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Growth and mortality rates of yellowfin tuna, *Thunnus albacares* (Perciformes: Scombridae), in the eastern and central Pacific Ocean

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ABSTRACT. Age and growth parameters were estimated for the yellowfin tuna *Thunnus albacares* (Bonnaterre, 1788). Atotal of 443 individuals were sampled from China longline fisheries in the eastern and central Pacific Ocean from February to November 2006. The von Bertalanffy growth parameters were estimated at L_∞ = 175.9 cm fork length, k = 0.52 year^{-1}, and t_0 = 0.19 year. The total mortality rate (Z) was estimated to be from 1.19 to 1.93 year^{-1}, the fishing mortality (F) and the natural mortality (M) were calculated to be 0.91 year^{-1} and 0.65 year^{-1}, respectively. The rate of exploitation (U) was estimated to be 0.46. This study provides estimates of growth and mortality rate for yellowfin tuna in the eastern and central Pacific Ocean, which may be used as biological input parameters in future stock assessments for the oceanic region. However, age analysis with other techniques, additional validation of the size composition and stock structure are also needed.

KEY WORDS. Biological parameters; size frequency analysis; yellowfin tuna.

The yellowfin tuna *Thunnus albacares* (Bonnaterre, 1788) is a commercially important species of tuna inhabiting tropical and subtropical seas worldwide, except the Mediterranean Sea (Margulies *et al.* 2001). The species supports major fisheries throughout its range (Collette & Nauen 1983, Nishikawa *et al.* 1985) and represents near half of the catch, both at the industrial and artisanal levels, in the equatorial Brazilian EEZ (Travassos 1999, Zagaglia *et al.* 2004). Little is known about key biological parameters of the yellowfin tuna, such as age and growth within the eastern and central Pacific region.

Biological parameters, including age, growth, mortality and age (or size) at maturity are vital for more reliable stock assessments and management plans, and to ensure a sustainable development of the fisheries (Chen & Paloheimo 1994). Age and growth information of yellowfin tuna can be obtained from a variety of techniques such as (a) length modes (Moore 1951, Yabuta & Yukinawa 1957, 1959, Hennemuth 1961, Yokota *et al.* 1961, Davidoff 1963, Le Guen & Sakagawa 1973, Fonteneau 1980, Wankowski 1981, White 1982, Yesaki 1983, Ingles & Pauly 1984), (b) weight modes (Kimura 1932, Moore 1951) and (c) direct aging of calcified tissues such as otoliths (Uchiyama & Struhsaker 1981, Wild 1986, Yamanaka 1990), scales (Nose *et al.* 1957, Yabuta *et al.* 1960, Yang *et al.* 1969, Le Guen & Sakagawa 1973, Draganik & Pelczarski 1984, Lessa & Duarte-neto 2004) and vertebrae (Aikawa & Kato 1938, Tan *et al.* 1965). Although the latter two methods are more precise, they are expensive, labor intensive and time consuming (Kolding & Giordano 2002). By contrast, length-frequency analysis is inexpensive, easy to apply, and has the potential to produce acceptable results (Mytilineou & Sardá 1995). This method has been given increasing importance, not only because it is often the only alternative for tropical stocks, but also because the necessary data are easily obtained, particularly after the introduction of computerized techniques (Kolding & Giordano 2002).

Despite these possibilities, very few validated age studies have been conducted for large tropical pelagic species like the yellowfin tuna in the eastern and central Pacific Ocean. The last study on yellowfin tuna's age and growth in the area was conducted in the late 80's (Eastern Pacific Ocean, Wild 1986), except for Hampton's (2000) (Western Tropical Pacific) and Su *et al.* (2003) (Western Pacific) studies.

In the present study, data on the growth and mortality of yellowfin tuna in the eastern and central Pacific Ocean is presented. The objective of the present study is to provide the first detailed information on the growth and mortality of yellowfin tuna collected in this area, by using fork length data and the ELEFAN I technique (Pauly 1987). This may be useful in managing the rapidly developing fishery of yellowfin tuna in the eastern and central Pacific Ocean.

