

Research Article

Age estimation and individual growth of dwarf hake *Merluccius productus* along the southernmost limit of the Baja California Peninsula

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ABSTRACT. The Pacific hake *Merluccius productus* is a commercially important species on the west coast of North America. A non-exploited population south of the Baja California Peninsula known as dwarf hake, from which little is known, has been described. The present study analyzed the age and growth of the dwarf hake off the west coast of Baja California Sur, Mexico. A subsample of 240 otoliths and standard length (SL) data from 932 specimens captured from May to December 2015 was used. The annual formation of increments in otoliths was verified by marginal increment ratio and edge analysis. Age was estimated from transversal sectioned otolith annuli counts, and SL growth was analyzed using a multimodel inference approach. The von Bertalanffy growth model (VBGM), generalized VBGM, Gompertz, logistic, and Johnson growth models were fitted to observed and back-calculated length-at-age data sets grouped by sex. SL records ranged from 11.5 to 27.5 cm, where females reached a larger size and older ages than males. The age structure was well represented for the first six years, with a mode at three years age class and maximum longevity registered in a female of 10 years. According to Akaike's information criterion, the generalized VBGM was most appropriate for females ($L_{\infty} = 31.36$ cm, $k = 0.15$), while VBGM provided the best fit for males ($L_{\infty} = 25.35$ cm, $k = 0.28$ cm yr⁻¹). The parameter values suggest that the dwarf hake is a fast-growing, small-size fish. These results provide the first estimated growth parameters for the dwarf hake off the southernmost limit of the Baja California Peninsula.

Keywords: *Merluccius productus*; Pacific hake; individual growth modelling; multimodel inference; back-calculation; *sagitta* otoliths

INTRODUCTION

Merluccius productus (Ayers, 1855) is a groundfish of commercial importance with a wide distribution, ranging from Alaska to the Gulf of Tehuantepec, Mexico (Lloris et al. 2005). Different populations of the species have been described: a very large migratory population shared between the USA and Canada that supports an important fishery (Alverson & Larkins 1969), some spatially restricted resident populations (e.g. the one located in the Strait of Georgia) (King et al. 2012), a population located in the northern Gulf of California area in Mexico (Iwamoto et al. 2015) which

has been recently commercially exploited, and a population present off the west coast of Baja California Sur (BCS), Mexico, defined as "dwarf hake" for its reduced sizes and low longevity, in contrast with other stocks described (Vrooman & Paloma 1977, Balart-Páez 2005, Hamel et al. 2015).

Due to its commercial and ecological importance (Hamel et al. 2015), *M. productus* has been widely studied in the USA and Canada (Best 1963, Bailey et al. 1982, Smith 1995, Benson et al. 2002, Malick et al. 2020); however, the information available in Mexico is limited, especially regarding the dwarf hake. This non-exploited and abundant population of dwarf hake

(Balart 1996, Godínez-Pérez 2013) is a potential resource. Nonetheless, there is little information on its biology and population dynamics; therefore, essential data for management, such as age and growth parameters, remain uncertain.

Age and growth have been well studied for the USA and Canada stocks, mainly based on otolith growth increment counts. Different techniques have been applied, such as complete otolith readings (Dark 1975), sagittal sections of otolith readings (Beamish 1979), and burnt otolith sections (MacLellan et al. 2021), obtaining different results. In Mexico, Álvarez-Trasviña et al. (2022) studied the Pacific hake of the northern Gulf of California, concluding that the logistic model best describes its growth. Regarding the dwarf hake, Vrooman & Paloma (1977) reported the size of first maturity (11.9 cm males and 12.5 cm females) and the age of first sexual maturity (one year) using analysis of otoliths, concluded that the dwarf hake has a lower growth rate than that observed for the USA hake. However, in addition to this work, there is no information about the age and individual growth of the population.

Age and growth studies provide essential information to understand the organism's life cycle and population dynamics. From these studies, it is possible to describe basic aspects, such as longevity, age at first maturity, and mortality rate (Morales-Nin 1992, Campana, 2001). Therefore, this research aims to estimate the age and describe the individual growth pattern to provide the first published study of the growth parameters of the dwarf hake stock off the western coast of BCS.

MATERIALS AND METHODS

Collection of samples

A prospective study was carried out in the southernmost portion of the California Current System off the central portion of the western coast of BCS, south of the Gulf of Ulloa in front of Bahía Magdalena (24.3°N, 112.1°W, Fig. 1). The study assessed the presence and abundance of dwarf hake and consisted of a total of 11 cruises on board of the oceanographic vessel BIP XII from May to December 2015. A hydroacoustic assessment to detect hake was performed, and posterior mid-water diurnal trawls were made. Nine hundred thirty-two specimens from 84 trawls were randomly selected and measured for standard length (SL, cm). Then, a subsample of 240 specimens was dissected to collect *sagitta* otoliths, maintaining well-represented length classes. A Kolmogorov-Smirnov distribution test was

used to examine for differences by sex in SL structure ($n = 932$).

