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Growth of *Octopus vulgaris* in the Northeastern Iyo-Nada of the Seto Inland Sea, Japan

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Monthly length-at-age data of six cohorts of *Octopus vulgaris* in the northeastern Iyo-Nada of the Seto Inland Sea, Japan, were fitted to the following four equations: the ordinary von Bertalanffy equation, the simplified logistic equation, the von Bertalanffy equation extended by a sine wave function, and the logistic equation extended by a sine wave function. As a result, we adopted the last equation ($L_t = L_\infty/(1+\exp(-(A\sin(2\pi(t-s)/12)-b+ct)))$, where L_t is the ventral mantle length in cm at t months after hatching) as the optimal fit growth model for *O. vulgaris*, based both on growth patterns during the early stages and on the Akaike's information criterion (AIC) analysis. Parameters of the October-hatching cohort, which was the main one in Iyo-Nada, were as follows: $L_\infty=11.64$; $A=0.524$; $s=-4.245$; $b=4.462$; $c=0.520$.

Key words: allometric equation, growth curve, Iyo-Nada, logistic curve, *Octopus vulgaris*

Introduction

The edible octopus, *Octopus vulgaris*, is an important commercial species in Japan. However, there are very few detailed reports about population ecology of this species. Tanaka (1958) described two spawning groups, spring- and autumn-spawning, on the east coast of the Boso Peninsula, Japan. Another two groups, animals living in coastal waters throughout the year and those migrating between regions, have also been observed (Tanaka, 1958; Akimoto and Sato, 1980). Growth rates of *O. vulgaris*, based on length- or weight-frequency data, have been reported from Japan (Tanaka, 1958; Itami *et al.*, 1963), the Mediterranean Sea (Mangold-Wirz, 1963; Mangold and Boletzky, 1973; Guerra, 1979), European waters (Nixon, 1969) and the northwest coast of Africa (Guerra, 1979; Hatanaka, 1979). Itami *et al.* (1963) described the growth in total length of individuals, which were reared in a glass vessel. Mangold-Wirz (1963) estimated growth of the animal with the dorsal mantle length for each sex. Nixon (1969) summarized the information given by Mangold-Wirz (1963), and calculated the averages of male and female body weights deduced from the relationship between the dorsal mantle length and the body weight. Nixon (1969) then derived a hypothetical growth curve from these averages, and the longitudinal and cross-sectional data of populations, which were further investigated. Hatanaka (1979) calculated curves using von Bertalanffy equations with averaged total length of spring- and autumn-spawning groups. Guerra (1979) calculated curves using von Bertalanffy equations with the mean mantle length. However, these estimates of growth rates were unlikely to be comparable with one another, because the population structures were not clarified in most waters and body size measurements differed among studies.

We estimated the population structure of *O. vulgaris* in the northeastern Iyo-Nada of the Seto Inland Sea, Japan, with length-frequency data from small beam-trawls and octopus-pots from 1997 to 1998 (Sakaguchi *et al.*, 2000). Six cohorts, which hatched in June, July, August, September, October and November, were discriminated. In the present paper, we propose mean growth equations for *O. vulgaris* fitted to each of these cohorts because the growth varies seasonally.

Materials and Methods

The following four equations were tested for fit to the monthly mean ventral mantle length of the six cohorts of *Octopus vulgaris*: the ordinary von Bertalanffy equation (Bertalanffy, 1938; Nose *et al.*, 1988), the simplified logistic equation (Nose *et al.*, 1988), the von Bertalanffy equation extended by a sine wave function (Pitcher and MacDonald, 1973), and the logistic equation extended by a sine wave function proposed by the present study. Pitcher and MacDonald (1973) gave an extended form of the von Bertalanffy equation as follows: $L_t=L_\infty(1-e^{-K_1})$, where $K_1=C\sin(2\pi(t-s)/12)+K(t-t_0)$, L_t=length (cm) at age t (months), L_∞=asymptotic length (cm) towards which fish are growing, C=additional constant, s=starting point for

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Table 1. Allometric equations of *Octopus vulgaris*. TL, total length; ML, mantle length; BW, wet body weight; VML, ventral mantle length.

