BOLETIM DO INSTITUTO DE PESCA
ISSN 1678-2305 online version
Scientific Article

USING STOCK ASSESSMENT TO INVESTIGATE THE SUSTAINABLE FISHERIES OF THE YELLOW MANDI *Pimelodus maculatus* IN THE UPPER URUGUAY RIVER, SOUTHERN BRAZIL

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Received: July 17, 2019
Approved: December 26, 2019

ABSTRACT

The yellow mandi *Pimelodus maculatus* is a medium-sized species with a wide geographical distribution. The species is very common in the Neotropical region, representing an important share of fishing activity in several Brazilian reservoirs. Therefore, the objective of this study was to evaluate the current situation of the yellow mandi fish stock in the Itá reservoir, located in the Upper Uruguay River. Data collected from January 2004 to December 2016 were used to estimate growth, mortality, and fish recruitment rates. In addition, a stock assessment was performed, and the results were used to verify the status of the fishery. The mean of the population parameters were: total length (L) = 55.65 cm; length at which 50% of fish are vulnerable to capture (L_c) = 23.08 cm, growth rate (k) = 0.260 year^{-1}, growth performance index (Ø) = 3.047, natural mortality rate (M) = 0.537, fishing mortality rate (F) = 0.413, total mortality rate (Z) = 0.95, exploitation rate (E) = 0.434, maximum age (T_{max}) = 6.68 years. The growth curve obtained via ELEFAN I revealed that fishing operates on eight of the eleven cohorts of the population. Yellow mandi stock assessment did not show signs of fish overexploitation or any risk of depletion.

Key words: Growth; mortality; fish stock; Uruguay River

USO DA AVALIAÇÃO DE ESTOQUE PARA INVESTIGAR A SUSTENTABILIDADE DA PESCA DO PINTADO-AMARELO *Pimelodus maculatus* NO ALTO RIO URUGUAI, SUL DO BRASIL

RESUMO

O pintado-amarelo *Pimelodus maculatus* é uma espécie de médio porte com ampla distribuição geográfica. Na região Neotropical é muito comum, apresentando importante participação na pesca em diversos reservatórios brasileiros. Nesse sentido, o objetivo desse estudo foi avaliar a situação atual do estoque pesqueiro do pintado-amarelo no reservatório de Itá, situado no alto rio Uruguai. Dados coletados no período de janeiro de 2004 a dezembro de 2016 foram utilizados para estimar as taxas de crescimento, mortalidade e recrutamento para a pesca. Adicionalmente foi realizada a avaliação do estoque e os resultados foram utilizados para verificar o estado da pescaria. A média dos parâmetros populacionais foram: comprimento total = 55,65cm ($L\infty$), comprimento no qual 50% da população está vulnerável à captura = 23,08cm (L_c), taxa de crescimento = 0,260 ano^{-1} (k), índice de performance de crescimento = 3,047 (Ø), taxa de mortalidade natural = 0,537 (M), taxa de mortalidade por pesca = 0,413 (F), taxa de mortalidade total = 0,95 (Z), taxa de explotação = 0,434 (E), longevidade máxima = 6,68 anos (T_{max}). Através da curva de crescimento obtida pelo ELEFAN I foi possível observar que a pesca atua sobre oito das onze coortes da população. O estoque do pintado-amarelo não apresentou sinais de sobre-explotação nem risco de depleção da espécie durante o período estudado.

Palavras-chave: Crescimento; mortalidade; estoque pesqueiro; Rio Uruguai

INTRODUCTION

Inland fishing, performed both in rivers and in reservoirs, stands out as an activity of great social and economic importance (Junk, 2007). In many Brazilian regions, fishing is the main source of income and food supply for local population, as well as being an important recreational activity (Junk, 2007; Schork et al., 2013).

Characterized as having a small scale and dispersed activity with little or no landing control, inland fisheries are difficult to manage, largely due to the difficulty of obtaining consistent data (Penha and Mateus, 2007; Agostinho et al., 2016). Nevertheless, understanding population structure and dynamics of fish stocks is essential to ensure the sustainability of fisheries (Jiménez-Badilho, 2004; Penha and Mateus, 2007; Campos and Freitas, 2014; Sá-Oliveira et al., 2015; Amarasinghe et al., 2017; Doll et al., 2017; Ellis et al., 2018; Kumari et al., 2018).

