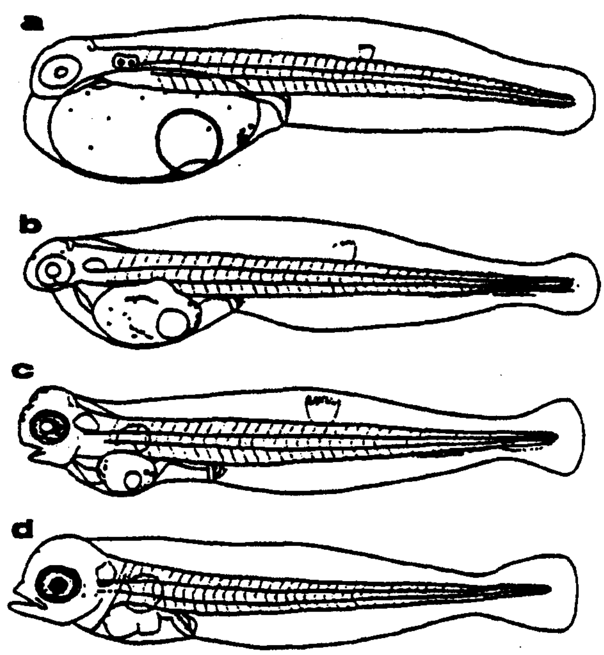

Figure 1. Larvae of bigeye tuna: a) newly-hatched (2.5 mm in TL); b) 24 hours after hatching (3.0 mm in TL); c) 48 hours after hatching (3.1 mm in TL); d) 86 hours after hatching. (After Yasutake *et. al.*, 1973).

The diagnostic keys to the larvae (3 to 12 mm standard length) of Family Scombridae (including Genus *Thunnus*) based on the morphological characters is given in Nishikawa and Rimmer (1987). Pigmentation is the most important feature for the identification of tuna larvae. The identification of larvae and juveniles from 12 mm to about 60 mm is very difficult because of morphological similarities among the tuna species and the overlapping counts in the meristic characters. Graves *et al.* (1988) conducted an electrophoretic analysis on tuna larvae and early juveniles in an attempt to separate bigeye and yellowfin. Their samples were all identified as yellowfin in spite of the fact that their samples included larvae which have morphological characteristics for bigeye and yellowfin. This result raised a question on the validity of the pigmentation pattern which is currently used for the species separation between bigeye and yellowfin larvae.

Nishikawa *et al.* (1985) reported average tuna larvae distribution based on the total of 63,017 net tows during 1956 to 1981. According to their results, bigeye tuna larvae are distributed very widely in the equatorial area of the western, central and eastern Pacific. The area where they occur is very broad in the western Pacific, extending from off the south coast of Japan to the northern Coral Sea. In the eastern Pacific, there are several 1-degree squares marked with higher larval densities than in the western and central Pacific. It appears, however, that, despite the huge spawning potential of the Pacific bigeye tuna inferred from the studies of sexual activities, the number of their larvae per unit of water strained is generally smaller than expected, especially compared to other tuna larvae such as yellowfin. This difference may suggest a possible different characteristic of bigeye tuna larvae which makes them less vulnerable to the ordinary sampling procedure.

4. AGE AND GROWTH

Yukinawa and Yabuta (1963) derived the growth curve based on scale samples. A total of 1,622 samples were collected from the central to western Pacific north of 10°S; of the total 463 were readable. In this study up to six rings were counted; the rings were reported to be formed twice a year, one in spring and the other in fall. Yukinawa and Yabuta (1963) reported that the rings were hard to detect for fish over 130 cm in fork length (FL).

Shomura and Keala (1963) estimated the growth curve by sex from the weight-frequency data of the fish unloaded by the Hawaiian longline fishery. They fitted normal distributions to those weight-frequency data with several assumptions, one of which was that fish entering the fishery in September at about 45 pounds were 17 months old. Sexual dimorphism was observed for fish over 130 cm in FL.

For the fish in the eastern Pacific, Kume and Joseph (1966) followed modal progressions of bigeye tuna taken by longline. Their data indicated that males and females grow at approximately the same rate up to 150 cm in length, but that males appear to grow faster at sizes greater than 150 cm. Therefore they did not use modes greater than 150 cm in their growth study.

Suda and Kume (1967) modified slightly the equation estimated by Yukinawa and Yabuta (1963) by taking observations on young bigeye into consideration.

Parameters of von Bertalanffy's growth equation from the above-mentioned papers are listed in Table 1. These growth curves were plotted in Figure 2 for comparison; the growth curve of Suda and Kume (1967) has been excluded since it is quite similar to that of Yukinawa and Yabuta (1963), particularly for 4 year old and older fish. It is noted that although the growth curves do differ from each other, the growth rates appears to be similar.

Length-weight relationship in the form of $W = a \cdot L^b$, where W is round weight in kg and L is fork length (FL) in cm, was estimated by Iversen (1955), Kume and Shiohama (1964), Nakamura and Uchiyama (1966) and Morita (1973). Samples taken in those studies were mostly from the western and central Pacific. Parameter estimates of a and b are listed in Table 2. As the original units of measurement were different among studies, equations are modified so as to use FL in cm and round weight in kg. For the conversion from gilled and gutted weight to round weight, the factor of 1.16 (Morita, 1973) was used.

Table 1. Von Bertalanffy's growth parameters estimated for Pacific bigeye tuna. Length is fork length in cm and weight is live weight in kg.

Unit	Max. Size	k	t0	Author(s)
Length	215	0.10412	-0.01056	Yukinawa and Yabuta (1963)
Weight	234.7	0.114	1.07	Shomura and Keala (1963), Male
Weight	164.9	0.167	1.06	Shomura and Keala (1963), Female
Length	186.95	0.095	2.11	Kume and Joseph (1966)
Length	214.8	0.2066	-0.12052	Suda and Kume (1967)

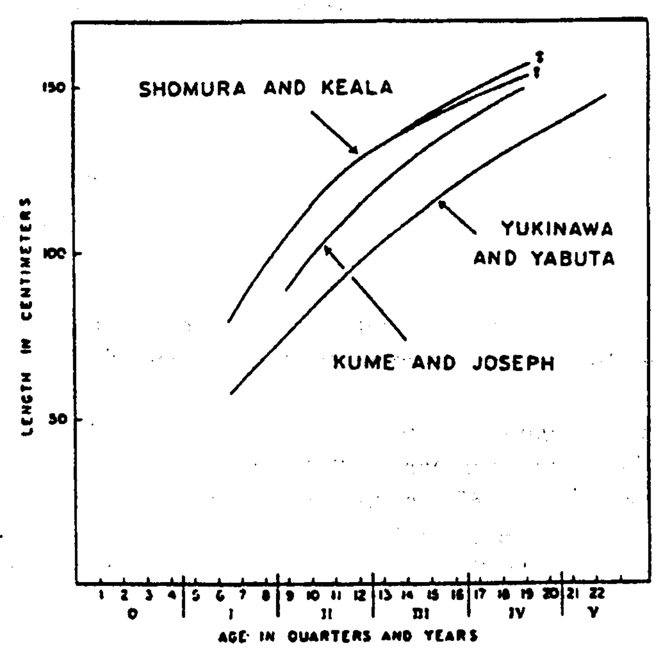

Figure 2. Growth curves of bigeye tuna estimated by various authors. (After Kume and Joseph, 1966).

These results are very similar in the common size range up to 150 cm, although the difference becomes greater as the fish becomes larger. The maximum difference in length among equations is about 10% when the length is 200 cm; at 200 cm the fish is close to the maximum size reported for bigeye tuna.

Table 2. Length-weight relationship ($W = aL^b$) estimated for Pacific bigeye tuna. L is fork length in cm and W is live weight in kg.

a	b	Area in Pacific	Sample #	Author(s)
2.9499×10^{-5}	2.9304	Central	?	Iversen (1955)
1.3504×10^{-5}	3.1056	Western-north	4121	Kume and Shiohama (1964)*
1.7265×10^{-5}	3.0475	Western equatorial	2538	Kume and Shiohama (1964)*
3.3263×10^{-5}	2.9180	Central	1832	Kume and Shiohama (1964)*
3.6562×10^{-5}	2.90182	Central	9144	Nakamura and Uchiyama (1966)
1.9729×10^{-5}	3.0247	Western	481	Morita (1973)

* Gilled and gutted weight is converted to live weight by a factor of 1.16.

5. MATURATION AND SPAWNING (SEX RATIO)

5.1 Maturation

The minimum size at first maturity of Pacific bigeye tuna is reported as 91-100 cm by Kikawa (1953). Yuen (1955) also reported minimum size at first maturity, but his results were given in weight (14-20 kg). These two values are equivalent and are supported by the later studies (Kikawa 1957; 1961; 1962).

As regards the Gonosomatic Index ($GSI = 10^4 \cdot GW/L^3$; GW=gonad weight in g, L=FL in cm) of longline-caught bigeye tuna by latitude, Kikawa (1957) found the main spawning ground in the western Pacific in the area of the equatorial counter current (2°N-10°N). Kikawa (1961) investigated seasonal and areal change of GSI and size composition of longline-caught fish in the equatorial Pacific. Kikawa (1966) further extended his study with additional data extending as far east as 100°W. He reported that the size of fish, CPUE, and group maturity (rate of mature fish) increased from west to east. Mature fish were seen throughout the year in all areas. The seasonality of group maturity was recognized, but it appeared to be similar among areas. Maturity was highest in June and July in the waters west of 140°E, April to July between 140°E and 180°, April to September between 180° and 140°W and February to July between 140°W and 100°W. Kume and Joseph (1966) confirmed a similar trend of seasonality of group maturity for the longline-caught fish in the eastern Pacific, and reported that in the area between the equator and 5°S the proportion of mature fish was considerably less than in the adjacent areas to the north and south.

5.2 Spawning

Nikaido *et al.* (1991) examined histologically the gonad samples taken by longline southwest offshore of Hawaii during May to July and in the waters off Java in the Indian Ocean during January to March. They limited their study to fish which were alive when they were hauled on the deck in order to investigate the spawning time and the developmental process of gonad with time. Nikaido *et al.* (1991) noted that most of the fish (> 100 cm in FL) were mature, *i.e.* in tertiary yolk stage or a more advanced stage of maturity. From the degeneration process of postovulatory follicles (POF), the developmental process of gonad and the change of GSI by time, bigeye was determined to be a multiple spawner. Out of the mature fish more than 90% were identified to have spawned within 24 hours. At the same time it was estimated that spawning took place approximately from 19:00 to midnight. Spawning frequency was calculated 1.00-1.57 (days per spawning) taking the inverse of the number of sample with POF divided by the total number of mature samples.