Size measurements		Allometric equations	n	r	P
X (range)	Y (range)				
TL (32–86 cm)	VML (5.3–13.5 cm)	$Y=0.3156X^{0.8502}$	183	0.868	<0.001
ML (4.2–22.0 cm)	VML (3.2–15.9 cm)	$Y=0.7847X^{1.0142}$	2984	0.976	<0.001
BW (23–4090 g)	VML (3.2–15.9 cm)	$Y=1.1250X^{0.3185}$	2984	0.968	<0.001

the sine function, K=von Bertalanffy rate parameter, and t_0=hypothetical time at which model predicts zero size. Following them, we gave the logistic equation extended by a sine wave function as follows: $L_t=L_\infty/(1+e^{-K_1})$, where $K_1=A\sin(2\pi(t-s)/12)-b+ct$, L_t=ventral mantle length (cm) at age t (months), L_∞=asymptotic length (cm), A=additional constant, s=starting point for the sine function, b=location parameter and c=rate parameter.

Monthly mean ventral mantle length, which were calculated for six cohorts in northeastern Iyo-Nada for the period of 1997–1998 by Sakaguchi *et al.* (2000), were used for the analysis. As the growth rates were similar between males and females (Sakaguchi *et al.*, 2000), we combined the data for both sexes and both years (1997 and 1998) and calculated averages for each calendar month (the monthly average of the ventral mantle length of each cohort) to obtain mean growth equations for yearly variable data. Based on the mantle length of early juveniles (Sakaguchi *et al.*, 1999), the initial size value, 0.2 cm, at $t=0$ was used for the fitting. The data were fitted to the models using the Marquardt method (Draper and Smith, 1966) by computer. The optimal fit growth model for *O. vulgaris* was selected based both on the form of growth curves during the early stages and on Akaike's information criterion (AIC) (Akaike, 1973). The lowest value of AIC indicates the best fit (Akaike, 1973).

Size-measurement methods differ among previous studies (Itami *et al.*, 1963; Mangold-Wirz, 1963; Nixon, 1969; Guerra, 1979; Hatanaka, 1979). Thus, body sizes used in the studies were transformed to ventral mantle length with allometric equations (Table 1) to compare the growth curves estimated here with previous estimates. For *O. vulgaris*, three size-measurements have been employed (Fig. 1): the total length (TL), *i.e.* the distance from the mantle end to the top of the longest arm, the mantle length (ML), *i.e.* the distance from the dorsal mantle end to the midpoint between the eyes, and the ventral mantle length (VML), *i.e.* the distance from the mantle end to the front edge on the ventral mantle. A total of 2,984 specimens collected over a two year period from January, 1997 to December, 1998 in northeastern Iyo-Nada waters (Sakaguchi *et al.*, 2000), were used to obtain the relationship between the ventral mantle length and the mantle length, and between the ventral mantle length and the wet body weight. A total of 183 specimens sampled from July, 1997 to April, 1998 were used to calculate the relationship between the ventral mantle length and the total length.

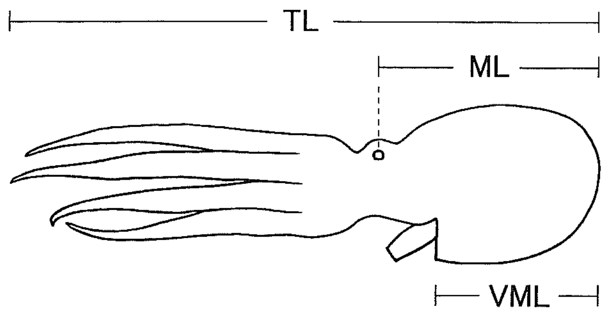

Figure 1. Size measurements of *Octopus vulgaris*. TL: total length, ML: mantle length, VML: ventral mantle length.

