Population dynamics and stock assessment of *Colossoma macropomum* caught in the Manacapuru Lake system (Amazon Basin, Brazil)

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Abstract *Colossoma macropomum* is the second largest scaled fish in the Amazon basin. Reduced harvests in recent decades suggest that populations of this species are already overexploited in some areas. In this study, the population dynamics of *C. macropomum* was investigated using length and weight data for fish caught in the Manacapuru Lake system, a large ria lake located along the lower reach of the Solimões River. A total of 1270 individuals of *C. macropomum* with standard lengths varying from 17 to 62 cm and mean length of 31.0 ± 6.7 cm were sampled. Weights varied from 165 to 8195 g, and mean weight was 1148.3 ± 883.8 g. Maximum sustainable yield was estimated at 285.8 g recruit⁻¹, corresponding to a fishing mortality of 0.51 year⁻¹. A scenario analysis based on changes in fishing mortality and age at first capture, two parameters potentially addressed by fishing management strategies, suggested that any improvement in fishing yield depends on increases in age at first capture.

Keywords: amazon basin, growth, maximum sustainable yield, mortality, overfishing, tambaqui.

Introduction

*Colossoma macropomum* is one of the most valuable fish species in the Amazon Basin. It is the second largest scaled fish in South America, growing to 100 cm and weighing over 30 kg. Known locally as tambaqui, it belongs to the Order Characiformes and Family Serrasalmidae and is endemic in the Amazon and Orinoco basins, where its life cycle is closely associated with floodplains. The larvae and young fish inhabit the floodplain lakes and flooded forest until they reach the adult phase, when they explore the main channels of the rivers in these basins, feeding during the dry season and breeding during the rising-water season (Goulding &
Carvalho 1982), with its feeding habits strictly related to the flood pulse (Oliveira et al. 2006).

Landings of this species have reduced dramatically in the main fishing harbours of the Amazon Basin, probably because of the heavy fishing effort on stocks of this species during the last three decades (Batista & Petrere 2003). In the 1970s, *C. macropomum* accounted for around 40% of the total fish catch landed in Manaus, the main fishing harbour for Amazonian freshwater fisheries (Petrere 1978). However, this figure fell to 10% in the 1980s (Merona & Bittencourt 1988) and to below 5% by the end of 2000 (Batista & Petrere 2003). While several studies on the population dynamics of *C. macropomum* have been carried out (Petrere 1983; Merona & Bittencourt 1988; Isaac & Ruffino 1996; Villacorta-Correa 1997; Costa 1998), studies of stock assessment for this species are scarce. One of the few such studies was by Petrere (1983), who reported that in the late 1970s, the central Amazon stock was still underexploited. Ten years later, Isaac and Ruffino (1996) reported overfishing when they studied the stock in the lower stretch of the Amazon River. In addition to being separated by more than 10 years, these two studies collected catch and effort data in a region with higher human population density, and consequently higher fishing intensity, than the central Amazon. In addition to the reported fall in landings, Freitas et al. (2007) observed indicators such as a severe reduction in the mean size of *C. macropomum* landed in the fishing harbours of Manaus, Amazonas State, and Santarém, Pará State.

The town of Manacapuru is located on the banks of the lower Solimões River and is the harbour for the second largest fishing fleet in the state of Amazonas (Gonçalves & Batista 2008). Most of the fish landed in the harbour is caught in the surrounding region, which includes a huge floodplain area known as Lago Grande de Manacapuru that extends over approximately 511 km² during the flood season. In the light of the importance of *C. macropomum* for Amazonian fisheries and indications of a reduction in stocks, this study sought to estimate population dynamic parameters, particularly those related to growth and mortality dynamics, and to develop a stock assessment model. This information could contribute to an understanding of the dynamics of *C. macropomum*, including its behaviour for different exploitation intensities. This knowledge is essential to support fishery managers in the development of management strategies.

**Material and methods**

**Study area**

*Colossoma macropomum* landed by the Manacapuru commercial fishing fleet were caught in Lago Grande de Manacapuru, a huge lake system (3°18′33″S and 60°33′21″W) located in the municipality of Manacapuru, in the state of Amazonas. Manacapuru is the main town and administrative centre of this municipality. With more than 80,000 inhabitants (IBGE 2014) and an area of 7330 km², it is the main centre for fish landings in this region. The lake system lies in a large floodplain located on the left bank of the Solimões River. It is a typical *ria* lake formed by the lower stretch of the Manacapuru River and the flooded area adjacent to the main channel of the Solimões River (Fig. 1). The annual variation in water level in the lake is approximately 10 m. During the low-water period, the limnological characteristics of Manacapuru River are dominant, while during high water, the Solimões River flows into the lake and changes its limnological characteristics. Together with the lower stretch of the Purus River, this floodplain is the most productive fishing ground in the lower stretch of the Solimões River.