Batch fecundity (number of eggs spawned per day) was also estimated (Table 3) based on the number of most advanced eggs. The estimated batch fecundity was different between two areas studied. For example, in the area off Hawaii the batch fecundity was estimated at 2.2 million eggs for fish at 150 cm in FL, while the batch fecundity was 2.8 million eggs for the same size fish in the Java area. Currently it is not known whether this reflects a difference in stocks. These spawning figures are smaller than those estimated by Yuen (1955). It is thought that Yuen (1955) might have included eggs in pre-tertiary yolk stage in his calculation.

Table 3. Batch fecundity (number of eggs spawned per day) by size. (After Nikaido *et al.*, 1991).

(Unit: 10^6)

Fork length (cm)	Off Java	South-western offshore of Hawaii
100	0.56	0.40
110	0.83	0.63
120	1.17	0.86
130	1.61	1.20
140	2.16	1.64
150	2.85	2.19
160	3.69	2.87
170	4.70	3.69
180	5.90	4.69

Currently information is not available on the length of the spawning season, thus it is not known how long the spawning season lasts for a fish and how many times the same fish spawns during a spawning season.

Kikawa (1966) calculated the spawning potential of bigeye and yellowfin tunas in the equatorial Pacific by two-month intervals utilizing the following equation:

$$K = a \cdot p \cdot s \cdot D$$

where a = mean weight of ovary, p = mean group maturity, s = mean sex ratio, and D = mean hook rate weighted by area surveyed. It was pointed out that the annual spawning potential was much higher in the eastern Pacific (between 140°W and 100°W) than in the western and central Pacific; the eastern Pacific comprising roughly 70% of the total spawning potential of bigeye tuna. This was attributable to not only the high hook rate but also the larger size of fish and the higher rate of group maturity in the eastern Pacific. The seasonal difference in spawning potential, which was considered to reflect the group maturity, was observed with its maximum in April-May in the area north of the equator, and in February-March in the area south of the equator. The minimum spawning potential occurred in October-January in the area north of the equator and August-November in the area south of the equator. It is also indicated that the seasonal difference in spawning potential in the longitudinal direction is similar both north and south of the equator, respectively.

5.3 Sex Ratio

Kikawa (1966) and Kume (1969b) analysed sex ratio of longline-caught bigeye tuna from the broad area of equatorial Pacific. Both studies summarized the data by area and quarter-of-the-year; however, Kume (1969b) provided the data in smaller units. There was a general tendency of predominance of male fish over the entire size range encountered. The dominance of males became more prominent as the size increased. They reported no discernible seasonal change in sex ratio by size. However, Kume (1969b) noted that in the eastern equatorial Pacific the sex ratio was close to 0.5 where sea-surface temperature (SST) was low (<24°C) and fishes were found to be immature, whereas male predominated over female (less than 40 % were female) in the adjacent areas where sea surface temperature (SST) was high (>25°C). For fish of all sizes caught by longline in the Pacific north of 28°N between 140°E and 180° the sex ratio was almost equal to 0.5, although a predominance of males was observed among fish smaller than 130 cm in the area east of 180° (Kume 1969a).

6. DISTRIBUTION, MIGRATION AND STOCK STRUCTURE

6.1 Distribution

Bigeye tuna inhabit the tropical to temperate waters of the Pacific Ocean. This species is found across the entire Pacific between northern Japan (45°N) and the north island of New Zealand (40°S) on the western side, and from about 40°N to 30°S on the eastern side (Figure 3). Significant bigeye catch has not been reported so far from the area along the coast of Mexico and Central America between about 10°N and 20°N. Isolated specimens have been reported from as far north as 47°10'N on the coast of North America (Radovich, 1961; Meehan, 1965).

6.2 Migration

Most of the information on this subject is obtained from the fisheries, *i.e.* through seasonal and areal change of fishing ground, catch, CPUE, size, *etc.*, assuming that these changes reflect the migration and/or movement of the fish.

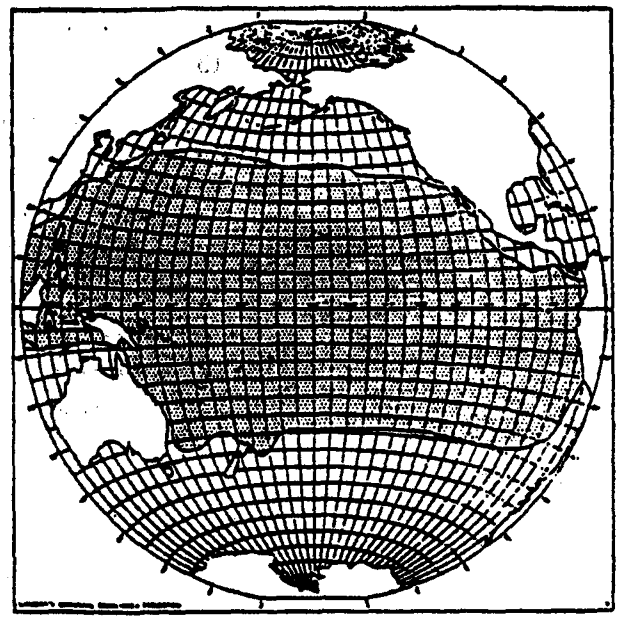

Figure 3. Distribution of bigeye tuna in the Pacific. (After Calkins, 1980).

Kawasaki (1958; 1960) and Kume and Morita (1967) reported the seasonal shift of baitboat fishing grounds and the size of fish caught around Japan. The Japanese baitboat fishery starts operations in April in Izu-Bonin Islands waters. The fishing grounds move progressively northeastward and reach the Tohoku area (north of 35°N, 140-165°E) in July and August. Subsequently, the fishery turns south to southwest until the end of the fishing season. Similar north-south movements of the fishing grounds are also reported for the longline fishery in higher latitudes of the North Pacific along 30°N from 130°E to 120°W (Kume, 1967), waters around north island of New Zealand (Kume, 1967), and waters off Chile (Miyabe and Bayliff, 1987). Since the main component of the bigeye tuna caught by the Japanese baitboat fishery is small (45-80 cm in FL), it is considered that this represents the movement of young bigeye tuna around Japan (Honma and Kamimura, 1955; Kume and Morita, 1967).

In the North Pacific area along 30°N, the majority of fish caught by longline are between 90-140 cm with more fish prevailing in the smaller size of this range (Kamimura and Honma, 1953; Kume, 1969a). Similar-sized fish are also caught in the area off Chile as shown in Miyabe and Bayliff (1987). In both areas fishing takes place in their respective winter. On the other hand, the fishing grounds in the equatorial Pacific are formed throughout the year and the size of fish caught is larger (110-160 cm). It is a well-known fact that those fish caught in the tropical Pacific are sexually mature but those encountered in the temperate waters are immature. Based on these observations, many investigators hypothesized that the spawning-feeding migration between equatorial waters and temperate waters must be in existence since fish in the both areas have to be intermingled through spawning.

Tagging data are also available but the amount of information is scarce because of fewer releases and resultant fewer recaptures compared to other tunas such as yellowfin. In Table 4, tagged bigeye tuna which were recaptured after substantial time at liberty are listed. Although there is a tendency for tagged bigeye to stay in the vicinity where they were tagged, some fishes did exhibit long-distance movement. It is worth noting that two fishes tagged in the Coral Sea were recaptured in the central Pacific after more than 900 days at liberty. The sizes at recapture of those two fishes are 131 and 160 cm, respectively, and are the largest of those listed in Table 4. The movement of adult bigeye may be more extensive than previously considered.

Table 4. Recapture records of tagged bigeye tuna with long time at liberty. Length and distance are given in fork length (cm) and nautical miles, respectively. LL-longline; HL-handline. (Modified from Calkins, 1980).

Release			Recapture				Dis-	Days	Direc-tion	Reference
Area	Date	Length	Area	Date	Length	Gear	tance	Free	(Deg.)	
30°59'N 171°14'W	Jan. 31, 1955	122.3	32°41'N 155°57'W	Nov. 24, 1955	126.8	LL	785	298	82	Otsu and Uchida (1956)
30°59'N 171°14'W	Jan. 31, 1955	109.0	29°50'N 177°50'W	Feb. 2, 1956	127.5	LL	348	368	259	Kume (1967)
32°59'N 143°19'E	May. 31, 1958	82	29°15'N 133°45'E	Nov. 11, 1959	110-115	LL	540	530	255	Kume (1967)
32°59'N 143°19'W	May. 31, 1958	81	35°27'N 141°10'W	Jan. 17, 1960	119	LL	182	597	324	Kume (1967)
3°18'N 90°50'W	May. 6, 1967	80	2°12'S 81°01'W	Jan. 13, 1968	?	?	664	253	117	IATTC unpublished*1
3°18'N 90°50'W	May. 12, 1967	50	4°32'N 107°50'W	Jun. 18, 1969	128.0	?	1,020	769	274	IATTC (1970)
1°01'S 157°18'E	Dec. 30, 1981	42	2°-4°N 152°-157°E	Feb. 15-Mar. 18, 1986	126	LL	200-700	1,508-1,539	330-360	FSFRL (1988)
15°10'S 146°22'E	Nov. 19, 1986	96	16°58'S 146°93'E	Oct. 29, 1987	112	HL	129	345	148	Peter Ward pers. comm.*2
15°10'S 146°22'E	Nov. 19, 1986	109	7°17'S 155°67'W	Jun. 2, 1990	160	LL	3,408	1,292	89	Peter Ward pers. comm.
15°10'S 146°22'E	Nov. 19, 1986	108	16°43'S 146°82'E	Nov. 2, 1987	127	HL	110	349	148	Peter Ward pers. comm.
15°27'S 146°13'E	Nov. 21, 1986	78	3°42'S 171°32'W	Jun. 17, 1989	131	LL	2,591	940	79	Peter Ward pers. comm.
15°27'S 146°13'E	Nov. 21, 1986	98	16°42'S 146°72'E	Nov. 1, 1987	124	HL	94	346	143	Peter Ward pers. comm.

*1 Cited in Calkins (1980).
*2 Ward, Peter. Personal Communication. Fisheries Resources Branch. Bureau of Rural Resources. Australia.

6.3 Stock Structure

Except for Fujino and Kang (1968), there have been no other studies on the genetic differences among bigeye tuna population(s) in the Pacific. Fujino and Kang (1968) analyzed serum-esterase groups of bigeye tuna taken in the Hawaiian waters, and found two phenotypes in the sample. This study, however, is not sufficient enough to draw any conclusions regarding the population structure of Pacific bigeye tuna.

The stock structure of Pacific bigeye tuna has been inferred by indirect evidence such as geographical distribution of fish, CPUE and fish size, and maturity and spawning by area and time. Evidence that supports a single stock includes: (a) continuous distribution of bigeye throughout the Pacific, (b) similar size frequencies in neighbouring areas, (c) broad spawning area and time, (d) the concurrent appearance of a dominant year class throughout the North Pacific as observed by the length-frequency studies. On the other hand, the existence of subpopulation(s) is supported by the cline shown in the size of bigeye tuna in the east-west direction and the limited movement of tagged fish; both features suggest a low level of intermingling of fish.