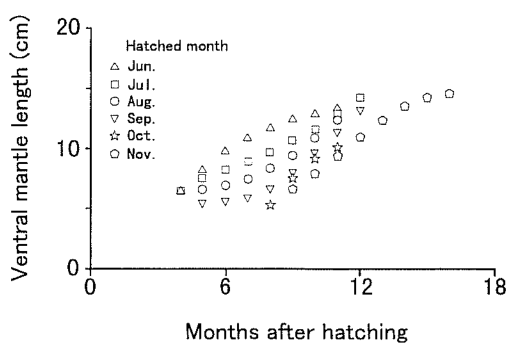

Figure 2. Monthly mean ventral mantle length of each hatching group. These values used in the present study were calculated from averages of both sexes and both years (1997 and 1998) from Sakaguchi *et al.* (2000).

Results

Growth equations were calculated for each cohort because the growth patterns of hatching groups were apparently different each other (Fig. 2). The AIC values of the four growth equations for each of the six cohorts are shown in

Table 2. AIC values for the fit of four different growth equations (the ordinary von Bertalanffy model, the simplified logistic model, the von Bertalanffy model extended by a sine wave function, and the logistic model extended by a sine wave function) to six monthly cohorts.

Month of hatching	AIC for growth equations			
	Bertalanffy	Logistic	Bertalanffy extended	Logistic extended
June	−16.33	−14.66	−45.50	−35.40
July	−10.75	2.17	−34.42	−24.15
August	−5.07	0.68	−29.52	−29.87
September	5.11	−0.81	−32.71	−25.67
October	5.54	−18.75	−39.33	−52.43
November	5.47	−29.31	−38.94	−64.37

Table 2. Both the extended von Bertalanffy equation and the extended logistic equation fit well. Itami *et al.* (1963) reported *O. vulgaris* hatching in June grew 2.8 g in average weight (19 mm in average mantle length) at two months-old. The Hiroshima Prefectural Fisheries Experimental Station (1989) described the animal grew 3.3 g in average weight at two months after hatching in August. Villanueva *et al.* (1995) noted the animal hatching in summer grew 8.5 mm in mantle length at two months-old. These reports also supported the results of the extended logistic equation. Finally, the extended logistic equation was judged to be the optimal growth model for *O. vulgaris*, because the growth rate calculated by the extended von Bertalanffy equation was too high for a few months after hatching in some of the cohorts (Fig. 3). The parameters of the extended logistic equation are presented in Table 3. These equations described the seasonal growth of *O. vulgaris* well. Growth rates decreased to low levels from December to April, when water temperatures were low (Figs. 4, 5). High rates of growth continued until death, although they varied seasonally (Fig. 5).

Discussion

Our six growth curves were compared with previous growth curves, which were obtained using ventral mantle length estimated from the allometric equations (Table 1). No previous reports have adopted a logistic curve as a growth equation for *O. vulgaris*. Guerra (1979) and Hatanaka (1979) described *O. vulgaris* growth by the von Bertalanffy curve. Others denoted the growth pattern by body sizes with no equations (Itami *et al.*, 1963; Mangold-Wirz, 1963; Nixon, 1969). The growth rate of the June-hatching cohort of the present study is close to that of Nixon (1969), except for young ages less than four months.

