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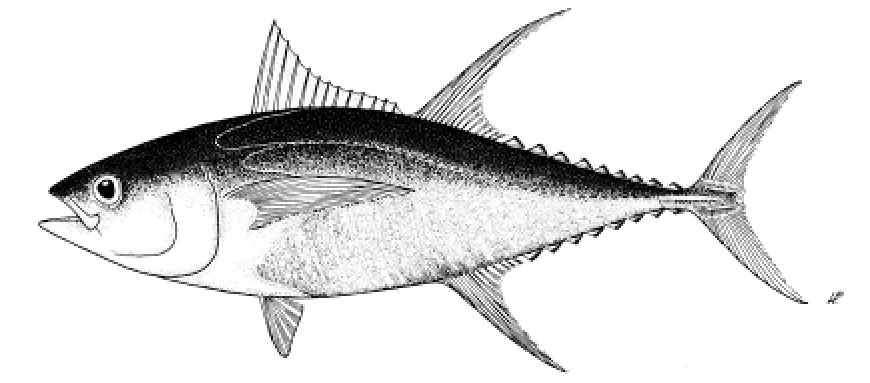
Excerpt from "Background Paper for Amendment 14 to the Pelagics Fishery Management Plan" – Chapter 1: Bigeye tuna (*thunnus obesus*) general description of the species within the Pacific Ocean.



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Background Paper for Amendment 14 to the Pelagics Fishery Management Plan

CHAPTER 1: BIGEYE TUNA *(Thunnus obesus)*
GENERAL DESCRIPTION OF THE SPECIES WITHIN THE PACIFIC OCEAN

May 9, 2005

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Note: This Information Paper contains one section of a larger management related document that describes the biology, life history, movement information, stock structure and recent stock assessments for bigeye tuna (*Thunnus obesus*) in the Pacific Ocean. This excerpt has been provided courtesy of the Western Pacific Regional Fishery Management Council as a reference document to the 1st Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, Noumea, New Caledonia, 8-19 August 2005.

1. GENERAL DESCRIPTION OF THE SPECIES WITHIN THE PACIFIC OCEAN

1.1 Background material and data sources

Several studies on the taxonomy, biology, population dynamics and exploitation of bigeye tuna *(Thunnus obesus*) have been carried out, which include comprehensive reviews by Alverson and Peterson (1963), Collette and Nauen (1983), Mimura and Staff (1963) and Whitelaw and Unnithan (1997). Calkins (1980), Martinez and Bohm (1983) and Miyabe (1994) provide descriptions of bigeye tuna biology and fisheries specific to the Pacific or Indo-Pacific region. Hampton, et al. (1998) provide a summary of information on the biology, fisheries and stock assessment of Pacific Ocean bigeye tuna. A great deal of information on the physiology and ecology of all tuna species, including bigeye is compiled by Block and Stevens [eds] (2001).

In November 1996, the Inter-American Tropical Tuna Commission (IATTC) hosted the First World Meeting on Bigeye Tuna at their headquarters in La Jolla, California. The objectives of the meeting were to review and compare the extant knowledge of the species and associated fisheries between ocean basins and to make recommendations for necessary areas of research. Review papers on the biology and fisheries for bigeye tuna in the Atlantic, Indian and Pacific Oceans were tabled by Pallarés et al. (1998), Stobberup et al. (1998) and Miyabe and Bayliff (1998) and published in the proceedings to the meeting (IATTC 1998).

The Second World Meeting on Bigeye Tuna was convened in March 2004 by the International Commission for the Conservation of Atlantic Tunas (ICCAT) in Madrid, Spain and is summarized in ICCAT (2005). This meeting served as a forum to gather scientists from around the world to discuss advances in bigeye related research since the first World Meeting on Bigeye Tuna and to plan future research objectives.

Specific information on the status of bigeye fisheries and stocks in the Pacific Ocean are contained in the collective research and publications of the IATTC and in seventeen years of annual meetings of the Standing Committee on Tuna and Billfish (SCTB) for the Eastern Pacific Ocean (EPO) and the Western/Central Pacific Ocean (WCPO) respectively. The information contained in this review relies heavily on these sources that represent the most recent information available on the biology, ecology, physiology and fisheries for bigeye tuna in the Pacific Ocean.

1.2 Generalized life history and habitat selection

Bigeye tuna are believed to have recently evolved from a common parent stock of yellowfin tuna (*Thunnus albacares*), remaining in a close phylogenetic position to yellowfin with similar larval form and development. Although the species shares a similar latitudinal distribution with yellowfin tuna worldwide, bigeye have evolved to exploit cooler, deeper and more oxygen poor waters when compared to yellowfin in a classic example of adaptive niche partitioning. Several investigators have demonstrated that this has been accomplished through a combination of physiological and behavioral thermoregulation and other anatomical adaptations for foraging at depth, e.g. respiratory adaptations, eye and brain heaters (Holland and Sibert 1994; Lowe, et al 2000; Fritsches, and Warrant 2001). In this way, the species is considered to be intermediate between a tropical tuna (e.g. yellowfin, blackfin <*T. atlanticus*>, longtail tuna <*T. tonggol*>) and the temperate water tunas (e.g. albacore <*T. alalunga*>, the bluefin tunas). This combination of traits can be characterized by rapid growth during the juvenile stage, movements between temperate and tropical waters to feed and spawn, equatorial spawning with high fecundity -- combined with a preference for cool water foraging and a protracted maturity schedule, an extended life span and the potential for broad spatial movements. It is believed that bigeye tuna are relatively long lived in comparison to yellowfin tuna but not as long lived as the three bluefin tuna species.

Feeding is opportunistic at all life stages, with prey items consisting of crustaceans, cephalopods and fish (Calkins 1980). There is significant evidence that bigeye feed at greater depths than yellowfin tuna, utilizing higher proportions of cephalopods, and mesopelagic fishes and crustaceans in their diet thus reducing niche competition (Whitelaw and Unnithan 1997).

Spawning spans broad areas of the Pacific and occurs throughout the year in tropical waters and seasonally at higher latitudes at water temperatures above 24°C (Kume 1967; Miyabe 1994). Hisada (1979) reported that bigeye tuna require a mixed layer depth of at least 50 m with a sea surface temperature (SST) of at least 24°C. While spawning of bigeye tuna occurs across the Pacific, the highest reproductive potential was considered to be in the EPO based on size frequencies and catch per unit of effort inferred abundance (Kikawa, 1966).

Basic environmental conditions favorable for survival include clean, clear oceanic waters between 13°C and 29°C. However, recent evidence from archival tags indicates that bigeye can make short excursions to depths in excess of 1000 m and to ambient sea temperatures of less than 3°C (Schaefer and Fuller 2002). Juvenile bigeye tuna in the smaller length classes occupy surface mixed layer waters with similar sized juvenile yellowfin tuna. Larger bigeye frequent greater depths, cooler waters and areas of lower dissolved oxygen compared to skipjack and yellowfin. Hanamoto (1987) estimated optimum bigeye habitat to exist in water temperatures between 10° to 15°C at salinities ranging between 34.5‰ to 35.5‰ where dissolved oxygen concentrations remain above 1 ml/l. Recent data from archival tagging has largely corroborated these earlier findings while extending the actual habitat range of the species.

The determination of age, growth and maturity schedules for bigeye tuna are only now becoming better defined. There is no doubt that bigeye tuna are considerably longer lived, slower growing and therefore more vulnerable than the yellowfin. It is now considered that bigeye mature at 3 – 4 years of age after which growth slows considerably with fish capable of living well past ten years. Critical to the understanding of bigeye biology and management are better estimates of maturity schedules by area which are just now beginning to become available. Preliminary results indicate that earlier assessments may have been utilized unrealistically low estimates of size at "maturity" for the species. For the purposes of this review paper, the following categories of bigeye life stage will be used, as explained fully in sections 1.3.3.2, 1.3.3.3, and 1.3.3.4.

1) egg/larval//early juvenile;	< 20 cm
2) juvenile;	20 – 75 cm
3) sub-adult;	76 – 110 cm
4) adult.	> 110 cm

1.3. Detailed life history stages

Egg, larval and early juvenile development

The eggs of bigeye tuna resemble those of several scombrid species and can not be differentiated by visual means. Therefore, the distribution of bigeye eggs has not been determined in the Pacific Ocean. However, the duration of the fertilized egg phase is very short, approximately one day, meaning egg distributions are roughly coincident with documented larval distributions. Eggs are epipelagic and buoyed at the surface by a single oil droplet until hatching occurs.

Kume (1962) examined artificially fertilized bigeye eggs in the Indian Ocean, noting egg diameters ranging from 1.03 to 1.08 mm with oil droplets measuring 0.23 to 0.24 mm. Hatching began 21 hours post-fertilization, and larvae measured 1.5 mm in length. Larval development soon after hatching has been described by Kume (1962) and Yasutake et al. (1973). Descriptions of bigeye larvae and keys to their differentiation from other *Thunnus* species are given by Matsumoto et al. (1972) and Nishikawa and Rimmer (1987). However, the early larval stages of bigeye and yellowfin are difficult or impossible to differentiate without allozyme or mitochondrial DNA analyses (Graves et al. 1988). An indexed bibliography of references on the eggs and early life stages of tuna is provided by Richards and Klawe (1972).

The distribution or areas of collection of larval bigeye in the Pacific has been described or estimated by Nishikawa et al. (1978), Strasburg (1960) and Ueyanagi (1969). Data compiled by Nishikawa et al. (1978) indicates that bigeye larvae are relatively abundant in the western and eastern Pacific compared to central Pacific areas and are most common in the western Pacific between 10EN and 15ES. The basic environment of bigeye larvae can be characterized as warm, oceanic surface waters at the upper range of temperatures utilized by the species, which is basically a consequence of preferred spawning habitat.

Bigeye larvae appear to be restricted to surface waters of the mixed layer well above the thermocline and at depths less than 50 to 60 m, with no clear consensus on diurnal preference by depth or patterns of vertical migration (Matsumoto 1961, Strasburg 1960, Ueyanagi 1969). Prey species inhabit this zone, consisting of crustacean zooplankton at early stages, shifting to fish larvae at the end of the larval phase and beginning of early juvenile stages. The diet of larval and juvenile bigeye tuna is similar to that of yellowfin tuna, consisting of a mix of crustaceans, cephalopods and fish (Uotani, et al. 1981).

The age and growth of larval, post-larval and early juvenile bigeye is not well known or studied. Yasutake et al. (1973) recorded newly hatched larvae at 2.5 mm in total length, growing to 3.0 and 3.1 mm at 24 and 48 hours. The early post-larval stage was achieved at 86 hours after hatching. However, it is likely that the early development of bigeye tuna is similar to that of yellowfin tuna which is the subject of current land based tank studies by the IATTC (IATTC 1997). The larval stages of bigeye tuna likely extend for approximately two to three weeks after hatching. The short duration of the larval stage suggests that the distribution of bigeye larvae is nearly coincident with the distribution of bigeye spawning and eggs. It has been suggested that areas of elevated productivity are necessary to support broad spawning events that are characteristic of skipjack, yellowfin and bigeye tuna whose larvae would subsequently benefit from being in areas of high forage densities (Sund et al. 1981, Miller 1979, Boehlert and Mundy 1994; Itano 2000).

Juvenile and sub-adult stages (20 – 110 cm)

The juvenile phase of bigeye is not clearly defined in the literature. Technically, the term "juvenile" should refer to all sexually immature fish. Calkins (1980) suggests grouping bigeye into larval, juvenile, adolescent, immature adult and adult stages. For the purposes of this management related review, length/age classes were selected in relation to their landings in major fisheries coupled with their size-related vulnerability to various gear types and fishing methods and what is known of bigeye maturity schedules.

Defined this way, the "Juvenile" category will refer to bigeye tuna of 20 – 75 cm fork length which closely corresponds to their size at first recruitment to surface fisheries and includes the majority of surface catches, e.g. purse seine, pole and line, troll. The "Sub-Adult" category of 76 – 110 cm includes the interesting middle size class of bigeye that first enter longline fisheries, are also taken by surface fisheries but are generally not sexually mature or contributing to the spawning biomass.

Juvenile and sub-adult – Habitat and feeding

It is well known that juvenile tunas, including bigeye aggregate strongly to floating objects or to large, slow-moving marine animals, such as whale sharks and manta rays (Calkins 1980, Hampton and Bailey 1993). This behavior has been exploited by surface fisheries to aggregate juvenile yellowfin and bigeye tuna to anchored or drifting FADs (Sharp 1978; Hampton and Bailey 1993). Juvenile, sub-adult and adult bigeye tuna are also known to aggregate near seamounts and submarine ridge features where they are exploited by pole-and-line, handline and purse-seine fisheries (Fonteneau 1991, Itano 1998a; Hallier and Delgado de Molina 2000; Itano and Holland 2000).

Juvenile bigeye form mono-specific schools at or near the surface with similar-sized tuna or may form mixed aggregations with skipjack and/or juvenile yellowfin tuna (Calkins 1980). Yuen (1963) has suggested that these mixed-species schools are actually separate single-species schools that temporarily aggregate to a common element such as food. Echo sounder, sonar data and test fishing strongly suggest a vertical separation of bigeye, yellowfin and skipjack schools that are aggregated to the same floating object. A great deal of circumstantial evidence supports species specific vertical stratification of tuna on drifting objects, with bigeye being the deepest, yellowfin intermediate and skipjack closest the surface. Several studies have come very close to defining these issues using sophisticated sonar and echo sounder equipment capable of measuring target strength readings of individual fish (Josse, et al. 2000; Josse and Bertrand 2000). However, species specific remote sensing of tuna needs further study. An added complication is that normal daytime deep diving behavior of bigeye tuna appears to break down when in association with drifting and anchored FADs where the fish tend to remain within the mixed layer (Schaefer and Fuller 2002; Musyl et al. 2003).

The majority of feeding studies on bigeye tuna have sampled gut contents of large longline-caught fish. Very few studies have specifically examined the feeding behavior of juvenile bigeye tuna. Collette and Nauen (1983) state that juvenile bigeye have been noted to feed opportunistically during day and night on a wide variety of crustaceans, cephalopods and fish in a manner similar to yellowfin of a similar size. Prey items include epipelagic or mesopelagic members of the oceanic community or pelagic post-larval or pre-juvenile stages of island-, reef- or benthic-associated fish and crustaceans. Alverson and Peterson (1963) state that juvenile bigeye less than 100 cm generally feed at the surface during daylight, usually near continental land masses, islands, seamounts, banks or floating objects. Much of this information should be considered dated or incomplete in nature.

Recent and ongoing work in Hawaiian waters may significantly alter the perception that juvenile bigeye feed on epipelagic fauna in a similar manner to similar sized yellowfin tuna. Grubbs et al. (2002) found that small and medium sized juvenile yellowfin and bigeye tuna in a size range of 40 – 80 cm exploited similar broad groups of prey but significantly different species. Yellowfin were noted to feed almost exclusively on epipelagic fish or crustaceans or mesopelagic organisms that vertically migrate into the shallow mixed layer at night. Bigeye tuna of the same size and in the same aggregations fed primarily on a deeper dwelling complex of mesopelagic crustaceans, cephalopods and fish, and fed more successfully near seamounts compared to yellowfin. Interestingly, neither species appears to feed well on anchored FADs but continue to exploit different species that are apparently advected past the FAD by currents or exist in the surrounding waters: yellowfin eating epipelagic organisms and bigeye concentrating on mesopelagic organisms of the sound scattering layer.

Schaefer and Fuller (2002) characterized vertical behavior by association type for bigeye archivally tagged in association with drifting FADs in the equatorial EPO. An interesting behavioral pattern was evident during 27.7% of the time (pooled data) with fish remaining shallow during the night and most of the day as is characteristic of FAD associated bigeye tuna. However, extended deep diving activity took place during afternoon which may have represented a temporary break in the association to forage at depth. Additional archival data in conjunction with acoustic surveys and gut analysis is necessary to resolve these issues.

Juvenile and sub-adult importance to fisheries

Juvenile bigeye are regularly taken as an incidental in surface fisheries, and occasionally as targeted catch, such as in the seamount and FAD associated offshore handline fishery of Hawaii (Adam et al. 2003). Juvenile bigeye tuna of very small sizes are taken in the equatorial Philippine ringnet and small purse seine fishery, but are poorly documented due to mixing in the statistics with yellowfin tuna and other tuna species (Lawson 2004). These fisheries are based on anchored FADs, taking advantage of the strong tendency of juvenile tuna to aggregate to floating objects.

