Captive Tunas in a Tropical Marine Research Laboratory: Growth of Late-larval and Early-juvenile Black Skipjack *Euthynnus lineatus*

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Little is known about the biology of tunas during larval and early-juvenile stages because they are relatively inaccessible to scientists. In the eastern Pacific Ocean fishermen seldom catch juveniles of less than about 30 cm in length. Concurrent laboratory and field studies of tuna growth and mortality are important to gain insight into the recruitment process. These considerations motivated the Inter-American Tropical Tuna Commission (IATTC) to establish a research center at Achotines Bay in the Republic of Panama, a site located near tuna spawning grounds (Fig. 1).

Black skipjack tuna *Euthynnus lineatus* are not commercially important; however, their similarity to other tunas makes them valuable subjects of study. Their distribution is limited to tropical and subtropical regions of the eastern Pacific Ocean (Collette and Nauen 1983), with two stray specimens reported from the Hawaiian Islands (Matsumoto 1976). For many years, *E. lineatus* was thought to inhabit only coastal waters and waters around islands (Calkins and Klawe 1963, Yoshida 1979). However, recent fishing records show that black skipjack also occur in oceanic habitat (Schaefer 1987, fig. 1; Bayliff 1988a, fig. 62).

Clemens (1956) reported the only previous information on rearing and growth rates of early-juvenile black skipjack. Some information was reported by Peterson (1983:54) on the growth of 32–51 cm fork length (FL) black skipjack in the field, based on tagging studies and length-frequency modal progression analysis. Houde and Richards (1969) described the growth of larval little tunny *E. alletteratus* reared in the laboratory from planktonic eggs. The larvae were fed unspecified quantities of mostly copepod nauplii and copepodites, and grew from less than 3.0 mm total length at hatching to almost 8.5 mm in 18 days, a rate of about 0.3 mm/day. No data are available on larval growth of kawakawa *E. affinis* (Yoshida 1979).

The purpose of this note is to report the establishment of the Achotines Laboratory in Panama, to describe sampling results and rearing procedures of late-larval and early-juvenile black skipjack tuna, and to report growth experiments on captive black skipjack.

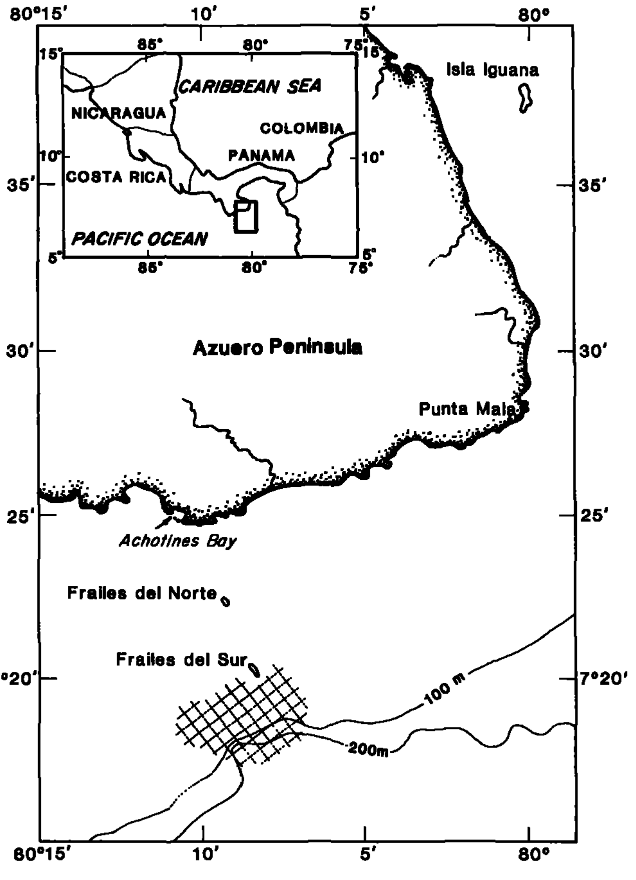

Figure 1
Location of the study site (cross-hatched) south of Achotines Bay, Panama. The IATTC's Achotines Laboratory is situated on the east side of the Bay.