Otolith preparation and reading

Due to the poor visualization of the growth marks in complete otoliths, the procedure described by Dark (1975) was followed. Otoliths were cleaned of tissue and other debris; they were washed with running water and 96° ethyl alcohol, after which they were dried at room temperature for 24 h. For age estimation, the left otolith was employed to maintain consistency. Following Cabrera-Neri (2002), the structures were toasted in a conventional microwave oven (2.45 GHz) for 45 s, aiming to enhance the contrast between the translucent and opaque growth bands.

Subsequently, otoliths were fixed with an epoxy resin and let dry for 24 h. After this, transversal sections were cut from each otolith using a low-speed saw (IsoMet® Buehler™) with a diamond blade (IsoMet Series 15LC; 0.3-mm thickness and 102-mm diameter). Sections were made, ensuring to cut over the nucleus of the otolith, and polished with 600 and 1500-grit wet sandpaper until a ~0.2 mm thickness was reached. The sections were viewed under a stereomicroscope at 20-40x magnification and transmitted light. Photographs from the sections were taken with a Zeiss AxioCam ERc 5s camera.

The reading of growth increments was based on the work of Piñeiro et al. (2009), taking as reference the presence of two to three evident marks before the first annual mark (annulus), corresponding to the changes of larval, pelagic, and demersal stages of the organisms respectively. Following the described methodology, the opaque bands were dark, while the translucent bands were bright. For the reading of otolith sections, the translucent bands were counted (Fig. 2). The dorso-ventral axis of the cuts was used as a counting reference, and the ventral portion was identified as the best area for reading (Beamish 1979, Piñeiro & Saínza 2003).

Precision and accuracy

Two readers counted the growth marks independently, and the otolith edge type was registered as opaque or translucent. Count reproducibility, as indicated by reader variability, was determined by calculating the percent of agreement (PA) by ± 1 annulus, the average percent error (APE) (Beamish & Fournier 1981), and the coefficient of variation (CV) (Chang 1982). In addition, a bias analysis was performed, the Bowker's test of symmetry (Bowker 1948).

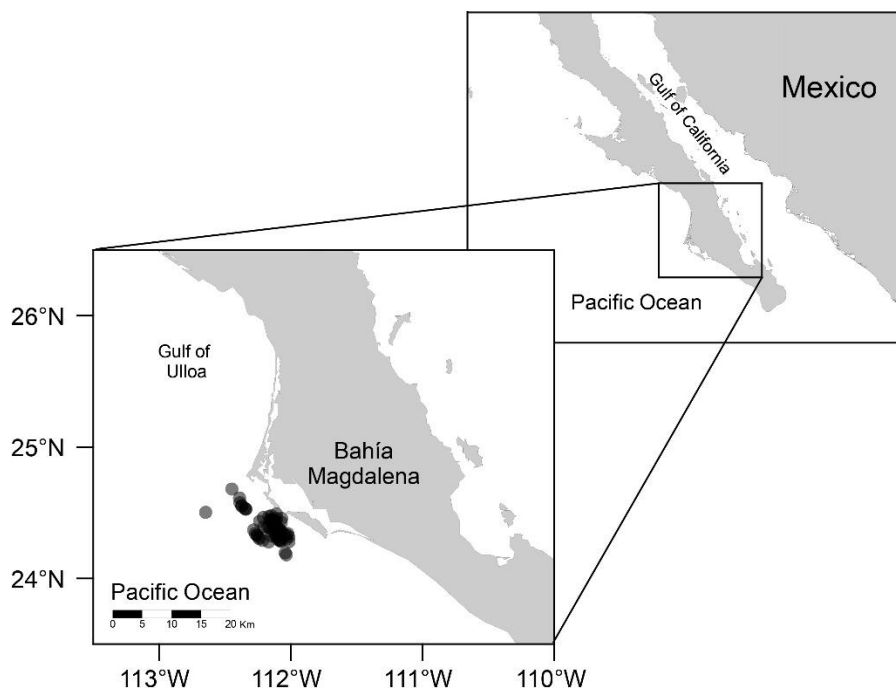


Figure 1. Location of the study area Bahía Magdalena on the Pacific coast of Baja California Sur and the sampling locations.



Figure 2. Transversal section of a *sagitta* otolith of a three-year-old male dwarf hake *Merluccius productus* specimen with 15.8 cm standard length. Photographs taken under transmitted light show the area around the nucleus (N) with three visible false rings (-3, -2, and -1) previous to the first annulus. Va: ventral apex, Da: dorsal apex, S: sulcus, AS: ant sulcus.