Juvenile bigeye are regularly taken as an incidental in pole and line fisheries, especially when floating objects or FADs are utilized. Tsukagoe (1981) describes interesting techniques used by distant water Japanese pole and line skipjack vessels to target juvenile and sub-adult bigeye tuna on drifting logs in the tropical western Pacific. However, bigeye as small as 32 cm are taken in the Japanese coastal pole-and-line fishery (Honma et al. 1973). Bigeye tuna have also been recorded from a seamount-associated handline fishery and FAD-based pole-and-line and handline fisheries in Hawaii as small as approximately 40 cm FL (Boggs and Ito 1993, Itano 1998). Smaller sized fish are apparently available but not retained due to marketing preferences. The smallest bigeye tuna of 7957 bigeye tag releases achieved during the Hawaii Tuna Tagging Project was 29.0 cm captured by handline gear (Itano and Holland 2000).

Both juvenile and sub-adult bigeye are taken as an incidental catch in floating object sets in western Pacific purse seine fisheries. In the eastern Pacific Ocean, purse seine catches of sub-adult bigeye have been quite high in some years and should be considered as a retained component of the catch in the skipjack floating object fishery. Schaefer and Fuller (2002) from archival tag data noted that bigeye less than 110 cm spent a greater percentage of their time in association with drifting FADs in the EPO but that the larger bigeye still had an affinity for aggregating to floating objects. Very small bigeye tuna are also taken in equatorial purse seine fisheries though may be discarded or poorly enumerated due to market demands and mixed reporting with juvenile yellowfin tuna.

Juvenile and sub-adult bigeye of increasing size appear in higher latitude fisheries, suggesting portions of the population move away from equatorial spawning/nursery grounds to feed and grow, only to return later to spawn. The distribution of these juvenile and sub-adult tuna becomes better understood as they begin to enter catch statistics of temperate water fisheries. The sub-adult size bigeye figure significantly in several handline and longline fisheries. For example, the Hawaii based longline fishery takes primarily sub-adult bigeye tuna. During the 16 year period 1987-2002, annual average size of bigeye ranged from 111 – 120 cm (WPFMC 2004).

Adult distribution and habitat preference

Adult bigeye are distributed across the tropical and temperate waters of the Pacific, between northern Japan and the North Island of New Zealand in the western Pacific, and from 40EN to 30ES in the eastern Pacific (Calkins 1980). Numerous references exist on the distribution of Pacific bigeye tuna in relation to general distribution and migration (Hanamoto 1986; Kume 1963, 1967, 1969a, 1969b; Kume and Shiohama 1965; Laevastu and Rosa 1963); the oceanic environment (Blackburn 1965, 1969; Hanamoto 1975, 1976, 1983, 1987; Nakamura and Yamanaka 1959; Suda et al. 1969; Sund et al. 1981; Yamanaka et al. 1969); the physiology of tunas

(Magnuson 1963; Sharp and Dizon 1978; Stretta and Petit 1989); and fish aggregation devices (Holland et al. 1990).

There is some consensus that the primary determinants of adult bigeye distribution are water temperature and dissolved oxygen levels. Salinity does not appear to play an important role in tuna distribution in comparison to water temperature, dissolved oxygen levels and water clarity. Hanamoto (1987) reasons that optimum salinity for bigeye tuna ranges from 34.5‰ to 35.5‰ given the existence of a 1:1 relationship between temperature and salinity within the optimum temperature range for the species. Alverson and Peterson (1963) state that bigeye tuna are found within SST ranges of 13° to 29°C with an optimum temperature range of 17° to 22°C. However, the distribution of bigeye tuna cannot be accurately described by SST data since the fish spend a great deal of time at depth in cooler waters. Hanamoto (1987) analyzes longline catch and gear configurations in relation to vertical water temperature profiles to estimate preferred bigeye habitat. He notes that bigeye are taken by longline gear at ambient temperatures ranging from 9° to 28°C and concludes from relative catch rates within this range that the optimum temperature for large bigeye lies between 10° and 15°C if available dissolved oxygen levels remain above 1ml/l. In a similar study in the Indian Ocean, the optimum temperature for bigeye tuna was estimated to lie between 10° and 16°C (Mohri et al. 1996).

According to several authors, bigeye can tolerate dissolved oxygen levels as low as 1 ml/l, which is significantly lower than the dissolved oxygen requirements of skipjack and yellowfin tuna (Sund et al. 1981). Brill (1994) has proposed a physiological basis to explain how bigeye are able to utilize oxygen in a highly efficient manner, thereby allowing them to forage in areas that are not utilized by other tuna species. He theorizes that bigeye tuna spend the majority of their time at depth, making short excursions to the surface to warm up. Lowe et al. (2000) demonstrate that the blood of bigeye tuna has a significantly higher affinity for O2 compared to other tunas, thus explaining their ability to exploit O2 poor regions and depths.

This vertical movement pattern, which has been clearly demonstrated by sonic tracking experiments of bigeye tuna, is exactly the opposite pattern demonstrated by skipjack and juvenile yellowfin tuna (Holland et al. 1992). Sonic tracking and archival tagging of bigeye tuna consistently indicate deep foraging during the daytime near or below the thermocline and shallow swimming behavior at night.

The use of sonic and archival tagging technologies have greatly expanded our knowledge of bigeye behavior and habitat selection. Schaefer and Fuller (2002) noted that bigeye in the EPO spend most of the day at depths of 200 – 300 m and ambient temperatures of 13 - 14°C, although dives to below 1500 m and ambient temperatures of < 3°C were noted.

Size at maturity and the classification "sub-adult" and "adult" bigeye

Estimates of size at maturity for Pacific bigeye vary widely between authors (Whitelaw and Unnithan 1997). This is likely due to a mixing between estimates and/or observations of "*size at first spawning*"; "*size of fish observed in running ripe condition*" or some estimate or guess of "*size at sexual maturity for the stock*" as determined by a variety of methods using vastly different temporal and spatial sampling protocols. Maturity of bigeye is most accurately indicated by the presence of hydrated oocytes in the ovarian lumen or microscopically observed post-ovulatory follicles of recent age or for the male, by a variety of visual observations of the testis (Nikaido, et al., 1991). Large-scale stratified sampling over multi-year periods may be necessary to adequately address area effects and inter-annual variation in oceanographic conditions, e.g. ENSO effects.

Kikawa (1957, 1961) estimated size at first maturity for males at 101–105 cm and 91–95 cm for female bigeye and selected 100 cm as a general size for "potential maturity" for Pacific bigeye. Kume (1962) recorded a running ripe female bigeye of 93 cm, and McPherson (1988) recorded mature bigeye of 100 cm using histological methods. The study by Yuen (1955) agreed with Kikawa (1953) with an estimated size at first spawning for central Pacific bigeye at roughly 90 – 100 cm. In a later study, Kikawa (1962) reported finding very few sexually mature female bigeye less than 100 cm in fork length. Sun (1999) reported on a year of bigeye port sampling of Taiwanese longline vessel catch from the far western Pacific and noted the smallest mature female sampled measured 99.7 cm. Nikaido et al. (1991) reported that most of the bigeye over 100 cm were "sexually very active" from taken near Java and from waters south of Johnston Atoll. These observations are incomplete and clearly unsuitable for stock assessment purposes.

The IATTC is in the process of concluding and publishing results of a two-year investigation on the reproductive biology of bigeye tuna from the Eastern Pacific Ocean that evaluated 1869 gonad samples from male and female bigeye ranging between 80 and 163 cm FL to determine spawning habitat, maturity, fecundity and sex ratios. Histological methods were used to evaluate sexual maturity, spawning periodicity and spawning time. The smallest female bigeye tuna histologically classified as mature was 120 cm FL and only 4 per cent of fish 120.0-124.0 cm FL (n=70) were mature (IATTC 2004). Approximately 54 per cent of samples 140.0-144.9 and 78 per cent of fish 150.9-154.9 were classified sexually mature.

These initial findings suggest considerably larger sizes at maturity for bigeye tuna in the EPO in comparison to observations made in the central and western Pacific. However, it should be noted that spawning of bigeye has been linked with sea surface temperatures above 24EC. It has been suggested that sexual maturity, or more accurately, the development into active spawning condition appears to be linked to mixed layer water temperatures above 26E C (Mohri 1998). Kume (1967) noted a correlation between mature but sexually inactive bigeye at SSTs below 23E to 24EC, which appears to represent a lower limit to bigeye spawning activity

Sea surface temperatures are considerably lower in the equatorial EPO compared to the WCPO which could depress and lengthen maturity schedules of bigeye tuna in the EPO if they remained in that area for extended periods. For example, mean annual SSTs measured at oceanographic buoys in the area of the EPO study at 0E, 95EW and at 0E, 180E during 2000 (the time period of the sampling by Schaefer) were 23.1 and 27.5EC respectively[1].

In other words, bigeye maturity schedules and spawning patterns need to be examined on a regional basis. A broad scale investigation of bigeye maturity and reproductive parameters using histological methodology is clearly indicated.

In review of the available information, the categorization of 100 cm bigeye tuna as "generally mature" may be inaccurate and potentially dangerous for stock assessment purposes. The selection of 100 cm to describe mature bigeye would be similar to selecting a size of ~ 60 cm to describe mature yellowfin when this actually represents the size when a few yellowfin first enter maturity. Estimates of L50 for WCPO and EPO yellowfin are 105 cm and 92 cm respectively (Itano 2000; Schaefer 1998).

For the purposes of this review, a conservative value of 110 cm has been selected to differentiate sub-adult populations from adult bigeye.

Reproduction

Sex ratios

Information on sex ratios of bigeye by area are incomplete and somewhat inconsistent though there is general agreement that males are more abundant, particularly in the larger size classes. Most studies agree that sex ratios of bigeye tuna are close to the expected 1:1 up to a fork length of approximately 140 cm after which several authors have noted an increase in the proportion of males in the population (Miyabe and Bayliff 1998; Miyabe 2001; Sun et al. 2004). Bigeye larger than 160 cm are predominantly males, and females appear to be completely absent from the largest size classes.

The cline in sex ratios after 140 cm may be related to a slowing of growth, increased natural mortality, increased catchability or some factor related to courtship and spawning. The cline in sex ratios toward males near the size of maturity for females has lead many investigators to speculate that the energetic costs of maturation and spawning may slow somatic growth in females, eventually leading to higher natural mortality. Estimates of differential cost of spawning on the basis of gonadal production, bioenergetics modeling (locomotion, metabolism, energy loss and growth) or some combination of both have been made for yellowfin tuna (Olson and Boggs 1986; Schaefer 1996: 1998). Although several energetic factors may not be fully addressed in these studies, they do agree that energetic costs for females and the massive cytoplasmic investment of females in daily expenditures of ova far outweigh that expended by the males. In short, it appears that female tuna, particularly the tropical tunas simply burn out and stop growing or die young as a consequence of massive reproductive output.

Reproductive parameters

Bigeye tuna spawn throughout the year in equatorial regions, engaging in night time mass spawning events in oceanic waters above approximately 24EC, but ideally closer to 26EC. Kume (1967) noted a correlation between mature but sexually inactive bigeye at SSTs below 23E to 24EC, which appears to represent a lower limit to

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[1] http://www.pmel.noaa.gov/tao/data_deliv/deliv-nojava.html

bigeye spawning activity. Bigeye tuna are serial spawners, capable of repeated spawning events at daily or near daily intervals during extended spawning periods of unknown length (Nikaido et al. 1991). Spawning takes place during the late afternoon or evening hours at or near the surface (McPherson 1991a). Spawning peaks in the evening from about 1900 to 2400 hours, with batch fecundities of millions of ova per spawning event. Batch fecundity, as with many fishes, increased dramatically with body length with estimates of bigeye batch fecundities ranging from around one to five million eggs per spawn for fish ranging from 120 to 180 cm FL (Nikaido, et al. 1991). Sun et al. (1999) estimated an average batch fecundity for western Pacific bigeye of 3.47 million oocytes, or 59.5 oocytes per gram of body weight for samples.

Additional information on the maturity and spawning of western and central Pacific bigeye is provided by Kikawa (1953, 1957, 1961, 1962, and 1966). However, none of these older studies applied histological techniques that are necessary to accurately define maturity stages and reproductive parameters of tuna populations (Schaefer 2001). Goldberg and Herring-Dyal (1981) provide one of the few accessible studies on bigeye maturity using histological techniques.

Spawning areas and seasons

In a general sense, bigeye tuna are believed to spawn throughout the year in tropical regions (10EN - 10ES) and during summer months at higher latitudes (Collette and Nauen 1983). A study by McPherson (1991a) in eastern Australian waters supports this concept of equatorial spawning of bigeye throughout the year with seasonal spawning of bigeye in the north Australian zone, e.g. higher latitudes. Hisada (1979) noted from a study in the central and eastern Pacific that a temperature of 24EC to a depth of 50 m were necessary for maturity and spawning, suggesting a similar seasonal pattern of spawning in the western Pacific. It can be assumed that bigeye spawning and larval development are common at SSTs above 26EC, but may occur in some regions with surface mixed layers of 23E-24EC and above.

Yuen (1955) found fully mature, spawning condition bigeye in samples collected in the western Pacific, Caroline and Marshall Islands (1E - 7E N latitude) throughout the period of his sampling (April – October). Sampling at similar latitudes among the central Pacific, Line Islands of Kiribati suggested two peak spawning periods in Jan-Feb and July-Oct. However, these results were considered preliminary due to restricted sample sizes and periods. A large data set from the Hawaiian Islands revealed no bigeye tuna in spawning condition with the nearest spawning condition bigeye sampled 400 miles southeast of Hawaii.

Two years of ovary sampling of Hawaiian bigeye revealed a definite increase in relative ovary weight from winter to summer, peaking in June, but no fully mature or spawning-condition bigeye were ever sampled (Yuen 1955). June also coincides with the annual low in the landings of large bigeye in Hawaiian waters. Yuen (1955) suggested that large bigeye in maturing stages leave Hawaii in spring and summer to spawn, presumably to the south. Gear selectivity was not considered a plausible explanation for the reduced summertime catches, as the same gear takes large, spawning condition bigeye at that time of year near Palmyra Atoll, 800 nmi south of Hawaii. This would also concur with a central equatorial spawning season of Jul-Oct, peaking in Aug-Sept as was inferred by the Line Islands samples examined in the same study.

Nikaido et al., (1991) noted bigeye in active spawning condition in waters described as "south-western offshore of Hawaii". Several tables and graphs in the paper are labeled as "Hawaii samples", which has lead to some confusion of the status of bigeye spawning in Hawaiian waters. His "Hawaii" samples were actually taken from locations 11E- 13EN, and 163E- 176EW which are well south of Johnston Atoll and over 700 miles from the closest Hawaiian island. Nevertheless, the sampling occurred from May 27 – July 10.

Boehlert and Mundy (1994), in larval fish tows around the Hawaiian island of Oahu tentatively identified five bigeye tuna larvae collected in June using visual criteria. However, these identifications are now considered suspect due to more recent work defining visual characters of tuna larvae using DNA techniques (Graves et al. 1988; Mundy, pers. comm.).

Sun et al. (1999), examined bigeye tuna gonads taken in the western Pacific longline fishery over a one year period. Based on monthly variation in gonad size and oocyte stage he proposed that the spawning season of western Pacific bigeye extended from February to September with peaks from March to June. These samples were taken primary from areas east and west of the Philippines; therefore around 10EN. 120-130EE.

Age and growth

Whitelaw and Unnithan (1997) provide a summary of early studies on the age and growth of bigeye tuna in the Pacific and Indian Oceans using primarily analyses of modal progression in size frequencies. Pertinent references include Iverson (1955), Kume and Joseph (1966), Marcille and Stequert (1976), Peterson and Bayliff (1985), Tankevich (1982) and Talbot and Penrith (1960). Yukinawa and Yabuta (1963) examined scale increments. Lehodey et al. (1999) and Sun et al. (2001) provide summarized tables of growth parameters derived by bigeye studies in the Pacific and Atlantic Oceans.

Significantly, the IATTC has completed an otolith age validation study on central Pacific bigeye tuna in collaboration with the University of Hawaii, Pelagic Fisheries Research Program (IATTC 2002). Saggital otoliths from recaptured bigeye tuna previously marked with oxytetracycline (OTC) from Hawaiian waters and the Eastern Pacific Ocean were evaluated. The study concluded that daily microincrements were deposited on bigeye otoliths within the range of sampling (38-135 cm FL), but that expanded sampling and evaluation was necessary to expand the significance of the work.

