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Short Communication

Empirical estimation of life history parameters of *Mugil galapagensis* and *Mugil thoburni* from the Galapagos Islands

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ABSTRACT. The yellow-tail (*Mugil galapagensis*) and black-tail mullet (*M. thoburni*) are the Galapagos artisanal finfish fishery's most commercially important mugilids species. Despite this, knowledge about their biological characteristics is scarce and limited. In this study, the basic biological parameters of *M. galapagensis* and *M. thoburni* were estimated using empirical equations for combined sex based on total length (TL, cm) data from landings on Santa Cruz Island. The von Bertalanffy growth parameters for *M. galapagensis* were L_∞ = 69.14 cm TL, k = 0.204 yr^{-1}, ϕ' = 2.989, and t_0 = -0.658 years, and for *M. thoburni* were L_∞ = 62.26 cm TL, k = 0.218 yr^{-1}, ϕ' = 2.927 and t_0 = -0.631 years. The size ($L_{50\%}$) and age ($t_{50\%}$) at maturity were estimated at 35.80 cm TL (2.92 years) and 32.41 cm TL (2.74 years) for *M. galapagensis* and *M. thoburni*, respectively. The theoretical maximum age (t_{max}) and natural mortality (M) for *M. galapagensis* were 12.28 years and 0.32 yr^{-1}, respectively. While for *M. thoburni*, both parameters were 11.28 years and 0.35 yr^{-1}. In conclusion, both mugilids species have slow growth, reach sexual maturity at about three years, are moderately long-lived, and have a slightly high natural mortality.

Keywords: *Mugil galapagensis*; *Mugil thoburni*; growth; size/age at maturity; natural mortality; maximum age

Fishes in the Mugilidae family include ~78 species, commonly called mullets (Fricke et al. 2023), have a wide distribution in tropical, subtropical, and temperate seas, and are important food fishes (Barletta & Dantas 2016). Mullets play a fundamental ecological role because they contribute to the functioning of coastal systems by decomposing organic matter into particles and primary production (Whitfield 2016). In the Galapagos Islands, mugilids are of commercial importance, representing an important source of income for local fishers, with the fish being used as food for humans and as bait (Ramírez-González et al. 2022).

The mullet fishery in the Galapagos occurs year-round. It is characterized by being artisanal, with most of this catch coming from waters surrounding San Cristobal, Santa Cruz, Santa Fe, Floreana, Santiago, and South Isabela islands (Andrade & Murillo 2002). Mullets are caught with two fishing gears, the throw or "chinchorro" net and the trammel or "mullet" net (Castrejón 2011). Six commercial species have been

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recorded for Galapagos, black-tail mullet (*Mugil thoburni*), Galapagos mullet or yellow-tail mullet (*M. galapagensis*), snouted mullet (*Chaenomugil proboscideus*), mountain mullet (*Agonostomus monticola*), flathead grey mullet (*M. cephalus*) and white mullet (*M. curema*) (Andrade & Murillo 2002).

The yellow-tail mullet (YTM) and black-tail mullet (BTM) are the most relevant from the commercial point of view due to their higher presence in the catch composition. For example, the catch of both species represented 10.4% of the Galapagos finfish fishery landings in 2003, corresponding to a total land of 19.8 t of BTM and 19.9 t of YTM (Molina et al. 2004). More recently, Barragán-Paladines & Chuenpagdee (2015) reanalyzed the catch data and suggested that the percentage of the mugilids catch maybe even higher (~16%). The average annual catch in Galapagos between 2017 and 2020 of YTM was 39.0 t (ranked 9th of 64 fishing species), and of BTM was 18.4 t (ranked 14th of 64 fishing species) (Ramírez-González et al. 2022).