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MATERIAL AND METHODS

Study area and data collection

Samples were collected from the eastern and central Pacific Ocean (11°00'S-05°00'N, 134°00'-153°00'W) (Fig. 1) using Chinese longline vessels from February to November 2006. Fork length (FL) measured to the nearest 1 cm (and pooled into 5 cm length classes), round weight (RW) and dressed weight (DW) to the nearest 1 kg were obtained. The specimens were sexed by inspecting gonad morphology. To examine the temperature experienced by yellowfin in the eastern and central Pacific Ocean, daily sea surface temperature (SST) data and vertical profile were obtained from the same Chinese longline vessels using a CTD (Conductivity Temperature and Depth sensors, Sea-Bird 37, Sea-Bird Electronics, Inc.), within the same time period.

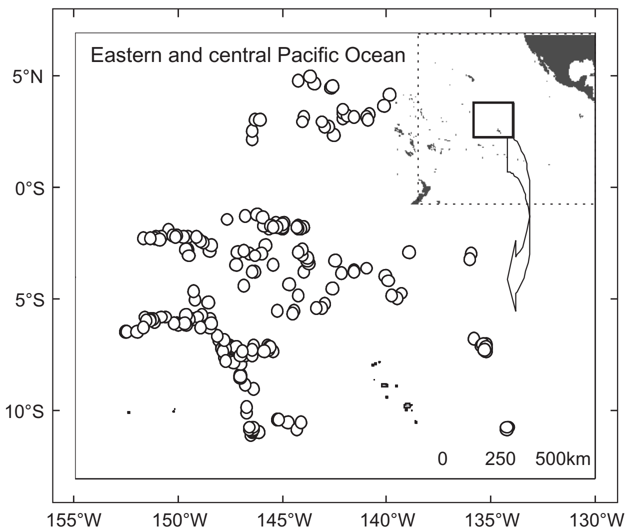

Figure 1. Map of the sampling area and sampling sites for yellowfin tuna in the eastern and central Pacific Ocean from February to November 2006.

Length-weight relationship

Confidence interval for mean FL was assessed by bootstrapping 1000 bootstrap pseudo-samples. We used Kolmogorov-Smirnov test (K-S test) to examine the difference in FL distributions between sexes.

The length-weight relationship was calculated by applying a power regression $W = aL^b e^{\epsilon}$, $\epsilon \sim N(0, \sigma^2)$, where W is the round weight (kg), L is the fork length (cm), and a (initial growth coefficient or condition factor) and b (growth coefficient, i.e., relative growth rate of fish) are both constants.

This equation may also be expressed in its logarithmic form: log W = log a + b log L. The parameters log a, b and the standard errors of b value ($S.E._b$) of W-L relationships were estimated by linear regression analysis (least-squares method) on log-transformed data, and the association degree between variables (log W and log L) was calculated by the determination coefficient (r^2). Regression analysis was employed on log-transformed data for males and females separately and the slopes were tested for significant differences between sexes through analysis of covariance (ANCOVA). The hypothesis of isometric growth (Ricker 1975) was tested using the t-test ($p < 0.05$).

The present study simulated the relationship between dressed weight and round weight using a linear regression analysis. The ANOVA analysis was used to verify whether the linear model is appropriate for describing the relationship.

Growth

The growth process can be described by growth velocity and growth acceleration. Length frequency data was also used to calculate the von Bertalanffy growth rate (k) and the asymptotic length (L_∞) by model progression analysis using the program ELEFAN I (Pauly 1987) within the FiSAT program (Gayanilo *et al.* 1994).

The growth performance index φ' (phi-prime) was calculated based on the growth parameter estimates following the equation of Pauly & Munro (1984). The index was compared with estimates obtained by other authors to facilitate the intra and interspecific comparison of the growth performance (Pauly & Munro 1984).

Mortality

For the calculation of the instantaneous annual mortality rate (*Z*) the length-converted catch curve (Pauly 1983, Munro 1984) was applied to the pooled length frequency data using the estimated growth parameter. The calculation was done with the FiSAT program (Gayanilo & Pauly 1997).