In more recent studies, Hampton and Leroy (1998) developed a von Bertelanffy growth curve fitted to tag recapture data and otolith readings for western and central Pacific bigeye tuna, resulting in the growth curve as depicted in Figure 10 of Hampton et al. (1998b). Lehodey et al. (1999) refit the composite model, excluding otolith readings from fish >110 cm FL due to difficulties in reading daily increments beyond three years. Figure 6 in Lehodey et al (1999) was felt to provide a reasonably good fit to both tagging and otolith data, with the tagging data providing estimated $L\infty$ within a more realistic framework.

Within the past few years, CSIRO has developed techniques to age bigeye tuna using seasonal annuli on otoliths (Farley et al. 2003). Annuli are not clearly defined during the first two years of life due to rapid growth but become easily discernable after two or three years of life. Leroy (1991) concludes that the second and third annuli can be accurately determined by visual enumeration of daily microincrements in prepared saggital otoliths. Therefore, a combination of daily and annular readings of otoliths should provide accurate estimates of bigeye growth.

In an independent study, Sun et al. (2001) used presumed annular marks on the first dorsal spine of western Pacific bigeye tuna to develop estimates of age and growth. Spines from 1149 specimens ranging between 45.6 – 189.2 cm FL were examined. Age estimates of mean and back calculated fork lengths of bigeye up to ten year estimates are provided.

Stequert and Conand (2004) examined the age and growth of bigeye tuna sampled from the western Indian Ocean. Presumed daily microincrements on saggital otoliths were interpreted using scanning electron microscope for 164 samples. A growth curve was derived indicating bigeye in this region measure 59 cm at year 1, 111 cm at year 3 and 147 cm at 6 years. Marks on the first dorsal spines of 140 bigeye were also interpreted. Comparable results were reached using otoliths and spines up to estimated ages of three years, but they did not feel that spines were suitable for ageing larger fish.

These studies in combination with tag recapture data suggest that bigeye growth is rapid and parallels yellowfin growth for the first two years, after which it slows down significantly prior to the onset of sexual maturity. The disparity in results by area also suggests that studies need to be carried out on a regional basis and results from one area should be used with caution in other areas if at all. Maximum age of bigeye is not known, but tag recapture data provides empirical evidence that bigeye tuna grow to at least 12+ years of age which is considerably longer than yellowfin. Recently, large bigeye tuna have been aged using a combination of daily and annular marks at 13 to 15 years of age (Leroy pers. comm.).

Adult diet and feeding

Several investigators have proposed that the greater depth distribution of bigeye is a foraging strategy to exploit regions less utilized by yellowfin or skipjack tuna, thus reducing niche competition. Bigeye tuna are opportunistic feeders like yellowfin, relying on a mix of crustaceans, fish and cephalopods with feeding taking place during the day and night (Calkins 1980; Collette and Nauen 1983). However, the composition of adult bigeye diet differs significantly from that of similar-sized yellowfin (Watanabe 1958, Talbot and Penrith 1963, Kornilova 1980). Adult bigeye prefer to forage at significant depths, utilizing a higher proportion of squid and mesopelagic fishes compared to yellowfin. Solov'yev (1970) suggests that the preferred feeding depth of large bigeye is 218–265 m, which is the most productive depth for longline catches. Miyabe and Bayliff (1998) summarize diet items of bigeye in the Pacific in tabular form from studies by Alverson and Peterson (1963), Blunt (1960), Juhl (1955), King and Ikehara (1956) and Watanabe (1958).

Any discussion of preferred bigeye habitat must address the vertical temperature structure, thermocline depth and local characteristics of the sound scattering layer (SSL) of the region in discussion. Josse et al. (1998) used tracking of bigeye and yellowfin marked with depth transmitting tags with simultaneous recording of biotic elements of the water column to examine tuna behavior during the day and night. The study clearly illustrated the importance of the SSL and prey to tuna movements and presumed feeding behavior. Sonic tracking and the use of archival data loggers have clearly shown the ability of adult bigeye to exploit prey and forage in a much deeper environment when compared to yellowfin (Dagorn et al. 2000; Musyl et al. 2003).

Bigeye tuna are also known to aggregate to large near surface concentrations of forage, such as the spawning aggregations of lanternfish (*Diaphus sp.*) [MYCTOPHIDAE] that occur seasonally in the Australian Coral Sea (Hisada 1973, McPherson 1991b).

Adult importance to fisheries

Large, mature-sized bigeye tuna are sought by high value sub-surface fisheries, primarily longline fleets landing sashimi grade product. Adult bigeye tuna aggregate to drifting flotsam and anchored buoys, though to a lesser degree than juvenile fish. Large bigeye also aggregate over deep seamount and ridge features where they are targeted by some longline and handline fisheries.

Regions of elevated primary productivity and high zooplankton density—such as near regions of upwelling and convergence of surface waters of different densities that are very important to the distribution of skipjack and yellowfin tuna—are less important to the distribution of adult bigeye. This is logical if one assumes skipjack and yellowfin are inhabitants of the upper mixed layer while adult bigeye are sub-surface in nature, more closely tied to the thermocline and organisms of the deep scattering layer. Water temperature, thermocline depth and season appear to have much stronger influences on the distribution of large bigeye (Calkins 1980). The fact that large bigeye take longline hooks at greater depths than yellowfin coupled with a rising demand for sashimi-grade tuna and improved storage techniques prompted a shift to deep longline gear to target bigeye tuna during the late 1970s and early 1980s (Sakagawa et al. 1987, Suzuki et al. 1977). This development promoted numerous studies on differential catch rates and gear configurations to define productive hooking depths for bigeye given different oceanographic conditions (Bahar 1985, 1987; Boggs 1992; Gong et al. 1987, 1989; Hanamoto 1974; Nishi 1990; Saito 1975; Shimamura and Soeda 1981; Suzuki and Kume 1981, 1982; Suzuki et al. 1979).

Hanamoto (1987) proposed that productive longline fishing grounds for bigeye do not necessarily equate to regions of higher abundance, but "are nothing more than areas where the hook depths happened to coincide with the optimum temperature layer and where the amount of dissolved oxygen happened to be greater than the minimum required for bigeye tuna (1ml/l)." Nakamura (1969) suggests that bigeye tuna are closely associated with particular water masses or current systems during different life stages. Fish taken in the higher latitude longline fishing grounds tend to be large sub-adults, reproductively inactive young adults, or spent (mature but reproductively inactive) adults, while the fish taken in the equatorial longline fishery are actively spawning adults (Calkins 1980).

1.4 Movement

Horizontal movements

There have been relatively few bigeye tagged in the Pacific in comparison to skipjack and yellowfin due to the difficulty in capturing quantities of bigeye in suitable condition for tagging. The South Pacific Commission tagged and released approximately 147,000 tuna between 1989 – 1992, of which only 5.5% were bigeye. As a result, horizontal movement data from conventional tagging programs is not conclusive.

Miyabe and Bayliff (1998) present summary information of some long distance movements of tagged bigeye in the Pacific. Hampton and Williams (2005) describes 8,074 bigeye releases made in the western Pacific by the South Pacific Commission (SPC) Regional Tuna Tagging Project (RTTP) during 1989–1992. An overall recapture rate of 12.5% of bigeye releases was reported.

For large release data sets in the Philippines and from the Coral Sea of Australia, more than 80% of recaptures were reported within 200 nmi of release. In contrast, about 50% of equatorial releases occurred beyond 200 nmi from their point of release and 10% beyond 1000 nmi. The authors suggest the difference may be due to a greater tendency for bigeye to remain close to large land masses, FADs or tightly packed island groups. The equatorial releases were made in high seas areas or near isolated, oceanic islands and atolls.

Approximately 63 per cent of all SPC/RTTP bigeye tag releases were made in the northeastern Australian EEZ, most of which were captured in large feeding aggregations in the Coral Sea at approximately 17-18E S latitude (Itano and Bailey 1991). Hampton and Gunn (1998) examined a release dataset of 4,277 bigeye using a tag-attrition model with seasonally variable catchability and targeting options. Tag recaptures supported some linkage of Australian bigeye to the broader western and central Pacific and as far east as 130-140 W longitude. However, the majority of recaptures came from the general area of release with a significant seasonal pulse during mid-year. Various explanations are given but some degree of localization of bigeye can not be discounted.

The Hawaii Tuna Tagging Project (HTTP) conventionally tagged and released 7,440 yellowfin and 7,957 bigeye tuna throughout the Hawaiian archipelago, primarily from 1996 – 1999. Most of the bigeye releases were juvenile fish (mean 59.8 cm) tagged and released near a large seamount feature in the Hawaii EEZ or on offshore buoys that were acting as fish aggregation devices (Itano and Holland 2000). Bigeye recaptures reached 15% overall, which were primarily short term recaptures at or near their point of release, reinforcing the importance of aggregation and schooling to juvenile bigeye tuna behavior. Recaptured bigeye apparently remained within the Hawaii zone for at least two or three years, repeatedly aggregating to the same seamount or FADs where recaptures continued to be reported. Adam et al. (2003) supported some degree of regional fidelity or island association of these juvenile and sub-adult phase bigeye with a low level of mixing with the broader WCPO. In this respect, the results were somewhat similar to those reported by Hampton and Gunn (1998) for bigeye tuna in the Australian Coral Sea.

Sibert et al. (2003) applied a Kalman filter statistical model to refine horizontal movement data from geolocating archival tags recovered from Hawaiian bigeye tuna. Juvenile and sub-adult bigeye recoveries showed little real movement and a strong tendency to remain at the seamount and FADs where they had been tagged. The only large bigeye (131 cm) apparently remained associated with the coastal features and nearshore bathymetry of the island of Hawaii during 84 days at liberty. The authors suggest that large features, such as islands may also act as points of attraction and aggregation for bigeye tuna. This is a commonly held belief of traditional handline fishermen in Polynesia who target deep swimming tunas at specific locations close to atolls and high islands. There are several of these traditional handline areas along the south shore of the island of Hawaii that are known to hold bigeye and yellowfin tunas (Rizutto 1983).

However, over time, increasing numbers of HTTP recaptures have been reported radiating out from the Hawaiian islands in all directions, but primarily to the south of Hawaii toward Johnston and Palmyra Atolls. This recapture pattern may reflect different life stages of bigeye tuna, with semi-resident juveniles and sub-adults strongly aggregated to island and seamount features, expanding out into oceanic environments and tropical spawning grounds with their development to maturity. It should be noted that higher recapture rates to the south of Hawaii are undoubtedly influenced by differential fishing effort, but effort and abundance are often closely related.

Horizontal movements of bigeye in relation to FADs and drifting objects are not well described, although a great deal of anecdotal information is available from the fishing industry. Schaefer and Fuller (2005) noted that bigeye tended to remain tightly aggregated and upcurrent of anchored FADs and downcurrent from the drifting research vessel during the day. At night, the bigeye aggregations became more diffuse when it was presumed that individuals were foraging on organisms of the SSL. Bigeye returned to their daytime positions at dawn, often forming monospecific schools at the surface, usually termed a “breezer”.

Bigeye tuna can move freely throughout broad regions of favorable water temperature and dissolved oxygen values; and are capable of large, basin-scale movements as documented by tag recoveries. However, most bigeye recaptures have occurred within 200 miles of their point of release. However, these results may be confounded by the preponderance of juvenile fish in tag release cohorts, a protracted time to reach adult stages, reporting problems for recaptures of large fish from high seas fleets and a general paucity of adequate tag release data.

If the majority of spawning takes place in equatorial waters, then this infers mass movements of juvenile and sub-adult fish to higher latitudes, and presumably some return movements of mature or maturing fish to spawn. However, the extent to which these are directed movements is unknown and the extent of bigeye movement between the western, central and eastern Pacific remains unclear. An increase in tag releases of medium and large bigeye tuna throughout their range, incorporating fishery independent technologies where possible is needed.

Vertical movements

A great deal of information on the vertical behavior of bigeye tuna has been inferred from commercial or research derived longline data. However, this indirect source of information has been largely superceded by fisheries independent depth data either transmitted or recorded *in situ* and at fine time scales using sonic and archival (data logging) tags. Holland et al. (1990) tracked FAD associated bigeye tuna (72.0, 74.5 cm) fitted with pressure-sensitive (= depth recording) ultrasonic transmitters in Hawaiian waters. The fish exhibited a deep daytime (220 – 240 m) vs shallow night-time (70 – 90 m) behavior. This pattern broke down when FAD-associated, when average on-FAD daytime depths of 50 – 60 m. were noted. Daytime behavior was characterized by large, regular, but brief vertical excursions between the thermocline and the bottom of surface mixed layer, oscillating between the 14E and 17EC isotherms.

Holland and Sibert (1994) examined thermoregulation in Hawaiian bigeye tuna with data produced by depth and temperature transmitters and simultaneous use of expendable bathythermographs for vertical temperature profiling. Juvenile and sub-adult bigeye (65 – 80 cm) exhibited regular vertical daytime movements as described in Holland et al. (1990). These excursions consistently began when internal body temperatures declined to 17.5 to 18EC, suggesting this may represent a lower body temperature limit for this medium size bigeye tuna.

Dagorn et al. (2000) tracked large bigeye in open ocean environments in French Polynesia, noting the same shallow night-time vs deep daytime behavior. The largest adult bigeye tuna (estimated 50 kg body weight) rose from daytime base depths of 400 – 460 m to mixed layer depths of 74 – 119 m moving through a temperature gradient of 11.5 – 25.6°C. This fish made only four upward excursions, one every 2.5 hours compared to eleven upward excursions per day recorded by Holland et al. (1990) for a much smaller bigeye tuna in Hawaii (74.5 cm). The authors attribute the difference to differences in body size, thermal inertia and the more frequent need for smaller bigeye to rise to the surface to warm core temperatures. A comparison of day and night swimming depth and simultaneous recording of the prey-rich sound scattering layer (SSL) indicated that bigeye tuna appear to maximize their time within the SSL; deep in the daytime and shallow at night. Vertical movements through the SSL were noted, possibly indicative of hunting/feeding behavior (Josse et al. 1998).

Schaefer and Fuller (2002) report on the largest documented archival dataset for bigeye: 27 sub-adult or potentially adult size fish (88 – 124 cm) tagged and released in drifting FAD aggregations in the equatorial Eastern Pacific Ocean. Vertical behavior was characterized into unassociated, drifting object associated, intermediate, or deep diving. Classic unassociated behavior was characterized as remaining at mostly < 50 m during the night and spending most of the day at 200 – 300 m within ambient sea temperatures of 13 - 14EC. Fish associated with a drifting FAD generally remained within the shallow mixed layer throughout the day and night above 50 m, although the daytime depth was slightly deeper. An intermediate behavior was noted in the data characterized by remaining shallow at night and day coupled with some deeper diving periods in the afternoon. The authors speculated that this behavior may have been representative of a fish associated with a drifting FAD that broke that association to feed at depth, or a fish feeding on forage aggregated unusually shallow during the daytime as sometimes occurs with some mesopelagic fishes. Sporadic, deep diving behavior was noted when bigeye tuna quickly dove to below 1000 m and ambient temperatures of < 3EC. The archival tags employed were only capable of reading to 1000 m, but it was inferred from ambient sea temperatures that some fish may have reached depths of 1500 m. It is not known why bigeye would dive so deep, but predator avoidance (i.e. marine mammals) or feeding was proposed.

Pooled data characterized the behavior of tagged bigeye as 54.3% unassociated, 27.7% intermediate-type behavior and only 18.7% of the time associated with a floating object, e.g. FAD as natural logs are very rare in this region of the EPO. Daytime diving depths were noted to be significantly shallower than those recorded in the central/western Pacific. The authors suggested that the main determinant of bigeye depth preferences at night and day had to do with their prey and feeding within the vertically migrating sound scattering layer. FAD associations were noted to be of short duration (mean residence time 3.1 days) but were though to contribute significantly to fishing mortality and vulnerability as evidenced by the high recapture rate of this tag release cohort (30 per cent overall).

Musyl et al. (2003) report on the vertical movements of bigeye tuna equipped with similar archival tags that had been released and recaptured from different types of aggregations in Hawaiian waters. Bigeye frequenting open-water areas exhibited the classic deep-daytime vs shallow-night time behavior observed by Schaefer and Fuller (2002). Bigeye periodically rose from daytime depths of ~300 – 500 m to spend short periods in the upper mixed layer, presumably to warm up after foraging at depth. All fish rose to very shallow depths at dusk only to sink down again at dawn. A strong positive correlation was found between body size and daytime depth as Dagorn et al. (2000) had suggested. Bigeye tuna tagged and later recaptured in association with an offshore anchored FAD spent the majority of their time in the upper mixed layer around 50 - 100 m. It is not known if the fish remained in association with the FAD during their entire time at liberty, but they exhibited this shallow "abnormal" behavior after release and when recaptured on the FAD. Bigeye tagged and recaptured on an offshore seamount feature exhibited vertical behavior similar to but not as regular as the vertical behavior of unassociated bigeye. In agreement with previous studies, bigeye in open water areas and on the seamount appeared to maximize their time within the SSL, presumably to maximize foraging success. In contrast to the observations of Holland et al. (1990) from brief sonic tracking data, internal temperatures of juvenile and sub-adult bigeye (52 – 86 cm) were recorded to fall to a minimum of ~ 12 - 13°C. The deepest recorded depth was 817 m and the coldest ambient temperature visited was 4.7°C, but fish spent very little time at these extremes.

