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Biological aspects of *Mugil liza* Valenciennes, 1836 in a tropical estuarine bay in the southwestern Atlantic

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ABSTRACT

Evaluation of population parameters of *Mugil liza* caught at Guanabara Bay was conducted using size frequency and biological data. Total length ranged between 22.0 and 81.5 cm. The spawning season occurred between March and August. The size of the first maturity was estimated as 49.8 cm. The estimated growth parameters were $L_\infty = 82.31$ cm and K = 0.30 y^{-1}. Instantaneous rate of total and natural mortalities were estimated as 1.02 and 0.56 y^{-1}. The fishing mortality ($F = 0.46\ y^{-1}$) was greater than the optimum ($F_{opt} = 0.28\ y^{-1}$) and the limit of biological reference point ($F_{limit} = 0.37\ y^{-1}$). The exploitation rate ($E = 0.45$) was higher than the $E_{0.5} = 0.33$, suggesting that decreasing the current fishing effort could reduce exploitation within sustainable limits.

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1. Introduction

The aggregate mullet landings in Brazil include more than 10 species of *Mugil* and averaged 18.277 t between 2009 and 2011 (BRASIL, 2011). The Lebranche mullet, *Mugil liza* Valenciennes, 1836, is an importanttrans boundary fishery resource, commercially exploited by Brazil, Uruguay and Argentina in the Southwestern Atlantic (Esper and Esper, 2001; Cousseau et al., 2005; González-Castro et al., 2009; Mai et al., 2014; Callicó-Fortunato et al., 2017). At least two stocks of *Mugil liza* are discriminated on the South-Southeastern coast of Brazil. One distributed in the southernmost range from Argentina to São Paulo (36°S – 23°S) and the other, from Rio de Janeiro towards the North into lower latitudes following the coast. The northernmost range this stock is still undetermined (Mai et al., 2014; Lemos et al., 2014). Most of our knowledge on the population biology and fisheries of *M. liza* comes from the southern stock where the fishing pressure is higher (Garbin et al., 2014).

Mullets use estuarine waters throughout most of their life cycle (Vieira, 1991; Araújo-Silva and Araújo, 2000; Albieri et al., 2010; Castellini et al., 2019; Mai et al., 2019). Young-of-the-year recruit into estuaries (Vieira, 1991), maturing after five years (Garbin et al., 2014), at least for the southern population when the species performs a massive reproductive migration in costal southwestern Atlantic waters (Vieira, 1991; Miranda et al., 2006; Lemos et al., 2014). The species ecological attributes provide varied patterns of biomass production over time (Miranda et al., 2006), which are strongly dependent on environmental conditions along its distribution. In fact, the reproductive migration is triggered by sudden falls in temperature and salt-water intrusions into estuaries, both caused by frontal passages in early autumn (Vieira and Castello, 1996; Seckendorff and Azevedo, 2007; Vieira et al., 2008). The uniqueness of the species life cycle allows the development of both, small and large-scale fisheries, supplying local and national markets with whole fish, and international markets with the roe (Haimovici et al., 2014; Mai et al., 2014). Since 2004, *Mugil liza* was considered overexploited in Brazil (IN/MMA nº 05/2004; (Mai et al., 2014) and after 2014 has been classified as Near Threatened (NT) following the IUCN criteria (BRASIL, 2018a). Its fishery is regulated by a management plan (BRASIL, 2015a), which includes quota regime, fishing gear restriction, catch size limits and fishing areas closure (BRASIL, 2005, 2015b, 2018a,b). Hence, due to the lack of knowledge of

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the northernmost stock unit of *Mugil liza*, those regulations were based on the southern stock unit. Understanding how population parameters may vary between stock units may help managers to adapt mullet fishery regulations to the northern stock as well.

Guanabara Bay, located in the metropolitan area of Rio de Janeiro, is one of the most important estuarine-bay ecosystems in the Brazilian coast (Silva et al., 2015). The importance of this bay is justified by its environmental, economic and social value. It is surrounded by a population of more than 10 million inhabitants, producing a daily organic load estimated at 470 t of BOD. There are also 6.000 industries, two refineries, two ports and several shipyards and oil and gas terminals discharging about 150 t of industrial wastes daily (Paranhos and Andrade, 2012). Despite these anthropic impacts of great magnitude (Soares-Gomes et al., 2016), Guanabara Bay still provides access to a diversity of fishery resources and serves as nursery for many commercially important fish species (Vianna et al., 2012; Prestelo and Vianna, 2016). *Mugil liza* is one of the most important fishery resources harvested within the bay (Jablonski et al., 2006; Loto et al., 2018). Recent mullet catches reported by FIPERJ highlight the importance of Guanabara Bay for the *M. liza* fishery in Rio de Janeiro. Between 2011 and 2018, the total catch of *M. liza* in the state ranged between 164 and 1020 t (FIPERJ, 2012, 2013, 2014, 2015, 2018b, 2019). Mullets landed in Rio de Janeiro, Magé, São Gonçalo and Niterói were mostly captured within Guanabara Bay, and represented, on average, more than 50% of the total landings reported to this period (FIPERJ, 2012, 2013, 2014, 2015, 2018b, 2019).

The knowledge on the reproductive and growth traits of stock units of commercially exploited populations is essential for the establishment of resource management priorities. According to Fonteles-Filho (2011), cohorts of a species are renewed through reproduction at regular intervals determined by their life cycle. Parameters such as length and age of individuals reaching sexual maturity are important population attributes that may help to understand the population's life cycle. Growth patterns, however, result from a potential interaction defined by the fish genotype and environmental conditions experienced by individuals from a given population (Wootton, 1998). Both factors define two important management strategies for protecting a commercial fisheries stock: the fisheries closure during the reproductive period, and the size at first capture, which ensures recruitment and, one breeding season at least, within the adult stock. These principles and many others are recommended in both national (MMA Instrução Normativa No. 53, November 22, 2005; Instrução Normativa IBAMA No 171, May 09, 2008) and international laws (FAO, 1995, 2015; Pedrosa and Lessa, 2017).

The aim of this study is to provide estimates of the life history parameters (reproduction and growth) for *M. liza* captured within Guanabara Bay, in order to provide scientific information for management purposes of the northern stock of *M. liza* in Southeast Brazil. A comparison of the results with the previous studies is also given.