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Laboratory studies of growth are important in light of evidence in other fishes that variability in growth rates in the wild can affect early-life-stage duration, potentially resulting in large changes in larval survival and subsequent recruitment (Houde 1987).

The Achotines Laboratory and study area

The IATTC's Achotines Laboratory is located on a broad south-facing headland on the southern tip of the Azuero Peninsula in the Los Santos Province of the Republic of Panama (Fig. 1). This site is located at the northwestern part of the Panama Bight, which extends from Panama to Ecuador (Forsbergh 1969). The Panama Bight is a region with large seasonal variations in atmospheric and oceanic characteristics, in part influenced by the seasonal position of the intertropical convergence zone (ITCZ). Sea-surface temperature data (Fig. 2) clearly show an upwelling cycle driven by the Caribbean trade winds when the ITCZ is displaced to the south, typically beginning in December and lasting at least through April. The continental shelf is narrow, 2–30 km in width, off the Azuero Peninsula, but widens abruptly on either side of the Peninsula. Thus, oceanic habitat, thought to be a requirement for tuna spawning, occurs close to shore. Scombrid larvae and early juveniles are routinely captured as close as 9 km from Achotines Bay. The following late-larval and early-juvenile scombrids have been captured and held in the laboratory with varying degrees of success: black skipjack tuna, yellowfin and/or bigeye tuna (*Thunnus albacares* and/or *T. obesus*)[1], frigate and/or bullet tuna (*Auxis thazard* and/or *A. rochei*)[2], sierra *Scomberomorus sierra*, chub mackerel *Scomber japonicus*, and Indo-Pacific bonito *Sarda orientalis*.

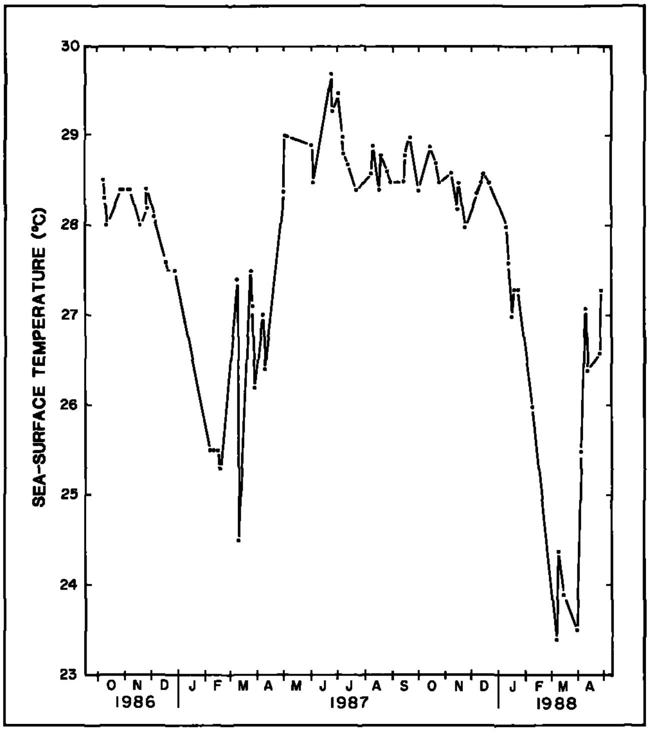

Figure 2
Sea-surface temperatures taken while nightlighting in the sampling areas (Fig. 1) off the Achotines Laboratory.

Materials and methods

Larval and early-juvenile fishes were attracted to a bright underwater light at night (nightlighting) in the vicinity of the 100- and 200-m isobaths (Fig. 1) during October 1986–April 1988. A 24-volt DC 300-watt light was lowered from a drifting boat to a depth of about 14 m, left for about 5 minutes, and slowly raised to a depth of 1–2 m. Late-larval and early-juvenile[3] black skipjack tuna approaching the light were collected by dipnet and quickly placed into 61 × 76 cm polyethylene bags with rounded corners containing aerated seawater. A water conditioner, Fritz-guard, was added to the water to minimize damage to the fish from mucous loss caused by abrasion. Time from capture to arrival at the laboratory ranged between 1 and 3 hours. Sea-surface temperature, weather, and sea conditions were recorded. The fish which did not survive nightlighting and transfer procedures were measured (standard length, SL, to nearest 0.1 mm) and weighed (round wet weight to nearest 0.001 g) soon after capture.