Currently, information on these species is limited, and there are only complete records of landings between 1997 and 2003 (Andrade & Murillo 2002, Castrejón 2011), a reconstructed catch time series between 1950 and 2010 (Schiller et al. 2013) and landings-based exports estimation between 2013 and 2016 (Tanner et al. 2019). The Galapagos National Park Directorate has landing volume data for both species from 2017 to date, but the database needs to be analyzed. From a biological point of view, size at maturity, size structure, and age growth based on scales have been estimated for BTM (Andrade & Murillo 2002, Espinoza 2004). By contrast, for YTM, only the maximum size has been reported (Andrade & Murillo 2002, Gelin & Gravez 2002).

Different approaches to evaluating data-limited fisheries use size composition and require life history parameters such as size at maturity, maximum size, individual growth, and natural mortality as input data (Apel et al. 2013). Based on the above, there is a notable need to estimate biological parameters for YTM and BTM usable in assessments based on methodologies for data-limited fisheries, thereby evaluating different exploitation strategies that promote the use and conservation of both fisheries resources. Therefore, we aimed to obtain preliminary estimates of biological parameters for *M. galapagensis* and *M. thoburni* using empirical estimators.

Length data of YTM and BTM were obtained from the landings at Puerto Ayora - Santa Cruz Island (Fig. 1), and collected for the Participatory Fisheries Research and Monitoring Program of the Galapagos National Park Directorate and the Charles Darwin Foundation. The data correspond to records of total length (TL, cm) from the tip of the head to the tip of the longest lobe of the caudal fin during 1998-2000 and 2002 for YTM and 1997-2002 for BTM.

Different empirical equations were implemented to estimate the von Bertalanffy growth function (VBGF) parameters [asymptotic length (L_∞, cm), growth constant (k, yr^{-1}), and the theoretical age at zero length (t_0, years)]. The L_∞ was estimated using the statistical relationship García-Carreras et al. (2016) proposed, which is $\log_{10} L_\infty = 0.068260 + 0.969112 \log_{10} L_{max}$. The value used for L_{max} was the estimated maximum length [L_{max_est}, cm], obtained using the maximum length estimation (MLE) routine of the Fisat II program (Gayanilo et al. 2005). As a previous step, annual length frequency distributions (LFD) were constructed for each species to calculate L_{max_est}. The class interval was determined using the optimal bandwidth, and this analysis was performed per month, and its median was estimated to construct the annual LFD. This procedure was performed using the routines implemented by Salgado-Ugarte (2002) in the statistical program Stata (StataCorp 2017).

For k (yr^{-1}) and t_0 (years) estimation, the relationships of Gislason et al. (2008) [$k = 3.07L_\infty^{-0.64}$] and Pauly (1979) [$\log_{10} - t_0 = - 0.3922 - 0.2752 \log_{10} L_\infty - 1.038 \log_{10} k$] were used. The absolute growth rate at age [$g = L_\infty ke^{-kt}$] and relative growth rate at age [$g = ke^{-kt}/1- e^{-kt}$] (Wang & Milton 2000) were also obtained, where t is the age in years. To compare individual growth with other species of *Mugil*, the growth index Phi prime [$\phi' = 2\log_{10}(L_\infty) + \log_{10}(k)$] (Pauly & Munro 1984) was applied. The size at maturity [$L_{50\%}$] was calculated as $L_{50\%} = 0.64\ L_\infty^{0.95}$ (Gislason et al. 2008) using the L_∞ estimates, and the age at maturity [$t_{50\%}$] was obtained by using the $L_{50\%}$ in the VBGF and solving for t as $t_{50\%} = t_0 - (1 / k) \ln [1 - (L_{50\%} / L_\infty)]$.

The theoretical maximum age or longevity [t_{max}] was calculated using the inverse of the VBGF assuming $t = 0$ because the larval period of *M. galapagensis* and *M. thoburni* is unknown. $t_{max} = [(\ln L_{95\%} - \ln (L_\infty - L_{95\%})] / k$, where $L_{95\%}$ represents 95% of L_{max} estimated and k and L_∞ was previously obtained from the VBGF parameters. Two equations were used to calculate natural mortality [M], $M = 4.118\ k^{0.73} L_\infty^{-0.33}$ where M remains constant throughout the fish's life (Then et al. 2015), and $\ln M_t = -0.063 + 0.998 \ln [k (L_t / L_\infty)^{-1.5}]$, where M does not remain constant (García-Carreras et al. 2016).