2. Material and methods

2.1. Dataset

Between July 2011 and June 2013 eighty-seven fishery landings from small-scale purse seiners (boat LOA < 10.0 m) and gill netters (mesh size 10 mm to 100 mm) were monitored every two weeks to obtain biometric data (total length—TL, cm). Main fishing areas are illustrated in Fig. 1.

An additional sample of 15 to 30 individuals of each monitored landing were randomly selected and taken to the laboratory (biological samples). For each specimen, total length (TL) was taken to the nearest centimeter (cm), and total (TW) and gutted (Wg) weights to the nearest gram (g), and then ventrally dissected for sex and maturity evaluation. Nevertheless, due to the great variability in the sex ratio and the limitations to identify all stages of gonadal development in males, the data were not discriminated by sex and treated as grouped sex.

2.2. Length–Weight Relationship

The length–weight relationship was estimated with the power equation: $\mathrm{TW} = a\mathrm{TL}^{b}$ (Le Cren, 1951) where, TW is the weight (g), TL is the fish total length (cm), *a* and *b*, are respectively, the intercept and the slope of the relation. The Student t-test was applied to determine whether growth was isometric (b=3) or allometric ($b \neq 3$).

2.3. Reproduction

Sexes were determined macroscopically and gonads classified into six stages of maturation (Vazzoler, 1996): immature, maturing, mature, ripe, spent and resting. Gonad weight was measured to the nearest 0.01g. Gonadosomatic index (GSI) was calculated monthly for grouped sexes of *M. liza* by the equation: $\mathrm{GSI} = \mathrm{WG}/\mathrm{Wg} * 100$, where: WG is the fish gonad weight and Wg is the fish gutted weight (Albieri and Araújo, 2010). The gonadal condition factor (ΔK) was also used to ratify the reproductive period, since it expresses, in a relative way, the portion of the energy reserves transferred to the gonads, as, for this purpose, the expression: $\Delta K = K - K'$, where $K = \mathrm{TW}/\mathrm{TL}^{\mathrm{b}}$ (total condition factor) and $\mathrm{K'} = \mathrm{WG}/\mathrm{TL}^{\mathrm{b}}$ (somatic condition factor). The mean length at first sexual maturity (L_{50}) was estimated by fitting a logistic function to the proportion of mature fish in 1.0 cm TL size categories and determined as the size at which 50% of individuals were mature. We used the sizeMat routine with logit approach from the R software (R Core Development Team).

2.4. Growth estimation

Data from both, purse seine and gillnet fisheries were pondered by selectivity (Sparre et al., 1989) to generate a theoretical year. The TropFishR package (Mildenberger et al., 2017a) within the R software was used for calculating population parameters. TropFishR includes enhanced versions of all functions in FAO-ICLARM Stock Assessment Tools II (FISAT II) (Gayanilo et al., 2005), and additional recent methods. The optimized electronic length–frequency analysis (bootstrapped ELEFAN_GA) (Mildenberger et al., 2017b; Schwamborn et al., 2019) was applied to the length–frequency distributions (LFD), allowing assessment of the uncertainties around the growth estimates. After this procedure, LFD data were corrected by taking into account gear selectivity, and new monthly 2 cm class intervals LFD was constructed for both sexes. Growth was investigated by fitting a seasonally oscillating von Bertalanffy growth function (soVBGF) (Somers, 1988): $L_t = L_\infty \left(1 - exp^{-(k(t-t_0)-\left(\frac{CK}{2\pi}\right)\sin 2\pi+\left(\frac{CK}{2\pi}\right)\sin 2\pi(t_0-t_s)}\right)$ where, L_∞ is the asymptotic length, K the von Bertalanffy growth coefficient, L_t the length at age t, C the amplitude of growth oscillations, typically ranging from 0 to 1 (a value > 1 implies periods of shrinkage in length, which is rare), t_0 is the theoretical age of the fish when Lt is equal to zero, and t_s is the fraction of a year (relative to the age of recruitment, $t = 0$) where the sine wave oscillation begins (*i.e.*, turns positive). One additional output of the ELEFAN run in TropFishR is the parameter t_{anchor}, which represents the fraction of the year where yearly repeating growth curves cross length equal to zero.