One way of studying fishing stocks is through the yield-per-recruit model (Munyandorero, 2018), which facilitates the estimation of the biomass that is being replaced in the population, to ensure an equilibrium condition. In this model, fishing catch data, species growth, and natural mortality are related to estimate the maximum fishing mortality (F_{max}) that guarantees the maximum yield-per-recruit for the renewal of the species stock, i.e., the maximum sustainable yield. However, in many situations, the maximum sustainable yield is only investigated when the population is already overfished (Mateus and Penha, 2007). Thus, Biological Reference Points (BRPs), which contain additional information to assess the current status of a fish stock, are usually selected depending on the type of data available about the target species.

In several Brazilian regions, different sizes of pimelodid species have been important for fishing activities (Doria et al., 2012; Sant'Anna et al., 2014). The yellow mandi *Pimelodus maculatus* Lacepede, 1803 is a medium-sized species with a wide geographical distribution, found from the north of South America to Argentina, in the La Plata River Basin (Godoy, 1967). In Brazil, this species is very common in the main rivers and their tributaries, as well as in reservoirs (Bizzoto et al., 2009). It is a moderate migratory species that performs small movements during its reproductive period. According to some studies on the species life cycle in the Upper Uruguay River, the adults leave the main river towards the tributaries to carry out their spawning (Cassini, 1998; Zaniboni-Filho and Schulz, 2003). The yellow mandi's reproductive period occurs mainly between October and March (Vazzoler et al., 1997; Sabinson et al., 2014), coinciding with a period of high rainfall. The species is omnivorous, with a wide adaptability with regard to diet (Menin and Mimura, 1992; Lolis and Andrian, 1996), and is considered as an opportunistic species, because it takes advantage of abundant food resources in short periods of time (Ramos, 2009).

The yellow mandi represents an important share of the fishing activity in several Brazilian reservoirs, mainly in the Paraná River Basin, where the species rank fourth among the most captured in biomass (Agostinho et al., 2007). In the Upper Uruguay River, Schork et al. (2012, 2013) also identified the yellow mandi among the most captured species in Machadinho and Itá reservoirs. However, the yellow mandi is more susceptible to fish mortality events due to hydroelectric dam operations (Loures and Pompeu, 2012); its population confined in reservoirs is at constant risk. Therefore, the aim of this study was to evaluate the current situation of the fishing stock of the yellow mandi *P. maculatus* in the Itá reservoir, based on data collected over a 15-year study.

MATERIAL AND METHODS

Study area

Itá reservoir is located in the Upper Uruguay River, between the border of Santa Catarina and Rio Grande do Sul states. The reservoir has a perimeter of approximately 800 km and a total area of 141 km^2, covering eight municipalities. Machadinho Dam is located around 6 km upstream the end of the reservoir.

Sampling and data processing

Total length (Lt, cm) and total weight (Wt, g) data were measured from yellow mandi specimens captured as part of continuous seasonal (4 per year) scientific fishing surveys in the Itá reservoir, between January 2004 and December 2016, totaling 52 collections. A voucher specimen was deposited in the Ichthyological Collection of the Universidade Estadual de Londrina, Brazil (MZUEL n° 09599). Additionally, monthly yellow mandi fishing catch data between 2004 and 2016 were obtained from artisanal fishermen, which used mainly drift nets, lines, and longlines as fishing gear.

Length data were grouped into classes determined in number and range using the Sturges' rule (Sokal and Rohlf, 1981). Subsequently, as described by Sparre and Venema (1997), fishing catch data were grouped and weighted according to the length classes defined by scientific data.

Growth

The length-weight relationship was estimated using the model $Wt = a \times Lt^{b}$, where Wt is the total weight (g), Lt is the total length (cm), and *a* and *b* are the linear equation coefficients, obtained through the least squares method.