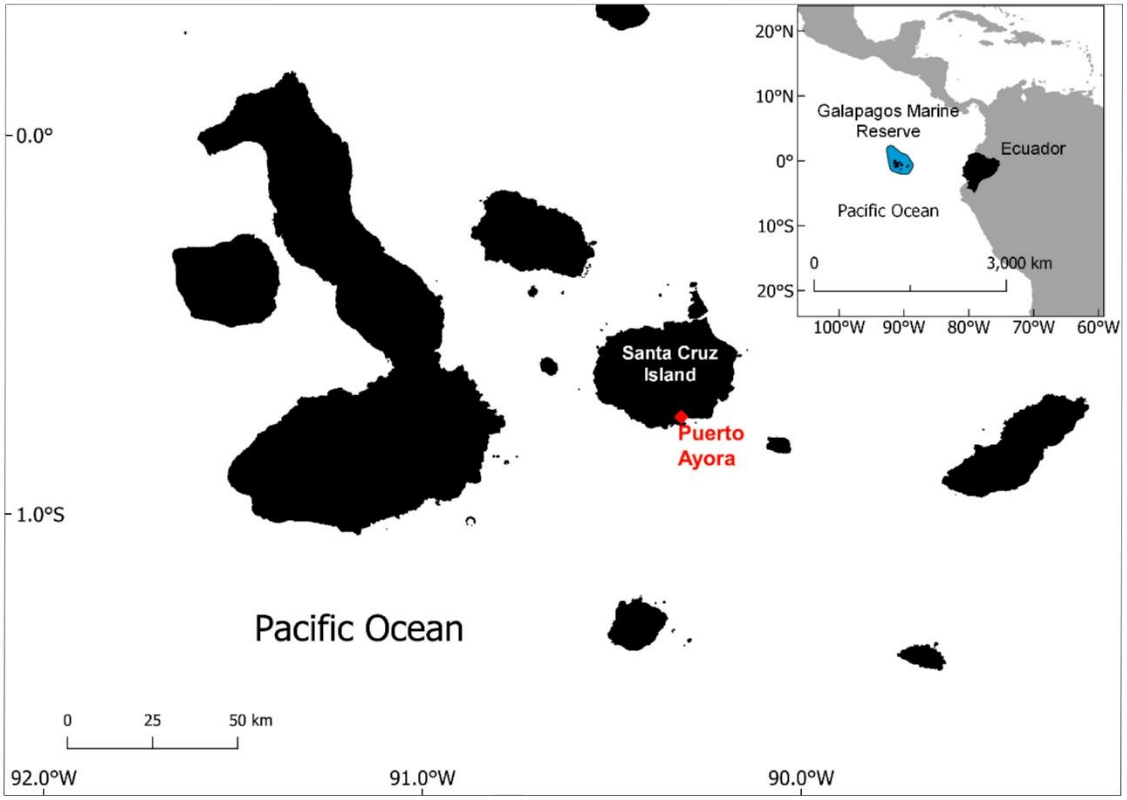

Figure 1. Geographic origin of the yellow-tail mullet (*Mugil galapagensis*) and black-tail mullet (*M. thoburni*) data from Galapagos Island.

For the period of analysis, a total of 535 individuals of YTM were measured (length range: 26.5-66.0 cm TL), while for BTM, 1887 individuals (length range: 16.9-58.2 cm TL). Based on the optimal bandwidth, we determined that the class interval was 1.88 cm for YTM and 1.14 cm for BTM, which generated L_{max_est} of 67.29 cm TL and 60.39 cm TL for YTM and BTM, respectively.

