NOTE

Modal and empirical lengths at sexual maturity for six deep-sea species in Ecuadorian oceanic waters

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ABSTRACT. The objective of the present work was to establish modal lengths, empirical lengths at sexual maturity, and proportions of mature individuals of six deep-sea species from the bycatch of the experimental fishery for Patagonian toothfish (*Dissostichus eleginoides*). Fishing was conducted in Ecuadorian oceanic waters by only one vessel between 2017 and 2021. Modal lengths were identified using frequency distributions. The length at sexual maturity (L_m) was estimated using the empirical equation: $\text{Ln } L_m = -0.1189 + 0.9157 * \text{Ln } (L_{max})$. Modal lengths presented a little annual increment in *Antimora rostrata* and *Coryphaenoides armatus* while the values decreased for *Centroscymnus owstonii*, *C. delsolari*, and *Hydrolagus melanophasma*. Interannual lengths were similar for *Etmopterus granulosus*. Modal lengths were higher than the sexual maturity length for *H. melanophasma*, *C. delsolari*, *C. owstonii* and *A. rostrata*. Furthermore, *Coryphaenoides armatus* showed a similar value while *E. granulosus* exhibited a lower modal length. Empirical length at sexual maturity was between 56.35 and 66.26 cm TL for all species except for *H. melanophasma*, which was 100.53 cm TL. *Antimora rostrata* and *C. armatus* presented an increment of mature individuals while the annual percentage decreased for *H. melanophasma*, *C. owstonii*, and *C. delsolari*. *Etmopterus granulosus* showed a lower proportion of mature individuals.

Key words: *Dissostichus eleginoides*, experimental fishery, kernel density, longline, mature individuals.

Longitudes modales y empíricas de madurez sexual para seis especies de aguas profundas en el océano ecuatoriano

RESUMEN. El objetivo del presente trabajo fue establecer tallas modales, tallas empíricas de madurez sexual y proporciones de individuos maduros de seis especies de aguas profundas provenientes de la captura incidental de la pesquería experimental de merluza negra (*Dissostichus eleginoides*). La pesca fue realizada en aguas oceánicas ecuatorianas por un solo barco entre 2017 y 2021. Las tallas modales se identificaron mediante distribuciones de frecuencia. La talla de madurez sexual (L_m) se estimó mediante la ecuación empírica $\text{Ln } L_m = -0,1189 + 0,9157 * \text{Ln } (L_{max})$. Las tallas modales presentaron un pequeño incremento anual en *Antimora rostrata* y *Coryphaenoides armatus*, mientras que los valores disminuyeron para *Centroscymnus owstonii*, *C. delsolari* e *Hydrolagus melanophasma*. Las tallas interanuales fueron similares para *Etmopterus granulosus*. Las tallas modales fueron mayores que las tallas de madurez sexual para *H. melanophasma*, *C. delsolari*, *C. owstonii* y *A. rostrata*. *Coryphaenoides armatus* mostró un valor similar y *E. granulosus* una talla modal menor. La talla empírica de madurez sexual estuvo entre 56,35 y 66,26 cm LT para todas las especies excepto

H. melanophasma que fue de 100,53 cm LT. *Antimora rostrata* y *C. armatus* presentaron un incremento de individuos maduros mientras que el porcentaje anual disminuyó para *H. melanophasma*, *C. owstonii* y *C. delsolari*. *Etmopterus granulosus* mostró una menor proporción de individuos maduros.

Palabras clave: *Dissostichus eleginoides*, pesquería experimental, densidad de núcleo, palangre, individuos maduros.

An experimental fishery for Patagonian toothfish (*Dissostichus eleginoides* Smith, 1898) was carried out between 2017 and 2021 in Ecuadorian oceanic waters (Sepa et al. 2022). The most frequent deep-sea species were *Antimora rostrata*, *Centroscymnus owstonii*, *Coryphaenoides armatus*, *C. delsolari*, *Etmopterus granulosus*, *and Hydrolagus melanophasma.* They are common bycatch species in longline fisheries for Patagonian toothfish (Collins et al. 2010; Aramayo 2016). Biological data on deep-sea species is scarce. Much of the information is related to *C. armatus*, mentioned as an abundant species living in deep habitats with maximum lengths over 87 cm total length (TL) and longevity of ca. 40 years (Iwamoto and Stein 1974; Yeh and Drazen 2011; Bergstad et al. 2021). *Hydrolagus melanophasma* was reported in the southeastern Pacific on the last decade as part of catches in the Patagonian toothfish fishery (Bustamante et al. 2012; Araya et al. 2020; Alfaro-Shigueto et al. 2022); however, its biological aspects remain unknown.