In summary, it might be appropriate to repeat the following interpretation by Suda and Kume (1967) that "It is rather difficult to consider that the mixing of Pacific bigeye is active enough to ensure the unified stock in the whole Pacific. At the same time there is no clear evidence to support the existence of plural subpopulations. Presumably, it seems reasonable to assume a single population in the Pacific where mixing of the fish takes place gradually through the whole life history."

7. NATURAL MORTALITY

Applying the Paloheimo method (Paloheimo, 1961), Suda and Kume (1967) estimated the instantaneous coefficient of natural mortality (*M*). Looking at the age composition of the fish taken by the longline fishery, they concluded that bigeye tuna are fully recruited to the fishery after age 4. Therefore the effective effort (*f*) and CPUE for age 5 and older fish during 1957-1964 were used, and fitted to the following equation assuming catchability (*q*) is constant among age and year for fully-recruited fish:

$$\log_e S = q \cdot f + M$$

where *S* is survival rate calculated from the ratio of CPUE of the fish older than 4 years old in one year and that of older than 5 years old fish in next year. They obtained the annual coefficient of 0.361.

In general it is likely that natural mortality is high at the younger ages, lower at the intermediate ages and again higher at the older ages.

8. OCEANOGRAPHIC FEATURES ASSOCIATED WITH SPECIES

In the developing stage of the Japanese longline fishery, Federation of Japan Tuna Fisheries Cooperative Association (1959) hypothesized that (a) tuna species distribute in different current systems, (b) even in the same species, tuna might have a habitat in the different current systems according to their developmental stages, and (c) the change of developmental stage and resultant change in tuna longline fishing grounds take place around March and September. Nakamura and Yamanaka (1959) also discussed the tuna distribution in relation to the ocean current and noted that bigeye tuna had a characteristic to aggregate around the boundary of currents. Yamanaka and Anraku (1962) discussed the relation between the distribution of tunas and water types in the central and western Pacific based on the T-S diagram.

Among oceanographic features associated with bigeye, water temperature is the most common feature that has been addressed by many workers to explain the spacial/temporal distribution of fish or fishing grounds. Uda (1957) cited the optimum water temperature (17.5°-22°C) for bigeye. This range of optimum water temperature for bigeye was supported by Suda *et al.* (1969) as coinciding with the temperature of the permanent thermocline, in which bigeye were considered to inhabit. In later studies (Saito and Sasaki, 1974; Saito, 1975; Hanamoto, 1976), it was found that bigeye were caught more efficiently in much deeper waters (133-245 m in waters southwest of Hawaii and 290-380 m in the western waters off Fiji) by the experimental vertical longline. In fact, the Japanese small-size class longliners introduced the so-called "deep longlining" to the western equatorial Pacific during the mid-1970s (Suzuki *et al.*, 1977) and it immediately prevailed among other boats and areas thereafter (Suzuki and Kume, 1981; Miyabe, 1989).

Hanamoto (1987) analyzed the oceanographic data (water temperature, dissolved oxygen, salinity) in relation to longline catch data. The latter included information on branch number, from which the depth at capture was estimated on the assumption that the main line formed a catenary curve. The results (Figure 4) showed the optimum water temperature to lie between 10° and 15°C which was much lower than that previously considered. Hanamoto (1987) stated that the same finding on water temperature could be applied to salinity, since, in the above-mentioned optimum temperature range, there was positive correlation between temperature and salinity. The optimum salinity was between 34.5 and 35.5 per mill in the South Pacific, between 34.0 and 34.7 per mill in the North Pacific, and between 34.7 and 35.2 per mill in the equatorial Pacific.

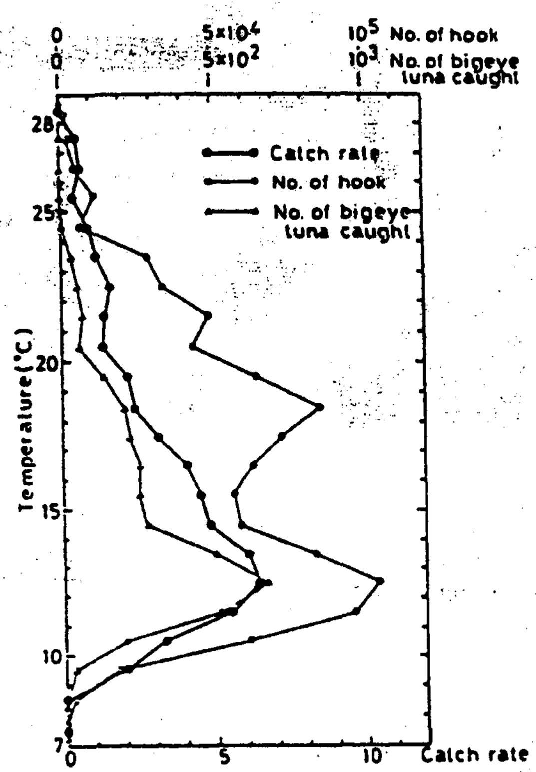

Figure 4. The catch, catch rate of bigeye tuna and the number of hooks used by water temperature at the depth of capture. (After Hanamoto, 1987).

As shown by Sund *et al.* (1980) and Sharp (1978), the minimum dissolved-oxygen requirements for bigeye are considered to be 0.5-1.0 ml/l. Hanamoto (1987) constructed the diagram showing the depth of the 1 ml/l surface of dissolved oxygen in the Pacific, and found that the poor catch of bigeye based on the long-term average of longline catch coincided with the shallow depth area (about 100 m) of the 1 ml/l surface. These poor catches were located in the eastern Pacific between 10°N and 20°N and in the area off Chile to 120°W in the south of equator.

It has been mentioned from fishing experience that the swimming depth of bigeye is deeper than that of other tuna species. Suda *et al.* (1969) compared the areas of high hook rate by longline with the depth of thermocline and found a significant correspondence between areas of high hook rate and the location of thermocline at the depth of 100-150 m, which was identical to the depth of hook set at the longline operation (Figure 5). Taking these into consideration, Suda *et al.* (1969) postulated that bigeye inhabit waters in or just below the thermocline. It is thought this assumption could explain to some extent the observed west-east cline in both size of fish and CPUE. If the assumption holds, ordinary longline gear is less effective and tends to catch smaller fish since hooks do not reach the thermocline in the western Pacific where larger fish are supposed to inhabit. Hanamoto (1987) also discussed the effect of oceanographic condition on the longline catch along this line. He suggested the possible distribution of this species in the area where the optimum water temperature was located. Those suggested areas were located in the middle latitudes along 20° in both hemispheres and high latitudes between 30°S and 40°S in the South Pacific.

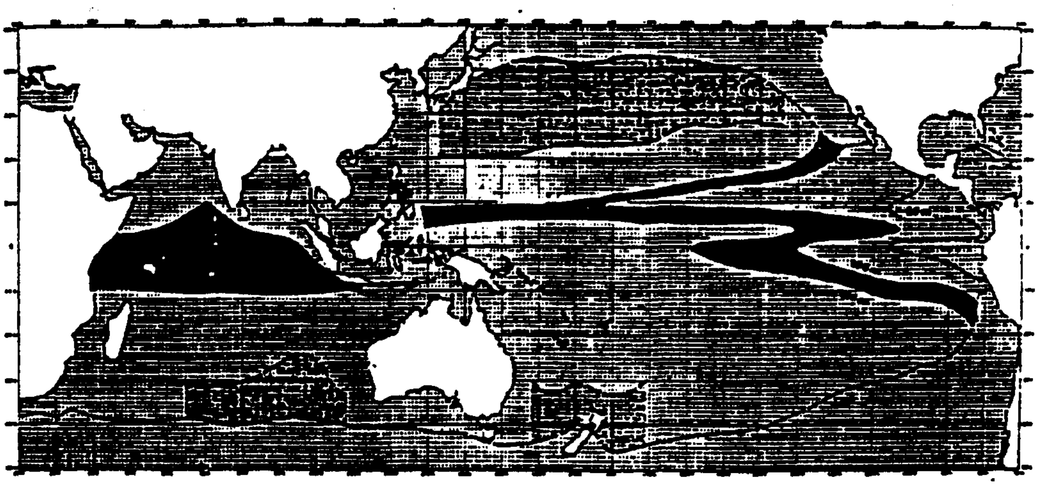

Figure 5. Illustration of the area in which effective catch of bigeye tuna by longline is supposedly expected. Shaded area indicating permanent thermocline is well developed and located at depth between 100 and 150 m. This range is approximately eqivalent to that of longline hooks. Dotted area shows that thermocline is not permanently formed and the habitat of bigeye tuna ranges from surface to some depth. (After Suda *et al.*, 1969).

Sonic tracking may give the answer to the above-mentioned hypotheses on the behavior of bigeye tuna. Several tracking studies have been done on this species, however, most tracks have been on small fish less than 70 cm. One exception was a 70 kg bigeye which was tracked by Carey and Lawson (1973) off the Atlantic coast of

Canada. Generally speaking, although the results were different among fishes tracked, the swimming depth ranged from the surface to 300 m and fish tended to stay in deeper waters during the day than during the night (Holland *et al.*, 1990; Koido and Miyabe, 1990).

The effect of large-scale oceanographic change on bigeye and its fishery in the eastern Pacific, known as El-Niño, was briefly analyzed after the very strong 1982-1983 event. Kume and Miyabe (1987) compared the location of the Japanese longline fishing grounds in the eastern tropical Pacific during El-Niño with that during normal conditions. It was reported that, during El-Niño periods, good fishing grounds were formed around the equator between 95°W and 130°W; fishing seldom took place in these areas during normal conditions. The possible influence of the El-Niño event on bigeye tuna stock was studied by Kiyota *et al.* (1988) based on CPUE and cohort analysis. It was suggested that cohorts born in the El-Niño year or one year before El-Niño were larger and that CPUEs were higher during El-Niño than during normal conditions. These effects might be caused by the changes of oceanographic condition, such as water temperature and the depth of thermocline, although the mechanism involved in the process is not well known.

9. INTERACTION WITH OTHER SPECIES

Based mainly on observations during fishing, many authors report that bigeye tuna are mixed with yellowfin, skipjack, kawakawa, and frigate tuna, particularly when they are young (< 100 cm). Around Japan, bigeye are caught by baitboat and purse-seine fisheries in pure or mixed school with yellowfin and/or skipjack. It is known bigeye tuna is seldom caught with albacore in the same operation. In the Coral Sea, small to medium bigeye (50-120 cm) as well as yellowfin are caught by handlining by the Japanese longliners during October to December (Hisada, 1973). It is reported that the types of school sought after are shark-associated, and, to a lesser extent, free-swimming schools with birds.

Recently the bigeye catches by the industrialized purse-seine fisheries in the western and eastern Pacific (Table 10) have accounted for about 5-10% and 0.2-5.0% of the total tuna catch by weight for the two areas, respectively. The former value is a rough estimate because purse-seine catch data of bigeye tuna for Korea, Philippines, Taiwan, USA, *etc.*, are lacking.