**Sample collection and data analysis**

Samples of *C. macropomum* landings were taken monthly from February 2007 to January 2008 at Panarizinha harbour (Manacapuru, AM). This harbour concentrates fish landings from the Lago Grande de Manacapuru. Standard length (cm) and total weight (g) were measured for least 100 individuals of *C. macropomum* randomly sampled during landing events.

The resulting data set was used to estimate the parameters for the growth equation proposed by von Bertalanffy$L_t = L_\infty [1 - e^{-k(t-t_0)}]$, where $L_t$ = length of fish at age $t$, $t_\infty$ = maximum theoretical length, $k$ = specific individual growth rate and $t_0$ = theoretical age at zero length (King 1995). These parameters were estimated using the ELEFAN I routine, which is available in the FISAT software (Gayanilo et al. 1994). Longevity, or maximum age ($A_{95}$), was estimated using the following equation proposed by Taylor (1958): $A_{95} = (t_0 + 2.996)/k$. The parameter $t_0$ was considered zero because the initial size of the individual is negligible and because this parameter has no biological relevance.

The parameters ‘$a$’ and ‘$b$’ in the weight and length relationship given by the equation $W = a \times L^b$, where $W$ is the total weight and $L$ the standard length, were estimated using a nonlinear model and the Levenberg–Marquardt algorithm. To estimate the maximum theoretical weight ($W_\infty$), equation $W_\infty = a \times L_\infty^b$ was used (Sparr & Venema 1997).

Natural mortality ($M$) was estimated by Pauly’s method (Pauly 1980), which uses the following empirical
equation to establish a relationship between natural mortality, growth parameters and the temperature the water surface: \( \log M = -0.0066 - 0.279 \times \log L^\infty + 0.6543 \times \log k + 0.4634 \times \log T \), where \( L^\infty \) and \( k \) are the parameters of the von Bertalanffy growth equation and \( T \) is the mean annual temperature at the water surface.

Total mortality \((Z)\) was estimated by the linearised catch curve (King 1995), assuming that stock density decreases by a rate proportional to the abundance of each age class. Age \((t)\) was estimated using the equation \( t = \left( -\ln(1 - Lt/L^\infty) \right)/k \). It was assumed that \( Z \) is the slope of the regression between the log-transformed values of density and age. Fishing mortality \((F)\) was estimated using \( F = Z - M \).

Age of recruitment \((Tr)\) and age at first capture \((tc)\) were assumed to be equal and were estimated using the following adaptation of the von Bertalanffy growth equation (King 1995; Sparre & Venema 1997):

\[
Tr = Tc = t_0 - \left( \frac{1}{k} \right) \times \ln \left[ 1 - \frac{Lt}{L^\infty} \right]
\]

Length at first capture and mean length at recruitment were estimated assuming that \( Lc = Lr \), the smallest length class fully represented in the sampling (King 1995; Sparre & Venema 1997). The yield-per-recruit curve was fitted to the model proposed by Beverton and Holt (1957), as described in Sparre and Venema (1997):

\[
\frac{Y}{R} = F \times \exp[-M \times (Tc - Tr)] \times W^\infty \times \left[ \frac{1}{Z} - \frac{3S}{Z + K} + \frac{3S^2}{Z + 2K} - \frac{3S^3}{Z + 3K} \right],
\]

where \( Y/R \) is the yield per recruit \((g/recruit)\); \( F \) the fishing mortality; \( M \) natural mortality; \( Tc \) age of recruitment; \( tc \) age at first capture; \( W^\infty \) maximum theoretical weight; \( Z \) total mortality; \( S = \exp[-k \times (Tc - t_0)] \); \( k \) intrinsic growth rate; and \( t_0 \) theoretical-age-at-zero-length parameter in the von Bertalanffy equation. Finally, as fishing mortality and age at first capture are the only parameters that can be controlled by management strategies, they were included in nonlinear scenarios of yield per recruit of \( C. \) macropomum.