Family Macrouridae (e.g. *Coryphaenoides*, *Antimora*) represents the major proportion of deep-sea fish (Middleton and Musick 1986). They could be considered a potential new fishery species as suggested for *C. delsolari* (Palacios et al. 2009), but their exploitation requires a previous understanding of the resource dynamic and the effects of fishing that modulate these populations. In that sense, the objective of this work was to establish modal lengths, empirical lengths at sexual maturity, and proportions of mature individuals of six bycatch deep-sea species of the experimental Patagonian toothfish fishery in Ecuadorian oceanic waters.

Data corresponded to total length (TL, cm) of the following species: *A. rostrata*, *C. owstonii*, *C. armatus*, *C. delsolari*, *E. granulosus*, and *H. melanophasma*. Individuals were fished by only one vessel, using longline with 1,000-1,500 circle hooks no 14/0, between 2017 and 2022 (Sepa et al. 2022). Annual modal lengths with the highest frequency described the species sizes per year. Modal lengths were identified using frequency distributions (LFD) built by kernel density estimators (Rosenblatt 1956). A Gaussian function (k = 6) was used, and the origin of LFD corresponded to the average of 30 histograms. Bandwidth (*b*) was the mean between the optimal Gaussian bandwidth (Silverman 1986) and the over-smoothed bandwidth (Scott 1992), without considering the LFD as unimodal (Zambrano et al. 2018; Zambrano and Galindo-Cortes 2019). The analysis was run in Stata software v16 using routines 'bandw' and 'warpdenm'. Modal lengths were identified using the command 'numo mo' (Salgado-Ugarte 2002; Salgado-Ugarte and Saito-Quezada 2020). Bandwidths were estimated annually for each species, but the LFD were constructed using the mean value. The length at sexual maturity (L_m) was estimated using the empirical equation $Ln\ L_m = -0.1189 + 0.9157 * Ln\ (L_{max})$ (Binohlan and Froese 2009), where L_{max} corresponded to the mean of annual maximum lengths of each species. The proportion of mature individuals was estimated in percentage, considering all individuals at maturity size and upwards.

Bandwidth values ranged between 2.45 and 4.99 cm. *H. melanophasma* presented the biggest individuals followed by *C. delsolari*, considering the mean of maximum lengths and modal. The other four species showed similar values. Modal lengths presented a little annual increment in *A. rostrata* and *C. armatus* while values decreased for

ZAMBRANO ET AL.: SEXUAL MATURITY IN DEPTH-SEA SPECIES

C. owstonii, *C. delsolari*, and *H. melanophasma*. Interannual lengths were similar for *E. granulosus*. Modal lengths were higher than the sexual maturity for *H. melanophasma*, *C. delsolari*, *C. owstonii*, and *A. rostrata*. In addition, *C. armatus* showed a similar value and *E. granulosus* had a lower modal length. Empirical length at sexual maturity fluctuated between 56.35 and 66.26 cm TL for all species except for *H. melanophasma*, which was 100.53 cm TL. The proportion of mature individuals changed temporally and by species. *Antimora rostrata* and *C. armatus* presented an increment of mature individuals while the percentage decreased for *H. melanophasma*, *C. owstonii*, and *C. delsolari*. *Etmofterus granulosus* exhibited the lowest proportion of mature individuals (Table 1).

Empirical lengths at sexual maturity were similar to reports based on gonadal analysis. Our estimates

Table 1. Bandwidth (BW), mean of maximum length (MML), empirical length at sexual maturity (L_m), number of individuals, modal lengths, and proportion of mature individuals estimated for six deep-sea species from Ecuadorian oceanic waters. TL: total length.