10. GENERAL DESCRIPTION OF FISHERIES

The longline fishery has landed the largest share of bigeye tuna catch since the initiation of the fishery in the early 1950s. The baitboat fishery has also accounted for a significant share of the bigeye tuna catch and has a long history as well. The purse-seine fishery, which was developed in later years (during the early 1960s in the eastern Pacific and during the mid-1970s in the western Pacific) and has replaced the baitboat fishery thereafter, has landed a substantial amount of the bigeye catch. Other local fisheries which catch small amounts of bigeye tuna exist in the coastal countries throughout the Pacific; these fisheries include trolling, hand-lining and small-scale purse seine.

10.1 Longline Fishery

Japan, Korea and Taiwan are the major countries catching bigeye tuna by longline gear. Some very minor catches are recorded by Australia, New Caledonia and Tonga. The size of distant-water longliners now operating ranges from 50 to 1000 gross tonnages (GT), and is mostly between 200 and 500 GT. In Japan and Taiwan there have been coastal to offshore tuna-longline fisheries carried on by the small-size vessels up to 50 GT.

10.1.1 Japan

The Japanese longliners operate in almost the entire Pacific; the principal exception is the central part of the South Pacific Ocean, south of 20°S. Fishing grounds are located in both tropical (10°N-15°S) and temperate (around 30°N and 30°S) waters extending in an east-west direction (Figure 6). In tropical waters the fishing takes place almost year around while in temperate waters it takes place in winter. Bigeye tuna is the most important tuna species for the Japanese tuna fishery in terms of the catch in weight (except skipjack) and value (Ministry of Agriculture, Forestry and Fishery of Japan, 1990). Bigeye tuna is the species most frequently aimed at and there are by-catches of yellowfin, albacore and billfishes. Catches by distant-water longliners are deeply frozen to below -60°C, and consumed as sashimi in the domestic market. In this fishery a limited-entry system has been adopted and vessels larger than 20 GT are required to obtain a permit from the Government. All longliners which have the permit are not allowed to unload catches in foreign countries except as transshipment to Japan; the total amount of transshipment by longliners is limited by the Government. The numbers of longliners fishing since 1977 are shown in Table 5. Smaller-sized boats (20-100 GT) are decreasing, while numbers of 100 to 200 GT class have doubled during that period. The number of longliners in the largest size class has been stable.

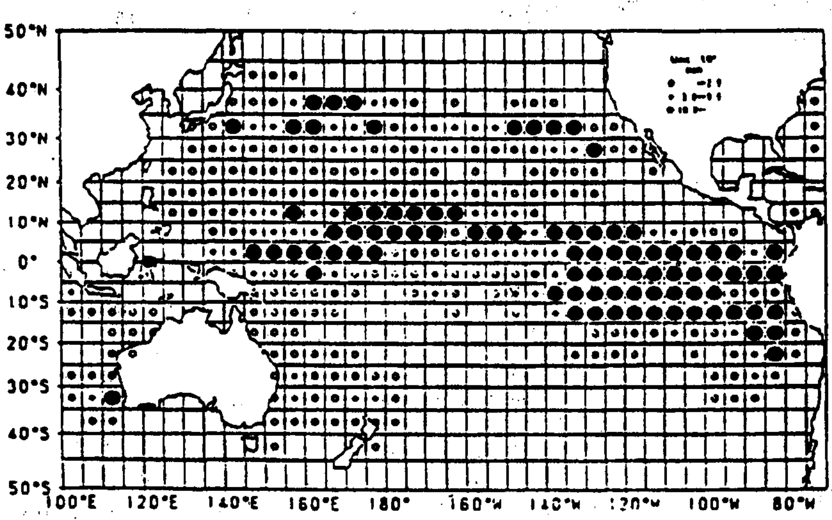

Figure 6. Distribution of bigeye catch (in number) for Japanese longline fishery by 5-degree square in 1987. (After Miyabe, 1991).

Table 5. Annual change in the number of tuna longliners by country, 1977-1989.

	Japan					Korea (100-500 ton)			Taiwan (50-1000 ton)			
	20-50 ton	50-100 ton	100-200 ton	200< ton	Total	Home based	Foreign based	Total	Pacific based	Takao based	Other	Total
1977	86	658	72	612	1,428	214	287	501	319		305	624
1978	87	707	69	617	1,480	216	266	482	302		313	615
1979	69	720	82	624	1,495	217	234	451	157	185	297	639
1980	57	715	103	645	1,520	219	220	439				
1981	55	706	100	661	1,522	208	199	407	146	204	289	639
1982	43	634	90	589	1,356	185	141	326	115	39	340	494
1983	38	593	89	550	1,270	169	101	270	65	88	298	451
1984	32	546	100	610	1,288	157	68	225	61	111	266	438
1985	28	534	109	628	1,299	156	64	220	44	72	307	423
1986	25	471	132	632	1,260	167	61	228	51	28	343	422
1987	23	398	147	649	1,217	189	61	250	60	39	308	407
1988	21	368	154	649	1,192	199	69	268	62	35	307	404
1989	20	334	152	653	1,159							

Data source
Japan : MAFFJ (1978-1990).
Korea and Taiwan : FAJ (1989).

10.1.2 Korea

The geographical distribution of fishing effort is shown in Figure 7. The main fishing ground is located in the South Pacific (0°-30°S, 160°E-120°W) and bigeye tuna is the target species. Less extensive operations are conducted in the North Pacific around Hawaii in winter. The number of longliners has decreased from 501 in 1977 to 268 in 1988 (Table 5).

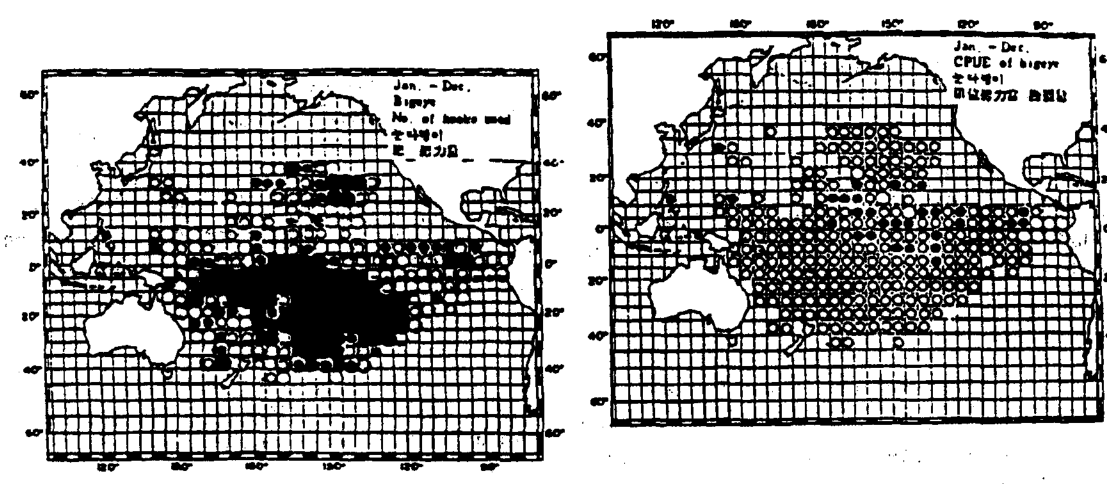

Figure 7. Distribution of fishing effort and bigeye CPUE for 1981 by Korean longline fishery. (After NFRDA, 1986).

10.1.3 Taiwan

Fishing grounds for Taiwanese longliners are similar to those of Korean longliners, but the centre is located from the central to western South Pacific (Figure 8). Seasonal change of fishing ground is clear for the fleet fishing in the southern part (20°S-40°S) during winter in the southern hemisphere (TRC, 1983). This is because albacore is the target rather than bigeye tuna. The number of longliners has also declined; in particular the number of Pacific-based boats declined from 319 in 1977 to 62 in 1988 (Table 5).

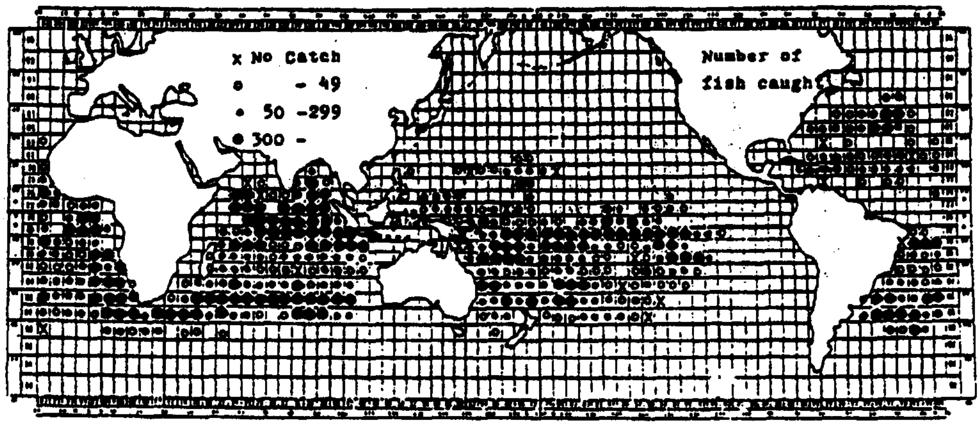

Figure 8. Distribution of bigeye catch (in number) for 1981 by 5-degree square for the Taiwanese longline fishery. (After TRC, 1982).

10.2 Baitboat Fishery

The Japanese distant-water baitboat fishery operates in the wide area of the western Pacific (40°N-10°S, 120°E-170°W, Figure 9). Bigeye tuna is a by-catch of this fishery which targets skipjack and albacore. The fishing takes place all year round in the tropical area while it occurs during spring to fall in the higher latitudinal waters. The number of licensed boats decreased in the 1980s, and in 1989 the fleet declined to less than one-third of the 1977 total (Table 6). In addition to this, a coastal to offshore baitboat fishery (vessels smaller than 100 GT) has been operating in more nearshore waters than the distant-water fishery.

In the eastern Pacific the baitboat fishery has been operating since the early 1900s primarily directing its fishing effort at yellowfin and skipjack. Starting from the early 1960s, purse seiners have replaced baitboats in the fishery. The baitboat fishing operations are confined to coastal waters and to the vicinity of offshore islands.

10.3 Purse-seine Fishery

There are two major fishing areas for this fishery, one in the western Pacific and the other in the eastern Pacific. In this fishery bigeye is a by-catch as in the baitboat fishery.