By using a combination of archival tags and ultrasonic telemetry, Schaefer and Fuller (2005) report on the vertical behavior of bigeye tuna in mixes species aggregations on an anchored FAD. A larger bigeye (108 cm) occupied significantly deeper waters, day and night, compared to a smaller fish (59 cm). For the large fish, mean depths were significantly deeper during the day vs night. However, this pattern was curiously reversed for the smaller bigeye. Generally, the presence of FADs or drifting objects appears to significantly influence the vertical behavior of bigeye tuna.

Archival tag data is essential to characterize the habitat and behavior of tuna and billfish to refine habitat based models and to estimate the impact of fisheries. Currently, the SPC is attempting to obtain data on the vertical behavior of principal tuna species across a wide expanse of the WCPO that covers a wide range of oceanic environments.

1.5 Stock structure

The geographic distribution of bigeye tuna is pan-Pacific with no physical or oceanographic barriers to movement within temperature extremes. Analyses of genetic variation in mitochondria1 DNA and nuclear microsatellite loci have been conducted on bigeye otoliths from nine geographically scattered regions of the Pacific (Grewe and Hampton 1998). The study noted some evidence for restricted gene-flow between the most geographically distinct samples (Ecuador and the Philippines). However, the data otherwise failed to reject the null hypothesis of a single Pacific-wide population of bigeye tuna. In other words, the study supported the possibility of some degree of population mixing throughout the basin; results that may be termed inconclusive. It should be noted that in a separate study, Grewe et al, (2000) found no evidence to suggest that bigeye from the Indian Ocean were genetically different from the Pacific Ocean samples examined in the earlier study. This suggests that the methodology currently used may be an inappropriate tool for determining the issue of stock structure.

Miyabe and Bayliff (1998) suggest that there is insufficient information currently available to definitively determine the stock structure of bigeye in the Pacific, and therefore, a single stock hypothesis is usually adopted for Pacific bigeye tuna.
However, consistent areas of low catch separate principal fishing grounds in the eastern and central/western regions (around 165 - 170EW) and there appears to be little mixing of tagged populations: although the tagging data is quite limited. Due to these considerations and the existence of two major, geographically separated fishing grounds and fisheries coupled with the possibility of ocean basin movements of Pacific bigeye tuna, stock assessments have been carried out on both a Pacifc-wide basis and a two-stock hypothesis: separating the central and western Pacific from the Eastern Pacific Ocean. The two-stock hypothesis conforms to the definition of yellowfin stocks proposed by Suzuki et al. (1978) as *".. an exploitable subset of the population existing in a particular area and having some uniqueness relative to exploitation*.".

The results of the genetic analyses are broadly consistent with SPC tagging experiments on bigeye tuna; most stay close but some go far. Bigeye tagged in locations throughout the western tropical Pacific have displayed eastward movements of up to 4,000 nautical miles (nmi) over periods of one to several years. The widespread distribution of bigeye spawning throughout the tropical Pacific and the greater longevity of bigeye relative to other tropical tunas, such as yellowfin (Hampton et al. 1998), are also consistent with a high *potential* for basin-scale gene flow. However, large-scale movements of bigeye > 1,000 nmi have accounted for only a small percentage of returns, with most recaptures occurring within 200 nmi of release (see section 1.4.1). In addition, a significant degree of site fidelity of bigeye tuna in some locations has been suggested, such as near large land masses, island-rich archipelagos and possibly areas of high FAD densities.

Sibert and Hampton (2003) estimated median lifetime displacements of skipjack and yellowfin tuna in the order of some hundreds of nautical miles, rejecting the notion that these tropical tuna species are widely ranging by nature and "highly migratory". These findings are consistent with the concept of "semi-discrete stocks" of yellowfin in the Pacific as proposed by Suzuki et al. (1978). Bigeye tuna, representing a unique blend of traits between a tropical and temperate tuna species with a protracted life span, may be expected to remain in a general area for extended periods of time and to also range further and have a higher potential for broader displacements throughout their extended life span.

1.6 Stock Assessments

As noted in section 1.5, stock assessments are currently carried out for 1) the entire Pacific bigeye stock; 2) the western and central Pacific regional stock and 3) the eastern Pacific regional stock. Due to the importance of fisheries in both regions and their differential characteristics, the different methodologies used in each stock assessment, and the fact that the each region is managed under a different authority, only the two separate regional stock assessments will be discussed in detail at this time. These regions are illustrated below in Figure 1.

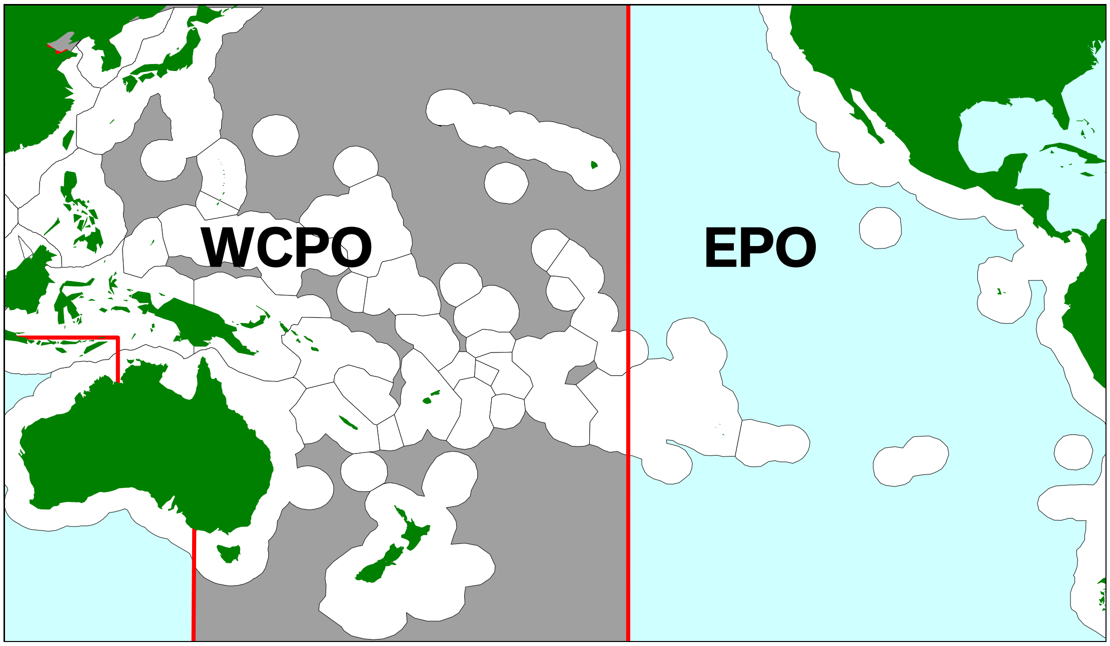

Figure 1. Geographical delineation of the western and central Pacific from the Eastern Pacific Ocean for statistical purposes.

Western and Central Pacific Ocean – Regional Stock Assessment

The most recent stock assessment for WCPO bigeye was presented at the 17th Meeting of the Standing Committee on Tuna and Billfish (Hampton et al. 2004). The assessment uses the stock assessment model and computer software known as MULTIFAN-CL (Fournier et al. 1998). The Pacific-wide distribution of bigeye catch by gear and the statistical areas used in the MULTIFAN-CL analyses are shown in **Figure 2**. The bigeye tuna model is both age (40 age-classes) and spatially structured (5 regions) and the catch, effort, size composition and tagging data used in the model are classified by 17 fisheries and quarterly time periods from 1950 through 2007. The last 4-5 years (depending on the fishery) constitute a projection period in which the last year's fishing effort for each fishery is assumed to continue into the future. The data used in the assessment were the same as those used in 2003, with the exception that pre-1965 Japanese longline size composition data became available recently and were used in the assessment, and an additional year of fishery data (2002 for longline, 2002 for Philippines and Indonesia, 2003 for purse seine) was included.

Five independent analyses were conducted to test the impact of using different standardizing fishing effort in the main longline fisheries, using estimated or assumed values of natural mortality-at-age, and assuming fixed or variable catchability for the main longline fisheries. These analyses are listed below:

- SHBS-MEST Statistical habitat-based standardized effort for LL1−LL5, constant catchability for LL1−LL5.
- SHBS-MEST-LLq Statistical habitat-based standardized effort for LL1−LL5, catchability for LL1−LL5 allowed to vary independently the initial catchability constrained to be equal.
- SHBS-MFIX Statistical habitat-based standardized effort for LL1−LL5, *M*-fixed levels, constant catchability for LL1−LL5.
- GLM-MEST General linear model standardized effort for LL1−LL5, constant catchability for LL1−LL5.
- GLM-MFIX General linear model standardized effort for LL1−LL5, *M*-fixed levels, constant catchability for LL1−LL5.

Recruitment showed an increasing trend from the 1970s onward, while biomass declined through the 1960s and 1970s after which it was relatively stable or declining slightly (**Figures 3** and **4**). The fisheries are estimated to have reduced overall biomass to around 40% of unfished levels by 2003, with impacts more severe in the equatorial region of the WCPO, particularly in the west. On the other hand, the current level of biomass is estimated to be high, around 1.7-2.3 times the equilibrium biomass expected at MSY. Current biomass has remained high because of above average estimated recruitment since about 1980.

The assessment suggested a high probability that current fishing mortality on bigeye tuna in the WCPO is above MSY levels, but that current biomass remains above the MSY level, hence overfishing is occurring but the stock is not yet in an overfished condition.

On the basis of all of the results presented in the assessment, it was concluded that maintenance of current levels of fishing mortality carries a high risk of overfishing. Should recruitment fall to average levels, or if recruitment was over-estimated in the models, current catch levels would result in stock reductions to near and possibly below MSY-based reference points. Reduction of juvenile fishing mortality in the equatorial regions would have significant benefits for both the bigeye tuna stock and the longline fishery.

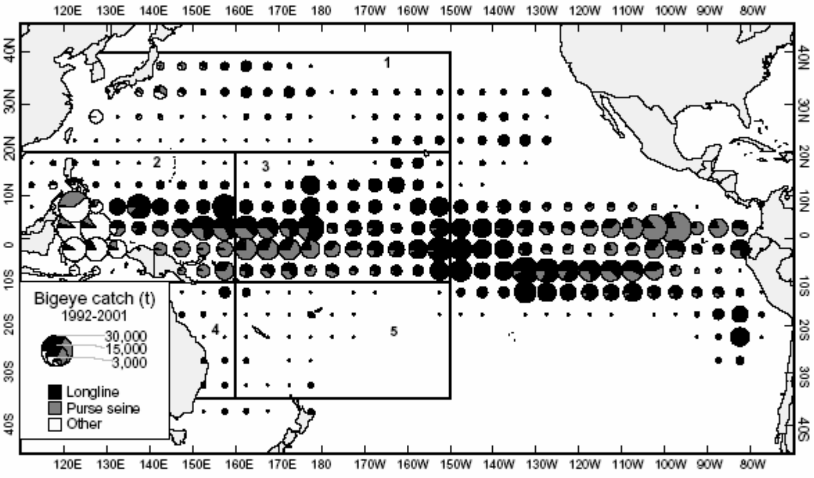

Figure 2. Distribution of bigeye catch (1992 – 2001) with spatial stratification used in the WCPO MULTIFAN-CL analyses (from Hampton et al. 2004)

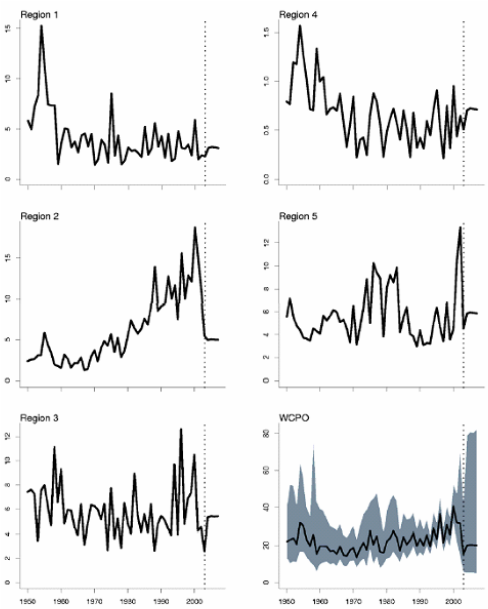

Figure 3. Estimated annual recruitment (millions) by region and for the WCPO (SHBS-MEST model). The shaded area for the WCPO indicates the approximate 95% confidence intervals. The dotted vertical line delineates data-supported model estimates from projections. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort (from Hampton et al. 2004).

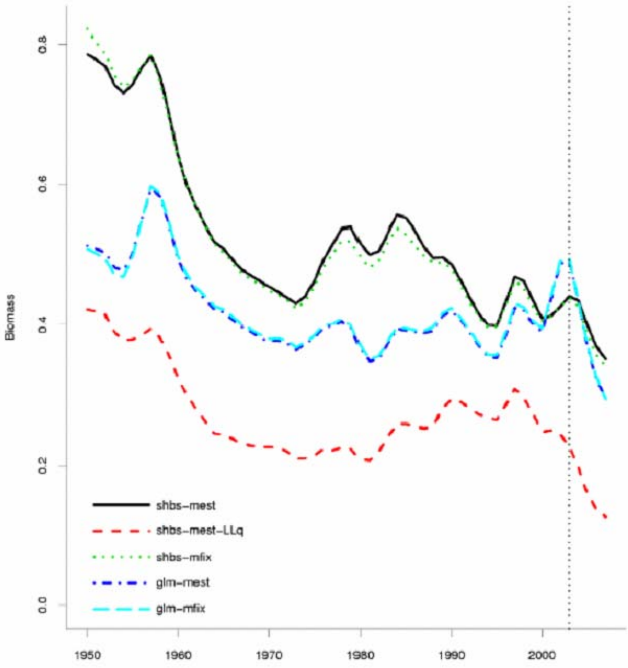

Figure 4. Estimated annual average total biomass (million t) for the WCPO obtained from three separate analyses. The vertical dotted line indicates the point at which population projections are made with assumed levels of effort. (from Hampton et al. 2004)

In summary, the assessment suggests a high probability that current fishing mortality on bigeye tuna is above MSY levels, but that current biomass remains above the MSY level. The results are somewhat more optimistic than those of the 2003 assessment for comparable analyses, although the LLq model produced a more pessimistic result.

On the basis of all of the results presented in the assessment, it appears that maintenance of current levels of fishing mortality carries a high risk of overfishing. Should recruitment fall to average levels, current catch levels would result in stock reductions to near and possibly below MSY-based reference points. Reduction of juvenile fishing mortality in the equatorial regions would have significant benefits for both the bigeye tuna stock and the longline fishery.

The latest MULTIFAN-CL stock assessment for WCPO bigeye tuna concluded that maintenance of current levels of bigeye fishing mortality carries a high risk of overfishing, particularly if predicted recruitment levels fall to average levels. The model predicts an approximate halving of virgin biomass by 1970 followed by a relatively stable or slightly declining condition. The model predicts increasing recruitment since 1980 and above average recruitment in recent years.

Overall, depletion was estimated to have been rapid, particularly since the mid-1980s. However, the predicted stability of total biomass since the 1970s appears to have only been sustained by concurrent above average predicted recruitment. If recruitment levels were to decline to average or below average levels, total biomass would be predicted to decline rapidly. The importance of accurate estimates of recruitment for bigeye and yellowfin can not be over-emphasized.

When examining the impact of various fisheries or groups of fisheries on stock depletion, the model indicated that longline fishing had the greatest impact throughout the entire region. However, the purse seine fishery and the combined Philippines/Indonesian fisheries had the largest impact in Regions 2 and to a lesser extent in Region 3 (**Figure 23**). Regions 2 and 3 are the most important and resource rich areas of the WCPO tropical tuna fishery and account for 90% of estimated bigeye catch in the MULTIFAN-CL model area (Molony 2004a). These areas also comprise the primary bigeye and yellowfin spawning grounds in the WCPO as indicated by SST data and studies on the reproductive biology of the species. All studies are in agreement that the floating object sector of the purse seine fishery is the main contributor to bigeye mortality in the purse seine category. In other words, longline, drifting object purse seine and the Philippine/Indonesian fisheries are the major components of predicted bigeye depletion in the WCPO.