Then, the von Bertalanffy Growth Function (VBGF) (Bertalanffy, 1938) was used to adjust the growth curve for length data: $Lt = L_{\infty} [1 - e^{-k(t - t_0)}]$, where t corresponds to age (year), Lt is the total length of the individual at age t (cm), L_{∞} is the asymptotic length or the maximum theoretical length, k is the individual growth coefficient ($year^{-1}$), and t_0 is the theoretical age (years) in which the length is zero. t_0 was estimated using Pauly's empirical equation (Pauly, 1979): $\log_{10}(-t_0) = -0{,}392 - 0{,}275 \times \log_{10} L_{\infty} - 1{,}038 \times \log_{10} k$.

The parameters considered in VBGF – L_{∞}, k, *C* (degree of oscillation = 0), *WP* ('winter point' = 0), *SS* (sum of squares = 2), and *SL* (standard length = 25.50 cm) – were determined using the FISAT II program (FAO-ICLARM Stock Assessment Tools; Gayanilo Júnior et al., 2005) using the ELEFAN I methodology (Eletronic Length-Frequency Analysis) (Pauly and David, 1981), which consists of the identification of peaks and adjustment of growth curves according to length-frequency histograms.

Longevity

The population longevity was calculated using the equation proposed by Taylor (1958): $t_{max} = t_0 + 2{,}996 \times k^{-1}$. The number of cohorts (1 cohort = 1 year) generated using the VBGF model was observed in order to confirm the estimated longevity values.

Growth performance index

The growth performance index (Ø') provides information that allows a comparison of the estimated parameters with parameters of other phylogenetically related species or groups (Gayanilo Júnior and Pauly, 1997). It is expected that population parameters estimated correctly would present similar values among related species (Gayanilo Júnior and Pauly, 1997). In this study, Ø' was calculated as proposed by Pauly and Munro (1984): $Ø' = \log_{10} k + 2 \times \log_{10} L_\infty$.

Recruitment

The number of recruitment pulses per year was obtained using both the frequency distribution of length classes and the estimated growth parameters for the species. The same was used to evaluate the relative importance of these pulses. These analyses were performed through the ELEFAN I routine, included in the FISAT software (Gayanilo Júnior and Pauly, 1997).

Mortality

The instantaneous natural mortality rate (M) was estimated based on the empirical relationship between L_∞, k, and the mean annual temperature (T) of the environment (21 ºC). For the determination of the temperature in freshwater environments, it is considered that the average annual water surface temperature corresponds to the average annual air temperature for the same area (Pauly, 1980). The model proposed by Pauly (1983) was used for the calculation of the aforementioned empirical relation: $\ln M = 0.0066 - 0.279 \times \ln L_\infty + 0.6543 \times \ln k + 0.4643 \times \ln T$.

The instantaneous total mortality rate (Z) was obtained through the linearized length-converted catch curve (Pauly, 1983). First, data were converted to age using the inverse equation of VBGF: $t = t_0 - k^{-1} \times \ln [(1-L) \times L_\infty^{-1})$, then, total mortality was calculated using the equation: $\ln [C (t, t + \Delta t) / \Delta t)] = c - Z \times (t + \Delta t / 2)$.

The instantaneous fishing mortality rate (F) was calculated as the difference between Z and M, i.e., $F = Z - M$.

Exploitation rate

The exploitation rate (E) indicates the fishery status of a stock, and can be determined using the coefficients of mortality F and Z, based on the relationship $E = F / Z$. This value allows estimating the other F values (F_{max}; $F_{0.1}$; $F_{0.5}$) using the following expression: $F = M \times E \times (1 - E)^{-1}$.

Biological Reference Points

The biological reference points (BRPs) were estimated based on the instantaneous fishing mortality (F), being defined as:

1) F_{max} – fishing mortality rate that maximizes the yield-per-recruit without considering whether the spawning stock is conserved to maintain recruitment in the future, estimated from the E_{max};
2) $F_{0.1}$ – rate at which the slope of the yield-per-recruit curve falls to 10% of its origin value, estimated from $E_{0.1}$;
3) $F_{0.5}$ – fishing mortality rate in which the slope of the yield-per-recruit curve falls to 50% of its original value while retaining a safety margin to maintain future recruitment rates, estimated at $E_{0.5}$.