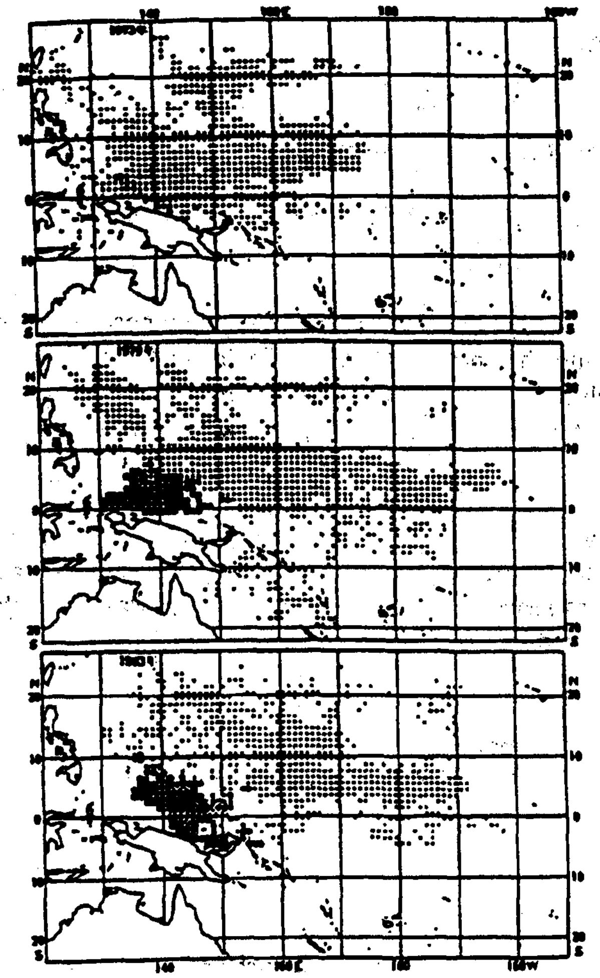

Figure 9. The fishing ground of the Japanese baitboat and purse-seine fisheries in the tropical Pacific. Large and small circles show purse-seine and baitboat fishing areas, respectively. (After Tanaka, 1989).

Table 6. Annual change in the number of fishing vessels for the Japanese distant-water baitboat and purse-seine fisheries, 1977-1989.

	Baitboat Distant-water fishery				Purse-seine Tropical fishery		
	<100ton	<200ton	>=200ton	Total	<200ton	>200ton	Total
1977	19	14	260	293	50	14	64
1978	24	10	251	285	47	14	61
1979	29	13	228	270	46	17	63
1980	32	10	198	240	50	16	66
1981	31	6	179	216	50	23	73
1982	35	6	138	179	52	33	85
1983	32	9	116	157	59	36	95
1984	27	10	105	142	54	33	87
1985	25	9	95	129	47	35	82
1986	20	9	91	120	53	38	91
1987	17	9	89	115	47	34	81
1988	16	11	70	97	48	39	87
1989	15	12	67	94	43	37	80

Data source : MAFFJ (1978-1990).

10.3.1 Western Pacific

The industrial purse-seine fishery commenced operation in the late 1970s, and by the mid-1980s vessels from Japan, Korea, Philippines, Solomon islands, Taiwan and the USA were operating in the South Pacific (SPC 1990a). At present (1st quarter of 1990), the USA has the largest fleet size (34 boats) followed by Japan (31), Taiwan (25), and Korea (8) (SPC 1990b).

Table 6 shows the annual change in numbers of the Japanese purse seiners operating both in the Pacific and the Indian Ocean. The Japanese distant-water purse-seine fishery started fishing in the tropical western Pacific in 1973 (Tanaka, 1989). In 1980, 14 vessels were counted. A total of 18 vessels was added during the following 2 years and thereafter the number of vessels operating has been constant in the Pacific. In the vicinity of Japan the offshore purse-seine fishery has operated for various pelagic fish species. Tunas and skipjack are caught seasonally during spring to early fall in the Pacific off Japan. A few of these offshore purse seiners (five to seven boats) are allowed to operate in the tropical waters seasonally (February to May). Based on the species composition of the catch unloaded at Yaizu fishing port (Table 7), the catch of bigeye tuna by the industrial purse-seine fishery is considered to be very minor (0.8-4.2% of total catch) in terms of catch in weight. A preliminary survey (National Research Institute of Far Seas Fisheries, internal data) conducted at the cannery showed that, in terms of numbers of fish, about 10% of fish sold as small yellowfin (smaller than 2 kg) were identified as bigeye.

Table 7. Species composition (%) of the Japanese purse-seine catch (in weight) in the tropical Pacific unloaded at Yaizu fishing port. (From Tanaka, 1989).

Year	Skipjack	Yellowfin*1 large	Yellowfin*1 small	Bigeye*2	Juvenile*3
1976	71.49	24.35		4.16	0.00
1977	68.48	28.19		3.33	0.00
1978	73.24	13.87	9.28	3.61	0.00
1979	65.62	12.71	18.54	3.06	0.07
1980	71.32	12.88	13.15	2.55	0.10
1981	57.71	9.35	28.82	3.38	0.74
1982	65.93	16.31	14.72	2.36	0.68
1983	77.79	6.04	14.11	1.75	0.31
1984	72.55	12.23	14.44	0.78	0.00
1985	70.82	13.81	14.06	1.31	0.00

*1 Large and small yellowfin are larger than 10 kg or less than 10 kg, respectively.
*2 Over 2 kg in round weight.
*3 This category includes juvenile yellowfin and bigeye (less than 2 kg) as well as small amount of damaged fish in other categories.

10.3.2 Eastern Pacific

Table 8 shows the numbers of vessels and capacities in the eastern Pacific purse-seine fleet during 1950-1988. In 1987 the fleet was composed of vessels from 10 countries. Major countries were the USA (54 vessels), Mexico (54), Ecuador (28), and Venezuela (25) (IATTC,1989). In the early 1960s the purse-seine fishery replaced the baitboat fishery and to date has been the dominant fishery. The fishing grounds were confined to the coastal area in the early stage of the fishery, but it began to expand into the offshore areas in the mid-1960s. By the mid-1970s the fishery covered the coastal waters between about 30°N to 15°S and extended offshore to about 145°W between 5°N and 15°N (Calkins *et al.*, 1988). The geographical distribution of catch by the surface fishery during 1982-1986 is shown in Figure 10. The most concentrated area of catch was adjacent to the coast of South America from the equator to about 7°S and from the coast to about 87°W. The geographical catch distribution during 1967-81 was similar to that during 1982-86. The catch was small (less than 3,000 short ton (ST)) until 1974 (Table 10) when it jumped to over 4,000 ST). During 1976-81 it was the highest (8,000-17,000 ST) and then decreased to 2,000-6,000 ST during 1982-86.

The length distributions for 1975-1986 show that the length for the fish in nearshore areas ranged from 30 to 180 cm. In general, most of them occurred between 60 to 120 cm with major modes between 80-110 cm (Figure 11). The size range in the offshore area is about the same as in the nearshore area, but more of the catch appears to fall in the 30 to 70 cm range.

11. TRENDS IN FISHING EFFORT, CATCH, AND CATCH-PER-UNIT OF FISHING EFFORT

11.1 Trends in Fishing Effort

Not all the data from the various fisheries are available. Information which is available is the number of fishing vessels operated or registered (Tables 5, 6 and 8). The annual change in fishing effort by the Japanese distant-water longline fishery in terms of the number of nominal hooks exerted is shown in Figure 12. The Japanese distant-water longline fishery is the largest component among fisheries for bigeye tuna. The nominal effort increased dramatically from 1952 to 1963 when it reached a high of 3.4×10^8 hooks. Thereafter it fluctuated between 2.5 and 3.0×10^8 hooks up until the mid-1970s, and then went up to a record high in 1981. Since then it has stayed at the highest level at around 3.5×10^8 hooks. Because of the limited-entry system adopted for this fishery, the recent change in the fishing effort is attributed to the increase in the number of hooks set per operation (day), and to the movement of the fleet into the Pacific Ocean or to other Oceans.

11.2 Trends in Catch

The annual catch of Pacific bigeye tuna is shown in Table 9 by country (FAO, 1965-1988), and in Table 10 by major gear, and in Figure 13. There is some difference between these two statistics (Tables 9 and 10) reflecting the difference in the source of data. Generally the catch shown in Table 10 is slightly larger except for 1987. As the Japanese longline catch accounted for over 70% and over 80% of the total catch and of

Table 8. Numbers and carrying capacities, in short ton, of vessels of the eastern Pacific tuna fleet. Bolicheras are small purse seiners with limited ranges. There is no information available on bolicheras or trollers for 1950-1954. The 1988 data are preliminary. (After IATTC, 1989).

Year	Seiners		Baitboats		Bolicheras		Trollers		Total	
	No.	Tons	No.	Tons	No.	Tons	No.	Tons	No.	Tons
1950	67	7,890	204	39,967	-	-	-	-	271	47857
1951	78	8,731	255	44,160	-	-	-	-	303	52891
1952	64	7,371	202	40,631	-	-	-	-	266	48002
1953	64	7,508	191	42,895	-	-	-	-	255	50,403
1954	69	7,960	182	40,647	-	-	-	-	251	48,607
1955	65	7,880	183	41,729	15	375	0	0	263	49,984
1956	66	7,999	182	41,425	55	1,375	0	0	303	50,799
1957	55	7,019	193	40,785	40	1,000	0	0	288	48,804
1958	49	6,614	180	39,220	29	725	0	0	258	46,559
1959	87	12,224	185	36,066	18	450	5	98	295	48,838
1960	112	22,806	117	16,820	15	375	0	0	244	40,001
1961	124	30,011	93	10,510	1	25	0	0	218	40,546
1962	130	33,945	89	6,725	27	675	0	0	246	41,345
1963	141	39,834	108	5,964	18	450	3	55	270	46,303
1964	134	40,307	88	4,712	3	65	0	0	225	45,084
1965	146	42,283	109	5,777	17	395	7	182	279	48,637
1966	126	39,869	113	6,217	7	140	2	29	248	46,255
1967	122	40,221	108	5,862	8	170	0	0	238	46,253
1968	139	50,613	89	5,743	4	100	2	24	234	56,480
1969	149	57,008	69	4,957	4	95	3	71	225	62,131
1970	162	67,508	49	4,302	0	0	9	177	220	71,987
1971	185	88,770	102	5,569	6	150	66	1,514	359	96,003
1972	206	112,361	108	6,707	4	100	74	1,946	392	121,114
1973	216	131,910	106	6,856	3	75	28	729	253	139,570
1974	230	146,990	111	7,766	4	110	7	150	352	155,016
1975	249	163,766	102	7,403	4	105	9	181	364	171,455
1976	250	176,469	99	7,071	4	115	38	909	391	184,564
1977	250	178,813	79	5,436	3	87	37	953	371	185,289
1978	262	180,781	68	5,044	9	272	50	1,303	389	187,400
1979	268	183,673	45	3,979	14	405	5	112	332	188,169
1980	258	184,647	46	3,838	12	355	4	106	320	188,840
1981	247	183,729	39	3,063	3	72	2	55	291	186,919
1982	221	167,780	36	2,713	2	60	4	131	263	170,684
1983	199	137,842	52	3,470	12	300	8	244	271	141,856
1984	165	113,168	40	3,055	0	0	9	232	214	116,455
1985	175	127,272	25	2,424	0	0	1	14	201	129,710
1986	165	122,564	17	1,939	0	0	0	0	183	124,503
1987	177	143,765	29	2,237	0	0	0	0	206	146,002
1988	182	147,931	36	3,081	0	0	3	70	221	151,082

the total longline catch, respectively, the trend of total catch is similar to that of the Japanese longline fishery (Table 10). Before 1957 the annual total catch was less than 50,000 mt. It increased to between 82,000 and 92,000 mt during 1958-1960, and then showed a sudden increase in 1961 to 136,000 mt. After a high of about 150,000 mt in 1963, it remained at a lower level between 73,000 mt and 100,000 mt up until 1974 except 1969 and 1973. Since then it has reached a higher level of over 100,000 mt. The catch was higher during 1976-1980 and 1985-1987.