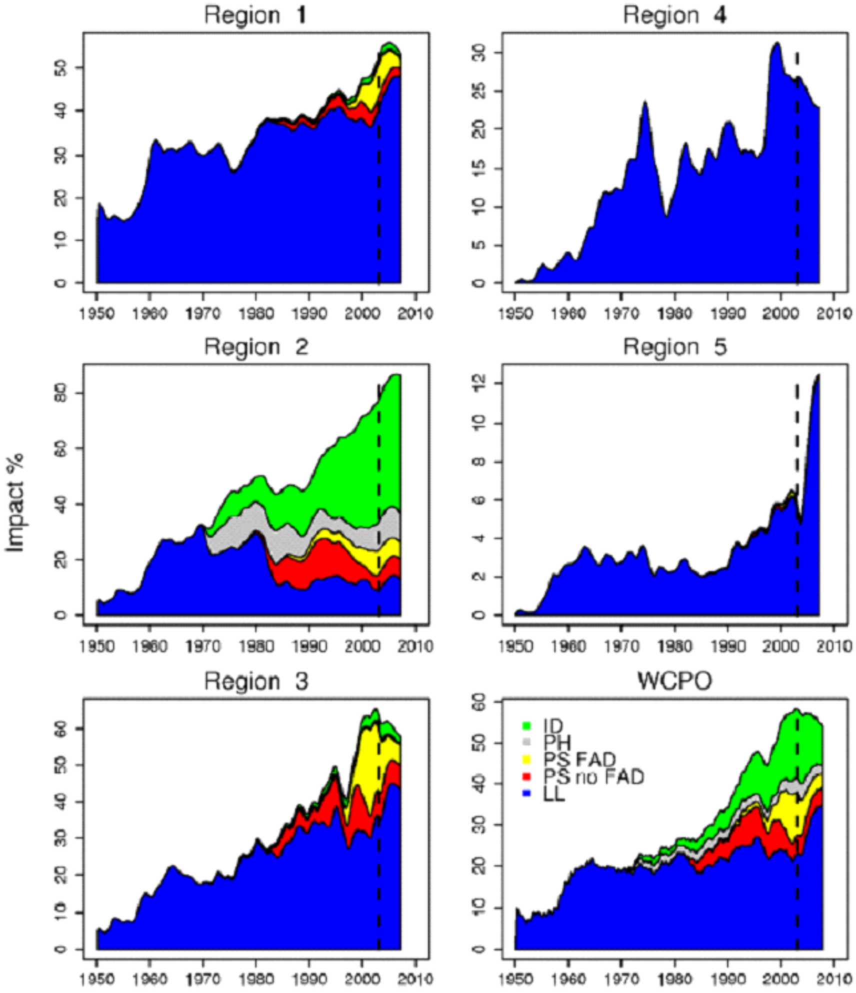

Figure 5. Estimates of reduction in total biomass due to fishing by region and for the WCPO attributed to various fishery groups (SHBS-MEST model). LL = all longline fisheries; ID = Indonesian domestic fishery; PH = Philippines domestic fisheries; PS FAD = purse seine FAD sets; PS non-FAD = purse seine log and school sets (from Hampton et al. 2004)

Purse seine fisheries

Purse seine catches of bigeye in the most recent period have been lead by Japan, PNG and the Philippines. This is most surely a consequence of the relative proportion of floating object sets or for PNG and the Philippine fleets, their reliance on sets made on anchored FADs. The US had very high rates of bigeye catch in the late 1990s coinciding with their increased use of drifting FADs during those years, and may also be a consequence of better reporting relative to other fleets.. However, their bigeye catch has dropped off considerably in recent years as the fleet has widely abandoned the use of drifting FADs.

The distribution of purse seine catches of bigeye by set type are shown in **Figure 6** (Molony 2004a). The increase in use of drifting FADs in the late 1990s and subsequent decline is clearly indicated as is the increase in anchored FAD sets during the same time period.

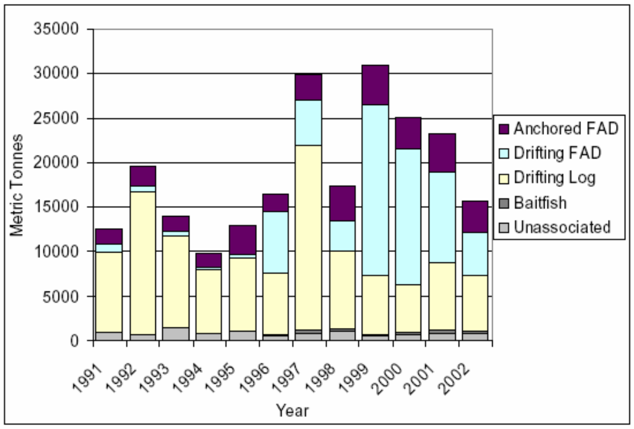

Figure 6. Distribution of purse seine bigeye catch by set type for the WCPO, 1991 – 2002.

The CPUE (t/set) of bigeye tuna by set type is shown in **Figure 7**. Drifting FAD, natural log and anchored FAD sets clearly have the highest bigeye CPUE values. However, the range of values varies somewhat, which is likely a consequence of differential reporting rates between fleets.

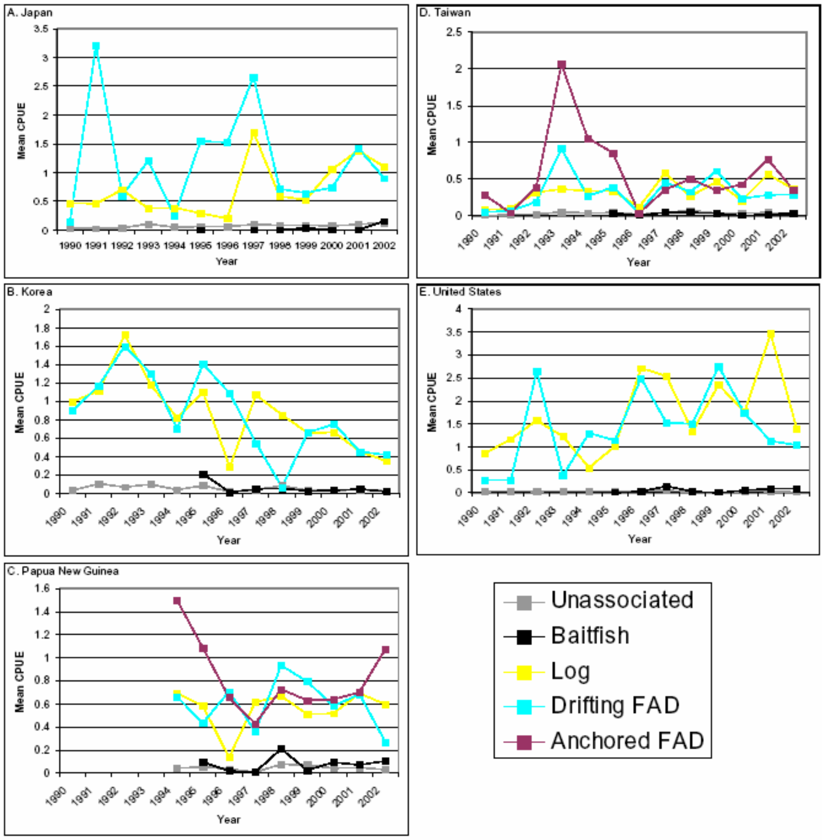

Figure 7. CPUE (t/set) of bigeye tuna by set type in the WCPO.

The spatial distribution of bigeye catches by purse seine in the WCPO confirms the importance of the MULTIFAN-CL areas 2 and 3. These areas are depicted in **Figure 26**. More than 90% of all bigeye catches made from 1990 – 2002 were made in areas 2 and 3 (**Figure 9**). This is simply a reflection of the spatial distribution of purse seine effort in the region.

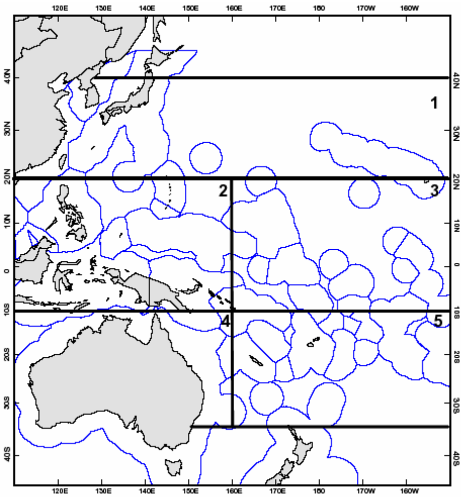

Figure 8. Approximate boundaries of the MULTIFAN-CL areas used in the model analyses.

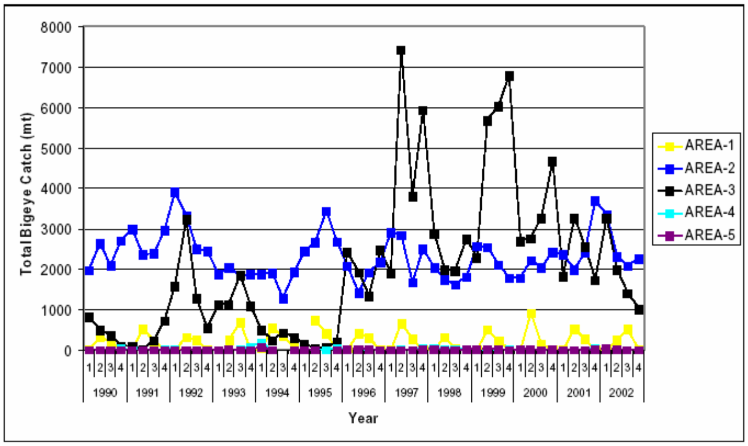

Figure 9. Total purse seine bigeye catch by MULTIFAN-CL region, 1990 – 2002.

The size of bigeye by set type was examined. Generally, the modal size of bigeye taken in all set types was around 50 cm, but bimodal and even trimodal distributions were evident in some years. Smaller bigeye were more common MF Area 2 on logs and FADs while slightly larger bigeye were more available in Area 3 on drifting FADs. Bigeye larger than 100 cm were rare in all set types.

In response to the recommendations of the second meeting of the Scientific Coordinating Group (SCG2) on Sustainable Fisheries Management, the fifth meeting of the Preparatory Conference (PrepCon) requested the Interim Secretariat to prepare a document on management options on how the Commission could respond to sustainability concerns in respect to bigeye and yellowfin tuna. The resulting paper, *Management Options for Bigeye and Yellow Tuna in the Western and Central Pacific Ocean* (Anonymous 2004) was available for discussion during PrepCon VI. Due to a lack of time for substantive discussion, PrepCon VI requested that SCG 3 "advise on the further analyses to support the consideration by PrepCon VII and the first session of the Commission of management options and how these analyses can carried out in a timely and effective manner."

In order to assist SCG 3, the Oceanic Fisheries Programme (OFP) undertook to compile available information from the OFP Regional Tuna Fishery Database relevant to bigeye and yellowfin conservation for WCPO purse seine and longline fisheries. The resulting paper, *Summarized fishery information for evaluating options for bigeye and yellowfin tuna. 1. Review of fleet capacity, catch, and effort of the purse seine fishery in the western* *and central Pacific Ocean, with emphasis on the use of fish aggregation devices (FADs)*, is summarized here (Molony 2004a).

Information was compiled as follows:

- Time series purse seine capacity classified by flag state and national/high seas zones, expressed in terms of number of vessels and/or GRT and/or carrying capacity;
- Time series of purse seine fishing effort (days and sets for purse seine, hooks and sets for longline) classified by flag state and national/high seas zones;
- Time series of bigeye and yellowfin catch for purse seine fisheries classified by flag state and national/high seas zones;
- Estimates of bigeye and yellowfin purse seine catch classified by set type (log, anchored FAD, drifting FAD, free school) by flag state for recent years;
- Estimates of bigeye and yellowfin purse seine catch by area/time strata to identify areas and times of consistently higher catches, if they exist;
- Estimates of recent purse seine effort (in days and number of sets) classified by set type (log, anchored FAD, drifting FAD, free school) by flag state;
- Distribution of bigeye and yellowfin catches by size, classified by area and flag state;

The study examined data back to 1975 referencing the FFA Regional Register of Fishing Vessels for capacity measurements. The US, Korean and Japanese vessels have been relatively stable in size since the early 1980s, while the Taiwanese, Philippine and FSM vessels have nearly doubled in GRT within a five to ten year period from the mid-1980s. Total purse seine capacity estimated for 2002 for all fleets has near quadrupled since the mid-1980s and vessel numbers have also increased. The Taiwanese and Korean fleets in particular have increased significantly while the US fleet has declined.

Langley (2004) examined the main factors that influence bigeye tuna catches in comparison between drifting FADs and natural logs. This study examined detailed observer data resulting from the USMLT Observer Program for US purse seine vessels in the WCPO. This data is considered far more detailed and reliable than unverified logsheet data. The observers routinely collect catch and effort data by set type and are trained in the differentiation between juvenile bigeye and yellowfin and coached in the importance of species specific reporting. Data was filtered to eliminate observers whose species identification skills were judged to be "unreliable". Also, observers are trained to classify logs that have been modified by the addition of man-made materials as a drifting FAD thus standardizing a source of ambiguity in logsheet data. The comparative analysis concentrated on the main area where US vessels make drifting FAD sets and logs sets also occur: from the equator to 10°S and 170°E – 170°W.

Overall, bigeye accounted for a slightly higher proportion of the total tuna catch from drifting FAD sets compared to log sets. The probability of catching bigeye within the area did not vary by latitude or longitude, but the area was relatively small. Virtually all bigeye catches were made in the early morning hours which is expected as this is when floating object and anchored FAD sets normally take place. Of significant interest, there was considerable variability in the probability of catching bigeye between individual vessels. In particular, two vessels had a significantly higher catch rate of bigeye in relation to the rest of the fleet.

There was a strong seasonal trend in bigeye catches note in the data. Bigeye catches were highest in the austral summer (Nov – Feb) and lowest in winter (May – Oct). During the 1996 – 2002 period, when 92% of the bigeye catch was taken. However, the summer period also accounted for 87% of the annual skipjack catch.

Bigeye catch and moon phase were found to be positively correlated around the new moon, with catch rates lowest during full moon. The converse relationship was noted for skipjack CPUE on drifting FADs with low CPUE during the new moon and high CPUE during full moon. Langly (2004) suggests this may be a means to reduce bigeye catch on drifting object sets without reducing skipjack catch during peak periods. He concluded that skipjack, yellowfin and bigeye all favor the same oceanographic conditions when near a FAD, thus making it impossible to completely avoid bigeye bycatch when landing significant amounts of the other two species.

However, restricting fishing on the new moon may be worth investigating. Also, he suggested that gear and vessel attributes and particulars of FAD construction by high bigeye-catching vessels should be investigated to look for common fishing techniques or gear configurations. The most significant hindrance and limitation on this and similar studies was felt to be the lack of accurate, species and set specific data for all fleets and over wide spatial and temporal strata.

Longline fisheries

Total effort in numbers of hooks set increased rapidly in the early years of industrialized fishing, and has experienced a four-fold increase between 1952 – 2002 when 680 million hooks were recorded. Effort in numbers of hooks and sets has been increasing slightly or been relatively stable since 1980 (**Figure 10**). However, there have been significant changes in gear and targeting during the same time period.

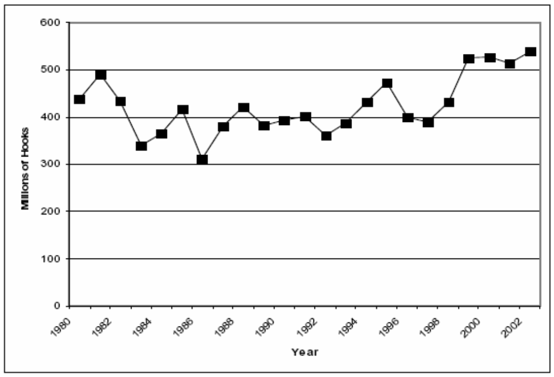

Figure 10. Total number of hooks set by combined WCPO longline fleets (Molony 2004b).

The distant water fleets of Japan, Chinese Taipei and Korea currently account for the majority of longline sets and hooks deployed despite considerable reductions in effort by the Japanese fleet. The FSM received most of the longline effort in recent years while high seas zones recorded increasing effort.