Periodicity of annulus deposition

The periodicity of increment formation in the otoliths was assessed using edge analysis and the marginal increment ratio (MIR) methods. The otolith edge analysis considers the last deposited growth band (opaque or hyaline) and relates it to the month of capture. The MIR is defined as the distance between the last completely formed increment to the edge of the otolith (marginal width) as a proportion of the previous increment width for every month (Ewing et al. 2003):

$$MIR = \frac{MW}{PW} = \frac{OR - R_n}{R_n - R_{n-1}} \quad (1)$$

where *MIR* is the marginal increment ratio, *MW* is the marginal width, *PW* is the previous increment width *OR*

is the otolith radius, R_n is the distance from the nucleus to the last completed growth mark, and R_{n-1} is the distance from the nucleus to the penultimate complete growth mark. The measures were taken using the SigmaScan Pro 5.0.0 Software (SPSS Inc., Chicago, IL, USA), and the individuals with only one annulus were excluded from the analysis.

A notorious consecutive reduction occurs in the width of the first three annuli, related to the fast growth observed in the annual increments in the first three years (Piñeiro et al. 2009). Accounting for this, in the calculation of MIR, the thickness of annulus 3 was scaled as a proportion of annulus 2 and annulus 4 as a proportion of annulus 3. In this sense, an arithmetic

mean was estimated for each proportion, and its significance was assessed with a Wilcoxon signed-rank test. Mean MIRs were plotted against months to examine trends in band formation, and a Kruskal-Wallis test was used to examine for differences among months, followed by a nonparametric Dunn *post-hoc* test to identify the months that showed differences.

Age structure

Considering the periodicity of increments deposition, the number of increments counted during the otolith section readings, and the capture date, each specimen was assigned to an age group. It was agreed that the assigned age would correspond to the number of translucent bands when the otolith edge was opaque.

Back-calculation

Due to the poor representation of young dwarf hakes in the sample, back-calculated lengths were calculated using the proportion-based back-calculated equation proposed by Francis (1990):

$$L_i = -\left(\frac{a}{b}\right) + \left(L_c + \frac{a}{b}\right) \left(\frac{OR_i}{OR_c}\right) \quad (2)$$

where L_i is the SL at time i , a and b are parameters obtained from the linear relation between SL and otolith radius, L_c is the SL at capture, OR_c is the OR at capture, and OR_i is the OR at age i .

Individual growth

A multimodel inference approach was used to determine the most appropriate growth model (Burnham & Anderson 2004). Considering the presence of scattered length-at-age data, the mean size of each age group was used to increase the accuracy of the estimation of the growth model parameters (Katsanevakis 2006). The following asymptotic growth models were considered:

1. The von Bertalanffy growth model (VBGM), which considers a linear growth rate decrease with size (von Bertalanffy 1938):

$$L_t = L_\infty [1 - e^{-k(t-t_0)}] \quad (3)$$

2. The generalized VBGM includes an additional parameter (δ), that provides an inflection point in the growth curve, offering greater flexibility (Pauly 1979):

$$L_t = L_\infty [1 - e^{-k(t-t_0)}]^\delta \quad (4)$$

3. The Gompertz growth model, a sigmoid alternative with an asymmetrical inflection point that considers exponential decrease of growth rate with size (Gompertz 1825):

$$L_t = L_\infty \times e^{(-e^{-k(t-t_0)})} \quad (5)$$

4. The logistic model, with an inflection point at t_0 (Ricker 1975):

$$L_t = \frac{L_\infty}{(1 + e^{(-k(t-t_0)})})} \quad (6)$$

5. The Johnson growth model, which is an asymmetrical sigmoid model with an inflection point close to zero (Hidalgo-De-La-Toba et al. 2015):

$$L_t = L_\infty * e^{-\left[\frac{1}{k}*(t-t_0)\right]} \quad (7)$$

where L_t is the SL at age t , L_∞ is the asymptotic length, t_0 is the theoretical age at size 0, k is the respective growth coefficient, and δ is a flexibility parameter; when $\delta = 1$, the model is equivalent to the VBGM. The growth models were fitted to a combination of sample data and back-calculated lengths for each sex, and the parameters were estimated, maximizing the negative log-likelihood with a nonlinear fit using the generalized reduced gradient method, assuming a multiplicative error in the residuals (Wang & Liu 2006). The objective function is expressed as follows:

$$\log L(\theta_i | data) = -\frac{n}{2} \times [\ln(2\pi) + 2 \times \ln(\sigma) + 1] \quad (8)$$

where n is the number of data, i indicates the number of parameters for each growth model, and for σ , the following equation was calculated (Hilborn & Mangel 1997):

$$\sigma = \sqrt{\frac{1}{n} \sum_{t=1}^n (\ln SL_O - \ln SL_E)^2} \quad (9)$$

where SL_O is the observed SL, and SL_E is the estimated SL. Once the best model for each sex was obtained, the likelihood test of Kimura (1979) was used to assess differences in the growth model parameters between sexes.