According to this, the VBGF parameter for YTM was L_∞ = 69.14 cm TL, k = 0.204 yr^{-1}, ϕ' = 2.989, and t_0 = -0.658 years, and for BTM were L_∞ = 62.26 cm TL, k = 0.218 yr^{-1}, ϕ' = 2.927 and t_0 = -0.631 years. The absolute growth rate was higher in the first three years of life in both species (Fig. 2). The YTM presented 11.48, 9.34, and 7.60 cm TL increments for ages 1, 2, and 3, respectively. The increments for BTM, on the other hand, were 10.87, 8.69, and 6.95 cm TL for ages 1, 2, and 3, respectively. The growth of both species gradually reduces from the fourth year when the average size is 42.71 cm TL for *M. galapagensis* and 39.60 cm TL for *M. thoburni*, which implies a relative growth rate of 16 and 15% during that year, respectively (Fig. 2).

The $L_{50\%}$ of YTM was 35.80 cm TL, and the $t_{50\%}$ was 2.92 years. For BTM, $L_{50\%}$ was 32.41 cm TL, and the $t_{50\%}$ was 2.74 years. The t_{max} or longevity of *M. galapagensis* was 12.28 years, and *M. thoburni*'s was 11.28 years. The values of M for YTM and BTM estimated from the equation proposed by Then et al. (2015) were 0.32 and 0.35 yr^{-1}, respectively. That is, *M. galapagensis* presented a lower mortality rate than *M. thoburni*. According to the model reported by García-Carreras et al. (2016), the value of M is greater in the first year of life, with an average value of 1.24 yr^{-1} for both species (Fig. 3).

In this study, we have applied an empirical equation-based approach as a methodological framework for data-poor species to calculate different life history parameters previously unknown for *M. galapagensis* and understudied for *M. thoburni*. Life history parameters are widely recognized in fisheries science because they are essential to assess the population status and determine fisheries indicators and management (Thorson et al. 2014).

Our analysis was based on the fact that the maximum size of an organism is a strong predictor for