Total longline bigeye catches have increased steadily since the beginning of the fishery and were the highest on record in 2002. However, significant inter-annual fluctuations are apparent with higher catches recorded every 2 – 4 years. The catches are dominated by the Japanese and Korean fleets that target sashimi grade bigeye tuna. Bigeye landings by Japanese vessels represent a five-fold level compared to those of Chinese Taipei, China and the US.

Bigeye CPUE (kgs/100 hooks) has stabilized since the early 1990s. Not surprisingly, the highest CPUEs were recorded from the major bigeye targeting fleets of Japan, Korea and the US. The Marshall Islands EEZ has recorded the highest CPUE for bigeye in the WCPO.

Most of the WCPO bigeye catch is taken from MULTIFAN-CL Area 3 with smaller amounts harvested from Areas 2 and 1 and minor catches from Areas 4 and 5. The total bigeye longline catch from Areas 2 and 3 fluctuate over time but show an increasing trend (**Figure 11**).

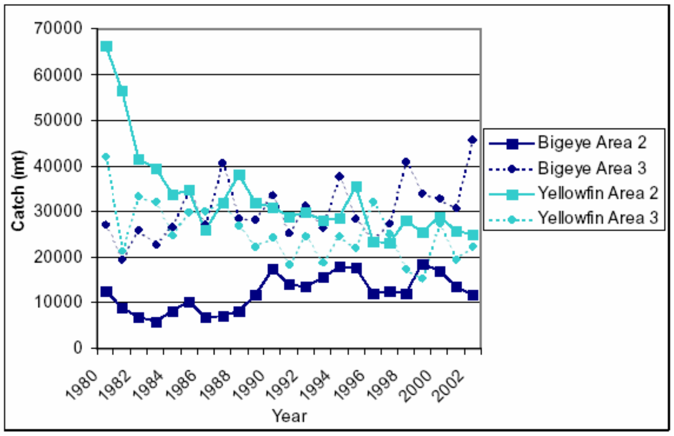

Figure 11. Total catch of bigeye and yellowfin from MULTIFAN-CL Areas 2 and 3 since 1980 (Molony 2004b)

The data examined indicate that most of the bigeye taken by longline in Area 2 are > 110 cm with few fish recorded < 90 cm. Area 3 shows a higher proportion of both smaller and larger fish taken in comparison to Area 3 (**Figure 12**). It should be noted that these data come from observer programs so should more accurately reflect total catch in comparison to logsheet data that normally does not reflect rejection or high-grading by the fishermen.

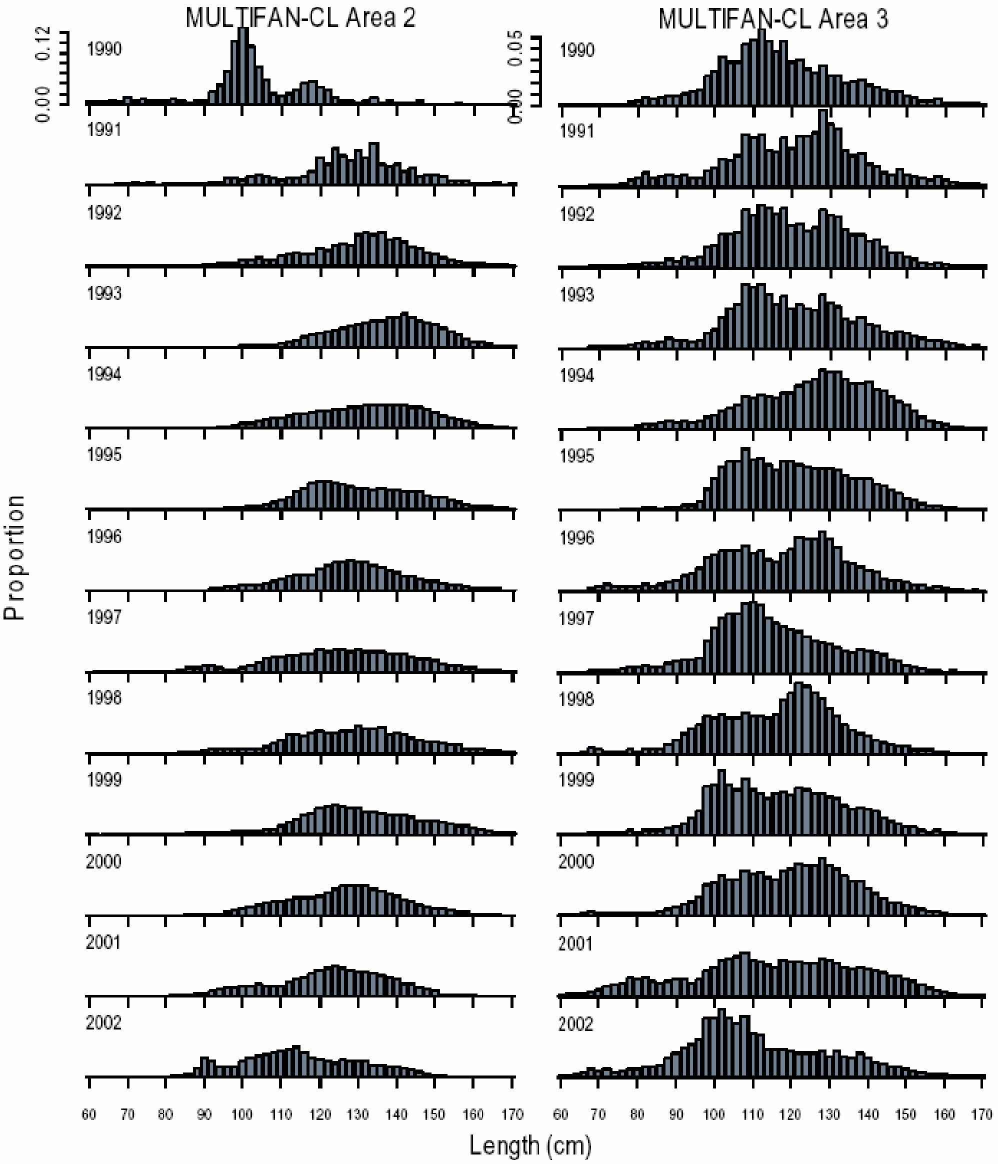

Figure 12. Length frequency of longline caught bigeye in MULTIFAN-CL Areas 2 and 3 from observer data (Molony 2004b)

Following PrepCon VI, the SCG was tasked with defining analyses necessary to address concerns over bigeye and yellowfin stock condition in the WCPO. In order to assist SCG3, the Oceanic Fisheries Programme (OFP) undertook to compile available information from the OFP Regional Tuna Fishery Database relevant to bigeye and yellowfin conservation for WCPO purse seine and longline fisheries. The first paper summarizing information on purse seine fisheries was described in the previous section. The second paper: *Summarized fishery information for evaluating options for bigeye and yellowfin tuna. 2. Review of fleet capacity, catch, and effort of the longline fishery in the western and central Pacific Ocean*, is summarized here (Molony 2004b).

Information was compiled as follows:

- Time series of longline capacity classified by flag state and national/high seas zones, expressed in terms of number of vessels and/or GRT and/or carrying capacity;
- Time series of longline fishing effort (days and sets for purse seine, hooks and sets for longline) classified by flag state and national/high seas zones;
- Time series of bigeye and yellowfin catch for longline and purse seine fisheries classified by flag state and national/high seas zones;
- Distribution of bigeye and yellowfin catches by size, classified by area and flag state;

Information on vessel capacity was obtained from the FFA Regional Register of Fishing Vessels (RR). Unfortunately, the RR generally does not record information on domestic fleets and may not record data for foreign vessels classified as domestic under some joint venture scheme. As a result, Molony (2004b) states, "*the FFA longline register greatly under-estimates the number of longline vessels currently operating in western and central Pacific Oceans (WCPO)*", representing only 23% of the total number of longline vessels operating in the region. Information in the paper is representative mainly of the larger DWFN longline vessels and does not reflect information from many domestic situations.

Also, the RR data for GRT was used to estimate capacity, which is an inconsistent and unverified statistic between fleets due to different ways in which GRT is calculated in different countries. Data on hold capacity was not yet available or has not been collected from enough vessels to utilize. Another significant problem of the RR that is not mentioned is that it may contain a number of entries of the same vessel under different names and registries or for vessels no longer active in the fishery.

Longline data was examined back to 1978, but 27% of RR records had no entry for GRT. Using available and estimated values, it appears that the number of longline vessels rose in the early 1980s, declined in the mid-1980s and have risen since to record highs. Mean GRT values for all fleets have remained relatively stable since the 1980s except for the Chinese fleet whose GRT values have been gradually increasing over time. Most fleets record GRT in the range of 50 – 150 GRT with the exception of the Korean longline fleet that consists of larger vessels to 400 GRT, presumably the large sashimi freezer boats.
Total longline capacity in GRT examined doubled between 1980 and the mid-1990s before stabilizing at a lower level around 1998. However, the actual number of domestic vessels is still increasing and are not captured in the Regional Register database. Japanese distant water effort has declined, primarily due to exclusion from the Australian and New Zealand EEZs while Korean effort has increased significantly.

Eastern Pacific Ocean – Regional Stock Assessment

The IATTC Working Group on Stock Assessment (Maunder and Hoyle 2005) found that their analysis suggests that by the beginning of 2004, the spawning stock biomass of bigeye in the EPO dropped below levels required to produce AMSY, dropping to historic lows in 2007 – 2008 due to recent weak recruitments and high fishing mortality. The average weight of fish in the catch of all fisheries combined has been below the critical weight (about 49.8 kg) since 1993, suggesting that the recent age-specific pattern of fishing mortality is not satisfactory from a yield-per-recruit perspective.

The EPO assessment assumes no stock recruitment relationship and estimates below average recruitment in recent years. The researchers agree that recruitment is highly variable and difficult to predict, strengthening the importance of gaining increased understanding of recruitment processes.

The impact of fisheries on the stock is considered to be highly significant. The analysis suggests that the initial decline in stock biomass was caused by longline fishing but accelerated declines since 2000 are mainly attributable to floating object based purse seine fishing. Under the current model, SBR levels are predicted to remain at very low levels for many years unless fishing mortality is significantly reduced or recruitment increases for several years.

Available information has shown that FADs substantially increase catchability of bigeye in offshore waters where they were formerly unexploited and that the floating object purse seine fishery has caused significant increases in fishing mortality of juvenile bigeye. A significant and more concerning matter is that that the EPO floating object FAD fishery takes a far higher proportion of sub-adult size bigeye compared to the WCPO fishery that harvests mainly smaller juvenile size bigeye. It might be expected that impacts on sub-adults would have a greater impact on potential spawning stock biomass and stock condition.

The authors conclude that the purse-seine fishery on floating objects has the greatest impact on the EPO bigeye tuna stock. Restrictions applied only to a single fishery (e.g. longline or purse-seine), particularly restrictions on longline fisheries, are predicted to be insufficient to allow the stock to rebuild to levels that will support the AMSY. Large (50%) reductions in effort (on bigeye tuna) from the purse-seine fishery will allow the stock to rebuild towards the AMSY level, but restrictions on both longline and purse-seine fisheries are necessary to rebuild the stock to the AMSY level in ten years. Simulations suggest that the restrictions imposed by the 2003 Resolution on the Conservation of Tuna in the EPO will not be sufficient to rebuild the stock.

There have been important changes in the amount of fishing mortality caused by the fisheries that catch bigeye tuna in the EPO. On average, the fishing mortality for bigeye less than about 20 quarters old has increased substantially since 1993, and that on fish more than about 24 quarters old has increased slightly. The increase in average fishing mortality on the younger fish was caused by the expansion of the fisheries that catch bigeye in association with floating objects. The base case assessment suggests that:

- the use of FADs has substantially increased the catchability of bigeye by fisheries that catch tunas associated with floating objects, and

- that bigeye are substantially more catchable when they are associated with floating objects in offshore areas.

Recruitment of bigeye tuna to the fisheries in the EPO is variable, and the mechanisms that explain variation in recruitment have not been identified. Nevertheless, the abundance of bigeye tuna being recruited to the fisheries in the EPO appears to be related to zonal-velocity anomalies at 240 m during the time that these fish are assumed to have hatched. Over the range of spawning biomasses estimated by the base case assessment, the abundance of bigeye recruits appears to be unrelated to the spawning potential of adult females at the time of hatching.

There are two important features in the estimated time series of bigeye recruitment. First, greater-than average recruitments occurred in 1977, 1979, 1982-1983, 1992, 1994, 1995-1997, and during the second quarters of 2001 and 2002. The lower confidence bounds of these estimates were greater than the estimate of virgin recruitment only for 1994, 1997, and the recruitment in 2001 and 2002. Second, aside from these two recruitment pulses in 2001 and 2002, recruitment has been much less than average from the second quarter of 1998 to the end of 2003, and the upper confidence bounds of many of these recruitment estimates are below the virgin recruitment. Evidence for these low recruitments comes from the decreased CPUEs achieved by some of the floating-object fisheries, discard records collected by observers, length-frequency data, and poor environmental conditions for recruitment. The extended sequence of low recruitments is important because, in concert with high levels of fishing mortality, they are likely to produce a sequence of years in which the spawning biomass ratio (the ratio of spawning biomass to that for the unfished stock; SBR) will be considerably below the level that would support the average maximum sustainable yield (AMSY).

The biomass of 1+-year-old bigeye increased during 1980-1984, and reached its peak level of about 586,000 t in 1986. After reaching this peak, the biomass of 1+-year-olds decreased to an historic low of about 156,000 t at the start of 2004. Spawning biomass has generally followed a trend similar to that for the biomass of 1+-year-olds, but lagged by 1-2 years. There is uncertainty in the estimated biomasses of both 1+-year-old bigeye and spawners. Nevertheless, it is apparent that fishing has reduced the total biomass of bigeye present in the EPO. Both are predicted to be at their lowest levels by the end of 2004. There has been an accelerated decline in biomass since the small peak in 2000. Analysis of the impacts attributed to each fishery indicates that the initial decline can be attributed to longline fishing but the most recent declines are mainly attributed to purse-seine fishing. The estimates of recruitment and biomass were not sensitive to the range of alternative parameterizations of the assessment model considered or to the alternative data source included in the assessment. However, in the current assessment, a narrower range of alternative analyses were considered.

At the beginning of January 2004, the spawning biomass of bigeye tuna in the EPO was declining from a recent high level. At that time the SBR was about 0.14, about 32% less than the level that would be expected to produce the AMSY, with lower and upper confidence limits (± 2 standard deviations) of about 0.07 and 0.21. The estimate of the upper confidence bound is only slightly greater than the estimate of SBRAMSY (0.20), suggesting that, at the start of January 2004, the spawning biomass of bigeye in the EPO was less than the level that is required to produce the AMSY. The dramatic change from being above the SBRAMSY level to below it has been predicted by the past three assessments. Estimates of the average SBR projected to occur during 2004-2014 indicate that the SBR is likely to reach an historic low level in 2007-2008, and remain below the level required to produce the AMSY for many years unless fishing mortality is greatly reduced or recruitment is greater than average levels for a number of years. This decline is likely to occur because of the recent weak cohorts and the high estimated levels of fishing mortality.

The average weight of fish in the catch of all fisheries combined has been below the critical weight (about 49.8 kg) since 1993, suggesting that the recent age-specific pattern of fishing mortality is not satisfactory from a yield-per-recruit perspective. The average weight of purse-seine-caught fish is currently about 10 kg, while the average weight of longline fish is about 60 kg. Recent catches are estimated to have been about 26% above the AMSY level. If fishing mortality is proportional to fishing effort, and the current patterns of age-specific selectivity are maintained, the level of fishing effort that is estimated to produce AMSY is about 62% of the current level of effort. Decreasing the effort to 62% of its present level would increase the long-term average yield by 8% and would increase the spawning potential of the stock by about 156%.

The AMSY of bigeye in the EPO could be maximized if the age-specific selectivity pattern were similar to that for the longline fishery that operates south of 15°N because it catches individuals close to the critical size. All analyses considered suggest that at the start of 2004 the spawning biomass was below the level that would be present if the stock were producing the AMSY. AMSY and the fishing mortality (F) multiplier are sensitive to how the assessment model is parameterized, the data that are included in the assessment, and the periods assumed to represent average fishing mortality, but under all scenarios considered, fishing mortality is well above the level that will produce the AMSY. Presently the purse-seine fishery on floating objects has the greatest impact on the bigeye tuna stock. Restrictions that apply only to a single fishery (e.g. longline or purse-seine), particularly restrictions on longline fisheries, are predicted to be insufficient to allow the stock to rebuild to levels that will support the AMSY. Large (50%) reductions in effort (on bigeye tuna) from the purse-seine fishery will allow the stock to rebuild towards the AMSY level, but restrictions on both longline and purse-seine fisheries are necessary to rebuild the stock to the AMSY level in ten years. Simulations suggest that the restrictions imposed by the 2003 Resolution on the Conservation of Tuna in the EPO will not be sufficient to rebuild the stock. Projections indicate that, if fishing mortality rates continue at their recent (2002 and 2003) levels, longline catches and SBR will decrease to extremely low levels. As the base case does not include a stock recruitment relationship, recruitment will not decline, so purse-seine catches are predicted to decline only slightly from recent levels under this model.