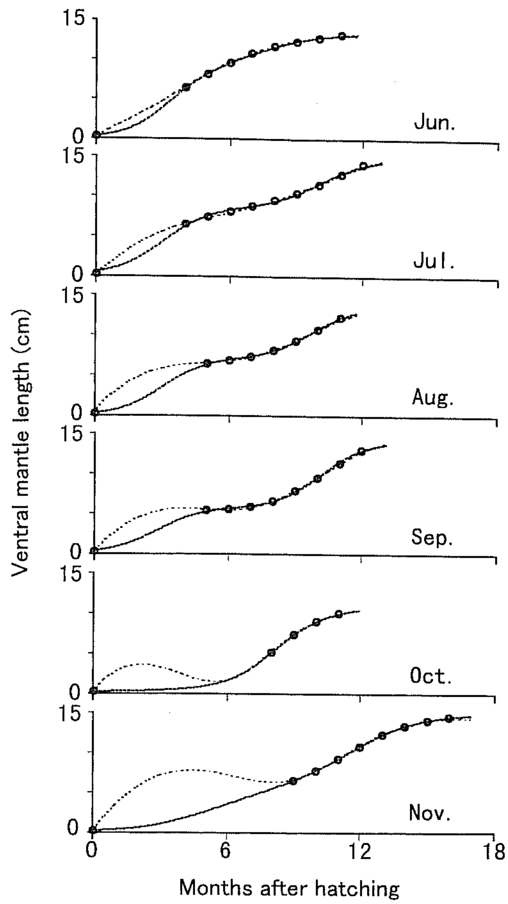

Figure 3. Fit of the growth models extended by a sine wave function to mean ventral mantle length of six cohorts, June-, July-, August-, September-, October-, and November-hatching groups, of *Octopus vulgaris* in the northeastern Iyo-Nada of the Seto Inland Sea, Japan. Solid and dotted curves denote the extended logistic model and the extended von Bertalanffy model, respectively. Open circles denote the data used to calculate the growth equations. The initial size value, 0.2 cm, at $t=0$ was used for the fitting. The other data were averages for each calendar month in ventral mantle length from a previous study (Sakaguchi *et al.*, 2000).

The November-hatching cohort has a similar growth pattern to those described by Guerra (1979). However, Guerra's curves are unrealistic during three months after hatching because of having zero in ventral mantle length during the period. Itami *et al.* (1963) carried out a rearing experiment with juveniles of *O. vulgaris* from the Seto Inland Sea, that hatched in June. The difference of the length among our growth curves for the June- to September-hatching cohorts and Itamis' result are less than 1.3 cm. The growth rates estimated by Mangold-Wirz (1963) and Hatanaka (1979) are low in comparison with ours at advanced age. These two authors may have misidentified cohorts of the same year age as cohorts of different year age.

Table 3. Parameters estimated for the logistic equation extended by a sine wave function: $L_t=L_\infty/(1+\exp(-(A\sin(2\pi(t-s)/12)-b+ct)))$ in which L_t=ventral mantle length (cm) at age t (months), L_∞=asymptotic length (cm), A=magnitude constant, s=starting point for the sine function, b=location parameter and c=rate parameter.

Month of hatching	Estimated parameters				
	L_∞	A	s	b	c
June	13.30	0.608	0.273	3.731	0.768
July	14.72	0.742	0.709	3.115	0.517
August	13.46	0.898	0.400	3.704	0.597
September	14.15	0.800	0.274	3.535	0.501
October	11.64	0.524	−4.245	4.462	0.520
November	15.11	0.292	2.008	4.049	0.436

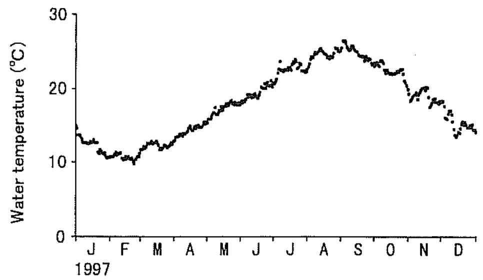

Figure 4. Daily water temperature in rearing tanks at the Ehime Prefectural Chuyo Fisheries Experimental Station in 1997. The temperature is almost equal to that of the coastal waters of eastern Iyo-Nada of the Seto Inland Sea, Japan.