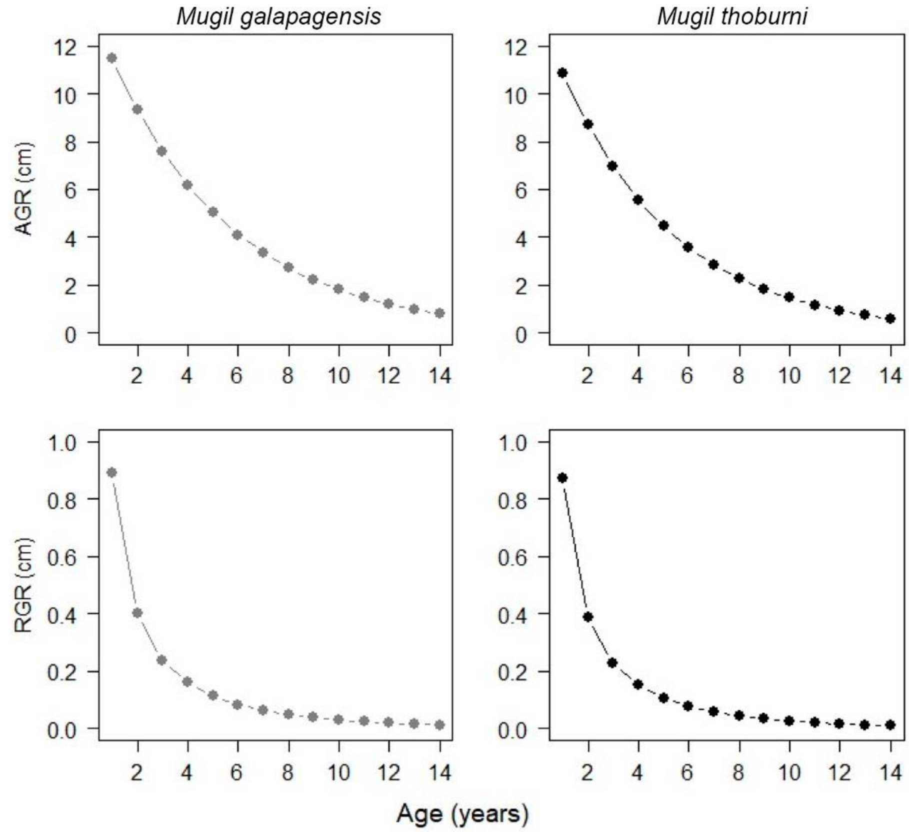

Figure 2. Absolute growth rate (AGR) and relative growth rate (RGR) of yellow-tail mullet (*Mugil galapagensis*) and black-tail mullet (*M. thoburni*) on Santa Cruz Island, Galapagos.

many life history parameters in fishes [e.g. L_∞ and $L_{50\%}$ (Froese & Binohlan 2000, Binohlan & Froese 2009)]. The L_∞ calculated for *M. galapagensis* using L_{max_est} is the first report in the literature for the species. In comparison, the value calculated for *M. thoburni* was higher than that reported by Espinoza (2004) (Table 1). Espinoza (2004) found L_{max} values of 42.5 cm TL for males and 44.2 cm TL for females and an estimated 37.7 cm TL for L_∞ using scales. Perhaps it implies a potential underestimation of L_∞ due to errors in age assignment and the low sample size of individuals with lengths greater than 39 cm that he reports.

On the other hand, the *k* reported by Espinoza (2004) for *M. thoburni* was higher than the one presented in this work (Table 1). Because of the negative correlation between *k* and L_∞ (Pauly & Munro 1984), it is likely an overestimation of the scale-based *k* value presented by Espinoza (2004), probably because age can be underestimated when scales are used (Ibañez 2016). When we recalculated the VBGF parameters using Espinoza's (2004) data and the empirical relationships for BTM females, we found that L_∞ = 46.01 cm TL and k = 0.265 yr^{-1} were more in line with those found in our and other studies of the *Mugil* genus in coastal lagoons and marine-coastal areas (Table 1).

The differences in growth parameters among *Mugil* species can be attributed to the type of ecosystem in which they are found, migrations, or food availability (Oren 1981). According to Ibañez et al. (2012) the species of the *Mugil* genus are characterized by being euryhaline, and their migratory behavior differs due to finding the best environment to feed, reproduce, and survive. Therefore, the values of L_∞ and *k* vary among species even though they occupy the same geographical area (Table 1). Furthermore, it is important to consider that the differences between growth parameters even within a species could also be explained by the wide distribution of some species, such as *M. cephalus*, compared to *M. galapagensis* and *M. thoburni*, species with limited distributions.

The values of the growth index (ϕ') for *M. galapagensis* [2.98] and *M. thoburni* [2.92] are justified as a good length growth performance index to compare with other species of the same genus. These values are within the range reported for the Mugilidae family (1.82-3.47; Ibañez 2016) and for some species of the