5.0 REFERENCES

Adam, M.S., J. Sibert, D. Itano, and K. Holland. 2003. Dynamics of bigeye (*Thunnus obesus*) and yellowfin (*T. albacares*) tuna in Hawaii's pelagic fisheries: analysis of tagging data with a bulk transfer model incorporating size-specific attrition. Fish. Bull. 101:215-228.

Alverson F.G., Peterson C.L. 1963. Synopsis of the biological data on bigeye tuna Parathunnus sibi (Temminck and Schlegel) 1844. FAO Fish Rep 6(2):482–514.

Anonymous. 2004. Management Options for Bigeye and Yellow Tuna in the Western and Central Pacific Ocean. WCPFC/PrepCon/WP 24, PrepCon VI, Bali, Indonesia, 19 – 23 April 2004. 26 pp.

Bahar S. 1985. Study on deep tuna long line for bigeye tuna (Thunnus obesus) fishing. A study on the use of deep tuna longline by employing various number of branchlines per basket to catch bigeye tuna (Thunnus obesus) in Banda Sea. Mar Fish Res Rep (32):39–51.

Bahar S. 1987. A study on the deep longlining for bigeye tuna (Thunnus obesus) in the waters west off Sumatra. J Mar Fish Res 40: 51–63.

Blackburn M. 1965. Oceanography and ecology of tunas. Oceanogr Mar Biol Annu Rev (3):299–322.

Blackburn M. 1969. Conditions related to upwelling which determine distribution of tropical tunas off western Baja California. Fish Bull US 68:147–76.

Block, B.A., E.D. Stevens [eds.] 2001. Tuna: Physiology, Ecology and Evolution. FISH PHYSIOLOGY, Volume 19, 468 pp. Academic Press.

Blunt CEJr. 1960. Observations on the food habit of longline caught bigeye and yellowfin tuna from the tropical eastern Pacific 1956–63. Calif Fish and Game 46(1):69–80.

Boehlert GW, Mundy BC. 1994. Vertical and onshore-offshore distributional patterns of tuna larvae in relation to physical habitat features. Mar Ecol Prog Ser 107:1–13.

Boggs CH. 1992. Depth, capture time, and hooked longevity of longline-caught pelagic fish—timing bites of fish with chips. Fish Bull 90(4):642–58.

Boggs, C.H. and R.Y. Ito. 1993. Hawaii's pelagic fisheries. *Mar. Fish. Rev*. 55 (2):69-82.

Brill RW. 1994. A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments. Fish Oceanogr 3(3):204–16.

Calkins TP. 1980. Synopsis of biological data on the bigeye tuna, Thunnus obesus (Lowe, 1839), in the Pacific Ocean. In: Bayliff WH, editor. Synopses of biological data on eight species of scombrids. Inter-American Tropical Tuna Commission. p 213–60. Special report nr 2.

Collette BB, Nauen CE. 1983. An annotated and illustrated catalogue of the tunas, mackerels, bonitos and related species known to date. FAO Fish Synopsis, Volume 2, nr 125. Rome: Food and Agriculture Organization. 137 p.

Dagorn, L., Bach P., and E. Josse. 2000. Movement patterns of large bigeye (Thunnus obesus) in the open ocean, determined using ultrasonic telemetry. Mar. Biol. (2000) 136: 361-371.

Farley, J.H, N.P. Clear, B. Leroy, T.L.O. Davis, and G. McPherson. 2003. Age and growth of bigeye (Thunnus obesus) from the eastern and western AFZ. Fisheries Research & Development Corporation Final Report No. 2000/100.

Fonteneau A. 1991. Sea mounts and tuna in the tropical eastern Atlantic. Aquat Living Resour 4(1):13–25.

Fritsches, K.A. and E.J. Warrant. 2001. New discoveries in visual performance of pelagic fishers. PFRP Newsletter, Vol. 6, No. 3., 1-3.

Fournier, D.A., Hampton, J., and Sibert, J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Can. J. Fish. Aquat. Sci.* 55: 2105−2116.

Goldberg SR, Herring-Dyal H. 1981. Histological gonad analyses of late summer-early winter collections of bigeye tuna, Thunnus obesus, and yellowfin tuna, Thunnus albacares, from the northwest Atlantic and the Gulf of Mexico. NOAA tech memo.11 p.

Gong Y, Lee JU, Kim YS. 1987. Fishing efficiency of Korean deep longline gear and vertical distribution of tunas in the Indian Ocean. In: Collective volume of working documents. Expert Consultation of Stock Assessment of Tunas in the Indian Ocean; 1986 Dec 4–8; Colombo. p 367–72.

Gong Y, Lee JUK, Kim YS, Yang WS. 1989. Fishing efficiency of Korean regular and deep longline gears and vertical distribution of tunas in the Indian Ocean. Bull Korean Fish Soc 22(2):86–94.

Graves JE, Simovich MA, Schaefer KM. 1988. Electrophoretic identification of early juvenile yellowfin tuna, Thunnus albacares. Fish Bull 86(4):835–8.

Grewe, P.M., and J. Hampton. 1998. An assessment of bigeye (Thunnus obesus) population structure in the Pacific Ocean, based on mitochondrial DNA and DNA microsatellite analysis. Report for the Forum Fisheries Agency and Pelagic Fisheries Research Program, CSIRO Marine Research, Hobart, Australia.

Grubbs, R.D., Holland, K., and D. Itano. 2002. Comparative trophic ecology of yellowfin and bigeye tuna associated with natural and man-made aggregation sites in Hawaiian waters. Fifteenth Meeting of the Standing Committee on Tuna and Billfish; 1998 May 28–June 6; Honolulu

Hallier, J-P, and A. Delgado de Molina. 2000. Baitboat as a tuna aggregating device. Tuna Fishing and Fish Aggregating Devices, October 15-19,1999, Martinique. J-Y Le Gall, P. Cayre, M. Taquet, *eds*. Session 5 – Biology and behaviour of pelagic fish aggregations. 553-578.

Hampton J., and Leroy B. 1988. Note on preliminary estimates of bigeye growth from presumed daily increments on otoliths and tagging data. Eleventh meeting of the Standing Committee on Tuna and Billfish; 1998 May 28–June 6; Honolulu, HI. 3 p. Working paper nr 18.

Hampton, J., K. Bigelow, and M. Labelle. 1998b. 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 Secretariat of the Pacific Community, Noumea, New Caledonia.

Hampton, J., and J. Gunn. 1998. Exploitation and movements of yellowfin tuna (Thunnus albacares) and bigeye tuna (T. obesus) tagged in the north-western Coral Sea. Mar. Freshwater Res., 1998, 49, 475-89.

Hampton J, Bailey K. 1993. Fishing for tunas associated with floating objects: a review of the western Pacific fishery. Noumea, New Caledonia: South Pacific Commission. 48 p. Tuna and Billfish Assessment Programme technical report nr. 31.

Hampton, J., Bigelow, K., and M. Labelle. 1998. 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 further research. Oceanic Fisheries Programme, Technical Report No. 36. 46 pp. Secretariat of the Pacific Community, Noumea, New Caledonia.

Hampton, W.J., A. Langley, P. Kleiber, and K. Hiramatsu. 2004. Stock assessment of bigeye tuna in the western and central Pacific Ocean. 17th Meeting of the Standing Committee on Tuna and Billfish, 9-18 August 2004, Majuro, Marshall Islands. Working Paper SA-2.

Hampton, J., and P. Williams. 2005. A description of tag-recapture data for bigeye tuna in the western and central Pacific Ocean. ICCAT SCRS/2004/058. Col. Vol. Sci. Pap. ICCAT, 57(2).

Hanamoto E. 1974. Fishery oceanography of bigeye tuna. Part 1, Depth of capture by tuna longline gear in the eastern tropical Pacific Ocean. La mer 12 (3):10–8.

Hanamoto E. 1975. Fishery oceanography of bigeye tuna. Part 2, Thermocline and dissolved oxygen content in relation to tuna longline fishing grounds in the eastern tropical Pacific Ocean. La mer 13 (2):58–79.

Hanamoto E. 1976. Swimming depth of bigeye tuna. Bull Jap Soc Fish Oceanogr 29:41–4.

Hanamoto E. 1983. Vertical distribution of bigeye tuna. Bull Jap Soc Sci Fish Oceanogr 44:126–7.

Hanamoto, E. 1986. Distribution of bigeye tuna catch in the Pacific Ocean. Bull Jap Soc Fish Oceanogr 51:9–15.

Hanamoto E. 1987. Effect of oceanographic environment on bigeye tuna distribution. Bull Jap Soc Fish Oceanogr 51 (3):203–16.

Hisada K. 1973. Investigations on tuna handline fishing ground and some biological observations on yellowfin and bigeye tunas caught in the north-western coral sea. Far Seas Fish Res Lab Bull 8:35–69.

Hisada K. 1979. Relationship between water temperature and maturity status of bigeye tuna caught by longline in the central and eastern Pacific ocean. Far Seas Fish Res Lab Bull 17:159–75.

Holland KN, Brill RW, Chang RKC. 1990. Horizontal and vertical movements of yellowfin and bigeye tuna associated with fish aggregating devices. Fish Bull 88(3):493–507.

Holland KN, Brill RW, Chang RKC. 1992. Physiological and behavioral thermoregulation in bigeye tuna (Thunnus obesus). Nature 358(6385):410–2.

Holland, K.N., and J.R. Sibert. 1994. Physiological thermoregulation in bigeye tuna, Thunnus obesus. Env. Biol. of Fishes 40:319-217.

Honma M, Warashina Y, Suzuki Z. 1973. Identification of young yellowfin and bigeye tunas in the western Pacific Ocean. Examination of practical standards based on external characteristics and the reliability in field survey. Far Seas Fish Res Lab Bull 8:1–23.

[IATTC] Inter-American Tropical Tuna Commission. 1998. Proceedings of the First World Meeting on Bigeye Tuna. IATTC Special Report 9. 292 pp. [R.B. Deriso, W.H. Bayliff, and N.J. Webb *eds*].

ICCAT. 2005. Report of the Second World Meeting on Bigeye Tuna (Madrid, Spain – March 10-13, 2004). Col. Vol. Sci. Pap. ICCAT, 57(2). 15 pp.

Itano DG. 1998a. Hawaii offshore handline fishery: a seamount fishery for juvenile bigeye tuna. Eleventh meeting of the Standing Committee on Tuna and Billfish; 1998 May 28–June 6; Honolulu, HI. 13 p. Working paper nr 44.

Itano DG. 1998b. Hawaii tuna tagging project. In: Deriso RB, Bayliff WH, Webb NJ, editors. Proceedings of the First World Meeting on Bigeye Tuna. La Jolla, CA: Inter-American Tropical Tuna Commission. p 235–7. Special report nr 10.

Itano, D.G. 2000. The reproductive biology of yellowfin tuna (*Thunnus albacares*) in Hawaiian waters and the western tropical Pacific Ocean: Project summary. Pelagic Fisheries Research Program, Joint Institute of Marine and Atmospheric Research, University of Hawaii. SOEST 00-01, JIMAR Contribution 00-328. 69 pp.

Itano D.G., and K. Bailey. 1991. Regional Tuna Tagging Project Activity Report – Australia 1: 12 October – 22 November 1991. Tuna and Billfish Assessment Programme, South Pacific Commission Tuna and Billfish Assessment Programme, RTTP Activity Report No. 16. South Pacific Commission, Noumea, New Caledonia. 30 pp.

Itano, D.G. and K.N. Holland. 2000. Movement and vulnerability of bigeye (Thunnus obesus) and yellowfin tuna (Thunnus albacares) in relation to FADs and natural aggregation points. Aquat. Living Resour. 13(2000) 213-223.

Iverson ES. 1955. Size frequencies and growth of central and western Pacific bigeye tuna. US Fish and Wildlife Service special scientific report on fish nr 162.

Juhl R. 1955. Notes on the feeding habits of subsurface yellowfin and bigeye tunas of the eastern tropical Pacific Ocean. Calif Fish Game 41(1):99–101.

Josse E. and A. Bertrand. 2000. In situ acoustic target strength measurements of tuna associated with fish aggregating device. ICES Journal of Marine Science, 57:911-918.

Josse E., Dagorn L., and A. Bertrand. 2000. Typology and behaviour of tuna aggregations around fish aggregating devices from acoustic surveys in French Polynesia. Aquat. Living Resour. 13(2000) 183-192.

Kikawa S. 1953. Observations on the spawning of bigeye tuna (Parathunnus mebachi, Kishinouye) near South Marshall Islands. Con Nankai Reg Fish Res Lab 1.

Kikawa S. 1957. The concentrated spawning areas of bigeye tuna in the western Pacific. Rep Nankai Reg Fish Res Lab 5:145–157.

Kikawa S. 1961. The group maturity of bigeye tuna Parathunnus mebachi in the spawning area of Pacific. Rep Nankai Reg Fish Res Lab 13:35–46.

Kikawa S. 1962. Studies on the spawning activity of Pacific tunas, Parathunnus mebachi and Neothunnus macropterus, by gonad index examination. p 43–56. Nankai Reg Fish Res Lab occassional report nr 1.

Kikawa S. 1966. The distribution of maturing bigeye and yellowfin and an evaluation of their spawning potential in different areas in the tuna longline grounds in the Pacific. Nankai Reg Fish Res Lab 23:131–208.

King JE, Ikehara II. 1956. Notes on feeding habits of subsurface yellowfin and bigeye tunas of eastern Pacific Ocean. Fish Bull US Fish Wildlife Serv 57:108.

Kornilova GN.1980. Feeding of yellowfin tuna, Thunnus albacares, and bigeye tuna, Thunnus obesus, in the equatorial zone of Indian Ocean. J Icthyol 20(6):111–9.

Kume S. 1962. A note on the artificial fertilisation of bigeye tuna, Parathunnus mebachi (Kishinouye). Rep Nankai Reg Fish Res Lab 15:79–84.

Kume S. 1963. Ecological studies of bigeye. Part 1, On the distribution of the bigeye tuna in the Pacific. Rep Nankai Reg Fish Res Lab 17:121–31.

Kume S. 1967. Distribution and migration of bigeye tuna in the Pacific ocean. Rep Nankai Reg Fish Res Lab 25:75–80.

Kume S. 1969a. Ecological studies of bigeye tuna. Part 5, A critical review of its distribution, size composition and stock structure of bigeye tuna in the North Pacific Ocean (north of 16°N). Far Seas Fish Res Lab Bull 1:57–75

Kume S. 1969b. Ecological studies of bigeye tuna. Part 6, A review of distribution and size composition in the equatorial and South Pacific Ocean. Far Seas Fish Res Lab Bull 1:77–98.

Kume S, Joseph J. 1966. Size composition, growth and sexual maturity of bigeye tuna, Thunnus obesus (Lowe), from Japanese longline fishery in eastern Pacific Ocean. Inter-Amer Trop Tuna Comm Bull 11(2):45–99.

Kume S, Shiohama T. 1965. Ecological studies on bigeye tuna. Part 2, Distribution and size composition of bigeye tuna in the equatorial Pacific. Rep Nankai Reg Fish Res Lab 22:71–83.

Laevastu T, Rosa H. 1963. Distribution and relative abundance of tunas in relation to their environment. FAO Fish Rep (6):1835–51.

Langley, A. 2004. An analysis of the main factors influencing the catch of bigeye tuna in purse seine drifting FAD sets and a comparison with log sets. 17th Meeting of the Standing Committee on Tuna and Billfish, 9-18 August 2004, Majuro, Marshall Islands. Working Paper FTWG-4. 20 pp.

Lawson, T. 2004. Proposal for monitoring the catches of highly migratory species in the Philippines and the Pacific Ocean waters of Indonesia – Prepared for the Preparatory Conference for the Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific. Information Paper INF-SWG-3. 46 pp.

Lehodey, P., Hampton J., and B. Leroy. 1999. Preliminary results on age and growth of bigeye tuna (Thunnus obesus) from the western and central Pacific Ocean as indicated by daily growth increments and tagging data. 12th Meeting of the Standing Committee on Tuna and Billfish, 16-23 June 1999, Tahiti. Working Paper BET-2. 18 pp.