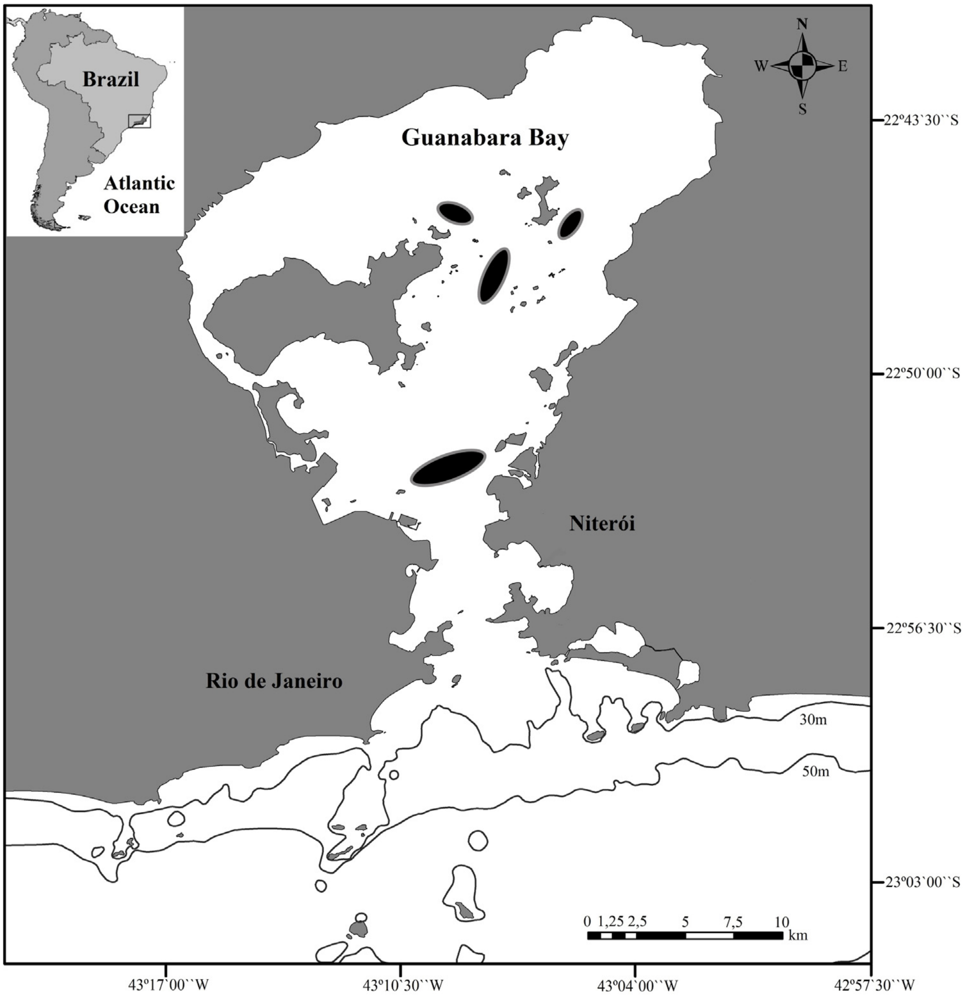

Fig. 1. Distribution of the main commercial fishing areas for mullets (ellipses) in Guanabara Bay.

The initial seed values of growth parameters were based on software FISAT II routines (Maximum Length Estimation and k-scan) (Gayanilo et al., 2005). For the more complex genetic algorithm ELEFAN_GA, some key settings were fine tuned for precision. Settings for precision optimized ELEFAN_GA were MA = 5, maxiter = 50, run = 10, pmutation = 0.2, for the dataset with popSize = 100.

The age at length zero (t_0) was estimated by Pauly's equation log(-t_0) = −0.3922–0.2752 log L_∞ - 1.038 log K (Pauly, 1980). Modal progression analysis was performed using the Bhattacharya's method (Bhattacharya, 1967), which infers growth from apparent modal shifts or means in a time series of length–frequency. Longevity was obtained according to the equation $t_{\max} = 3/\mathrm{K}$, where, $t_{\max}$ is the maximum age the fish of a given population would reach, and K is the curvature parameter. On comparing estimated growth parameters in the present study with previous ones, the growth performance index, ϕ' (Pauly and Munro, 1984) was calculated according to the equations: $\phi' = \log \mathrm{K} + 2 \log L_\infty$.

2.5. Recruitment pattern

The fisheries recruitment pattern was obtained by backward projection on the length axis of the set of available length–frequency data as described in FiSAT II. This routine reconstructs the recruitment pulse from a time series of length–frequency data to determine the number of pulses per year and the relative strength of each pulse (Amin et al., 2009). Input parameters included L_∞ and K. Normal distribution of the recruitment pattern was determined by NORMSEP in FiSAT II (Pauly and Caddy, 1985). The midpoint of the smallest length group in the catch was estimated as the length at first recruitment (Lr) (Gheshlaghi et al., 2012).

2.6. Mortality

Total instantaneous mortality rate Z was calculated using the length converted catch curve (FISAT II) developed from the pooled gear length–frequency distribution of *M. liza*, which simulated a steady state population. Natural instantaneous mortality M was estimated using Pauly's empirical formula (Pauly, 1980): Ln(M) = −0.152–0.279 Ln(L_∞)+0.6543 Ln(K)+0.463Ln(T) where, L_∞ and K are VBGF parameters and T is the mean annual temperature, which was considered in this study 23.0 °C. The annual instantaneous fishing mortality rate F was obtained by subtracting the natural mortality rate M from the total mortality rate Z derived from length converted catch curve, $F = Z - M$. The histogram showing the probability of capture for each size class was estimated by backward extrapolation of the straight portion of the right descending part of the catch curve. The actual exploitation rate E was estimated as the proportion of the fishing mortality relative to total mortality, i.e., $E = F/Z$. The maximum allowable limit of exploitation ($E_{\max}$) allowing a maximum relative yield per recruit was estimated from the routine Beverton and Holt analysis (knife-edge). Also, $E_{0.1}$, the exploitation rate at which the marginal increase in relative yield-per-recruit is 10% of its value at *MSY* ($E_{\max}$) and $E_{0.5}$, the exploitation rate corresponding to 50% of the unexploited relative biomass-per-recruit, were estimated. Stock status was evaluated by comparing estimates of the fishing mortality rate with target F_{opt} and limit F_{limit} biological reference points which were defined as: F_{opt} =0.5M and F_{limit} = 2/3M (Patterson, 1992).

3. Results

3.1. Size distribution

A total of 11,825 individuals were measured in the 87 landings. Size of individuals ranged from 21.0 to 81.7 cm with mean of 52 ± 0.01 cm TL. The specimens caught by gillnet showed a mean TL of 56.7 ± 4.5 cm (41.0 to 77.0 cm) and those from purse seine 51.3 ± 0.01 cm (21.0 to 81.7 cm). The original uncorrected and fishing gear selectivity corrected length–frequency distributions for *M. liza* are presented in Fig. 2a and b, respectively.

3.2. Length–Weight Relationship

Constants *a* and *b*, estimated through regression analysis, resulted in the length–weight relationship equation TW = 0.010*LT $^{2.95}$ with a regression coefficient $R^2 = 0.95$. The *b* value showed a significant difference in isometric growth (t-test, $p < 0.05$), with *M. liza* showing a negative allometric growth in which individuals tend to reach the maximum length (L_∞) at relatively small weights.

3.3. Reproduction and Fisheries recruitment pattern

The average GSI ranged from 0.16 to 4.72, and ΔK from 1.65E−08 to 4.71E−07, with both indices showing monthly changes (Fig. 3). During the period, higher values occurred in July/2011 and May/2012. Indices increased from March to July (austral autumn and winter months) and dropped in the following months (austral spring and summer), suggesting that the spawning season occurred from March to August (Fig. 3). The fisheries recruitment pattern obtained by backward projection of length–frequency data indicated highest recruitment from April to August, corroborating these results. The mean length at first sexual maturity for *M. liza* was estimated at 49.8 cm TL (confidence intervals = 49.1|--|50.6 cm). All individuals greater than 60 cm TL are considered mature (Fig. 4).