At the laboratory, the captive fish were placed in 1.2-m diameter circular fiberglass tanks containing 0.3 m^3 of aerated seawater with a weak current. Water

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[1] Early-juvenile *T. albacares* and *T. obesus* cannot be distinguished on the basis of meristic, morphological, pigmentation (Matsumoto et al. 1972), or osteological characters (Potthoff 1974). However, an electrophoretic distinction between yellowfin and bigeye adults provides a means of separating the larvae and early juveniles (Graves et al. 1988).

[2] Larval and early-juvenile *Auxis thazard* and *A. rochei* have been distinguished by minor differences in pigmentation and body depth, but identifications are ambiguous (Uchida 1981). Gill raker counts can be used for identification of juveniles >25 mmSL, but gill rakers are too tiny and difficult to count in smaller specimens (Uchida 1981).

[3] Late larvae are defined as the "postflexion larvae" and "transformation larvae," and early juveniles as the "pelagic or special juveniles" of Kendall et al. (1984).

Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

from Achotines Bay was pumped through a sand filter containing #20 silica sand and added to the tanks at a rate sufficient to exchange the water several times per day. Wild zooplankton, predominantly copepods, caught with a 505-μm mesh net were provided as food in densities of approximately 50–150/L two or three times per day until the black skipjack grew to about 13–17 mmSL. Then, whole *Poecilia latipinna* and *Poeciliopsis turrubarensis* fry or chopped fish of several species were provided four to six times per day. The black skipjack were fed until satiated. Maximum rations were provided throughout the growth experiments. When the fish reached about 35–45 mmSL, they were transferred into 3.0-, 4.6-, or 6.4-m diameter plastic-lined pools containing 2.3, 11.4, or 24.6 m^3 of water.

Water temperature in the laboratory aquaria was recorded to the nearest 0.1°C several times per day with a mercury thermometer. Salinity was measured to the nearest 1‰ (readability) several times per month with an optical salinometer. Daylight illumination was supplemented by fluorescent lights over the containers. At night, low levels of indirect fluorescent lighting were maintained to prevent the fish from colliding with the container walls.

Because black skipjack are delicate, initial lengths of those held for growth experiments were estimated by visually comparing them with a ruler held near the tank and adjusting for the magnifying effect of the water. Lengths of fish that had recently died or were near death in the tanks soon after capture were estimated in the same way, and subsequently measured (SL to nearest mm) after retrieval from the tanks to improve estimating skills and to provide a measure of estimation error. The maximum error measured was used to calculate the largest potential errors in growth rates that could have resulted.

Weights were calculated from lengths based on a weight-length relationship derived from 184 black skipjack measured (SL to nearest 0.1 mm) and weighed (round wet weight to nearest 0.001 g) soon after capture. Length and weight measurements were converted to natural logarithms (ln), and regression parameters ln$a$ and b were estimated by the method of least squares,

$$\ln W = \ln a + b \ln SL, \quad (1)$$

where W = weight in g, and SL = standard length in mm. Validity of the assumptions of linear regression were tested using residual analyses (Draper and Smith 1981).

Standard lengths and weights at the end of the growth experiments were measured to the nearest 0.1 mm and 0.1 g, respectively. The experiments were terminated when the fish died from some accidental or unknown cause or were near death.

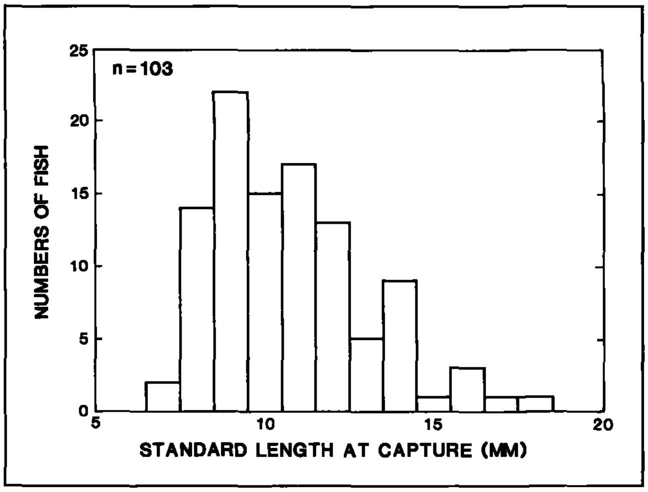

Figure 3
Standard lengths of late-larval and early-juvenile black skipjack tuna measured soon after capture by nightlighting in the waters south of the Achotines Laboratory, October 1987–April 1988.