**Results**

A total of 1270 individuals of \( C. \) macropomum with standard lengths varying from 17 cm to 62 cm and mean length of 31.0 ± 6.7 cm were sampled. Weights varied from 165 to 8195 g, and mean weight was 1148.3 ± 883.8 g. The length–weight relationship was \( W = 0.044 \times L^{2.95} \). The standard error for \( b \) was 0.040, and the correlation coefficient \((r^2)\) was 0.97. Once the growth parameters (Table 1) had been obtained from the length-frequency distribution, the growth curve was plotted. Longevity \((A_{95})\) was estimated as 16.64 year, indicating that the fishing operates on at least four cohorts in the tambaqui population (Fig. 2).
Table 1. Population parameters of Colossoma macropomum caught at Lago Grande de Manacapuru (Brazil) between 2007 and 2008

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2007/2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth rate (k) (year⁻¹)</td>
<td>0.18</td>
</tr>
<tr>
<td>Asymptotic growth (L∞) (cm)</td>
<td>65.10</td>
</tr>
<tr>
<td>Longevity or maximum age (A∞,o) (year)</td>
<td>16.64</td>
</tr>
<tr>
<td>Maximum theoretical weight (W∞) (g)</td>
<td>8605.49</td>
</tr>
<tr>
<td>Natural mortality (M) (year⁻¹)</td>
<td>0.48</td>
</tr>
<tr>
<td>Total mortality (Z) (year⁻¹)</td>
<td>1.10</td>
</tr>
<tr>
<td>Fishing mortality (F) (year⁻¹)</td>
<td>0.61</td>
</tr>
<tr>
<td>Age at recruitment (Tr) (year)</td>
<td>1.68</td>
</tr>
<tr>
<td>Age at first capture (tc) (year)</td>
<td>1.68</td>
</tr>
<tr>
<td>Length at first capture (Lc) (cm)</td>
<td>17.10</td>
</tr>
</tbody>
</table>

Estimated total mortality (Z) was 1.1 year⁻¹, and natural mortality (M) was 0.48 year⁻¹. Fishing mortality (F) was therefore 0.62 year⁻¹ (Table 1). Recruitment age (Tr) and age at first capture (tc) were assumed to be 1.68 year because the age at which fish are caught is the age at which they become vulnerable to fishing gear (Table 1). The length at first capture (Lc) was 17 cm and was assumed to be the smallest C. macropomum completely represented in the fishery landing (Table 1).

Yield per recruit (Y/R) was analysed as a function of F and Lc, which was 17.0 cm, corresponding to the smallest fish caught in this study. Based on the estimated value of F of 0.62 year⁻¹, the yield was calculated at 284.1 g recruit⁻¹ (Fig. 3). Assuming the other conditions remain constant, the maximum sustainable yield was estimated at 285.8 g recruit⁻¹, which corresponds to a fishing mortality of 0.51 year⁻¹ (Fig. 3).

Yield-per-recruit curve scenarios presented as areas between isolines for different values of age at first capture and fishing mortality (Fig. 4) suggest the current status of stock exploitation (represented by the white area in the centre of the graph) was contained between the isolines crossing the tc axis at 1.7 and 1.9 year. An increase in fishing mortality between these isolines will not result in improvements in yield. Indeed, improvements in yield depend on increases in the age at first capture in the grey areas between the isolines in the upper part of the graph. For comparison, a tc of approximately 3 years corresponded to a Lc of 28.0 cm, the size of the smallest C. macropomum caught in the Santarém region between the years 1992 and 1993 (Isaac & Ruffino 1996). The values of fishing effort represented by the grey area in the right bottom corner are not viable as they are associated with very low values of age at first capture.
Discussion