3.4. Growth parameters

Monthly length–frequency distributions were predominantly unimodal although successive modes were observed indicating modal displacement over time. Smaller size individuals (25 cm TL) appeared in January (austral summer), but larger (>70 cm TL) occurred almost every month. The ELEFAN_GA method provided the visual fit of the growth curve, indicating the presence of at least nine cohorts (Fig. 5).

Eight robust cohorts (followed for at least five months) were confirmed through Bhattacharya's modal decomposition. Monthly mean lengths of each cohort indicated that fishes smaller than the length of first sexual maturity from all cohorts were captured throughout the year, with fisheries acting mostly on individuals between the juvenile and adult phases (C3, C4 and C5). Following the length–frequency modes, three cohorts (C3, C5 and C6) were tracked over twelve months while the others occurred in ten months or less (Fig. 6).

The optimized values of L_∞ and K obtained through the genetic algorithm (ELEFAN_GA) presented the maximum density values after 500 resamples, closer to the lower limit of the respective confidence intervals. The maximum density estimates of L_∞ and K were 82.35 and 0.30, respectively (Fig. 7). The maximum density estimate of t_{anchor} was 0.48, representing the month of June, where yearly repeating growth curves cross length equal to zero. The growth performance index for length and weight was estimated as 3.3. The life span of *M. liza* in its natural habitat was estimated to be around 10 years (Table 1).

Table 1
Parameter estimates (mode of marginal distribution, Mod) of the seasonally oscillating von Bertalanffy growth function of the *Mugil liza* from Guanabara Bay assessed with the bootstrapped length–frequency analysis with genetic algorithm function of TropFishR. Estimates based on the pooled length–frequency data (theoretical year) collected from July 2011 to June 2013. Lower and upper denote 95% confidence interval of the estimates.

Parameter	Mod	Lower	Upper
L_∞	82.31	81.57	83.00
K (/yr)	0.30	0.27	0.32
t_0	−0.42	−0.48	−0.39
t_{anchor}	0.48	0.35	0.61
C	0.42	0.33	0.52
ts	0.43	0.32	0.58
ϕ	3.31	3.25	3.34
$t_{\max}$	9.99	10.61	9.36

Table 2
Estimated mortality values (Z, M, and F), exploitations rates (E_{cur}, E_{10}, E_{50} and $E_{\max}$), and biological reference points of fishing mortality (F_{opt}, F_{lim}, $F_{0.1}$, $F_{0.5}$) for the *Mugil liza*. Mod: mode of the marginal distribution. Low (lower) and Upp (upper) denote 95% confidence interval of the estimates. Estimates based on the pooled length–frequency data (theoretical year) collected from July 2011 to June 2013.

Parameter	Mod	Lower	Upper
Z	1.02	0.81	1.13
M	0.56	0.52	0.58
F	0.46	0.29	0.55
E_{cur}	0.45	0.35	0.48
E_{10}	0.50	0.56	0.51
E_{50}	0.33	0.34	0.33
$E_{\max}$	0.63	0.65	0.63
$\mathrm{F}_{\mathrm{opt}}$	0.28	0.26	0.29
$\mathrm{F}_{\mathrm{lim}}$	0.37	0.35	0.39

3.5. Mortality and assessment

The annual instantaneous rate of total mortality Z, derived from length converted catch curve was 1.02 y^{-1} (95% confidence interval: $0.81 \geq Z \geq 1.13$). The length at first capture Lc was estimated as 49.2 cm TL (95% confidence interval: $47.7 \geq \mathrm{Lc} \geq 49.5$), which was slightly smaller than the mean size at first sexual maturity ($L_{50} = 49.8$ cm). The natural mortality coefficient M obtained through Pauly's empirical formula at 23.0 °C temperature was 0.56 y^{-1}. The computed instantaneous fishing mortality coefficient ($F = 0.46\ \mathrm{y}^{-1}$) was considerably greater than the target ($F_{\mathrm{opt}} = 0.28\ \mathrm{y}^{-1}$) and close to the limit ($F_{\mathrm{limit}} = 0.37\ \mathrm{y}^{-1}$) of the biological reference point (see the CI), suggesting overexploitation. The current exploitation rate E_{cur} was 0.45, whereas the exploitation level that maintains the spawning stock biomass at 50% of the virgin spawning biomass ($E_{0.5}$) was estimated to be 0.33 (Table 2). These results indicated that a reduction in the current fishing effort towards the target reference point would reduce the exploitation rate within sustainable limits.

4. Discussion

Mugil liza is a fishery resource of traditional importance for small scale fishing communities in Rio de Janeiro. International

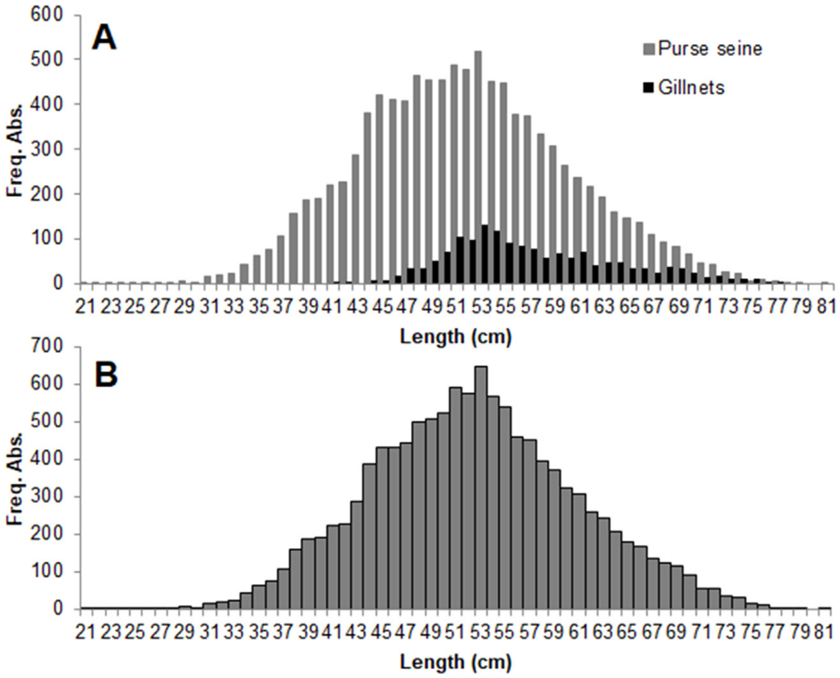

Fig. 2. Total length–frequency distributions (cm) of *Mugil liza* captured by the commercial gillnet and purse-seine fisheries in Guanabara Bay (A) and pooled by a selection curve to adjust catch samples to create one theoretical year (B).