The average daily growth rate of each fish over the duration of captivity was expressed as growth in SL (mm) during captivity divided by days in captivity. The average daily weight increase of each fish was calculated using final weights of the fish and the estimated SL at capture converted to weight.

Results

Late-larval and early-juvenile scombrids have been captured in all months of the year, but not in every month since the inception of routine sampling in 1984. During the period of October 1986–April 1988, 212 late-larval or early-juvenile black skipjack tuna were captured and transferred to the laboratory. Specimens which did not survive live transfer procedures ranged between 7.1 and 18.4 mmSL soon after capture (Fig. 3). A total of 79 (37%) survived handling and lived longer than 48 hours. Sampling dates, numbers caught, and other information are given in Table 1. Young black skipjack were caught during 16 of the 18 months in which sampling took place during this period. No nightlighting took place during January 1987 due to poor weather conditions. The greatest catches were made during November and December 1986, December 1987, and January 1988. Sampling frequency was governed by weather conditions, boat availability, and other factors. At times, sampling was terminated prematurely due to poor weather, which resulted in no catch. For this and other reasons, the

Table 1

Sampling information, numbers of late-larval and/or early-juvenile black skipjack which survived at least 48 hours after transfer to laboratory aquaria, and standard lengths of those which did not survive nightlighting and transfer procedures. Accurate measurements were not obtained from all those which did not survive.