	Antimora rostrata	*Centroscymnus owstonii*	*Coryphaenoides armatus*	*Coryphaenoides delsolari*	*Etmopterus granulosus*	*Hydrolagus melanophasma*
BW (cm)	2.67	3.95	3.46	4.99	2.61	2.45
MML (cm, TL)	93.00	99.00	105.00	111.00	97.00	175.00
L_m (cm TL)	56.35	59.67	62.97	66.26	58.57	100.53
Number of data						
2017	184.00			69.00		1,438.00
2018	80.00	97.00		57.00	38.00	1,729.00
2019	187.00	235.00	158	199.00	192.00	2,525.00
2020	265.00	477.00	276	134.00	479.00	2,724.00
2021	577.00	349.00	674	454.00	312.00	2,160.00
Modal lengths (cm, TL)						
2017	63.01			84.50		115.97
2018	64.79	76.89		84.50	51.50	116.62
2019	63.01	76.36	62.98	83.17	52.55	108.78
2020	65.86	52.14	63.54	83.83	52.55	104.86
2021	68.71	51.61	69.20	82.50	51.50	102.57
Mature individuals (%)						
2017	75.00			83.00		90.00
2018	87.00	50.00		80.00	10.00	89.00
2019	80.00	66.00	65.00	75.00	18.00	76.00
2020	90.00	31.00	64.00	71.00	11.00	67.00
2021	92.00	34.00	79.00	78.00	9.00	61.00

were slightly higher for *A. rostrate* (42.1-45.1 cm TL), into the range of *E. granulosus* (53-62 cm TL), and slightly lower for *C. owstonii* (70-75 cm TL) (Yano and Tanaka 1988; Magnússon 2001; Irvine et al. 2002). In this sense, we assumed that the empirical method is usable for deep-sea species and that our results are a good approximation to the biology of the analyzed species. However, it is useful and necessary to validate our estimates by gonadal analysis as well as separate the results by sex, considering the sexual dimorphism.

Modal lengths are poorly reported in deep-sea species, and sometimes comparisons are limited due to the type of measurement recorded (i.e. total length, preanal), time elapsed between studies, and fishing gear. Our work presented total lengths; however, previous reports of *C. delsolari* have used preanal lengths (Palacios et al. 2009). In *C. owstonii*, reported modal lengths (TL) for mature individuals vary between intervals 75.0-79.9 cm (males) and 90.0-94.9 cm (females) (Yano and Tanaka 1988). Those values are higher than our results and correspond to a three-decade time series. Differences in size ranges could be a population response to environmental conditions. Yano and Tanaka (1988) worked in Japan waters including shallow waters (300 m). On the other hand, sizes found in our study could reflect the effect of fishing pressure, which should be verified with data from the Eastern South Pacific region.

Lower length values for *A. rostrate* (31.54-43.91 cm TL) have been observed when compared to this work (Magnússon 2001). It could be due to gear selectivity. Likewise, individuals were caught by a standard two-panel Grantor trawl of various dimensions and riggings, while a longline was used for this work. Our modal lengths were slightly lower in *E. granulosus* compared to other length intervals reported, namely 55-60 cm males and 65-70 cm females (Wetherbee 1996). Differences in length ranges between reports could be due to fishing gear and the time of the study. Other authors used bottom trawls but their results date back to more than two decades ago.

Length frequency distribution of *A. rostrata*, *C. armatus* and *E. granulosus* could show population recruitment, which would help the perpetuity of the species. The situation is different in *C. owstonii*, *C. delsolari*, and *H. melanophasma*, where LFD may indicate a potential impact on these populations, requiring further analysis for clarification. On the contrary, it is important to take into account the decrease in mature individuals among *E. granulosus*, *H. melanophasma*, *C. owstonii* and *C. armatus*. It is worth noting that none of these species are primary targets of fisheries. Presented length data can be used to develop indicators and implement a management plan to improve conservation strategies and regulate future fishery activities (Shin et al. 2005; Lappalainen et al. 2016; Baldé et al. 2019; Harford et al. 2021).

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Competing interests

The author(s) declare none.

Author contributions

René Zambrano: definition, conceptualization, methodology, formal analysis, writing-original draft, writing-review and editing, visualization. Dialhy Coello: definition, conceptualization, methodology, writing-original draft. Marco Herrera: definition, conceptualization, project administration, funding acquisition.

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