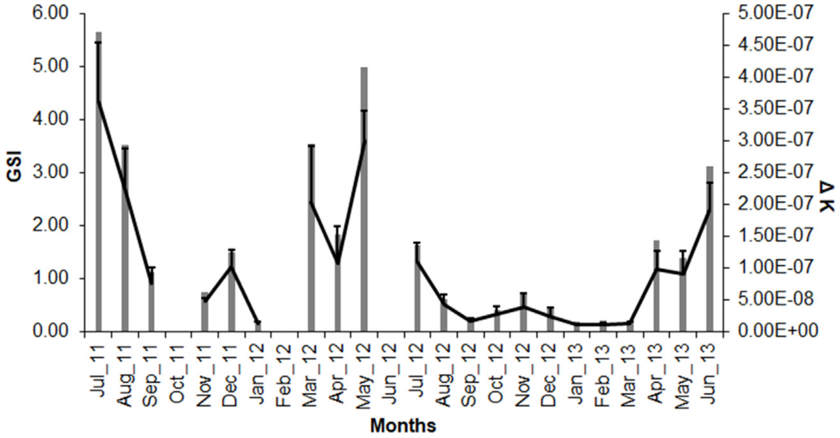

Fig. 3. Monthly averages and standard deviation of Gonadosomatic index (GSI) and gonadal condition factor (ΔK) for *M. liza* from Guanabara Bay, Brazil.

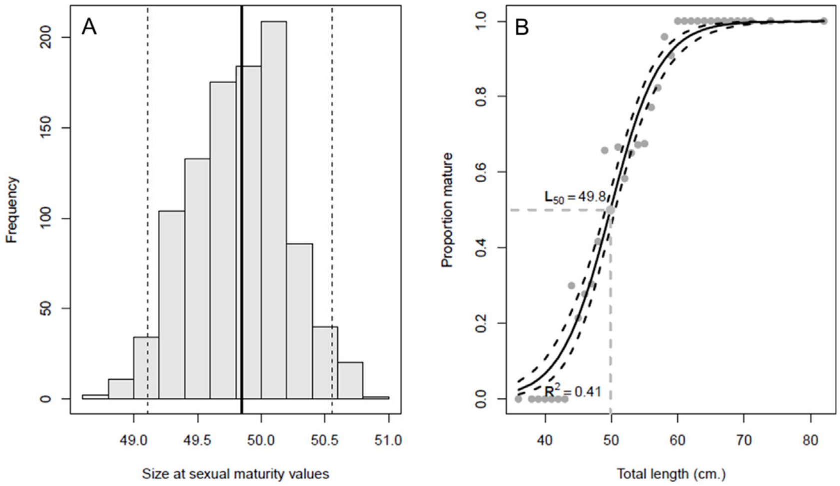

Fig. 4. Confidence Intervals of size at sexual maturity values (A) and logistic maturity curves fitted to length (cm) for grouped sexes of *M. liza* (B) captured in Guanabara Bay.

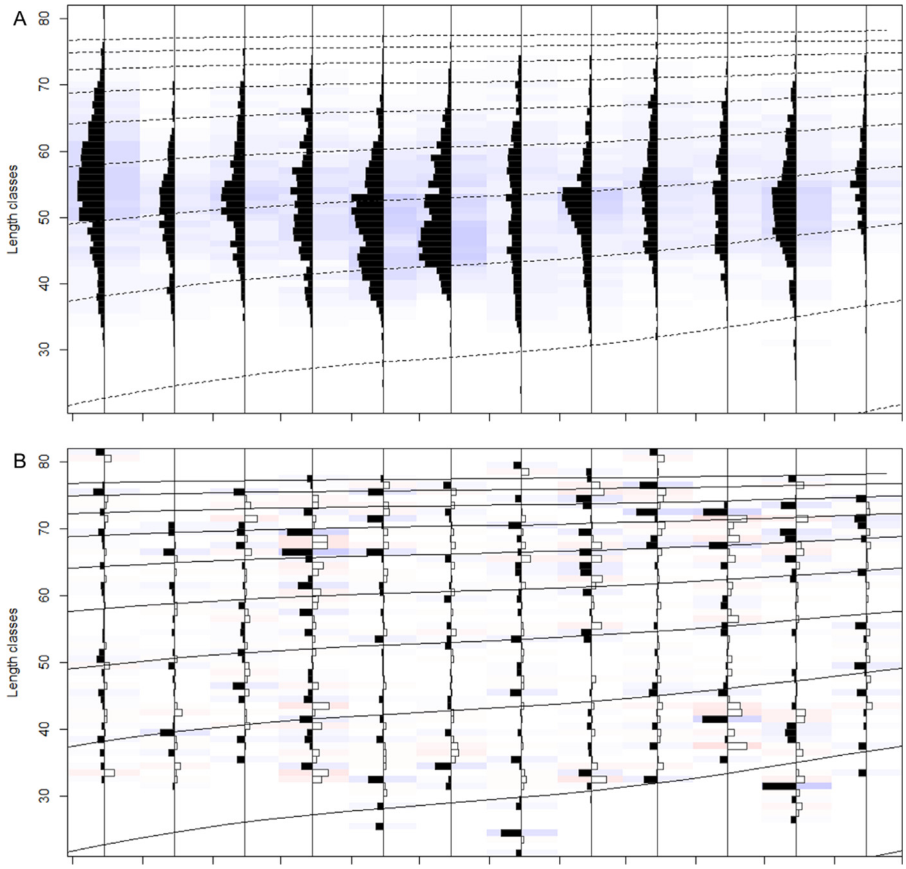

Fig. 5. Monthly length–frequency data (A) and restructured modal progression (B) with cohorts estimated from the size structure of the *M. liza* drawn using a seasonally oscillating von Bertalanffy growth function.