Confidence intervals

The confidence intervals (CI) were estimated for the θ_i parameters of each adjusted growth model using the likelihood profile method (Hilborn & Mangel 1997) considering a chi-square distribution with 1 degree of freedom (df), and values equal or less than 3.84 were accepted within the CI (Zar 2010). The CIs were defined as values of θ_i that satisfied the next:

$$CI = 2[L(Y|\theta) - L(Y|\theta_{best})] < \chi_{1,1-\alpha}^2 \quad (10)$$

where $L(Y|\theta_{best})$ is the corresponding negative log-likelihood for the most likely value of the θ_i parameter and $\chi_{1,1-\alpha}^2$ are the values of the chi-square distribution.

Model selection

Akaike's information criterion (AIC) was used to evaluate the model performance, and the best model showed the lowest AIC value. For comparison between

models, the Akaike differences (Δ_i) and Akaike weights (w_i) were calculated (Burnham & Anderson 2004). The Δ_i measures a candidate growth model relative to the best model ($\Delta_i = AIC_i - AIC_{\min}$) where AIC_i is the value for model i and AIC_{\min} is the value of the best model. Values of $\Delta_i = 0-2$ indicate substantial support, $\Delta_i = 4-7$ considerably less support, and $\Delta_i > 10$ no support. The Akaike w_i represents the probability of choosing the correct model from the candidate growth models and is calculated as follows:

$$w_i = \frac{e^{-0.5\Delta AIC}}{\sum_{i=1}^R e^{-0.5\Delta AIC}} \quad (11)$$

RESULTS

Collection of samples

Significant differences in SL were found between sexes ($D = 0.4333$, $P < 0.001$, $n = 932$), with the females larger than the males (Fig. 3). From a total of 240 otolith pairs that initially were used for the aging study, 190 (80%) were readable. One hundred nine otolith pairs corresponded to females, ranging in size from 11.5 to 27.5 cm SL, and 81 to males, ranging from 12 to 23.5 cm SL, with a well-represented sample for each sampled month of the year (Table 1). A significant linear relationship ($P < 0.001$) between otolith radius and SL was found for females ($SL = 0.3098 + OR \times 0.082$, $R^2 = 0.7148$) and males ($SL = 0.1626 + OR \times 0.0922$, $R^2 = 0.6455$), confirming the suitability of otoliths for age estimation.

Precision and accuracy

A high precision was found between readers. Annulus counts resulted in a PA of 68.7% and PA \pm by one annulus of 95.1%, with APE between readers of 4.6% and CV of 6.5%. The Bowker's test of symmetry ($\chi^2 = 15.62$, $df = 6$, $P = 0.98$) indicated no systematic differences between readers (bias). These results indicate a high level of reproducibility.

Periodicity of growth marks

The presence of many checks observed in the otolith structure complicated the readings. However, the identification of two to three evident checks before the first annulus, as described by Piñeiro et al. (2009), was identified in most otoliths. The classification of growth bands at the edge of the otoliths as translucent or opaque as possible and the calculation of the thickness of annulus 3 as a proportion of annulus 2, as well as annulus 4 to annulus 3 was significant ($\bar{x}_{3-2} = 1.82$, $P < 0.40$; $\bar{x}_{4-3} = 1.66$, $P < 0.81$). In this sense, differences in monthly marginal increments were found ($P <$

0.001). Both edge analysis and MIR showed an increasing trend observed from November to a maximum in October (Fig. 4), and the *post-hoc* test showed significant differences between October and November ($P < 0.001$). The results suggest the annual formation of a growth mark (annulus), completing its deposition in October.

Considering the formation of one annulus each year, 10 age groups were identified (Fig. 5). The third age group was the predominant, followed by age groups 2 and 4. The 6, 7, and 10 age groups were only represented by one fish, and groups 8 and 9 were not represented in the sample. The males were only represented in 1-5 years age groups. The age-length keys by sex can be found in Tables 2-3.

Growth estimation and model selection

The adjusted growth models showed a L_{∞} value between 26.2-31.3 cm SL for females and 20.1-31.3 cm SL for males, being males smaller in general (Table 4). However, the differences found in the parameters between sexes were not significant ($P = 0.290$). The interpretation of the k parameter varies depending on the inflection point in each model, which is not comparable between models. On the other hand, the theoretical age at size zero t_0 was found with values near the abscissa for all models. Both females and males showed a fast growth tendency in the first two years (Fig. 6), after which growth became slower, achieving similar size-at-age, but no males older than five years were observed. For both sexes, the growth curves in the graph do not reach the asymptotic size suggested by the growth models that are best suited for them.