	Sea-surface temp. (°C)	No. caught	Standard length at capture				No. surviving
Date			Mean	Range	SD	*n*	
1986							
8 Oct.	28.5	7	15.8	13.6–17.0	1.279	5	2
9 Oct.	28.3	0	—	—	—	—	—
11 Oct.	28.0	0	—	—	—	—	—
28 Oct.	28.4	17	11.4	9.4–15.3	1.631	16	1
29 Oct.	28.4	10	11.8	10.2–12.8	1.124	5	5
31 Oct.	28.4	0	—	—	—	—	—
5 Nov.	28.4	0	—	—	—	—	—
8 Nov.	28.4	0	—	—	—	—	—
19 Nov.	28.0	11	9.3	7.7–11.1	1.047	8	2
20 Nov.	28.0	2	—	—	—	—	1
26 Nov.	28.2	9	—	—	—	—	4
27 Nov.	28.4	4	—	—	—	—	0
4 Dec.	28.1	3	11.5	9.4–13.2	1.930	3	0
18 Dec.	27.6	2	10.5	10.0–11.0	0.707	2	0
22 Dec.	27.5	1	—	—	—	—	0
29 Dec.	27.5	0	—	—	—	—	—
1987							
6 Feb.	25.5	0	—	—	—	—	—
16 Feb.	25.5	0	—	—	—	—	—
17 Feb.	25.3	4	9.8	7.7–11.9	2.970	2	2
18 Feb.	—	0	—	—	—	—	—
9 Mar.	27.4	0	—	—	—	—	—
12 Mar.	24.5	0	—	—	—	—	—
25 Mar.	27.5	2	11.9	—	—	1	1
26 Mar.	27.1	0	—	—	—	—	—
30 Mar.	26.2	0	—	—	—	—	—
3 Apr.	—	0	—	—	—	—	—
8 Apr.	27.0	0	—	—	—	—	—
9 Apr.	26.4	0	—	—	—	—	—
1 May	28.4	0	—	—	—	—	—
4 May	29.0	2	9.4	—	—	1	1
6 May	29.0	0	—	—	—	—	—
1 June	28.9	0	—	—	—	—	—
3 June	28.5	0	—	—	—	—	—
4 June	28.5	0	—	—	—	—	—
25 June	29.7	0	—	—	—	—	—
26 June	29.3	0	—	—	—	—	—
2 July	29.5	0	—	—	—	—	—
7 July	29.0	3	12.0	—	—	1	2
9 July	28.8	0	—	—	—	—	—
1987 (continued)							
14 July	28.7	3	—	—	—	—	2
23 July	28.4	5	12.8	11.5–14.0	1.770	2	0
10 Aug.	28.6	0	—	—	—	—	—
11 Aug.	28.9	0	—	—	—	—	—
18 Aug.	28.4	0	—	—	—	—	—
20 Aug.	28.8	4	—	—	—	—	4
27 Aug.	28.6	0	—	—	—	—	—
31 Aug.	28.5	0	—	—	—	—	—
15 Sep.	28.5	3	10.5	—	—	1	2
17 Sep.	28.8	3	16.4	14.4–18.4	2.830	2	1
23 Sep.	29.0	6	8.1	—	—	1	1
2 Oct.	28.4	7	12.7	11.2–13.7	1.162	4	3
15 Oct.	28.9	0	—	—	—	—	—
23 Oct.	28.7	1	—	—	—	—	1
26 Oct.	28.5	1	—	—	—	—	0
9 Nov.	28.6	4	11.5	10.0–13.7	1.565	4	0
16 Nov.	28.2	3	—	—	—	—	3
17 Nov.	28.5	1	—	—	—	—	1
23 Nov.	28.0	0	—	—	—	—	—
9 Dec.	28.4	37	8.6	7.1–9.5	0.728	24	5
15 Dec.	28.5	8	10.3	9.5–11.7	1.217	3	5
16 Dec.	28.6	4	—	—	—	—	4
22 Dec.	28.5	4	8.0	7.9–8.0	0.071	2	2
1988							
1 Jan.	28.0	0	—	—	—	—	—
13 Jan.	27.6	0	—	—	—	—	—
18 Jan.	27.0	0	—	—	—	—	—
20 Jan.	27.3	36	11.3	9.0–14.4	1.717	13	23
25 Jan.	27.3	0	—	—	—	—	—
10 Feb.	26.0	1	12.2	—	—	1	0
8 Mar.	23.4	0	—	—	—	—	—
10 Mar.	24.4	2	10.9	—	—	1	1
16 Mar.	23.9	0	—	—	—	—	—
30 Mar.	23.5	0	—	—	—	—	—
5 Apr.	25.5	0	—	—	—	—	—
11 Apr.	27.1	1	9.2	—	—	1	0
13 Apr.	26.4	1	—	—	—	—	0
26 Apr.	26.6	0	—	—	—	—	—
28 Apr.	27.3	0	—	—	—	—	—
Total		212				103	79

capture frequency of black skipjack in Table 1 is not meant to reflect the true spawning frequency of the adults.

Thirty-nine specimens were held for laboratory growth experiments. Their estimated lengths and weights at capture are shown in Figure 4. The larger fish in the catch (Fig. 3) survived capture and transfer in greater proportions than the smaller ones (Fig. 4). The captive fish survived an average of 36 days in the laboratory; most (64%) died in 30 days or less. Three fish survived in excess of 130 days. The longest-lived black skipjack grew in captivity for 167 days, and attained an SL of 259 mm and weight of 336 g. It was sacrificed when it ceased feeding due to eye infec-

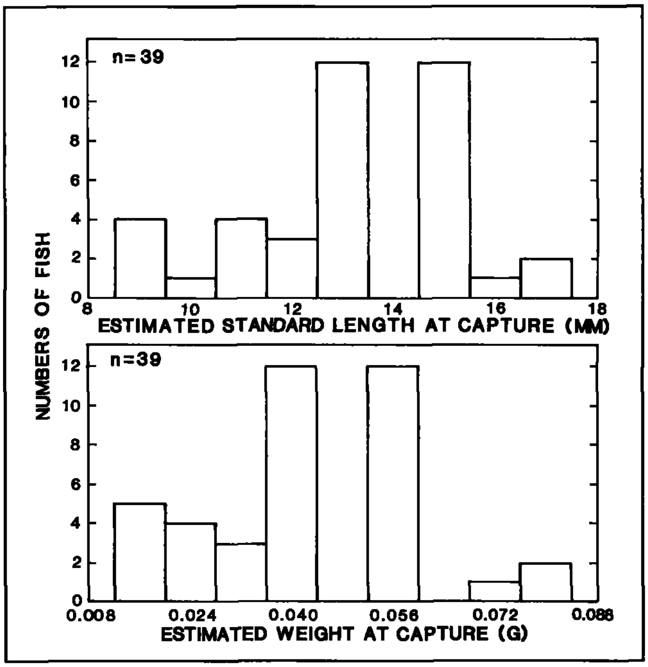

Figure 4

Standard lengths estimated in the laboratory and weights calculated from a weight-length regression (Fig. 6) for 39 black skipjack tuna held for growth experiments.