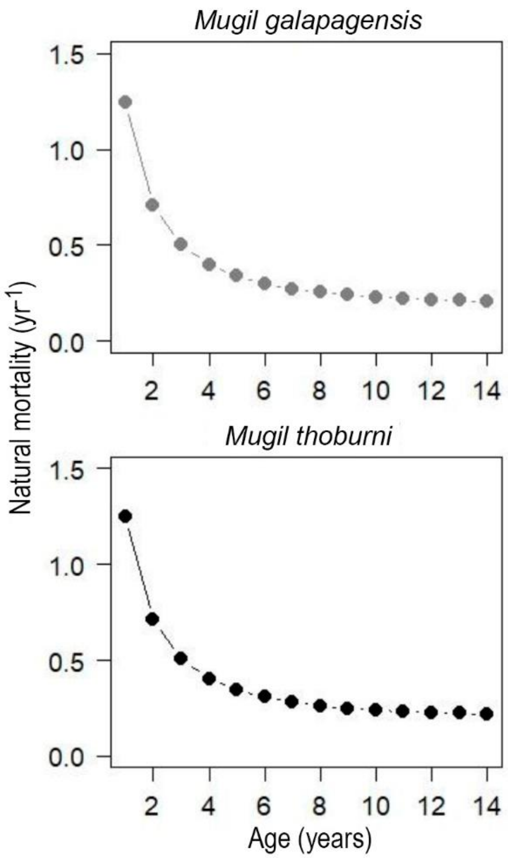

Figure 3. Natural mortality rate of yellow-tail mullet (*Mugil galapagensis*) and black-tail mullet (*M. thoburni*) based on age.

Mugil genus (1.57-3.53; Table 1). Salinity has been shown to affect the growth rate in mugilids directly. Cardona (2000) explains that in high salinities, the growth performance of *M. cephalus* is negatively affected due to the high energy expenditure required for osmoregulation. The effect of salinity on growth has also been documented by Ibañez (2016).

The $L_{50\%}$ for *M. thoburni* (32.41 cm TL) was below the reported value by Andrade & Murillo (2002), and the methodology used by these authors can explain the differences. Also, this previous $L_{50\%}$ value was smaller than the estimated for *M. galapagensis* (35.80 cm TL) and differs from other *Mugil* species. For example, the $L_{50\%}$ for both sexes for *M. cephalus* in the Gulf of Mexico was 37.5 cm TL (Ibañez & Gallardo-Cabello 2004). In Brazil, *M. liza* had a $L_{50\%}$ of 35.0 cm TL (Albieri & Araújo 2010), while *M. platanus* had a higher value (44.68 cm TL) in Argentina (González-Castro et al. 2011). These differences may be because maturity is generally reached at a larger size at higher latitudes than in lower latitude regions (González-Castro & Minos 2016).

The t_{max} estimated for *M. galapagensis* and *M. thoburni* (12.28 and 11.28 years) are within the range of ages reported for other species of the same genus. The highest t_{max} was reported by Ibañez-Aguirre et al. (1999) for *M. cephalus*, with 57.6 years in the Black Sea, and the lowest value in the north and north-west of Florida, USA, with an age of 3.7 years reported by the same authors. Differences in t_{max} values could be partly explained by the habitat these species are found and the proportional relationship between seawater temperature, latitude, and asymptotic length. Nevertheless, it is also important to consider that it is not an estimate through a direct method (e.g. otolith).

No studies have reported *M* for YTM or BTM. However, the values estimated here (0.32 and 0.35 yr^{-1}, respectively) are slightly higher than other species of the same genus. For example, *M* values reported for *M. cephalus* are from 0.10 to 0.90 yr^{-1} (Ibañez-Aguirre & Gallardo-Cabello 1995, Panda et al. 2018), 0.16 to 0.20 yr^{-1} for *M. curema* in Mexico (Ibañez-Aguirre & Gallardo-Cabello 1995), 0.17 to 0.37 yr^{-1} for *M. liza* in Brazil (Garbin et al. 2014) and 0.29 yr^{-1} for *M. platanus* in Argentina (González-Castro et al. 2009). These differences could be attributed to competition for food or the geographical area where they are found (Gelin & Gravez 2002). Still, perhaps the most important is due to the different estimation methods of *M* used.

Knowing basic biological information in a data-limited fishery is important for subsequent fishery assessments, and the life history parameters calculated for *M. galapagensis* and *M. thoburni* in our work should be seen as preliminary because there are many biases or uncertainties that this type of estimation generates. However, the methodological framework used in this study is valid and justified as an *ad hoc* approach to estimate L_{max}, L_{∞}, k, $L_{50\%}$, $t_{50\%}$, t_{max}, and M to assess the status of this species with length-based indicators (e.g. Cope & Punt 2009) or length-based methods (e.g. Canales et al. 2021), at least for *M. thoburni* for the period of data available (1997-2002).