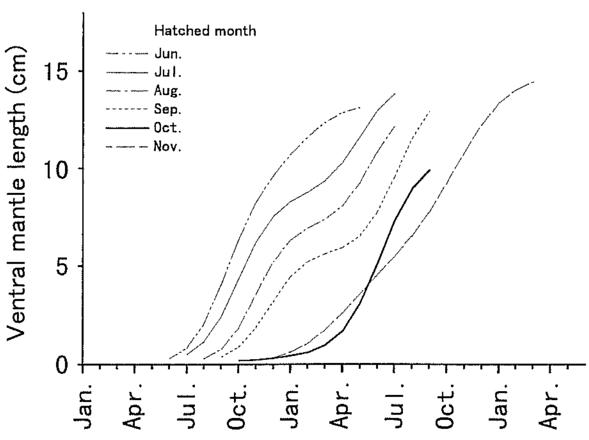

Figure 5. Growth curves of six cohorts, June-, July-, August-, September-, October-, and November-hatching groups from equations in the present study of *Octopus vulgaris* in the northeastern Iyo-Nada of the Seto Inland Sea, Japan. The equation for the November-hatching cohort is doubtful because the curve of the October-hatching cohort and that of the November-hatching cohort unnaturally crossed each other.

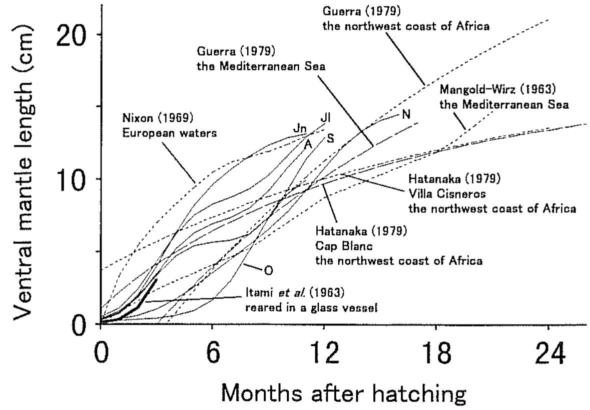

Figure 6. Comparison with previous results on growth of *Octopus vulgaris*. Solid curves denote growth curves from the present study. Dotted, broken and bold curves are those from previous studies. Jn, Jl, A, S, O and N indicates the hatching month of each cohort of June, July, August, September, October and November, respectively. Body sizes used in previous studies were transformed to ventral mantle length using allometric equations in Table 1. Individuals of Itami *et al.* (1963) were from the Seto Inland Sea, Japan.

Sakaguchi *et al.* (2000) reported that there were two groups within the November-hatching cohort whose lifespans were approximately 11 months and 16 months. We suggest that the group with the shorter lifespan grow and sexually mature faster. However, we cannot distinguish the two groups from the size frequency distribution, so the growth of the November-hatching cohort is expressed as a single curve. The curve of the October-hatching cohort and that of the November-hatching cohort unnaturally crossed each other as a result. Consequently, the equation for the November-hatching cohort is doubtful although the AIC indicated it fit well (Table 2, Figs. 3, 5, 6). To obtain a full picture of *O. vulgaris* growth, it is necessary to investigate the growth and behavior of each group in detail.

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伊予灘北東海域におけるマダコ *Octopus vulgaris* の成長

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愛媛県伊予灘のマダコの6発生群について求められていた月齢と月別平均外套腹面長の値に対し，成長式として，ベルタランフィー式，ロジスティック式，周期関数を含むベルタランフィー式，周期関数を含むロジスティック式，を適用した．その結果，AICで比較したところ，周期関数を含む2つの式の当てはまりが良かったが，最終的には，幼稚仔期の成長パターンを考慮し，周期関数を含むロジスティック式が最良であると判断した．採用した式は以下のとおりである：$L_t=L_\infty/(1+\exp(-(A\sin(2\pi(t-s)/12)-b+ct)))$，$L_t$は月齢$t$歳の外套腹面長 (cm): L_∞，A，s，b，cは定数．当海域における主産卵群である10月発生群の定数はそれぞれ，$L_\infty=11.64$; $A=0.524$; $s=-4.245$; $b=4.462$; $c=0.520$と計算された．

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