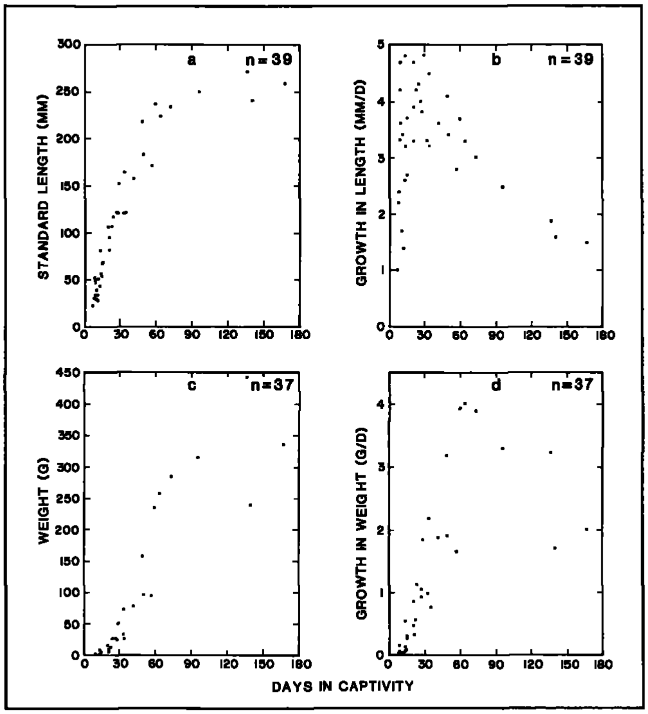

Figure 5

Standard lengths (a), growth rates in standard length averaged over the duration of captivity (b), weights (c), and growth rates in weight averaged over the duration of captivity (d) of juvenile black skipjack tuna at the end of laboratory growth experiments versus days in captivity. Two fish held 11 days were not weighed.

tions. Water temperature and salinity in the laboratory aquaria ranged from 23.7 to 29.1°C and 29 to 34‰, respectively, over all the experiments.

Growth in length

Captive black skipjack fed *ad libitum* grew in a curvilinear relationship of SL with time (Fig. 5a). The data were not fitted to derive a predictive growth equation because they are inadequate for that purpose. The fish were fed to satiation, but the rations were not measured.

The highest rates of growth in length were attained during the first month in captivity (Fig. 5b). After about 4 weeks, the fish had progressively lower average growth rates. Black skipjack from experiments that terminated during the first 15 days of captivity grew at extremely variable rates, from 1.0 to 4.8 mm/day. After 15 days, there was a significant negative correlation between growth rate and days in captivity ($r = -0.877$, $n = 23$, $P \ll 0.001$). All the fish that survived between 15 and 50 days grew rapidly, 3.2–4.8 mm/day. After about 50 days in captivity average growth rates declined drastically.

Errors in estimating lengths of newly-captured fish that had recently died or were near death in the tanks soon after capture ranged up to ±4 mm, although most were less. Maximum potential errors in growth rates were calculated based on the assumption that ±4-mm errors were made when estimating capture lengths of all the experimental fish. In general, the importance of measurement error diminished with increasing time in captivity. Potential errors ranged from only ±0.8 to a high of ±53.3% for one fish held the least time of all experimental fish (7.5 days). The next greatest error estimates were −26.1 and +23.8%, and the means were ±8.8%. Potential errors for the majority (85%) of the samples were ±13.5% or less, and less than 10% for all fish held in captivity more than 15 days ($n = 25$).

Growth in weight

Growth in weight appeared to follow a sigmoidal relationship with time in captivity (Fig. 5c). The rate of weight gain during the first 30 days was low, increasing dramatically between about 30 and 70 days, and then tapering off after 70 days.