According to the model selection criteria AIC, the best-fit growth model differed between sexes (Table 5). For females, the generalized VBGM was the only candidate model with empirical support ($\Delta_i < 2$), having an Akaike weight $w_i = 93\%$. For males, the VBGM obtained the lowest AIC value ($\Delta_i = 0$), with $w_i = 62\%$, and the generalized VBGM also showed empirical support ($\Delta_i < 2$), with $w_i = 24\%$.

DISCUSSION

Information on the age and growth of dwarf hake is very limited. Previously, Vrooman & Paloma (1977) estimated the age of dwarf hake on full otolith readings with a reduced sample size. Still, the periodicity of the formation of increments in the structure has yet to be verified. Verification of periodicity of increment formation is vital for the definition of age groups and

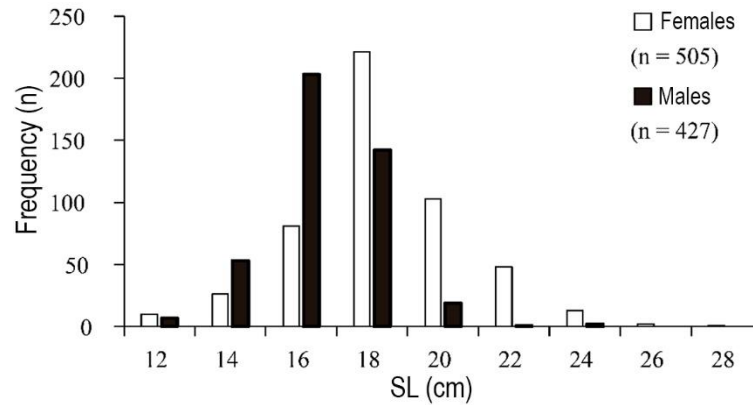


Figure 3. Length-frequency distribution of dwarf hake *Merluccius productus* females and males collected off Bahía Magdalena from May to December 2015. SL: standard length.

Table 1. The monthly sample size of dwarf hake *Merluccius productus* specimens obtained from May to December 2015 analyzed in this study.

Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sample size Females	12	18	18	11	16	8	13	13
Sample size Males	11	9	8	15	13	11	7	7

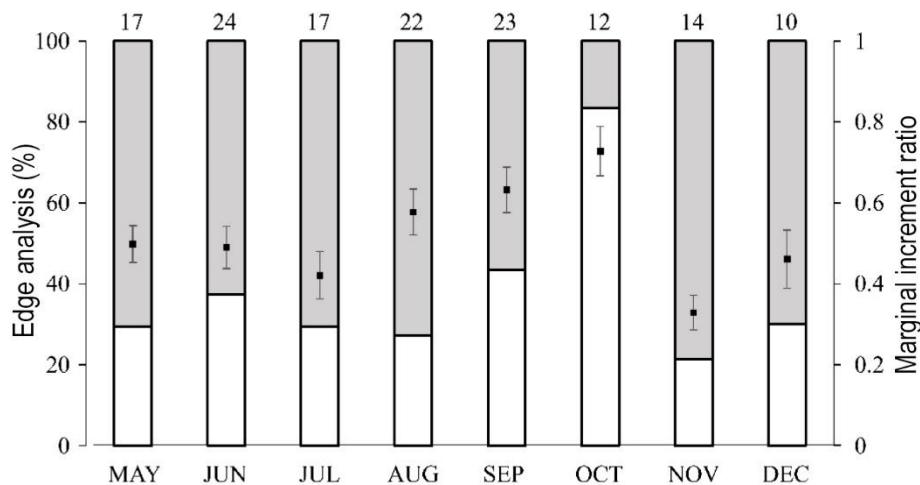


Figure 4. Monthly frequencies of otolith edge and marginal increment ratios. Translucent (□) and opaque bands (■) determined from otolith sections; mean monthly MIR (■); bars show the standard error for monthly values. The sample size is indicated at the top of the graph.

management (Campana 2001), as increment formation is a physiological process possibly related to environmental variations (Panfili et al. 2002). In our study, the formation of one annual increment in otoliths was verified through marginal increment analysis and edge analysis. Likewise, this has also been verified for northern Pacific hake stocks (Beamish 1979) and other species of the genus, such as *M. merluccius* (Colloca et

al. 2003), *M. australis* (Horn 1997) and *M. hubbsi* (da Costa et al. 2018).