Yield-per-recruit

The yield-per-recruit was calculated using the equilibrium yield model of Beverton and Holt (1966), represented by the expression:

$$Y/R = F \times e^{-M \times (Tc-Tr)} \times W_\infty \times [Z^{-1} - 3H \times (Z + k)^{-1} + 3H2 \times (Z + 2k)^{-1} - H3 \times (Z + 3k)^{-1}]$$

where Y/R is the yield-per-recruit; $H = e^{-k \times (Tc-t0)}$; k = growth coefficient; t_0 = parameter of the VBGF Model; Tc = age of first capture; Tr = age of recruitment; W_∞ = asymptotic weight from the growth model; F = fishing mortality; M = natural mortality; Z = total mortality.

RESULTS

In 798 specimens captured as part of scientific fishing surveys from 2004 to 2016, length ranged from 15 to 53 cm. The most abundant length frequency was 22-33 cm, with class of 27 cm being the most frequent (Figure 1). The length growth curves obtained using ELEFAN I showed that fishing was operating on eight *P. maculatus* cohorts, with the highest catches occurring mainly on five cohorts. Additionally, it was possible to observe

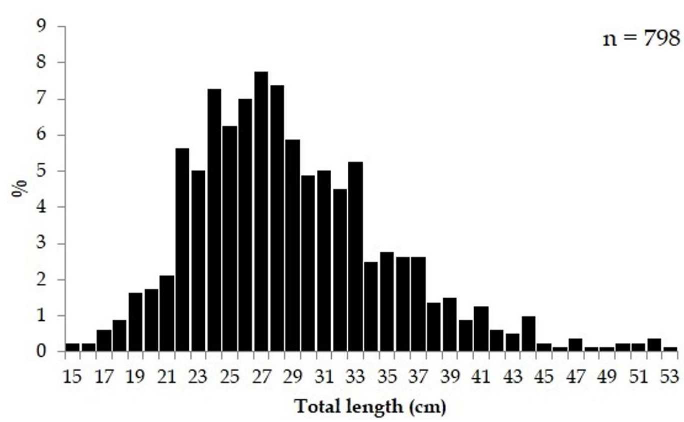

Figure 1. Total length frequency distribution of yellow mandi *Pimelodus maculatus* specimens sampled in the Itá reservoir between 2004 and 2016.

the presence of a higher number of individuals captured from different cohorts during the winter season (Figure 2).

Length-weight relationship parameters for *P. maculatus* were calculated as: $a = 0.0077$, $b = 3.0695$, with $R^2 = 0.8621$ (Figure 3), which is similar to those obtained by Nuñer and Zaniboni-Filho (2009) studying the same region.

The highest recruitment frequencies of specimens to the fishing area in the Itá reservoir occurred between April and August (Figure 4).

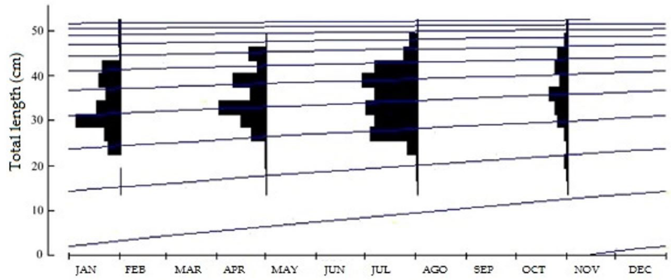

Figure 2. Length growth curves frequency distribution of yellow mandi *Pimelodus maculatus* sampled in the Itá reservoir between 2004 and 2016.