While the greatest and most variable growth rates in length took place during the first 30 days, average rates of weight gain during that period were less than

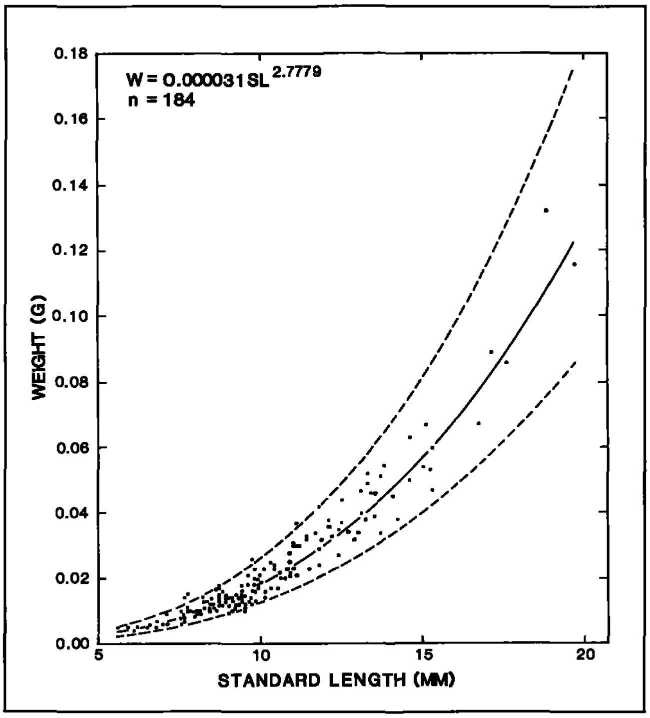

Figure 6

Weights (W) and standard lengths (SL) of 184 late-larval and early-juvenile black skipjack tuna measured soon after capture. The power function of the log-log fitted regression line and 95% prediction belts of weight on length are included. The r^2 of the log-log fit was 0.927, the 95% confidence limits of the regression coefficient were 2.6641–2.8917 g/mm, and the standard error of the estimate was 0.1790.

those for fish held longer (Fig. 5d). The greatest average growth rates in weight (3.9–4.0 g/day) were recorded for fish surviving 60–73 days ($n = 3$). After that time, average daily weight increases declined drastically ($n = 4$).

Weight-length relationship

Capture weights of the live black skipjack held for growth experiments (Fig. 4) were estimated using a weight-length regression equation based on fresh measurements and weights of 184 other black skipjack ranging from 5.6 to 19.7 mmSL and 0.004 to 0.132 g (Fig. 6). The power function of the fitted regression is $\ln W = -10.3806 + 2.7779 \ln SL$. The standard errors of parameters $\ln a$ and b are 0.1326 and 0.0577, respectively.

Tests for normality of the residuals (Filliben 1975), independence or lack of autocorrelation of the residuals (Durbin-Watson statistic), and a constant variance (homoscedasticity) of the residuals (Wesolowski 1976) failed to indicate any violation of the assumptions of linear regression.

Effect of temperature

Sea-surface temperatures during each sampling trip are shown in Figure 2. The data show a gradual decline in temperatures commencing in November or December, reaching lows of about 23–25°C in March, followed by a gradual warming to maximum stable temperatures of about 28–29°C from April or May until October or November. Black skipjack spanning the entire size range encountered (7.1–18.4 mmSL) were taken when the temperature ranged between 28.0 and 29.0°C. Only smaller individuals (7.7–12.2 mmSL) were caught when sea-surface temperatures were below 27.0°C, but the sample size was low ($n = 4$).

Neither the growth rates nor final sizes attained in captivity were significantly correlated with mean water temperatures in the aquaria over the course of the experiments. However, the final lengths ($r = -0.559$, $P<0.001$) and weights attained ($r = -0.572$, $P<0.001$), average daily growth in weight ($r = -0.503$, $0.001 < P < 0.002$), and the number of days in captivity ($r = -0.568$, $P<0.001$) were negatively correlated with minimum temperatures recorded in the laboratory. No such relationships were observed with the maximum temperatures recorded.