For *M. productus* and other species for which age estimation is based on growth marks reading in otoliths, the age estimation depends largely on the interpretation of the pattern of increment formation in the structures, which is why measuring the accuracy and precision of readings is so important (Campana 2001). The high

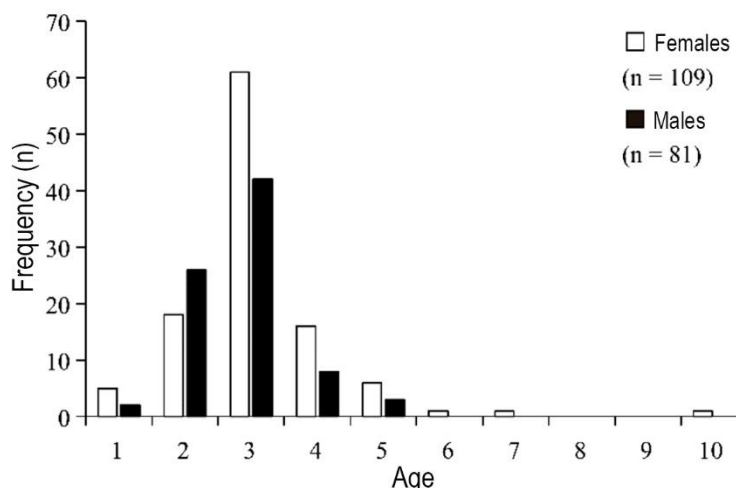


Figure 5. The age frequency distribution of dwarf hake *Merluccius productus* from the west coast of Baja California Sur.

Table 2. Age-length distribution of dwarf hake *Merluccius productus* females obtained from annuli counting of *sagitta* otolith sections and back-calculated.

Standard length (cm)	Age group										n
	1+	2+	3+	4+	5+	6+	7+	8+	9+	10+	
12	3										3
14	2	4									6
16		9	6	1							16
18		5	36	3							44
20			14	8	2						24
22			5	4	2	1					12
24					2		1				3
26											0
28										1	1
Total	5	18	61	16	6	1	1	0	0	1	109

Table 3. Age-length distribution of dwarf hake *Merluccius productus* males obtained from annuli counting of *sagitta* otolith sections and back-calculated.

Standard length (cm)	Age group					n
	1+	2+	3+	4+	5+	
14	2	6				8
16		20	27	2		49
18			13	4		17
20			2	2	1	5
22					1	1
24					1	1
Total	2	26	42	8	3	81

precision of our work is consistent with that proposed by Campana (2001), with APE values < 5.5% and CV < 7.6%, suggesting a high reproducibility of the readings. However, it is important to mention that, to date, there is no standard approach for annulus reading

in otoliths of dwarf hake, so this work aims to lay the foundations for future approaches.

Despite the small sample size analyzed, we assume the samples represented the dwarf hake population. This idea is supported by sampling across the year, and the size distribution found was similar to that previously reported by Vrooman & Paloma (1977), even representing a greater size range than that described by said authors.

The maximum age and size observed for dwarf hake in our analysis were 10 years and 27.5 cm SL, contrasting with the reported for other *M. productus* stocks. For the coastal Pacific hake stock off the west coast of the USA and Canada, a maximum age of 17 years has been reported (Best 1963). A maximum age of 15 years has been considered for management (Edwards et al. 2022), with maximum sizes over 80 cm total length. For the *M. productus* stock in the northern

Table 4. Parameter values of adjusted growth models to dwarf hake *Merluccius productus* data. Confidence intervals estimated from log-likelihood profiles are shown in parentheses. VBGM: von Bertalanffy growth model, L_{∞} : asymptotic length, t_0 : theoretical age at size 0, k: growth coefficient, δ : flexibility parameter.

Sex	Parameter	VBGM	Generalized VBGM	Gompertz	Logistic	Johnson
Females	L_{∞}	28.236 (27.6-28.9)	31.362 (30.9-31.875)	26.989 (26.1-27.9)	26.243 (25.1-27.35)	30.595 (29.3-31.85)
	k	0.251 (0.238-0.266)	0.154 (0.148-0.16)	0.380 (0.335-0.433)	0.523 (0.43-0.64)	0.517 (0.463-0.575)
	t_0	0 (-0.21-0.11)	0.181 (0.08-0.275)	1.775 (1.5-2.06)	2.737 (2.35-3.1)	0 (-0.47-0.16)
	δ		0.708 (0.68-0.73)			
Males	L_{∞}	25.352 (24.3-26.4)	31.358 (30.6-32.1)	21.285 (20.5-22.1)	20.115 (19.75-21.05)	25.155 (24-26.4)
	k	0.281 (0.26-0.303)	0.144 (0.138-0.151)	0.612 (0.54-0.7)	0.925 (0.775-1.125)	0.654 (0.59-0.73)
	t_0	0.022 (-0.14-0.18)	0.236 (0.145-0.31)	1.419 (1.26-1.58)	1.947 (1.732-2.161)	0 (-0.27-0.1)
	δ		0.708 (0.685-0.73)			