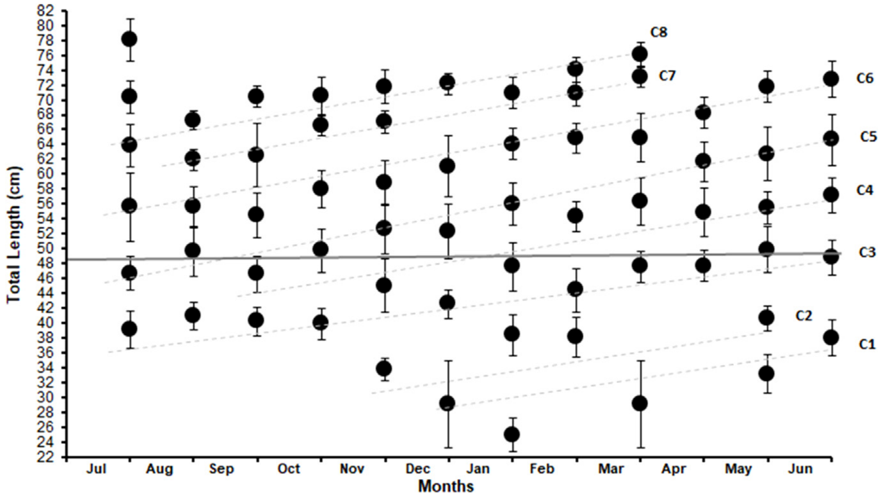

Fig. 6. Mean total length (bars represent standard deviations) of *M. liza* cohorts throughout the months of the year in the Guanabara Bay estuary. Gray horizontal line represents the L_{50}.

market demands for the roe (*Bottarga*) (BRASIL, 2015a) could be an opportunity to generate additional income for the sector. Public policies or private initiatives could provide access to these communities to the global value chain. In either case, strategies should include a management plan considering the biological potential of the stock, and sustainable capture and handling practices. Thus, scientific data at the stock unit level of *M. liza* is extremely necessary for regulatory measures to be applied to different regions and/or stocks along the southwestern Atlantic. Our results aim to establish life history benchmarks for the northern stock, providing a basis for further comparative analysis of cross-ocean basin fisheries and the development of sustainable fisheries policies.

Length–weight relationships (LWRs) are the building blocks of stock assessment and population structure, providing ways for estimating several population dynamic attributes of stocks. The estimated *b* value estimated by the non-linear regression analysis of the length–weight relationship was significantly below 3, which shows that *Mugil liza* within Guanabara Bay exhibits allometric growth. Values of *a* and *b* differ not only among species

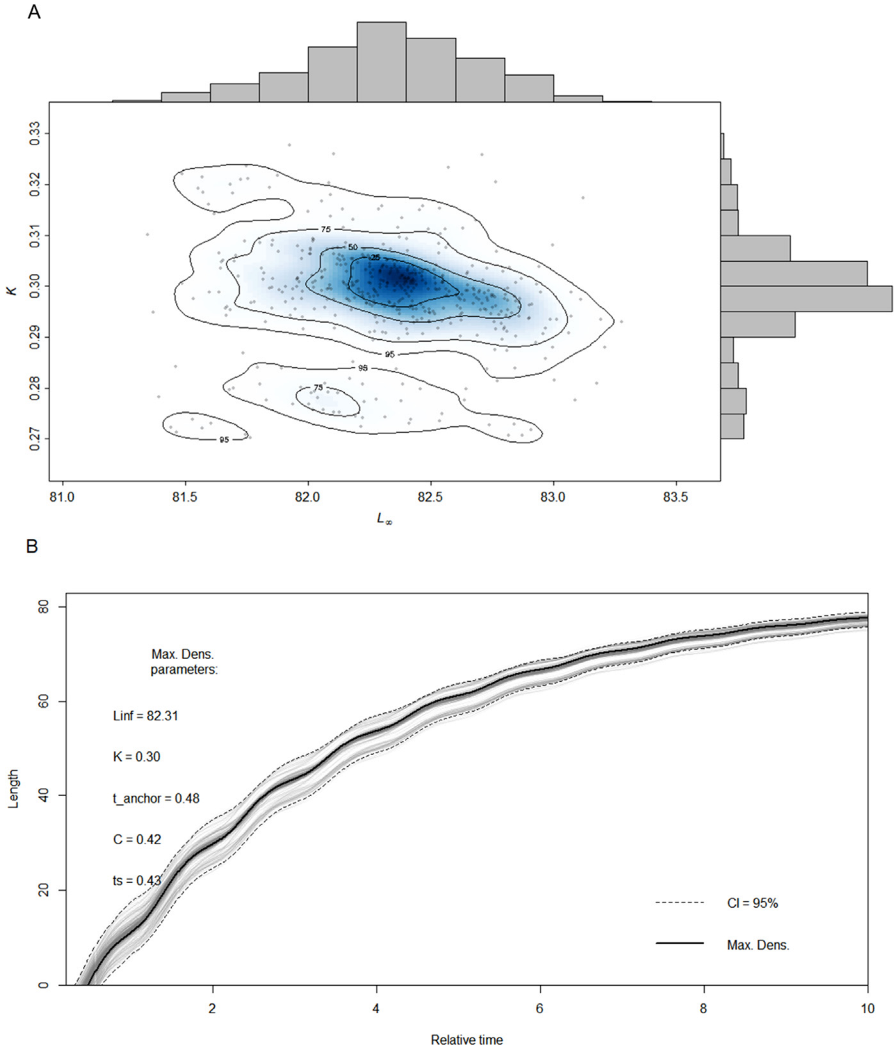

Fig. 7. (A) Scatter histogram of bootstrapped ELFFAN with genetic algorithm optimization for the *M. liza* using TropFishR. The points represent the individual combinations of L_∞ and K estimates, while the contours represent the density of the combinations. The histograms represent the marginal distributions of the L_∞ and K estimates, respectively. (B) Curves warms (gray lines) and 95% confidence contours (dashed lines) for the *M. liza* dataset. Thick black line: growth curve that represents the mode of the kernel density distribution (maximum density peak). Full Bootstrap, Nruns = 500.

but also within species depending on a multitude of factors including sex, maturity stage, feeding intensity (Fonteles-Filho, 2011). Regardless of the variation in length and weight amplitudes, our estimate of *b* was similar to that reported in the literature for the southern Brazilian region (Costa et al., 2014). The exponent *b* of the weight–length relationship has a strong correlation with the condition of the fish in the respective catch areas at a given time (Froese, 2006). In the estuary of Lagoa dos Patos, Mai et al. (2019) suggested that part of the reproductive population returns to the estuary, and that weight loss is associated with a post reproductive period. *Mugil liza* with less weight at larger sizes in Guanabara bay reported by the weight–length relationship, suggests that the bay may be used as a resting area after the reproductive period. Ecological knowledge from fishers at the mouth of Guanabara bay indicated that post reproductive individuals (lean) are captured between July and August (Tubino et al., 2014), possibly returning to their feeding and resting grounds. Thus, variations in intraspecific allometric growth must be carefully considered, and must be accompanied by an assessment of relative growth, that is directly associated with ontogenetic changes in body proportions.