The natural mortality was calculated by Pauly's empirical equation: $\log M = 0.1228 - 0.192 \log L'_\infty + 0.7485 \log k + 0.2391 \log T$, where: T = the mean annual temperature (in °C), which is assumed to reflect the locally sea surface temperature in the survey area (Pauly 1980) (in the present study, T = 26.4°C); M = natural mortality.

In order to obtain the L'_∞ value, the present study used the relationship between fork length and total length (TL) on yellowfin tuna from the Fishbase database (TL = 1.108L, www.fishbase.org) and combined the L_∞ value estimated from the equation.

For the calculation of the fishery mortality (F), the M value was subtracted from the Z value in order to get the fishing mortality (F = Z – M) (Sainsbury 1982, Appeldoom 1984, 1988).

With the estimated values of F and Z the rate of exploitation (U) was calculated according to Landau (1979) and Gulland (1985).

RESULTS

Dressed weight – round weight relationship

The relationship between dressed weight and round weight estimated using a linear model led to the following equation where RW = 2.0961DW+1.0906 (r^2 = 0.9897, n = 88, $p < 0.001$) (Fig. 2). F value from ANOVA test indicated that the linear model is appropriate for describing the relationship (F = 8228.9, df = 87, $p < 0.001$).

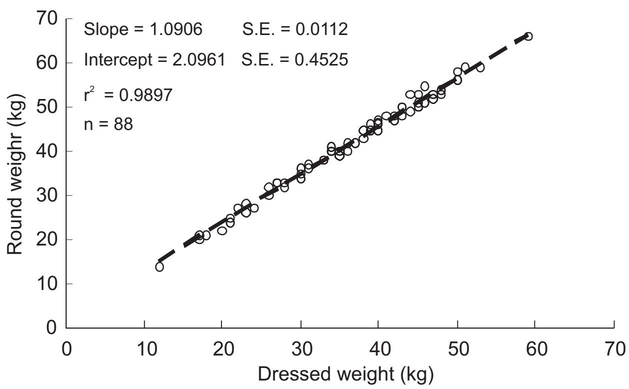

Figure 2. Linear relationship between dressed weight and round weight for yellowfin tuna in the eastern and central Pacific Ocean from February to November 2006.

Length-weight relationship

Among the 443 specimens collected, 387 (90/215 females/males) were used for growth analysis because the fork lengths of some specimens were not measured. The length of yellowfin tuna ranged between 93 and 167 cm FL and mean FL was 130.2 cm (128.7-131.7 cm for the bootstrapped 95% confidence interval). The fork length of about 80% individuals ranged from 110 cm to150 cm (Fig. 3). The maximum size of males (93-167 cm FL) slightly exceeded that of females (99-162 cm FL). The mean FL of females and males were 128.4 cm (125.5-130.0 cm) and 131.9 cm (129.8-133.9 cm) respectively. K-S test found no significant differences between FL distributions of females and males (H = 1.2040, $p > 0.05$).

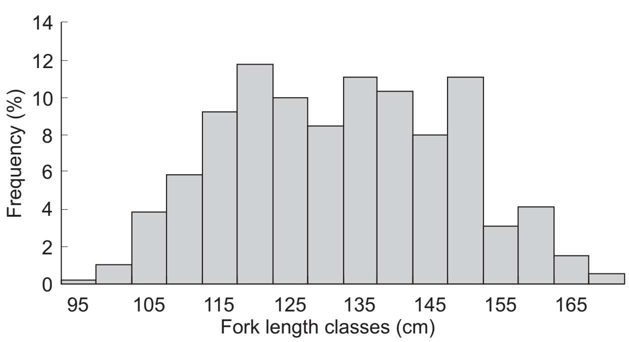

Figure 3. Length frequency distribution of yellowfin tuna in the eastern and central Pacific Ocean from February to November 2006.