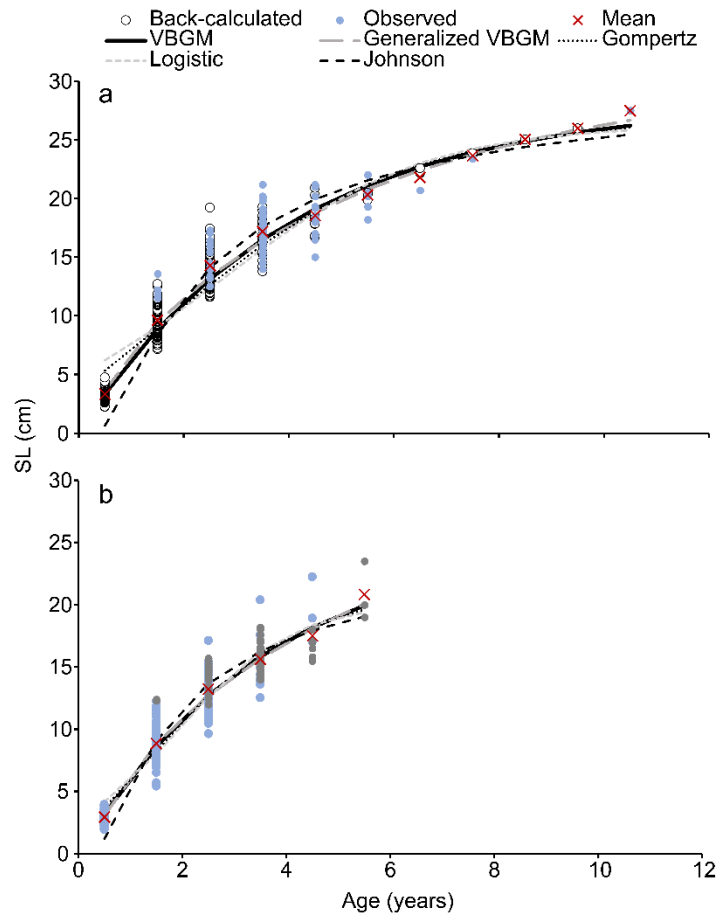


Figure 6. Candidate growth models adjusted to dwarf hake *Merluccius productus*: a) females, and b) males, sampled off the west coast of BCS. SL: standard length.

Table 5. Ranking of the five models based on the Akaike information criterion (AIC) with their respective number of parameters (θ_i), Akaike differences (Δ_i), Akaike weights (w_i), and percent Akaike weights (w_i (%)).

Sex	Model	θ_i	AIC	Δ_i	w_i	w_i (%)
Females	Generalized VBGM	4	25.98	0.00	0.93	93.05
	VBGM	3	31.22	5.23	0.07	6.80
	Gompertz	3	39.21	13.23	0.00	0.12
	Johnson	3	43.14	17.16	0.00	0.02
	Logistic	3	44.12	18.13	0.00	0.01
Males	VBGM	3	17.98	0.00	0.62	61.50
	Generalized VBGM	4	19.85	1.86	0.24	24.23
	Gompertz	3	21.67	3.69	0.10	9.72
	Logistic	3	24.43	6.44	0.02	2.45
	Johnson	3	24.74	6.75	0.02	2.10

Gulf of California, Mexico, Alvarez-Trasviña et al. (2022) described a maximum age of 13 years with a maximum size of 105 cm SL.

The difference in sizes and longevity described for Pacific hake stocks concerning the results for dwarf hake here is remarkable; dwarf hake was formerly described as a different species (*M. angustimanus*) (Mathews 1975, Balart-Páez 2005). However, despite the dimorphism between populations, it is considered to belong to the same *M. productus* species based on genetic and meristic analysis (Silva-Segundo et al. 2011, García-De León et al. 2018). Although more information is needed, differences in size could be due to different conditions of food supply and environmental variables such as temperature, considering that species distributed over large areas may show growth differences (Silva et al. 2008, da Costa et al. 2018), particularly organisms living at its southern distribution limits may present lower sizes and longevity (Hidalgo-De-La-Toba et al. 2015).

The different growth models tested in this study represent different growth pattern hypotheses. For the dwarf hake population, we found that the individual growth was better described by a negative exponential pattern than a sigmoid. Moreover, although not significant, differences were observed concerning growth between sexes, especially regarding the maximum observed size. Sexual dimorphism has also been reported for northern Pacific hake stocks (Stewart et al. 2011) and the northern Gulf of California stock (Álvarez-Trasviña et al. 2022), and other species of the genus such as *M. merluccius* (Piñeiro & Saínza 2003) and *M. hubbsi* (da Costa et al. 2018).

The growth of dwarf hake females was best represented by the generalized VBGM, followed by the VBGM with considerably less support ($\Delta_i = 5.23$). In

contrast, two models with substantial support represented the males' growth, the VBGM ($\Delta_i = 0$) and the generalized VBGM ($\Delta_i = 1.86$). Asymptotic size observed in females was greater ($L_\infty = 31.4$ cm SL) than in males ($L_\infty = 25.4$ cm SL). The growth rate was not comparable because of differences between growth models; since the δ values of the generalized VBGM adjustment for both sexes were close to 1, it can be considered that the models were close to VBGM, which showed a lower growth coefficient for females ($k = 0.25$ yr⁻¹) than males ($k = 0.28$ yr⁻¹). Moreover, it was possible to observe that similar mean size-at-age was presented between sexes, with the males maintaining a constant lower mean size. Considering this phenomenon and the fact that the growth curves do not reach asymptotic size, both sexes of dwarf hake could reach larger sizes beyond their respective observed older ages. Further studies are recommended to increase the sample size to test this hypothesis.