It should be noted that in the western Pacific there has been no catch record of this species in the FAO statistics from countries such as the Philippines and Indonesia where substantial catch was reportedly made. Several possible reasons for this may be considered. One is lack of a system whereby catch may be estimated. The other is that species separation between tunas, especially for the small fish, is often difficult because of the similarity of their morphological appearances and because, due to the nature of the catch, bigeye tuna sometimes get caught with other tunas at the same time. In the near future this should be clarified and catches from these countries included in the statistics.

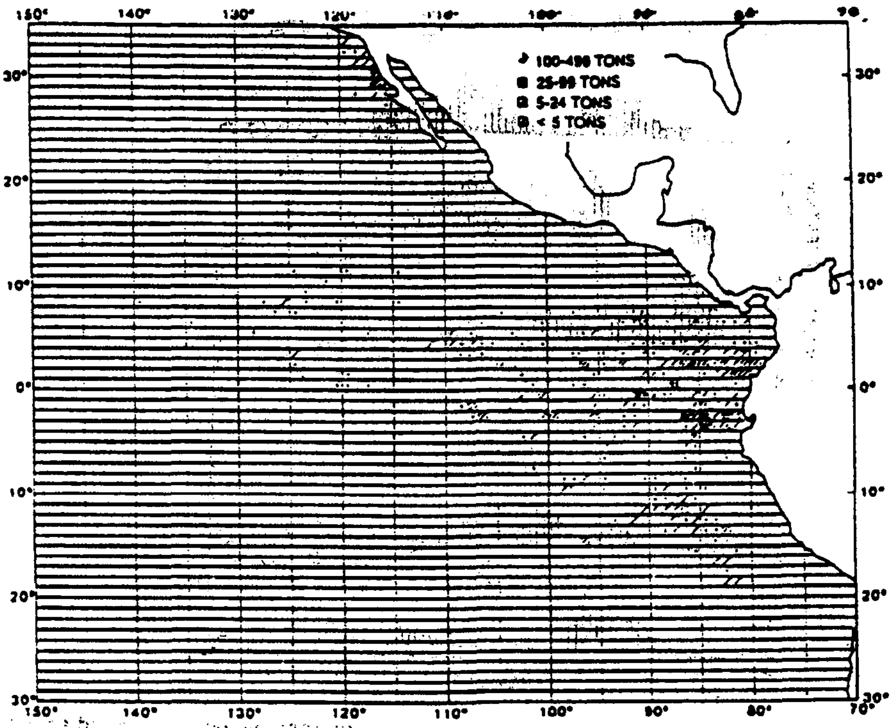

Figure 10. Annual average of distribution of bigeye catch by the eastern Pacific surface fishery, 1982-1986. (After Calkins *et al.*, 1988).

11.3 Trends in Catch-per-Unit of Fishing Effort (CPUE)

The series of studies (Suda and Schaefer, 1965; Kume and Schaefer, 1966; Kume and Joseph, 1969; Shingu *et al.*, 1974; Miyabe and Bayliff, 1987) on the Japanese longline fishery in the eastern Pacific analyzed the relationship between nominal fishing effort and catch (CPUE). It is shown in Figure 14 for the equatorial area east of 150°W. From this figure three periods can be separated, *i.e.* 1957-1961, 1962-1964 and 1965-1980. During 1957-1961 CPUE was high at about 3 fish per 100 hooks. In the following period in 1962-1964 it quickly decreased to less than half of this. Thereafter, it has been very constant at slightly less than one fish per 100 hooks.

Miyabe (1991) estimated the standardized CPUE for the total Pacific stock, applying the Honma method (Honma, 1974) based on the Japanese longline catch and effort data. Deep longlining, a newly-introduced longline gear setting, was also adjusted to the conventional one employing the ratio of CPUEs from both gear settings and the proportion of fishing effort deployed by deep longline. The results showed that CPUE decreased from the late-1950s to the mid-1960s, but after that it fluctuated moderately without any appreciable trend until 1988 (Figure 15). The current level of CPUE is about 45% of the initial level in the 1950s.

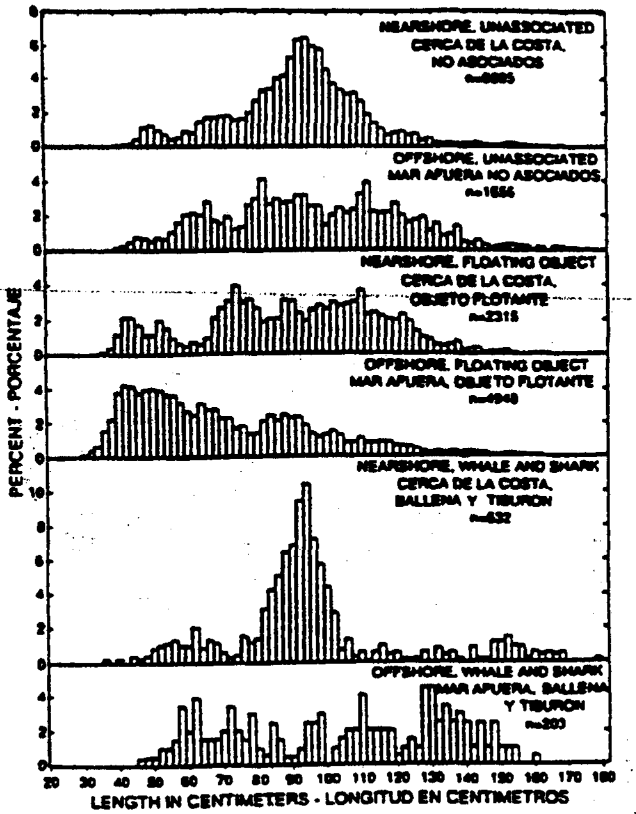

Figure 11. Combined annual length-frequency distributions for 1975-1986, by school type and area, of bigeye tuna caught by the surface fishery in the eastern Pacific. (After Calkins, *et al.*, 1988).

Kume (1979a) presented CPUE by age and area for 1955-1976 (Figure 16). Nominal CPUEs by area and 5-year intervals averaged for 2 succeeding years were constructed into age-specific CPUEs applying the length frequency data. It is observed that CPUE decreased greatly between 1960-61 and 1965-66 for fish older than 3 years in all areas. After that, CPUE for older age group is generally decreasing although the trend is not so clear as before.

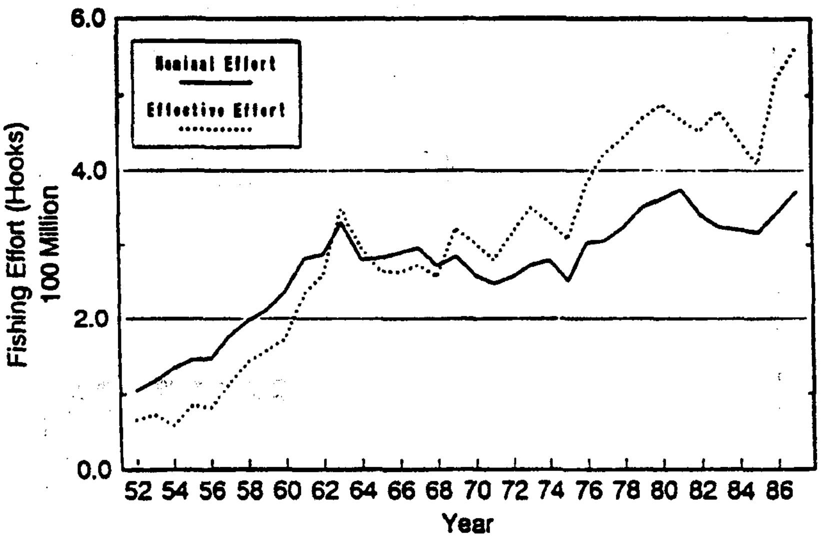

Figure 12. Annual trend of fishing effort by Japanese longline fishery. (After Miyabe, 1991).

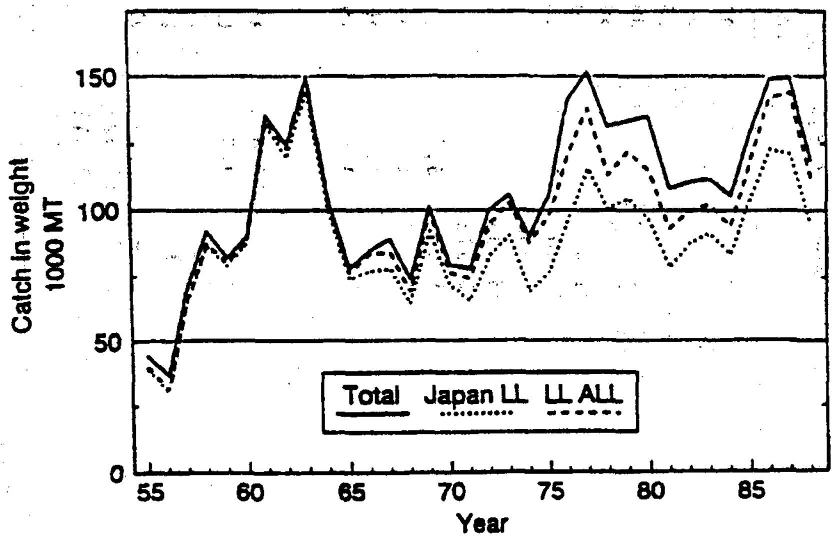

Figure 13. Annual catch trend of Pacific bigeye tuna.

12. POPULATION DYNAMICS

Because of the shortage of data essential for the comprehensive analysis of Pacific bigeye tuna, studies done on this subject so far are almost exclusively based on the Japanese longline data.

Table 9. Annual catch (MT) of Pacific bigeye tuna by country.