The length-weight relationship was log(RW) = -13.1189+ 3.3.3980 × log(FL) (r^2 = 0.9557, n = 215, $S.E._b$ = 0.0502) for males and log(RW) = -12.3937+3.2466×log(FL) (r^2 = 0.9285, n = 90, $S.E._b$ = 0.0961) for females (Fig. 4). The slope was significantly different between sexes (t-test: t = 14.16, df = 109.88, $p < 0.001$), and significantly lower than the theoretical value of 3 for males (t-test: t = 7.936, $p < 0.001$) and females (t-test: t = 2.568, $p < 0.001$), indicating positive allometric growth for both sexes. The ANCOVA indicated no significant difference between males and females ($p = 0.6273 > 0.05$); thus the length-weight relationship with sexes combined was expressed as log(RW) = -12.7744+3.2466×log(FL) (r^2 = 0.9448, n = 387, $S.E._b$ = 0.0410). The slope was also significantly lower than the theoretical value of 3 for sex combined (t-test: t = 7.988, $p < 0.001$).

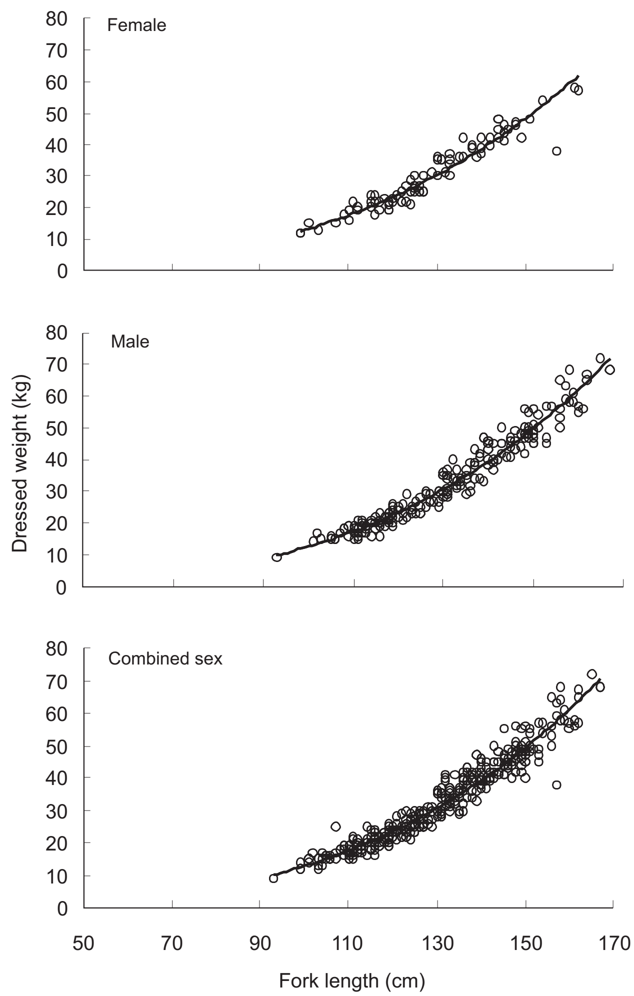

Figure 4. Relationship between dressed weight (DW) and fork length (FL) of yellowfin tuna in the eastern and central Pacific Ocean from February to November 2006.

Age and growth

The growth parameters estimated by ELEFAN I routine and the performance index (ϕ') were as follow: L_∞ = 175.9 cm, k = 0.52 $year^{-1}$, t_0 = 0.19, ϕ' = 4.21. The value of L_∞ was higher than the maximum observed fork length of 167 cm (Fig. 5). The goodness-of-fit index Rn was 0.332.

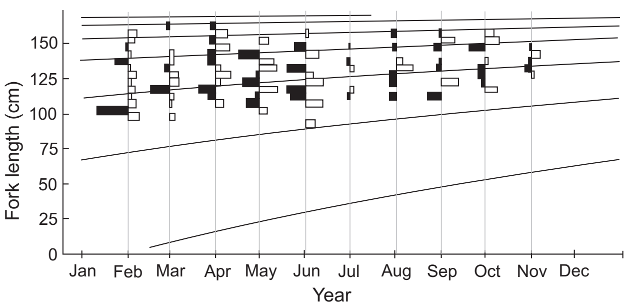

Figure 5. The von Bertalanffy growth curves of yellowfin tuna in the eastern and central Pacific Ocean as superimposed on the length-frequency histograms.