Discussion

Except for the black skipjack held in shipboard aquaria by Clemens (1956), these experiments are the first in which late-larval or early-juvenile tunas were collected in the wild and reared in captivity for experimental growth studies. Similar experiments on other scombrids are being conducted at the Achotines Laboratory. To our knowledge, 167 days is the longest time any scombrid has been held in captivity beginning at an early life stage. Harada et al. (1973) held *Auxis tapeinosoma* (= *A. rochei*) larvae for 52 days, Harada et al. (1974) reared *Sarda orientalis* larvae up to 99 days, and Harada et al. (1980) grew *Thunnus albacares* larvae for a maximum of 38 days. These larvae were all hatched from artificially-fertilized eggs obtained from ripe females, and fed unspecified rations of zooplankton and fish larvae. Previous to our studies, young *E. lineatus* were reared on only one occasion. Clemens (1956) collected black skipjack by dipnet at night, and held 10 individuals averaging about 27 mmSL for up to 12 days in shipboard aquaria. Average growth in length was 3.1–3.6 mm/day. The paper does not state at what water temperature the fish were held nor how much food was provided during the experiment. The growth rates measured in Harada et al.'s (1973, 1974, 1980) experiments were 3.0, 3.0, and 1.3 mm/days, respectively. The growth rates reported by Clemens

(1956) and Harada et al. (1973, 1974, 1980) are within the range of growth rates reported here, although we obtained greater rates too, up to 4.8 mm/day. Clemens (1956) stated that his results probably approximate minimum growth rates in nature.

An undesirable aspect of our study was the necessity of estimating, rather than measuring, lengths at the time of capture. This may have contributed to the large variance in the data reported for the first 15 days (Fig. 5b). Estimation errors were minimal, however, because the second author's ability to estimate lengths of live fish was continually refined by estimating, then measuring the fish that died in the tanks soon after capture. Except for a few fish held for short times, maximum estimation errors of ±4 mm translated to low potential error in growth rates.

Despite unavoidable estimation errors, this study reveals some interesting aspects of growth of young tunas. Black skipjack are capable of growing at high but variable rates when food is plentiful. The growth rates we measured might be considered upper limits for this species; feeding to satiation in the wild would likely be detrimental to survival because laboratory observations suggest that the added weight of food in the gut inhibits mobility. The variability in rates measured during the early part of the experiments may be due in part to the stress of captivity. However, high, variable growth rates suggest a large scope for growth (Brett 1979), an advantageous characteristic for fish that spend their early life stages in the epipelagic zone where predation risk is great. A large scope for growth permits rapid growth when food is abundant, providing young tunas an earlier transition to piscivorous feeding and early formation of schools. The decline in growth rates with increasing time in captivity may be related in part to inadequate-sized rearing containers (Theilacker 1980). Further laboratory growth experiments should concentrate on maintaining constant, controlled rations.

Growth rates of late juvenile and/or adult black skipjack from the commercial catch in the eastern Pacific Ocean are much lower, as expected, than those reported here. Tagging and length-frequency modal progression analyses provided rates that agree with each other (Peterson 1983:54–55). Black skipjack measuring 32–45 cmFL grew about 0.36 mm/day. Larger fish, 45–51 cm, grew more slowly, 0.22 mm/day. The upper seven data points in Figure 5a, corresponding to the largest fish (224–272 mmSL) which were held for the longest times (59.5–167.5 days), appear to represent a slower growth stanza than a previous stanza <60 days. A straight line fitted to these seven points yielded a significant slope of 0.28 mm/day, comparable to the natural growth rates reported for 32- to 51-cm black skipjack (Peterson 1983:54–55). Skipjack tuna *Katsuwonus pelamis*, another primitive species of the tribe Thunnini, measuring 37.5–42.5 cmFL when tagged and released east of 100°W longitude grew an average of 1.22 mm/day in 31–180 days at liberty (Bayliff 1988b).

Much additional work on growth of tunas under controlled conditions, as well as growth studies in nature, is needed to understand how physical and biotic variability in the ocean affects growth rates and life-stage duration. By virtue of black skipjack's biological similarities to commercially important tunas, we believe that such studies utilizing black skipjack tuna will yield important information that would be applicable to other tunas.

Acknowledgments

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