Year	Bermuda	Cuba	Ecuador	Fiji	Japan	Korea	Other Nei A (Taiwan)	Other Nei B	Panama	Solomon Islands	Tonga	USA	Vene-zuela	Pacific Total
1965					66,200	700	2,000							68,900
1966					70,700	2,900	3,500							77,100
1967					75,200	3,200	3,200							81,600
1968					62,400	600	4,000							67,000
1969					72,600	2,500	4,600							79,700
1970					71,000		5,000					0		76,000
1971		100			57,900	4,700	4,300					800		67,800
1972					77,200	7,800	3,800					100		88,900
1973					76,300	8,900	3,700					400		89,300
1974					70,392	14,444	4,420					132		89,388
1975	85				81,170	15,484	5,348					330		102,417
1976	0				101,040	21,395	3,078					1,039		126,552
1977	307				120,929	17,663	4,507					581		143,987
1978	0				104,640	8,456	4,402					423		117,921
1979	0				107,389	12,804	4,491					1,331		126,015
1980	0				99,692	13,975	4,637		1,465			3,196		122,965
1981	0				83,721	10,608	3,849		770	40		2,113		101,101
1982	0		1,100	8	94,113	10,050	2,111		177	23		1,207		108,789
1983	0		1,249	14	97,224	7,706	3,477			34		726	400	110,830
1984	0		1,814	16	88,867	7,478	2,943			55		696	1680	103,549
1985	0		2,410	133	106,486	10,898	3,031			46		62	820	123,886
1986	0		1,116	94	125,570	15,927	2,879			0		101	1120	146,807
1987	0		240	49	125,816	19,544	3,280	130		259	14	867	260	150,459
1988	0		240	27	87,959	13,681	3,610	130		1,085	7	1,956	260	108,955

Data source : FAO (1965-1988).

Table 10. Annual catch (MT) of Pacific bigeye tuna by fishing gear, 1955-1988. LL=longline, BB=baitboat, PS=purse seine.

	Longline					Surface fishery						Grand	% of
				Sub-	% of	Japan			Solomon	IATTC	Sub-		
Year	Japan	Korea	Taiwan	Total	Japan LL	BB	Trop. PS	Others	PS+BB	PS+BB	Total	Total	Japan LL
1955	39,200		800	40,000	98	4,009		342		117	4,468	44,468	88
1956	30,700		900	31,600	97	4,373		957		40	5,370	36,970	83
1957	64,400		900	65,300	99	5,198		435		68	5,701	71,001	91
1958	86,500		1,000	87,500	99	4,196		114		232	4,542	92,042	94
1959	79,300		800	80,100	99	1,729		74		150	1,953	82,053	97
1960	87,600		700	88,300	99	1,524		152		183	1,859	90,159	97
1961	132,200		1,500	133,700	99	1,837		111		213	2,161	135,861	97
1962	119,800		3,400	123,200	97	824		213		328	1,365	124,565	96
1963	144,400		3,600	148,000	98	1,822		39		75	1,936	149,936	96
1964	99,500		3,500	103,000	97	1,142		260		68	1,470	104,470	95
1965	73,500	700	2,000	76,200	96	1,254		231		118	1,603	77,803	94
1966	76,900	2,900	3,500	83,300	92	1,108		96		267	1,471	84,771	91
1967	77,700	3,200	3,200	84,100	92	2,803		314		1,663	4,780	88,880	87
1968	63,939	600	4,000	68,539	93	2,272		250		2,559	5,081	73,620	87
1969	91,885	2,500	4,600	98,985	93	1,679		158		576	2,413	101,398	91
1970	71,165		5,000	76,165	93	1,579		247		1,332	3,158	79,323	90
1971	65,059	4,700	4,300	74,059	88	931		218		2,567	3,716	77,775	84
1972	82,632	7,800	3,800	94,232	88	2,364		781		2,238	5,383	99,615	83
1973	90,313	8,900	3,700	102,913	88	852		251		1,978	3,081	105,994	85
1974	68,730	14,444	4,420	87,594	78	729		456		889	2,074	89,668	77
1975	76,913	15,484	5,348	97,745	79	3,522		743		3,722	7,987	105,732	73
1976	96,816	21,395	3,078	121,289	80	7,982		889		10,185	19,056	140,345	69
1977	115,833	17,663	4,507	138,003	84	5,096		970		7,054	13,120	151,123	77
1978	100,557	8,456	4,402	113,415	89	3,330		1,987		11,710	17,027	130,442	77
1979	104,776	12,804	4,491	122,071	86	1,967		1,239		7,530	10,736	132,807	79
1980	96,637	13,975	4,637	115,249	84	2,205		1,021		15,417	18,643	133,892	72
1981	78,630	10,608	3,849	93,087	84	2,357		1,733	40	10,089	14,219	107,306	73
1982	87,571	10,050	2,111	99,732	88	4,057		2,516	23	4,103	10,699	110,431	79
1983	91,200	7,706	3,477	102,383	89	3,847	1,559	645	34	3,260	9,345	111,728	82
1984	83,504	7,478	2,943	93,925	89	3,447	884	745	55	5,853	10,984	104,909	80
1985	104,208	10,898	3,031	118,137	88	2,895	1,163	1,382	46	4,531	10,017	128,154	81
1986	123,103	15,927	2,879	141,909	87	2,227	1,672	1,009	0	1,979	6,887	148,796	83
1987	121,386	19,544	3,280	144,210	84	1,834	1,765	1,002	259	771	5,631	149,841	81
1988	94,666	13,681	3,610	111,957	85	2,900	1,044	953	1,085	1,053	7,035	118,992	80
1989	103,326					2,472	1,741	1,317		1,807			

Data source :
Japan LL >20 GT for 1955-1973 : Kume (1979b) and FAO (1974-1988).
Japan LL <20 GT for all years : MAFFJ (1955-1990).
Japan surface catch : MAFFJ (1955-1990).
Korea LL : FAO (1965-1988). All are assumed by LL.
Taiwan LL : FAO (1965-1988). other nei A. All are assumed by LL. Before 1965 data are taken from Kume (1979b).
Solomon : FAO (1981-1988).
IATTC : IATTC (1989).

12.1 Production Model Analysis

It may not be appropriate to apply the method of production model analysis if the assumptions that (a) the rate of natural increase of the stock responds immediately to changes in population density, and (b) the rate of natural increase of the stock at a given level of biomass is independent of the age (or size) composition of the stock, are not satisfied. In the case of Pacific bigeye tuna it is considered that it takes 4 years for the fish to recruit into the longline fishery (Suda, 1970b) so that the first assumption is not matched satisfactorily. Furthermore, the second assumption also appears seldom satisfied for long-lived species such as tunas. On the other hand, the fact that the fishing condition and the fishery have been stable, and that the changes in the age (or size) composition of the catch seem to be smaller than for other tunas, may provide a basis for the application of this method. Irrespective of the above-mentioned drawbacks, production model analysis might give a general picture of stock status, MSY, *etc.*, for the species under consideration, especially since there is a lack of complete and detailed data for more sophisticated analysis such as cohort analysis.

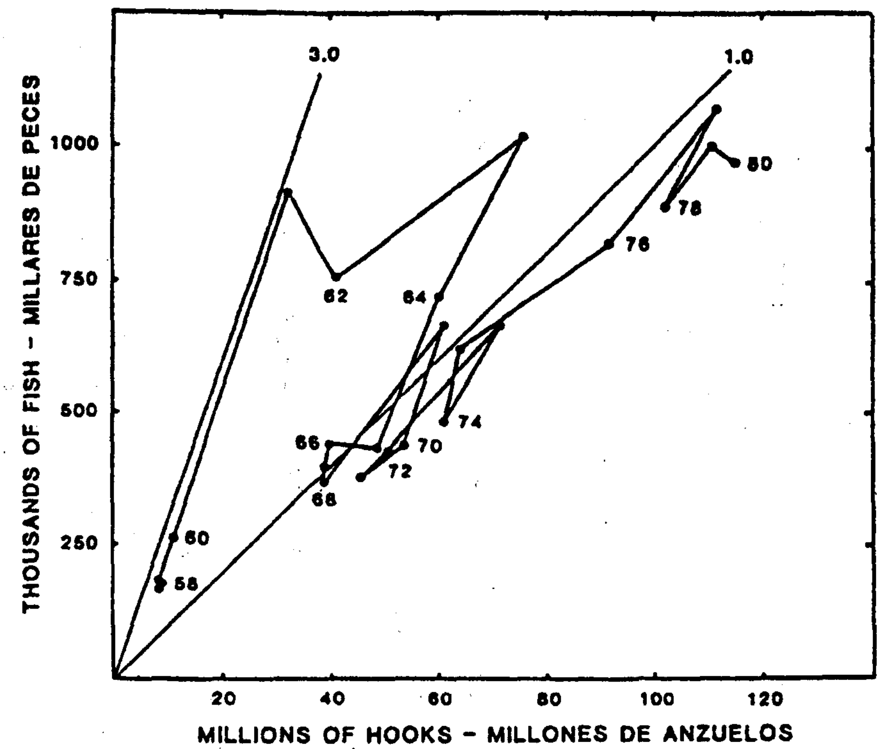

Fig. 14. Relationship between estimated Japanese longline catch and effort for bigeye tuna in the eastern tropical Pacific for 1957-1980. The fine lines and figures in two digits denote hook rates in numbers of fish per 100 hooks and year, respectively. After Miyabe and Bayliff (1987).

Production model analysis requires catch and fishing effort or CPUE. Since complete fishing effort data are not available, Kume (1979b) and Miyabe (1989; 1991) used the Japanese longline effort as basic data. The effective fishing effort, standardized by the Honma method (Honma 1974) of the Japanese longline fishery, was raised to the total effective effort using the proportion of the Japanese longline catch relative to the total catch. As stated above, the proportion of the Japanese longline catch has been very high (70-90%). The programme "PRODFIT" of Fox (1975) is used, applying the number of year classes that contributes significantly in the catch set at four. The results are shown in Figure 17 and Table 11. Kume (1979b) estimated the MSY between 100,000-106,000 mt with best fit at shape parameter $m = 0.0$. Miyabe (1991) estimated the MSY between 130,000-167,000 mt with best fit at m=0.0. Although the shape of the production curve is not known, and the current level of fishing effort is the highest recorded to date, the fishing effort does not appear to exceed considerably the level that gives the MSY.

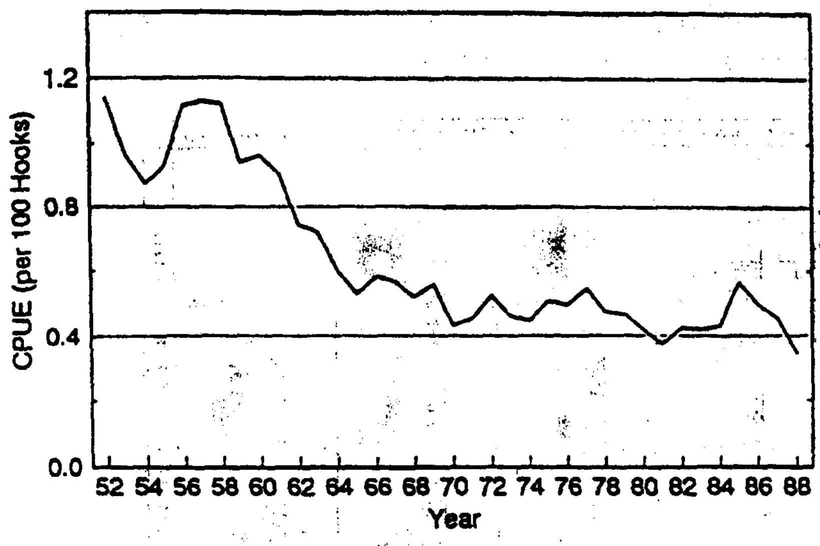

Fig. 15. Annual trend in the Japanese longline CPUE standardized by Honma method. After Miyabe (1991).