Comparing the present findings with previous works, we find a close similarity between studies conducted in similar waters (Tab. I, Fig. 6). The ϕ' value of yellowfin tuna in the eastern Pacific (3.76-4.19) is lower than that in the western Pacific Ocean (4.08-4.62) (Tab. I). Generally, our results fall within a reasonable range (Fig. 7).

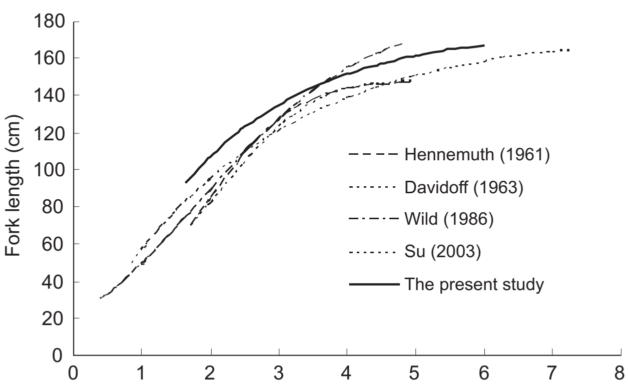

Figure6. Comparison of the growth curve for yellowfin tuna inhabiting the eastern and central Pacific Ocean estimated in the present study (heavy solid line) with the growth curves estimated by other authors.

Mortality

The length-converted catch curve is shown in figure 8. The estimated instantaneous rates of mortality for all fish were

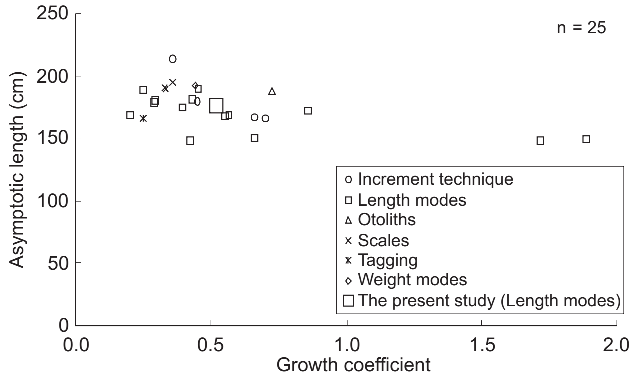

Figure 7. Comparison on the relationship between estimate of growth coefficient and asymptotic length for yellowfin tuna in the eastern and central Pacific Ocean in the present study with the relationship estimated by other authors. n = data source. The data are partly sourced from Table I of the present study and Fishbase's data about yellowfin tuna. (Source: http://www.fishbase.org/PopDyn/PopGrowthList.cfm?ID = 143&GenusName = Thunnus &SpeciesName = albacares&fc = 416).

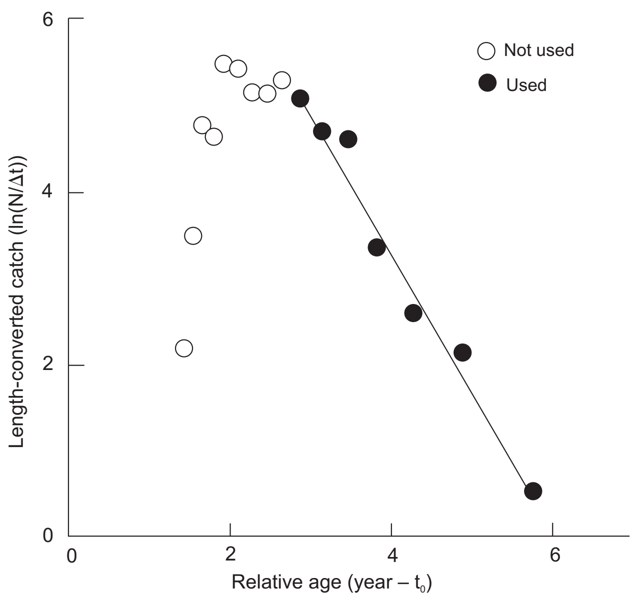

Figure 8. Length-converted catch curve for all yellowfin tuna specimens collected from the eastern and central Pacific catch samples from February to November 2006. "Not used" indicate the data refer to length classes not fully recruit to the fishery.