Monthly variation in GSI and condition factor (ΔK) demonstrated that the spawning season, beginning in early autumn continuing throughout almost of the winter, is consistent with previous findings for the northern stock of *M. liza* off the Brazilian coast (Albieri and Araújo, 2010). Nevertheless, there is a great variation in the literature regarding the reproductive season. For instance, González-Castro et al. (2011) identified two periods (April–May and November–December) in Mar Chiquita lagoon, Argentina. Lemos et al. (2014) reported a peak spawning season in June, Esper et al. (2001) observed spawning from May to September in Paranaguá bay, whereas Romagosa et al. (2000) indicated a period from August to October in Cananéia (São Paulo, Brazil) for the southern Brazilian stock. In tropical waters, reproduction occurred in August and September at Alagoas State (Sousa et al., 2015), February and March at Ceará State (Alves and Lima, 1978), both in the northeast Brazil, and November to December in Cuba (García-Cagide et al., 1994).

It is a common trait of mugilids to perform the reproductive migration towards the sea, after the resting and maturing periods in sheltered waters (Ibáñez and Gutiérrez-Benítez, 2004; Fazli et al., 2008; Kendall and Gray, 2008; González-Castro et al., 2009). *Mugil liza* is a single spawner, and its reproductive migration is triggered by specific oceanographic and weather conditions including variations in water salinity and temperature, and the passage of weather fronts (Lemos et al., 2014). Evidences from the artisanal and industrial mullet fisheries indicated that large mullet shoals start their migration in the southwestern Atlantic at water temperatures between 19 and 21 °C (Vieira and Scalabrin, 1991; Herbst and Hanazaki, 2014).

The length at first sexual maturity (L_{50}) of *M. liza* obtained from the maturation curve was of 49.8 cm TL corresponded to the transitional length classes between the juvenile and adult phase (cohorts C2 and C3). Comparing with studies in the southwestern Atlantic, the present value was higher than previously reported. For instance, Albieri and Araújo (2010) found that the length at maturity for *M. liza* in Sepetiba Bay (southwards of Guanabara Bay) in small-scale fisheries was 35.0 cm for females and L_{100} was 55 and 57 cm for males and females, respectively. Esper et al. (2000) reported 41.2 cm as L_{50} and Lemos et al. (2014) 40.0 cm for males and 42.2 cm for females (40.8 cm for pooled sexes) for the southern stock between São Paulo (Brazil) and Argentina for both small-scale (beach seine and gillnets) and large-scale purse seine fisheries. González-Castro et al. (2011) reported $L_{50♀} = 45.4$ cm TL and $L_{50♂} = 43.9$ cm for Mar Chiquita Lagoon, Argentina (fisheries survey). Such variability may be due to environmental differences determining phenotypic variability. For instance, Guanabara bay is strongly influenced by episodic intrusions of the SACW (Moraes and Lavrado, 2017), progressing through the deep channel, reaching most for the areas where the mullet fishery occurred (see Fig. 1). This phenomenon does not occur in Sepetiba bay due to its geographical location and physiography. On the other hand, the effects of sampling biases may not be ruled out, since data was derived from fisheries catches. While most catches in Guanabara bay came from artisanal purse seiners working in deeper waters near the bay channel, catches from Sepetiba bay came from gill netters fishing in the inner bay shallow waters where smaller individuals predominate (Albieri and Araujo, 2010; FIPERJ, 2018a).

Another hypothesis is that L_{50} is under strong evolutionary selection pressure and possible evolutionary changes for a smaller maturation size are derived from the different fishing pressures that each stock undergoes. In fact, the southern stock supports a higher fishing pressure from multi gear small-scale artisanal fisheries acting upon estuarine and coastal waters, and the industrial fishery (BRASIL, 2015a). The latter is aiming at the mullet roe for 'Bottarga' production and export (Bannwart, 2013). On the other hand, the northern stock is subjected to lower fishing pressure coming mostly from small-scale artisanal fisheries occurring in estuarine waters, including Guanabara bay (BRASIL, 2015a). For instance, in 2018 the total mullet production from the southern stock in the state of Santa Catarina reached approximately 11.000 metric tons, whereas the production from the northern stock in the whole state of Rio de Janeiro was about 776,0 metric tons (UNIVALI, 2018; FIPERJ, 2018a,b; Coachman et al., 2019).

The values of L_∞ and K for grouped sexes of *M. liza* were calculated as 82.4 cm and 0.30 y^{-1} using a bootstrapped ELEFAN with genetic algorithm optimization function (bootstrapped ELEFAN_GA). The growth performance index ϕ' was estimated as 3.3. These values are within the range of previously reported estimates for southeastern Brazil ($L_\infty = 73.4$ cm TL, $K = 0.24$ y^{-1} and $t_{\max} = 12.2$ years, (Miranda et al., 2006), and Cuba ($L_\infty = 68.1$ cm TL, $K = 0.24$ y^{-1} and $t_{\max} = 12.5$ years, (Valle et al., 1997). The small range of the estimated ϕ' (3.0 to 3.3), probably expresses a similarity between the growth patterns of different populations of the species (Pauly, 1991). Garbin et al. (2014) estimated the age and growth of *M. liza* from southern and southeastern coastal regions of Brazil based on otoliths readings. According to them, growth parameters were $L_\infty = 66.2$ cm TL and $K = 0.17$ y^{-1}. The reported K-value suggests that this population has a lower growth rate but attains a smaller maximum size and larger longevity (17.6 years) when compared with our results ($t_{\max} = 10$ years). On the other hand, the growth parameters estimated in Argentina waters were $L_\infty = 102.0$ cm TL, $K = 0.19$ y^{-1} (Milessi, 2008) and $L_\infty = 56.3$ cm, $K = 0.3$ y^{-1} (González-Castro et al. 2009), with $t_{\max} = 15.7$ and 10 years, respectively. These variations in population parameters may be attributed to different conditions including sample size, sexes and maturation, but also environment conditions.