Mean fish length in this study was smaller than values reported in previous studies carried out in the Amazon Basin: 69 cm for fish landed by commercial fishing fleets in Manaus (Petere 1983); 40 cm for fish landed in Santarém, on the lower Amazon River (Isaac & Ruffino 1996). Indeed, the mean length in the present study was 56% below the legal minimum landing length in Brazil, indicating that the C. macropomum being landed in the study area are primarily young individuals. The theoretical maximum length ($L_{\infty}$) was also the smallest estimated to date for Amazonian populations of C. macropomum. Previous estimates for theoretical maximum length were 121.2 and 85.1 cm for the lower Amazon River (Isaac & Ruffino 1996) and the Middle Solimões River (Penna et al. 2005), respectively (Table 2). As fishing in the Manacapuru Lake system takes place predominantly in a floodplain area, an environment favoured by this species as a nursery and developing grounds for young fishes (Araújo-Lima & Goulding 1998; Araújo-Lima & Ruffino 2003; Garcez & Freitas 2011), small fishes should be expected to predominate in catches. However, this could be an indication that fishing has already changed the size structure of this population. Batista & Petere (2007) reported continuous growth of the commercial fishing fleet and, consequently, fishing effort in the Manacapuru region. As the value of $L_{\infty}$ estimated here was much lower than in other studies, given the inverse relationship between $L_{\infty}$ and $k$ (Taylor 1958), the $k$ coefficient would be expected to be larger. Nevertheless, no significant differences were observed between the value of $k$ estimated in this study and the values in previous studies (Table 2).

As natural mortality and growth rate are inversely related (Sparrer & Venema 1997), the low estimate of the former was consistent with the biological characteristics of C. macropomum, a large and slow-growth species. Nonetheless, the stock assessment model indicated over-fishing, with fishing mortality approximately 20% higher than mortality for maximum sustainable yield.

As $t_c$ and $L_c$ are closely related, the results corroborate those described for C. macropomum caught in the lower stretch of the Amazon River by Isaac and Ruffino (1996), who reported that younger ages at first capture will result in lower yield per recruit. The length at first capture of C. macropomum in the Manacapuru Lake system is less than a third of that permitted by law, and 98% of the fish captured were less than 55 cm long. In other words, a larger number of fish would need to be caught to ensure profitable production. Despite lack of data to test this hypothesis, the continuous increase in fishing effort and reduction in size of large individuals could result in changes in somatic growth and, consequently, reduced population productivity (Conover & Munch 2002). Like the findings of Isaac and Ruffino (1996), the present results show that an increase in the age at first capture of C. macropomum results in higher yields and potential recovery of the stock, probably as a consequence of the biological characteristics of this species. As highlighted by Petere (1983) and Isaac and Ruffino (1996), C. macropomum is a large omnivorous species that is relatively independent of other fish species and subject to limited natural predation.

The estimated overfishing status of the C. macropomum stock in the Manacapuru Lake system shows that some management actions are necessary to avoid irreversible damage and to promote a recovery of this stock. Currently, two main actions have been adopted by the Brazilian government to protect this species: (1) a 6-month restriction on its capture that coincides with the species’ reproductive season and (2) a minimum landing length of 55 cm. However, ensuring adequate enforcement is vital for the success of these actions. Corrêa et al. (2014) proposed that the combination of fishing restrictions and financial compensation for fishers in the

Table 2. Previous estimates of growth coefficient ($k$) and asymptotic length ($L_{\infty}$) for Colossoma macropomum in the Amazon Basin

<table>
<thead>
<tr>
<th>Authors</th>
<th>Region</th>
<th>Data source</th>
<th>Method</th>
<th>Period/Year</th>
<th>$K$ (year$^{-1}$)</th>
<th>$L_{\infty}$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penna et al. (2005)</td>
<td>Médio Solimões — AM</td>
<td>—</td>
<td>Scale</td>
<td>—</td>
<td>0.105</td>
<td>107.40</td>
</tr>
<tr>
<td>Present Study</td>
<td>Manacapuru — AM</td>
<td>Landing</td>
<td>Length distribution</td>
<td>2007/2008</td>
<td>0.180</td>
<td>65.10</td>
</tr>
</tbody>
</table>

AM = Amazon State; PA = Pará State.
absence of enforcement could have serious effects on fishing stocks by acting as a perverse incentive.

As pointed out previously, the results highlight the importance of an increase in age at first capture. Thus, efforts to enforce legislation are essential for any management strategy to succeed and should be tackled first to ensure sustainable C. macropomum stocks. Nevertheless, as enforcement of a size limit could prove difficult because of the inherent characteristics of small-scale fisheries in the Amazon Basin (Isaac & Ruffino 1996), it is believed that other strategies besides those already implemented are needed to recover these stocks. Some parameters estimated here, such as age at first capture and fishing mortality, indicate that natural stocks of this species have been strongly depleted. Therefore, it is suggested that other measures be implemented, including catch quotas based on scientific information and a complete fishing closure for some tributaries, which would be considered colonisation sources.

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