Z = 1.56 (with 95% confidence interval of 1.19-1.93) $year^{-1}$, F = 0.91 $year^{-1}$. The instantaneous natural mortality rate (M) obtained using the equation of Pauly (1980) was 0.65 $year^{-1}$. The reliability of the estimated M was ascertained using the M/K ratio because this ratio has been reported to be within the range 1.12-2.50 for most species (BEVERTON & HOLT 1957). The value of M/K ratio was 1.25. The rate of exploitation was U = 0.46.

DISCUSSION

Yellowfin tuna growth has been studied by various methods in the Pacific Ocean (Tab. I). The study of growth using length-frequency analysis has long been the most frequently used method, even in other oceans, such as the Atlantic Ocean (LE GUEN & SAKAGAWA 1973, FONTENEAU 1980, GAERTNER & PAGAVINO 1991) and the Indian Ocean (MARSAC & LABLACHE 1985, MARSAC 1991).

The growth curves estimated from this study agree well with the growth curves estimated earlier by other authors (such as MULTIFAN technique, SU *et al.* 2003) and even scales (such as LE GUEN & SAKAGAWA 1973) using other length-frequency analyses. Estimations on L_∞, k and ϕ' in the present study is close to the results from a similar area in the central Pacific concluded by MOORE (1951) (L_∞ = 172.7 cm, k = 0.86 $year^{-1}$ and ϕ' = 4.41) and SU *et al.* (2003) (North-Western Pacific, L_∞ = 175 cm, k = 0.39 $year^{-1}$ and ϕ' = 4.08).

Differences in growth patterns may be the result of differences in genetic structure and/or differences in temperature, density of food and diseases (PAULY 1994, WOOTTON 1998). The estimation of ϕ' value was 4.21 in the present study and is

Table I. Comparison of growth parameters of yellowfin tuna reported by different authors and by date. Partly reproduced from table 1 of SUZUKI (1971), Table I of WILD (1993) and table 2 of SUZUKI (1994). Eq. = equation, R = RICHARDS (1959), G = GOMPERTZ (RICKER 1979), B = VON BERTALANFFY (1938), L_∞ = the asymptotic fork length, k = growth parameter, t_0 = the age at length 0.

Source	Region	Data type	Eq.	Sex	Range	L_∞ (cm)	k ($year^{-1}$)	t_0 (year)	ϕ'
MOORE (1951)	Central Pacific	Length modes	G	both	47-168	172.7	0.857		4.41
MOORE (1951)	Hawaiian waters	Weight modes	B	both	70-120	192.0	0.440	0.220	4.21
YABUTA & YUKINAWA (1957)	Japanese waters	Length modes	B	both	30-150	168.0	0.550	0.350	4.19
YABUTA & YUKINAWA (1959)	Western Pacific	Length modes	B	both	80-150	150.0	0.660	0.400	4.17
YABUTA *et al.* (1960)	Western Pacific	Scales	B	both	70-140	190.0	0.330	0	4.08
HENNEMUTH (1961)	Eastern Pacific	Length modes	R	both	70-148	148.0	1.720		4.58
DAVIDOFF (1963)	Eastern Pacific	Length modes	R	both	70-148	149.0	1.888		4.62
DIAZ (1963)	Western coast of America	Increment technique	B	both	80-140	180.0	0.450		4.16
DIAZ (1963)	Western coast of America	Increment technique	B	both	80-140	167.0	0.660		4.26
DIAZ (1963)	Western coast of America	Increment technique	B	both	80-140	214.0	0.360		4.22
DIAZ (1963)	Western coast of America	Increment technique	B	both	80-140	166.0	0.700		4.29
YANG *et al.* (1969)	Western Pacific	Scales	B	both	60-139	195.2	0.360	0.270	4.14
LE GUEN & SAKAGAWA (1973)	Western Pacific	Scales	B	male	58-119	202.1	0.276	0	4.05
LE GUEN & SAKAGAWA (1973)	Western Pacific	Scales	B	female	57-119	174.9	0.372	0	4.06
WANKOWASKI (1981)	Western Pacific	Length modes	B	both	30-96	180.9	0.292	0	3.98
WHITE (1982)	Philippine waters	Length modes	B	both	20-60	189.0	0.250		3.95
WHITE (1982)	Philippine waters	Length modes	B	both	20-70	169.0	0.200		3.76
WHITE (1982)	Philippine waters	Length modes	B	both	20-60, 90-150	182.0	0.430		4.15
WHITE (1982)	Philippine waters	Length modes	B	both	20-60	179.0	0.290		3.97
YESAKI (1983)	Philippine waters	Length modes	B	male	20-60, 120-160	175.0	0.300		3.96
YESAKI (1983)	Philippine waters	Length modes	B	female	20-60, 120-160	173.0	0.320		3.98
INGLES & PAULY (1984)	Philippine waters	Length modes	B	both		148.0		0.420	
WILD (1986)	Eastern Pacific	Otoliths	R	both	30-168	188.2	0.724		4.41
WILD (1986)	Eastern Pacific	Otoliths	G	male	50-168	194.7	0.617		4.37
WILD (1986)	Eastern Pacific	Otoliths	G	female	54-142	184.2	0.591		4.30
SU *et al.* (2003)	North-Western Pacific	Length modes	B	both	50-165	175.0	0.392	0.003	4.08
The present study	Eastern and Central Pacific	Length modes	B	both	93-167	175.9	0.520	0.190	4.21