As the species is a single spawner, an assumption supported by modal decomposition analysis, we may assume that the Lc is equivalent to a fish between 2 to 3 years of relative age (see Fig. 5). In addition, the selectivity corrected length–frequency distribution also shows that this TL is amongst the most frequent. However, the pattern observed by the fishing gear shows that purse seines act on 45.1% of individuals with TL lower than Lc. On the other hand, gillnets catch a smaller proportion (14.2%) of fish with TL lower than Lc and L_{50} as well. Regardless of these considerations, the minimum mullet catch size for the southeastern and southern Brazilian coast was established at 35 cm (MMA IN N °. 53 of November 22, 2005). According with the present study, the diagnosis of the purse seine mullet fishery within Guanabara Bay indicates a low selectivity that may be affecting a significant part of the stock that has not yet reached this age of first sexual maturation. Therefore, if growth overfishing occurs, then minimum landing size (MLS) should be precautionarily increased to reduce growth overfishing. Thus, the level of compliance with the MLS regulations depends on the fishing gear and its selectivity and is generally higher in highly selective gear that target low number of species.

The linearized catch curve based on length composition data showed a recruitment age for the fishery between 2–3 years. According to González-Castro et al. (2011) in the Mar de Chiquita (Argentina), females and males mature with 45.4 and 43.9 cm TL, respectively, which corresponds to ages between 5–6 years. Individuals not fully recruited (cohort C3 or less) were excluded from the regression. From this regression, Z was estimated to be approximately 1.02 year $^{-1}$, natural and fishing mortalities were estimated as 0.56 and 0.46 y^{-1}. These mortality results match previously reported values proposed by Garbin et al. (2014) for the southeastern and southern Brazilian coast.

The specified precautionary target $F_{\text{opt}} = 0.5\text{M}$ and limit $F_{\text{limit}} = 2/3\text{M}$ values, applied as biological reference points, demonstrated to be good limits for the valuation of this stock given the current stock re-building and resource conservation management objectives. The current fishing mortality ($F = 0.46$ y^{-1}; 95% confidence interval: $0.29 \geq F \geq 55$) was relatively greater than the optimum level ($F_{\text{opt}} = 0.28$ y^{-1}; 95% confidence interval: $0.26 \geq F_{\text{opt}} \geq 29$) and similar to the limit ($F_{\text{limit}} = 0.37$ y^{-1}; 95% confidence interval: $0.35 \geq F_{\text{limit}} \geq 39$) of the biological reference point. The results also concluded that the current fishing mortality is higher than the optimum, regarding the exploitation rate ($E_{\text{cur}} = 0.45$). Which in fact was higher than the exploitation rate which maintains the spawning stock within 50% of the stock biomass ($E_{0.5} = 0.33$).

Using the three mortality estimates we calculated the rate of exploitation (E) which was slightly less than 0.5 considered as a limiting expectation of death by fishing in a given cohort. Therefore, its validity as a management decision tool can be compromised by variations in recruitment and availability between the years. Thus, such an estimate should be used only as a preliminary indication of the fishery's operating status. From the results presented here, it is recommended not to stimulate the increase of the fishing effort with less selective fishing gear that capture mullets smaller than the length of first sexual maturation defined for Guanabara Bay.

According to Prestelo and Vianna (2016), the fishing areas restricted for purse seines represent 68.8% of the study area.

Furthermore, net heights exceed the water depth in all areas where this gear is permitted. The authors have concluded that this fishing gear jeopardizes fisheries within Guanabara Bay. A considerable proportion of the *M. liza* stock of Guanabara Bay did not reach the first sexual maturity. Therefore, to protect the species, the regulation for purse seine inside the study area must be re-evaluated. In fact, there is a need for constant monitoring of fisheries for new definitions of minimum catch size and the adoption of the precautionary principle and careful consideration of the levels of exploitation of this species in different catch areas, whether through artisanal or industrial fisheries.

5. Conclusions

In conclusion, this contribution provides information on the biology and stock status of the northmost population of *Mugil liza,* one of the keystone species in the Guanabara Bay and local fishery community. This investigation could strongly help the establishment of effective and sustainable management plans of fishery resources of the Southeast region. From the present study it is evident that the spawning season of *M. liza* from the northern stock occurs from March to August and the length at first sexual maturity is around 50 cm. Thus, it is necessary to reduce the fishing pressure coming from less selective gear that capture mullets smaller than the length of first sexual maturation during the spawning season. The results also revealed that the length at capture is slightly smaller than the length at first maturity, so we can say that the fish must be caught at least at 50.0 cm TL to get the chance to spawn at least once. The results also concluded that the current fishing mortality is higher than the optimum and the present level of exploitation rate ($E = 0.45$; CI $= 0.35 \geq E_{\text{cur}} \geq 48$) was higher than the exploitation rate ($E_{0.5} = 0.33$) which maintains 50% of the stock biomass as spawning stock $F_{\text{opt}} = 0.28$. Decreasing the current fishing effort could reduce exploitation of *M. liza* within sustainable limits in Guanabara Bay.

CRediT authorship contribution statement

Marcus Rodrigues da Costa: Conceptualization, Methodology, Data curation, Supervision, Writing - original draft, Writing - review & editing. **Raquel Rennó Mascarenhas Martins:** Methodology, Data curation, Writing - original draft, Writing - review & editing. **Acácio Ribeiro Gomes Tomás:** Data curation, Writing - original draft, Writing - review & editing. **Rafael de Almeida Tubino:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Cassiano Monteiro-Neto:** Conceptualization, Methodology, Data curation, Supervision, Writing - original draft, Writing - review & 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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