12.2 Virtual Population Analysis (VPA)

Kume (1979b) estimated the catch-at-age for fish caught by the Japanese longline fishery for 1957-1975 using the length-frequency samples and the growth equation by Suda and Kume (1967). Then, assuming that the Taiwanese and Korean longline fleets caught the same size of fish in a given area, catch-at-age was prorated to include the catch by Taiwan and Korea. Minimum stock size analysis (Honma 1978), which is one of the variety of VPA analyses, was applied in order to estimate the recruitment. Natural mortality rate (0.361) was employed from Suda and Kume (1967). The estimated recruitment (age 1 fish) was about 9 millions for 1956-57 cohorts and 6 to 6.5 millions for 1964-66 cohorts. The recruitment at age 1 was also estimated assuming the constant recruitment number using the relationship between fishing effort and reciprocal of CPUE (Suda 1970a). The estimate was 7.4 million and very close to Kume's (1979b) results.

Similarly, Miyabe (1989) constructed the catch-at-age for 1965-1987 but solely for the fish caught by the Japanese longline fishery. Miyabe (1989) tuned the VPA with standardized CPUE from the Japanese longline fishery in a way described by Parrack (1986). A value of 0.4 was used for *M*. The objective function to be minimized is:

$$SSQ = \Sigma\ (CPUE_{cal} - CPUE_{obs})^2$$

where SSQ = sum of squares, $CPUE_{cal}$ = calculated CPUE by VPA, and $CPUE_{obs}$ = observed CPUE. $CPUE_{cal}$ can be calculated by regressing population number (N) from the VPA to observed CPUE applying the equation $CPUE_{cal} = q \cdot N$. Here q is catchability coefficient.

The estimated population number at age 1 ranges between 11 to 13 million with smaller fluctuations (10-20%) among years. This is similar to the findings of Kume (1979b) although the level of recruitment is different.

It should be noted that data, in particular length samples, are often less than the desired level, and the assumptions used may not be appropriate since they cannot be proved practically. Because of this, the results should be interpreted with caution.

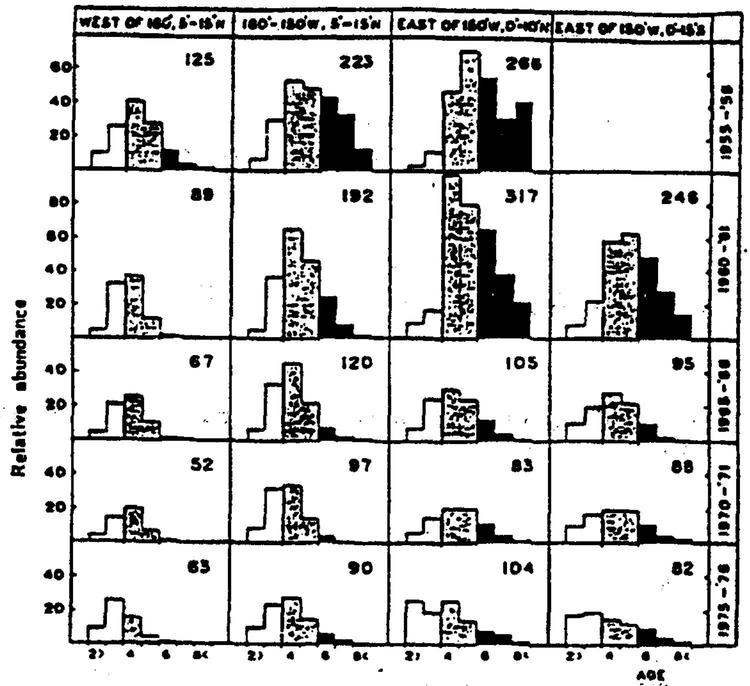

Fig. 16. Changes in CPUE by age of bigeye tuna in the equatorial Pacific, shown by 5-year intervals. Numbers in the panels are total CPUE. After Kume (1979a).

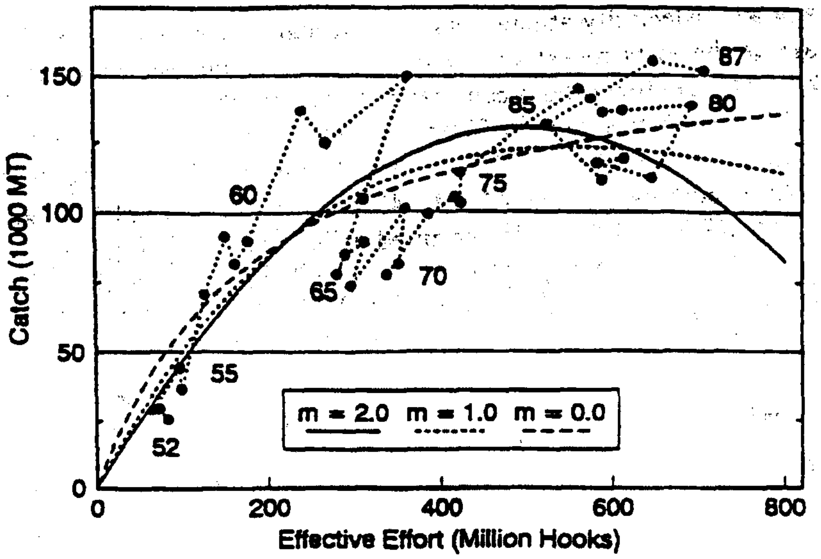

Fig. 17. Annual catch against annual fishing effort and estimated production curves for Pacific bigeye tuna. After Miyabe (1991).

Table 11. Results of production model analysis on Pacific bigeye tuna. After Miyabe (1991).

m (shape parameter)	MSY (1,000 MT)	F_{opt} (million hooks)
0.0	167	∞
1.001	130	500
2.0	130	550

12.3 Yield-per-Recruit (Y/R) Analysis

Suda (1970b) presented the results of Y/R analysis incorporating the Ricker-type stock-recruitment relationship, which was estimated from the spawning potential. Effective fishing effort and *M* (0.361) were taken from Suda and Kume (1967) for 1957-1964. The estimated equilibrium yield curve is shown in Figure 18. The MSY is about 90,000 mt when *F* is 0.5-0.6 assuming the knife-edge-type recruitment at age 4. He also presented the results of several combinations of input parameters, such as recruitment age and *F*.

Thompson-and-Bell-type Y/R analysis was done by Miyabe (1991). The inputs are *M*, weight-at-age and selectivity-at-age. Ages 1 through 7 are included in the calculation. Selectivity-at-age in the most recent year was estimated by the Pope and Shepherd's (1982) separable VPA applying the recent catch-at-age for the Japanese longline catch. The estimated Y/R, which is shown in Figure 19, increases to about 8 kg as *F* becomes larger up until approximately 0.8 and then levels off thereafter. Judging from the current information on the average size of bigeye (40-45 kg) caught by longline gear, it appears *F* is in moderate range (0.2-0.4) for fully-recruited ages.

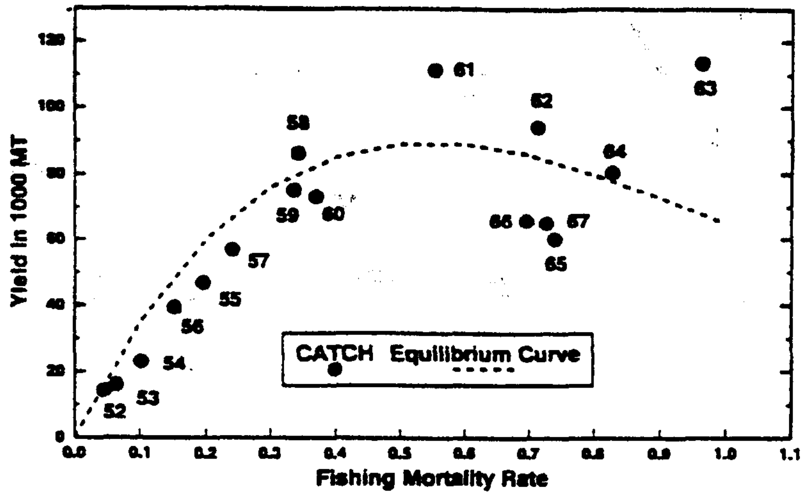

Fig. 18. The estimated equilibrium curve for Pacific bigeye tuna. After Suda and Kume 1967.

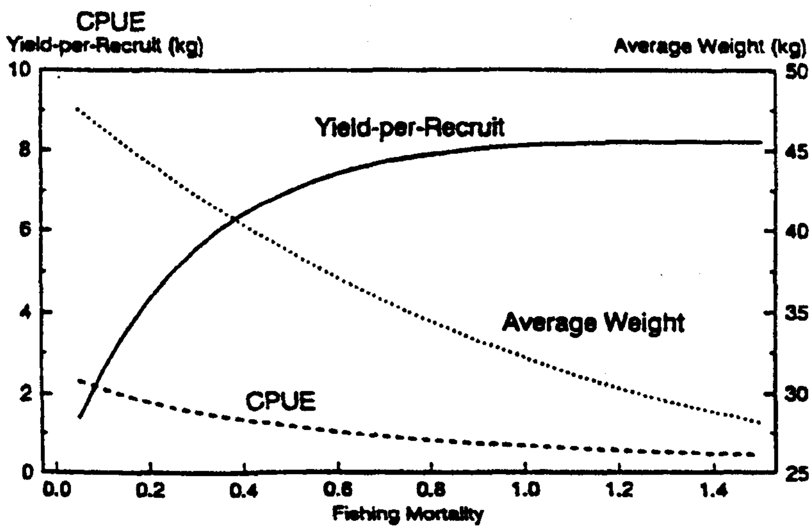

Fig. 19. Thompson and Bell type Y/R curve estimated for the Pacific bigeye tuna. After Miyabe (1991).

13. INTERACTIONS

Among tunas, bigeye seems to be one of the species with the lowest level of gear interaction. There are several fishing gears which harvest bigeye tuna, such as longline, purse seine, baitboat and other miscellaneous gears (trolling, hand-lining, ring net, gill net, *etc.*). In Table 10, the catch was shown divided into surface and longline catch, which consists of smaller to medium and medium to large fish, respectively. It indicated that the longline catch accounted for more than 85% of the total catch. This means there is less within-generation interaction between fisheries. In addition to this, the major distributional pattern of catch by two gear categories differs geographically. The greater catch occurs in coastal or island areas for the surface fishery but in high seas for the longline fishery.

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