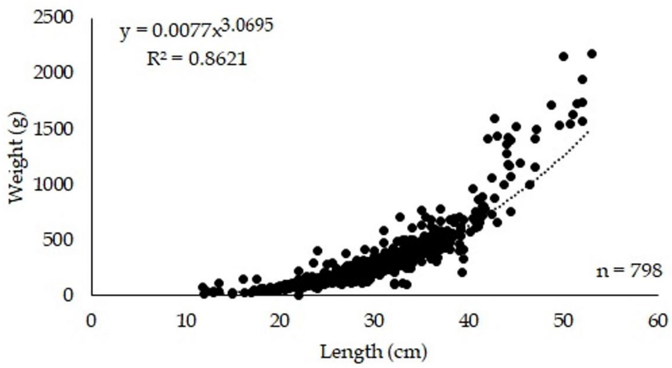

Figure 3. Length-weight relationship dispersion diagram of *Pimelodus maculatus* captured in the Itá reservoir between 2004 and 2016.

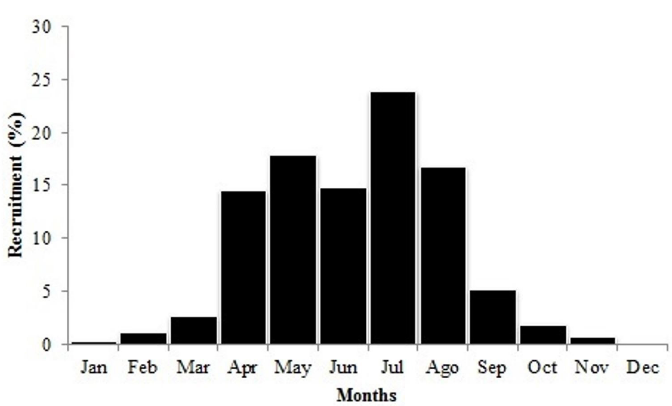

Figure 4. Monthly recruitment percentage of the yellow mandi *Pimelodus maculatus* population in the Itá reservoir between 2004 and 2016.

For the period between 2004 and 2016, the mortality rates calculated using the linearized length-converted catch curve showed the following coefficients: Z = 0.95, M = 0.537, F = 0.413, and E = 0.434 (Figure 5). It was observed that the F was below the two biological parameters F_{max} and $F_{0.1}$, and above $F_{0.5}$ (Figure 6). The yield-per-recruit curve showed values of 128 g for the mortality rates found in the present study.

The estimated parameters of t_0, growth performance index, longevity, and L_{50} are presented in Table 1. Table 2 shows the growth parameters L_∞, Lc, and k, in addition to the exploitation rates.

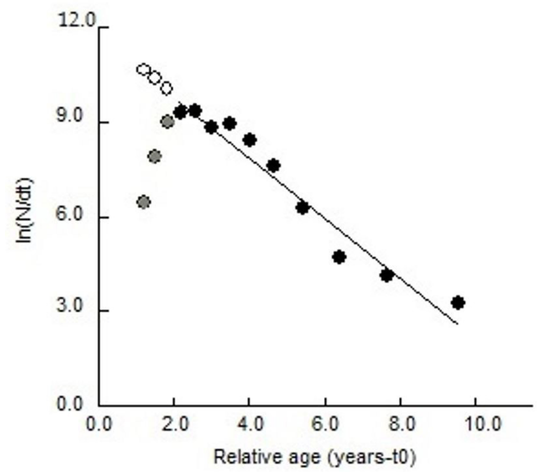

Figure 5. Linearized length-converted catch curve for yellow mandi *Pimelodus maculatus* population in the Itá reservoir from 2004 to 2016.

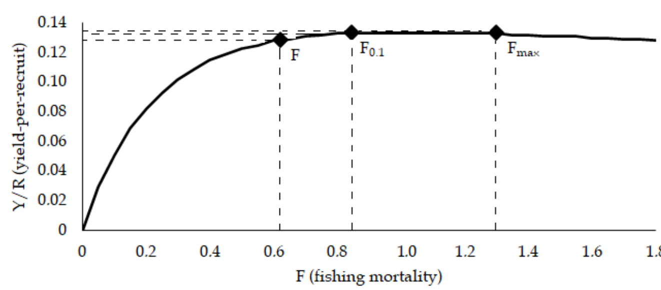

Figure 6. Yield-per-recruit curve for fishing mortality values (F = 0.622 and Y/R = 0.128 kg, F_{max} = 1.285 and Y/R = 0.133 kg, and $F_{0.1}$ = 0.847 and Y/R = 0.133 kg).