Based on our empirical estimates, we can conclude that both mugilids species have slow growth, reaching sexual maturity after 2.5 years, are moderately long-lived, and have a high natural mortality rate. In the future, it is recommended to validate and improve the estimates of the life history parameters of this study using direct methods (e.g. otolith-based estimates) as well as to estimate other parameters such as total and fishing mortality (Z and F), and length at maximum yield per recruit (L_{opt}). A formal monitoring program for both mullet species is required to obtain these estimates.

Table 1. Growth parameters (L_∞, k and t_0) and the performance index Phi prime (ϕ') of yellow-tail mullet (*Mugil galapagensis*), black-tail mullet (*M. thoburni*) and other species of the *Mugil* genus. Emp: empirical, LDF: length frequency distribution, O: otoliths, S: scales, Tag: tagging, ---: method not reported. *Taken from Ibañez et al. (1999).

Geographic areas	Species	Method	L_∞	k	t_0	ϕ'	References
Marine-coastal zones							
Galapagos, Ecuador	*Mugil galapagensis*	Emp	69.14	0.20	-0.658	2.989	This study
Galapagos, Ecuador	*Mugil thoburni*	Emp	62.26	0.22	-0.631	2.927	This study
Galapagos, Ecuador	*Mugil thoburni*	S	37.70	0.61	-0.802	2.938	Espinoza (2004)
Brazil coastal regions	*Mugil liza*	O	66.20	0.17	-1.700	2.867	Garbin et al. (2014)
Central Pacific Mexican	*Mugil cephalus*	O	60.00	0.11	-2.630	2.617	Espino-Barr et al. (2015)
Texas, USA	*Mugil cephalus*	S	45.00	0.24	-0.900	2.687	Cech & Wohlschlag (1975)*
Florida, USA	*Mugil cephalus*	S/Tag	37.40	0.82	-0.160	3.060	Broadhead (1958)*
Senegal	*Mugil cephalus*	LFD	65.76	0.32	-0.418	3.141	Ndour (2016)
Coastal lagoons							
Mar Chiquita, Argentina	*Mugil platanus*	O	56.38	0.30	-0.057	2.979	González-Castro et al. (2009)
La Habana, Cuba	*Mugil curema*	Spine	53.20	0.10	-5.90	2.452	Alvarez (1979)*
Nicoya, Costa Rica	*Mugil curema*	---	43.20	0.60	-0.244	3.049	Phillips et al. (1987)*
Veracruz, Mexico	*Mugil cephalus*	S	47.77	0.17	-2.367	2.589	Ibañez-Aguirre & Gallardo-Cabello (1996)
Veracruz, Mexico	*Mugil cephalus*	O	64.24	0.09	-2.849	2.611	Ibañez et al. (1999)
Colima, Mexico	*Mugil curema*	S	36.47	0.22	-1.557	2.464	Gallardo-Cabello et al. (2005)
Veracruz, Mexico	*Mugil curema*	S	40.03	0.16	-3.839	2.412	Ibañez-Aguirre & Gallardo-Cabello (1996)
Veracruz, Mexico	*Mugil curema*	O	46.14	0.14	-3.624	2.474	Ibañez et al. (1999)
Virginia, USA	*Mugil curema*	---	40.34	0.78	-0.06	3.104	Richards & Castagna (1976)*
Lago Chilika, India	*Mugil cephalus*	LFD	70.00	0.70	-0.097	3.535	Panda et al. (2018)
Bonny Estuary, Nigeria	*Mugil cephalus*	LFD	33.20	0.55	-0.152	2.786	Aleleye-Wokoma et al. (2001)
Tunisia	*Mugil cephalus*	S	69.30	0.19	-0.630	2.960	Farrugio (1975)*
Venice, Italy	*Mugil cephalus*	S	61.10	0.21	-0.465	2.894	Morovic (1954)*
Vransko, Yugoslavia	*Mugil cephalus*	S	59.00	0.23	-0.083	2.903	Morovic (1957)*

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