Lowe, T.E., Brill, R.W., and K.L. Cousins. 2000. Blood oxygen-binding characteristics of bigeye tuna (Thunnus obesus), a high-energy-demand teleost that is tolerant of low ambient oxygen. Mar. Biol. (2000) 136: 1087-1098.

Magnuson JJ. 1963. Tuna behaviour and physiology: a review. FAO Fish Rep (6):1057–66.

Marcille J, Stequert B. 1976. Croises des jeunes albacores Thunnes albacares et patudo, Thunnus obesus de la cote nord-ouest de Madagascar. Cah ORSTOM (Oceanogr) 14(2):152–62.

Martinez FZ, Bohm SG. 1983. Biological synopsis of Thunnus obesus (Lowe) with special reference to the eastern Pacific Ocean. Regional seminar on fish resources and their fisheries in the southeast Pacific. Rev Com Perm Pac Sur 13:103–23.

Matsumoto WM. 1961. Identification of larvae of four species of tuna from the Indo-Pacific region. Part 1, The Carlsberg Foundation's oceanic expedition round the world 1928–30 and previous Dana expeditions. Dana Rep 5:16.

Matsumoto T. 1998. Preliminary analyses of age and growth of bigeye tuna (Thunnus obesus) in the eastern Pacific Ocean based on otolith increments. In: Deriso RB, Bayliff WH, Webb NJ, editors. Proceedings of the First World Meeting on Bigeye Tuna. La Jolla, CA: Inter-American Tropical Tuna Commission. p 238–42. Special report nr 10.

Matsumoto WA, Alhstrom EH, Jones S, Klawe WJ, Richards WJ, Ueyanagi S. 1972. On the clarification of larval tuna identification, particularly in the genus Thunnus. US Fish Bull 70(1):1–12, figs 1–6.

Maunder MN, and SD Hoyle. 2005. Status of Bigeye Tuna in the Eastern Pacific Ocean in 2004 and Outlook for 2005. IATTC Working Group on Stock Assessment Document SAR-06-07B.

McPherson GR. 1988. Reproductive biology of yellowfin and bigeye tuna in the eastern Australian Fishing Zone with special reference to the north-western Coral Sea. Queensland, Australia: Dept Prim Ind Res Branch. 80 p. Technical report nr FRB 88/10.

McPherson GR. 1991a. Reproductive biology of yellowfin and bigeye tuna in the eastern Australian Fishing Zone, with special reference to the north western Coral Sea. Aust J.Mar Freshwater Res 42:465–77.

McPherson GR. 1991b. A possible mechanism for the aggregation of yellowfin and bigeye tuna in the north-western Coral Sea. Queensland, Australia: Dept Prim Ind Res Branch. 11 p. Information series nr Q191013.

Miller JM. 1979. Nearshore abundance of tuna (Pisces: Scombridae) larvae in the Hawaiian Islands. Bull Mar Sci US 29:19–26.

Mimura K et al. 1963. Synopsis on the biology of bigeye tuna, Parathunnus mebachi Kishinouye 1923 (Indian Ocean). p 350–79. In: Rosa H Jr, editor. Proceedings of the World Scientific Meeting on the Biology of Tunas and Related Species;Rome: Food and Agriculture Organization of the United Nations. 2272 p. FAO fish report nr 6(2).

Miyabe N. 1994. A review of the biology and fisheries for bigeye tuna, Thunnus obesus, in the Pacific Ocean. In: Shomura RS, Majkowski J, Langi S, editors. Interactions of Pacific tuna fisheries. Proceedings of the First FAO Expert Consultation on Interactions of Pacific Tuna Fisheries; 1991 Dec 3–11; Noumea, New Caledonia. Rome: FAO. Volume 2; p 207–43.

Miyabe, N. 2001. Recent sex ratio data of the bigeye tuna caught by the Japanese longline fishery in the Pacific Ocean. NRIFSF Internal Data, 12 pp. NRIFSF, Shimizu, Japan.

Miyabe N, Bayliff WH. 1998. A review of the biology and fisheries for bigeye tuna, Thunnus obesus, in the Pacific Ocean. In: Deriso RB, Bayliff WH , Webb NJ, editors. Proceedings of the First World Meeting on Bigeye Tuna. La Jolla, CA: Inter-American Tropical Tuna Commission. p 129-170. Special report nr 9.

Mohri, M. 1998. Correlation between sexual maturity of bigeye tuna and water temperatura in the Indian Ocean. Journal of the National Fisheries University. 46(4) 175-181.

Mohri M, Hanamoto E, Takeuchi S. 1996. Optimum water temperatures for bigeye tuna in the Indian Ocean as seen from tuna longline catches. Nippon Suisan Gakkaishi 62(5):761–4.

Molony, B. 2004a. Summarized fishery information for evaluating options for bigeye and yellowfin tuna. 1. Review of fleet capacity, catch, and effort of the purse seine fishery in the western and central Pacific Ocean, with emphais on the use of fish aggregation devices (FADs). 17th Meeting of the Standing Committee on Tuna and Billfish, 9-18 August 2004, Majuro, Marshall Islands. Working Paper GEN-2. 49 pp.

Molony, B. 2004b. Summarized fishery information for evaluating options for bigeye and yellowfin tuna. 1. Review of fleet capacity, catch, and effort of the longline fishery in the western and central Pacific Ocean, 17th Meeting of the Standing Committee on Tuna and Billfish, 9-18 August 2004, Majuro, Marshall Islands. Working Paper GEN-2. 31 pp.

Musyl M.K., Brill R.W., Boggs C.H., Curran D.S., Kazama T.K., and M.P. Seki. 2003. Vertical movements of bigeye tuna (Thunnus obesus) associated with islands, buoys, and seamounts near the main Hawaiian Islands from archival data. Fish. Oceanogr. 12:3, 152-169.

Nakamura EL. 1969. A review of field observations on tuna behavior. FAO Fish Rep 62(2):59–68.

Nakamura H, Yamanaka H. 1959. Relation between the distribution of tunas and the ocean structure. Oce Soc Jap J 15:143–9.

Nikaido H, Miyabe N, Ueyanagi S. 1991. Spawning time and frequency of bigeye tuna, Thunnus obesus. Bull Nat Res Inst Far Seas Fish 28:47–73.

Nishi T. 1990. The hourly variations of the depth of hooks and the hooking depth of yellowfin tuna (Thunnus albacares) and bigeye tuna (Thunnus obesus) of tuna longline in the eastern region of the Indian Ocean. Mem Fac Fish Kagoshima Univ (Kagoshimadai Suisangakabu Kiyo) 39:81–98.

Nishikawa Y, Kikawa S, Honma M, Ueyanagi S. 1978. Distribution atlas of larval tunas, billfishes and related species. Results of larval surveys by R/V Shunyo Maru and R/V Shoyo Maru, 1956–75. Far Seas Fish Res Lab, S Series (9):99 p.

Nishikawa Y, Rimmer DW. 1987. Identification of the larval tunas, billfishes and other Scombroid fishes (Suborder Scombroidei): an illustrated buide. CSIRO Marine Laboratories. 20 p. Report nr 168.

Olson, R.J., and C.H. Boggs. 1986. Apex predation by yellowfin tuna (Thunnus albacares): Independent estimates from gastric evacuation and stomach contents, bioenergetics, and cesium concentrations. *Can. J. Fish. Aquat. Sci*. 43, 1760-1775.

Pallares P, Pereira J, Miyabe N, Fonteneau A. 1998. Atlantic bigeye tuna: overview of present knowledge (November 1996). In: Deriso RB, Bayliff WH, Webb NJ, editors. Proceedings of the First World Meeting on Bigeye Tuna. La Jolla, CA: Inter-American Tropical Tuna Commission. p 20–80. Special report nr 9.

Peterson CL, Bayliff WH. 1985. Size composition, growth and sexual maturity of bigeye tuna Thunnus obesus (Lowe), from the Japanese longline fishery in the eastern Pacific Ocean. Bull IATTC 11:45–100.

Richards WJ, Klawe WL. 1972. Indexed bibliography of the eggs and young of tunas and other scombrids (Pisces, Scombridae), 1880–1970. NOAA. 107 p. Tech report nr NMFS SSRF 652.

Rizutto, J. 1983. Fishing Hawaii Style, Volume 1, A Guide to Saltwater Angling. Fishing Hawaiian Style, Ltd. Honolulu, Hawaii. 146 pp.

Saito S. 1975. On the depth of capture of bigeye tuna by further improved vertical longline in the tropical Pacific. Bull Jap Soc Sci Fish 41(8):831–41.

Sakagawa GT, Coan AL, Bartoo NW. 1987. Patterns in longline fishery data and catches of bigeye tuna, Thunnus obesus. Mar Fish Rev 49 (4):57–66.

Schaefer, K. M. 1996. Spawning time, frequency, and batch fecundity of yellowfin tuna, *Thunnus albacares*, near Clipperton Atoll in the eastern Pacific Ocean. *Fish. Bull.* 94:98-112.

Schaefer, K. M. 1998. Reproductive biology of yellowfin tuna (*Thunnus albacares*) in the Eastern Pacific Ocean. *Inter-Am. Trop. Tuna Comm., Bull.* 21(5), 205-272.

Schaefer, K.M., and D.W. Fuller. 2002. Movements, behavior, and habitat selection of bigeye tuna (*Thunnus obesus*) in the eastern equatorial Pacific, ascertained through archival tags. Fish. Bull. 100(4):765-788.

Schaefer, K.M., and D.W. Fuller. 2005. Behavior of bigeye (*Thunnus obesus*) and skipjack (*Katsuwonus pelamis*) tunas within aggregations associated with floating objects in the equatorial eastern Pacific. Mar, Biol., 146 (4): 781-792.

Sharp GD. 1978. Behavioral and physiological properties of tunas and their effects on vulnerability to fishing gear. In: Sharp GD, Dizon AE, editors. The physiological ecology of tunas. New York: Academic Pr. p 379–449.

Sharp GD, Dizon AE, editors. 1978. Physiological ecology of tunas. New York: Academic Pr. 485 p.

Shimamura T, Soeda H. 1981. On the catch by deep-layer tuna fishing. Bull Jap Soc Sci Fish 47(12):1559–65.

Sibert, J.R., M.K. Musyl, and R.W. Brill. 2003. Horizontal movements of bigeye tuna (Thunnus obesus) near Hawaii determined by Kalman filter analysis of archival tagging data. Fish. Oceanogr. 12:3, 141-151.

Sibert, J., Hampton, J., 2003. Mobility of tropical tunas and the implications for fisheries management. *Marine Policy* 27 (2003) 87-05.

Strasburg EW. 1960. Estimates of larval tuna abundance in the central Pacific. Fish Bull US Fish Wildl Serv 60(167):231–55.

Stequert, B., and F. Conand. 2004. Age and growth of bigeye tuna (Thunnus obesus) in the western Indian Ocean. *Cybium* 2004, 28(2): 163-170.

Strobberup KA, Marsac F, Anganuzzi AA. 1998. A review of the biology of bigeye tuna, Thunnus obesus, and fisheries for this species in the Indian Ocean. In: Deriso RB, Bayliff WH, Webb NJ, editors. Proceedings of the First World Meeting on Bigeye Tuna; La Jolla, CA: Inter-American Tropical Tuna Commission. p 81–128. Special report nr 9.

Stretta JM, Petit M. 1989. In: Le Gall JY, editor. Physiological aspects of thermoecology in tunas. 3.2, Catchability/surface temperature relationship. Satellite geosensing and oceanic fisheries: teledetection. p 49–50. FAO document technlogique peches nr 302.

Suda A, Kume S, Shiohama T. 1969. An indicative note on a role of permanent thermocline as a factor controlling the longline fishing ground for bigeye tuna. Bull Far Seas Fish Res Lab 1:99–114.

Sun, C-L, Chu S-L, and S-Z Yeh. 1999. Note on the reproduction of bigeye tuna in the western Pacific. 12th Meeting of the Standing Committee on Tuna and Billfish, 16-23 June 1999, Tahiti. Working Paper BET-4. 6 pp.

Sun, C-L, Yeh, S-Z, and P-Y Liu. 2004. Sex ratio of the bigeye tuna caught by the Taiwanese offshore longline fishery for 1998 and 2002-2004 in the western and central Pacific Ocean. 17th Meeting of the Standing Committee on Tuna and Billfish, 9-18 August 2004, Majuro, Marshall Islands. Information Paper INF-BIO-3. 8 pp.

Sun, C-L, Huang C-L, and S-Z Yeh. 2001. Age and growth of the bigeye tuna *Thunnus obesus*, in the western Pacific Ocean. Fish. Bull. 99:502-509.

Sund PN, Blackburn M, Williams F. 1981. Tunas and their environment in the Pacific Ocean: a review. Oceanogr Mar Biol Annu Rev 19:443–512.

Suzuki Z, Kume S. 1981. Fishing efficiency of deep longline for bigeye tuna in the Atlantic as inferred from the operations in the Pacific and Indian Oceans. Document prepared for the SCRS Symposium of the ICCT; 1981 Nov 30 p.

Suzuki Z, Kume S. 1982. Fishing efficiency of deep longline for bigeye tuna in the Atlantic as inferred from the operation in the Indian and Pacific Oceans. Inter Comm Cons Atlan.Tunas, Coll Vol Sci Pap 17(2):471–86.

Suzuki, Z., P.K. Tomlinson, and M. Honma. 1978. Population structure of Pacific yellowfin tuna. Bull.I-ATTC, 17(5):273-441.

Suzuki S, Warashina Y, Kishida M. 1977. The comparison of catches by regular and deep tuna longline gears in the western and central Pacific. Bull Far Seas Fish Res Lab 15:51–89.

Suzuki Z, Warashina Y, Kaneko K. 1979. The comparison of length of catches by regular and deep longline gears for bigeye, yellowfin and blue marlin in the western and central equatorial Pacific. Background Paper, Workshop on the Assessment of Selected Tunas and Billfish Stocks in the Pacific and Indian Oceans; 1979 Jun 13–22; Shimizu, Japan. Rome: FAO. Report nr SAWS/BP/16.

Talbot FH, Penrith MJ. 1963. Synopsis on the biological data on species of the genus *Thunnus* of South Africa. FAO Fish Rep 6 (2):609–46.

Tankevich PB. 1982. Age and growth of bigeye tuna *Thunnus obesus* (Scombridae) in the Indian Ocean. J Icthyol 22(4):26–31.

Tsukagoe, T. 1981. Fishing skipjack tuna schools associated with shoals and drifting objects. Suisan Sekai, Vol. 30, No. 2. p 78-81, February 1981. NMFS Translation No. 83, T. Otsu, Southwest Fisheries Science Center, Honolulu Laboratory, National Marine Fisheries Service, Honolulu, Hawaii, July 1983.

Ueyanagi S. 1969. Observations on the distribution of tuna larvae in the Indo-Pacific Ocean with emphasis on the delineation of spawning areas of albacore, Thunnus alelunga. Bull Far Seas Fish Res.Lab 2:177–256.

Uotani I, Matsuzaki K, Makino Y, Noka K, Inamura O, Horikawa M. 1981. Food habits of larvae of tunas and their related species in the area. Bull Jap Soc Sci Fish 47(9):1165–72.

Watanabe H. 1958. On the difference of stomach contents of the yellowfin and bigeye tunas from the western equatorial Pacific. Rep Nankai Reg Fish Res Lab 12:63–74.

Whitelaw AW, Unnithan VK.1997. Synopsis of the distribution, biology and fisheries of the bigeye tuna (Thunnus obesus, Lowe) with a bibliography. CSIRO Marine Laboratory. 62 p. Report nr 228.

WPFMC 2004. Pelagic Fisheries of the Western Pacific Region: 2003 Annual Report. Printed June 30, 2004. Prepared by the Pelagics Plan Team and Council staff, Western Pacific Regional Fishery Management Council, Honolulu, Hawaii.

Yamanaka H, Morita J, Anraku N. 1969. Relation between the distribution of tunas and water types of the North and South Pacific Ocean. Bull Far Seas Fish Res Lab 2:257–73

Yasutake H, Nishi G, Mori K. 1973. Artificial fertilization and rearing of bigeye tuna (Thunnus obesus) on board, with morphological observations on embryonic through to early post-larval stage. Bull Far Seas Fish Res Lab 8:71–8.

Yuen HSH. 1955. Maturity and fecundity of bigeye tuna in the Pacific. US Fish and Wildlife Service. p 1–30. Special report nr 150.

Yuen HSH. 1963. Schooling behavior within aggregations composed of yellowfin and skipjack tuna. FAO Fish Rep 6(3):1419–29.