According to the Δ_i values, the VBGM and generalized VBGM showed substantial support to describe the growth in males (<2). However, the Akaike weight (w_i) allowed us to determine that VBGM was the best-fit data model with 62% evidence, in contrast with 24% from the generalized VBGM; the integration of more length-at-age data could improve the analysis to define a single model to describe the growth of the specie. The von Bertalanffy growth model parameters for males in this study ($L_\infty = 25.4$ cm SL and $k = 0.28$ yr⁻¹) indicate a reduced maximum size and a high growth rate, the latter being similar to the growth rate reported for the coastal Pacific hake stock off the west coast of USA and Canada ($k = 0.35$ yr⁻¹), although in such stock the maximum size is markedly larger ($L_\infty = 55$ cm SL) (Stewart et al. 2011) (Table 6), indicating that both stocks have fast growth concerning the maximum size they reach, the northern stock reaches larger sizes.

Table 6. Summary of growth parameters estimates of Pacific hake, *Merluccius productus*, previously reported by various authors. VBGM: von Bertalanffy growth model, L_{∞} : asymptotic length, t_0 : theoretical age at size 0, k : growth coefficient, δ : flexibility parameter. FL: fork length, SL: standard length.

Reference	Growth model	Sex	Age (years)	L_{∞} (cm)	k	t_0	δ	Study area
Dark (1975)	VBGM	Female	13	61.23 FL	0.3	0.01		USA west coast
		Male	12	56.29 FL	0.34	0.2		
McFarlane & Beamish (1985)	VBGM	Both	20	44.5 FL	0.457	-0.173		Strait of Georgia, Canada Offshore stock
		Both	19	56.9 FL	0.233	-3.043		
		Both	5	32.733 SL	0.282	-0.828		
Balart-Páez (2005)	VBGM	Female	5	32.87 SL	0.287	-0.798		Western coast of Baja California Sur, Mexico
		Male	4	33.04 SL	0.27	-0.881		
Zamora-García (2021)	Gompertz	Female	13	87.16 SL	0.28	2.24		Northern Gulf of California, Mexico
		Male	9	78.27 SL	0.3	199		
Álvarez-Trasviña et al. (2022)	Logistic	Female	13	113.23 SL	0.32	6.53		Northern Gulf of California, Mexico
		Male	9	82.33 SL	0.41	4.55		
Present study	Generalized VBGM	Female	10	31.362 SL	0.154	0.181	0.708	Western coast of Baja California Sur, Mexico
	VBGM	Male	5	25.352	0.281	0.022		

Our results indicate that the dwarf hake presents its greatest growth during the first two years of life. Vrooman & Paloma (1977) reported that the dwarf hake is similar in size to the USA-Canada coastal stock during its first year of life, after which the growth of the dwarf hake is much slower. In our study, the mean observed SL for age group one of dwarf hake was 12.2 cm, a lower length than the 13.6 cm reported by Vrooman & Paloma (1977) and the 13.7 cm reported for USA-Canada coastal stock by Best (1963). Nonetheless, it is recommended to reassess this comparison since, from 1990, a dramatic reduction of the maximum size and its corresponding increase in the growth rate was observed in the USA-Canada coastal stock (Stewart et al. 2011).

Vrooman & Paloma (1977) defined one year old as the age of first maturity for the dwarf hake, between 11.9 and 12.5 cm SL. Therefore, considering that over 93% of our sample were two years old or older, and our study's most abundant age group was three (over 15 cm SL), it is possible to assume that most of the analyzed catch corresponded to mature organisms. Even so, we recommend analyzing the age and size at first maturity of the dwarf hake to define management measures such as minimum catch size.

The results presented are the first approach to account for the growth parameters of the dwarf hake off the west coast of BCS, and they are a vital point of comparison since it is a virgin stock. We recommend assessing the months that are not sampled to update the increment periodicity verification in complementary studies. Finally, a special effort will be required to

capture older specimens and enhance the growth parameters estimates in the dwarf hake.

Credit authorship contribution statement

P. Mora-Zamacona: conceptualization, formal analysis, investigation, methodology, software, validation, visualization, writing-original draft, writing-review and editing. C.A. Salinas-Mayoral: conceptualization, data curation and methodology. S.S. González-Peláez: formal analysis, methodology, software, investigation, writing-review and editing. C.A. Salinas-Zavala: conceptualization, investigation, funding acquisition, project administration, resources, writing-review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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