similar to those of many other studies on growth of yellowfin tuna in the Pacific Ocean (White 1982) (Tab. I). However, the ϕ' value of Li *et al.* (1995) is only 3.62, partly because of the narrow size range and also because sampling individuals over 100 cm FL can not represent a whole life history. The smaller growth parameters of Wankowaski (1981), White (1982) and Hampton (2000) and the lower asymptotic length of Yabuta & Yukinawa (1957, 1959), Hennemuth (1961), Davidoff (1963), Pauly (1978), and Ingles & Pauly (1984) are result of limiting larger sampling of larger individuals.

For the calculation of the instantaneous annual mortality rate (*Z*), age-structured catch curve are often used (Ricker 1975). However, for short-lived fish species, a length-converted catch curve is more suitable (Gayanilo & Pauly 1997), even though the results from the latter estimation are more precise (Pauly *et al.* 1995). The Z value in the present study is 1.56 $year^{-1}$ using the length-converted catch curve and is closer to the Z value of Schaefer (1967) (1.72 $year^{-1}$) and Su *et al.* (2003) (1.71 $year^{-1}$). Wise (1972) concluded three different Z values from three different tuna fisheries: Z = 1.52 $year^{-1}$ for the pole and line fishery with live baits, Z = 2.32 $year^{-1}$ for the purse seine fishery and Z = 1.88 $year^{-1}$ for the tuna longline fishery. Wise (1972) also showed that the reasonable Z value ranged from 1.4 to 2.4 $year^{-1}$ and the Z value in the present study is similar to other results (Schaefer 1967).

The estimation of natural mortality poses some difficulty because it may be affected by the selection of the estimation method and the study area (Su *et al.* 2003). The natural mortality in the present study was 0.65 $year^{-1}$ using Pauly's (1980) empirical equation and is similar to the M values of Hennemuth (1961) (M = 0.64-0.90 $year^{-1}$) and Hampton (2000) (M = 0.7-1.2 $year^{-1}$ for the individuals with fork length over 100 cm) and Su *et al.* (2003) (M = 0.56 $year^{-1}$). The records on yellowfin's natural mortality ranged between 0.6-1.2 $year^{-1}$ (Murphy & Sakagawa 1977) and M in the present study was within a similar range.

Mortality and exploitation rate estimates should be treated carefully since they were estimated from two discontinuous sampling periods and may be biased by annual differences in year class strength. It is rather difficult, and probably unwise, to describe the current state of the stock because of the lack of information on the effect of fishing on the recruitment, behavior and migration pattern of yellowfin tuna in the eastern and central Pacific Ocean.

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