Table 1. Population parameters estimates for *Pimelodus maculatus* stock in the Itá reservoir: age at zero size (t_0), growth performance index (Ø'), maximum age (t_{max}) and length at which 50% of fish are vulnerable to capture (L_c).

Parameters	
t_0 (year)	-0.39
Ø'	3.047
t_{max} (year)	6.68
$L_{50} = L_c$	23.08

Table 2. Estimates used for the application of the Beverton and Holt model (1966) and results of the stock assessment of *Pimelodus maculatus* in the Itá reservoir between 2004 and 2016.

Inputs		Outputs			
L∞ (cm)	55.65	**E**	0.434	**F**	0.413
$\mathbf{L_c}$ (cm)	21.98	$\mathbf{E_{max}}$	0.642	$\mathbf{F_{max}}$	0.963
K (year^{-1})	0.260	$\mathbf{E_{0.1}}$	0.501	$\mathbf{F_{0.1}}$	0.539
Z (year^{-1})	0.950	$\mathbf{E_{0.5}}$	0.332	$\mathbf{F_{0.5}}$	0.267
M (year^{-1})	0.537				

DISCUSSION

The results obtained in this study indicate that the stock of yellow mandi *P. maculatus* in the Itá reservoir is neither overexploited nor at risk of depletion.

Maintaining fisheries resources at sustainable and profitable levels is the main objective of most management actions (Brooks, 2013). According to Mateus and Penha (2007), it is important to consider rates of exploitation that keep the target population at acceptable levels, i.e., that allow the species stock renewal, avoiding overfishing. In the present study, the observed fishing mortality rate for yellow mandi in the Itá reservoir from 2004 to 2016 showed values lower than the maximum fishing mortality rate (F_{max}) calculated for the species. However, increasing fishing effort up to this maximum yield-per-recruit may be undesirable because it does not lead to a safety level of exploitation (Deriso, 1987; Sant'Anna et al., 2014).

Although the instantaneous fishing rate did not reach the BRPs $F_{0,1}$ and F_{max}, this does not mean that the fishing effort on the species can be increased randomly without damage to the species stock renewal. The values obtained in this study were based on the existing fishing effort in the Itá reservoir, not taking into account the possible fishing effort increase applied by artisanal fishermen in the same environment during following years, nor the biotic and abiotic factors that can affect the recruitment of the species. Increased *P. maculatus* catches, such as those observed several years during the study period, 2012−2015, may result in cumulative losses and should be evaluated periodically, always considering population responses to fishing effort.

Additionally, fish stock assessments mainly take into account fishing mortality data (Ellis et al., 2018), without considering other factors, typical of river stretches under the influence of hydroelectric power plants, such as the mortality events due to the operational management of hydroelectric dams. These may increase the mortality of this species, making its stock even more vulnerable.

In this study, estimates were based on historical fishing data in the region. Therefore, they are subject to change. During the analyzed period it was possible to observe that the yellow mandi biomass captured by fishermen presented a considerable increase in the last six years (2011 to 2016), which may be related both to an increase in fishing effort as well as to an increase in the yellow mandi population. Thus, a periodical re-assessment of these data might be essential to ensure that the yellow mandi fishery in the Itá reservoir does not collapse, causing environmental, social, and economic damages to the region. It is worth remembering that the stock status is directly influenced by fishing and reflects its current conditions in relation to the estimated reference points (Brooks, 2013).

CONCLUSIONS

The fishing stock assessment of yellow mandi *P. maculatus* in the Itá reservoir based on data from 2004 and 2016 showed no signs of overexploitation or any risk of depletion. However, a periodical re-assessment of these data might be important to ensure a continuous yield and yellow mandi fishery in the region.

ACKNOWLEDGMENTS

We thank Ronaldo Silva, Pedro Iaczinski, Mauricio Machado, and Luis Fernando Beux for their assistance in collecting data from scientific surveys, and for their enormous support in collecting information on artisanal fishing. In addition, we are especially grateful to the various artisanal fishermen who shared their fishing information. This research was supported by Consórcio Machadinho, Consórcio Itá e Engie Brasil Energia.

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