



Population dynamics and movements of Atlantic tarpon, *Megalops atlanticus*, in the Parnaíba Delta Protected Area, Brazil: challenges for local fishery management planning

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Abstract Fishery management in Brazil has many challenges, including the engagement of fishers, building institutional (NGO, university, etc.) relationships to carry out research and provide key data for managers, and strengthening the capacity to articulate effective management strategies (policy institution). Here we report on recent work to address some of these challenges for the Atlantic tarpon (*Megalops atlanticus*) fishery in the Parnaíba Delta Protected Area. These include meetings to create inter-sector communication, citizen science and ethnobiology to support data collection and biological sampling,

satellite tagging to discern tarpon movements, and the first data-limited stock assessment. The research occurred between September 2018 and April 2020 in the Parnaíba Delta and adjacent marine area, specifically in the Canárias Islands (MA), Pedra do Sal (PI), and Bitupitá (CE). Gonadosomatic indices (GSI > 5%) of female tarpon suggested that tarpon migrate to the Parnaíba Delta to spawn in the dry season (July–December). These GSI findings corresponded with the ethnobiology results in which the fishers confirmed more intense fishing effort in the dry periods due in part to the added value of the

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gonads. Satellite-tagged tarpon remained close to the Buraco and Boca da Barra fishery areas, thus, close to the Parnaíba Delta region. The information collected here will enhance the collaborative formulation of an unprecedented management plan for the tarpon fishery in this region.

Keywords Marine fish reproduction · Artisanal fisheries · Fish tagging · Local ecological knowledge · Data-limited stock assessment

Introduction

Atlantic tarpon (*Megalops atlanticus*) are widely distributed in tropical and subtropical waters of the Atlantic Ocean, with records occurring from North America (Massachusetts) south to the coast of Brazil, the Gulf of Mexico and Caribbean Sea, the west coast of Africa (from Mauritania to Angola), Europe (e.g., Portugal), and the Panama Canal, with new records for the Pacific Ocean (Ault 2007; Adams et al. 2014; Garrone-Neto and Rodrigues 2018; Banon et al. 2019; Castellanos-Galindo et al. 2019). During its ontogeny, the post larvae, juvenile and young phases occur in marine and estuarine habitats. After the recruitment and feeding phase, energy allocation and growth occur in other coastal habitats (Woodcock and Walther 2014; Mace et al. 2018; Griffin et al. 2018; Kurth et al. 2019; Luo et al. 2019; Wilson et al. 2019;). In Brazil, large adult tarpon (> 1 m TL) are called *Camurupim*, while small immature tarpon (< 1 m TL) are called *Pema*.

Previous studies from throughout the region, though not occurring in Brazil, provide a description of tarpon life history. During the reproductive season and after gonad maturation, tarpon perform migrations from inshore waters to the continental shelf, reefs, and offshore banks where spawning occurs on days near new and full moon (Luo et al. 2019). Maximum depths recorded by tagged tarpon (pop-up satellite tags) were approximately 100 m at 26 °C water temperature, suggesting spawning behavior (Luo et al. 2019). Larval samples from sites near where satellite-tagged tarpon likely spawned and from other offshore areas support the hypothesis that tarpon spawn offshore (Smith 1980; Crabtree et al. 1992). Tarpon leptocephali remain in offshore waters for the early stages of development before moving

into coastal wetland habitats (Smith 1980; Mace et al. 2018) after a larval duration of 20–40 days (Shenker et al. 2002). Tarpon are long-lived (~ 60 years), with slow growth and late maturity (sexual maturity at 7–10 years), which increases vulnerability in relation to fishing effort, climate change, habitat degradation, and pollution (Crabtree et al. 1995, 1997; Ault 2007; Baldwin and Snodgrass 2008; Luo et al. 2008; Spotte 2016) that cause population declines.

Tarpon are classified as vulnerable by IUCN due to harvest and habitat loss, and as summarized in Adams et al. (2014), the characteristics of the tarpon fishery vary regionally: the tarpon fishery is recreational and mostly catch and release in the USA; tarpon are catch and release only in Belize; Mexico has an active longline and gill net fishery as well as a recreational, catch, and release fishery; there are significant subsistence fisheries throughout the Caribbean Sea. Where a recreational fishery occurs, it tends to bring economic benefits. For example, tarpon is part of the flats fishery that also includes bonefish (*Albula vulpes*) and permits (*Trachinotus falcatus*), which has an estimated annual economic impact exceeding \$465 million (USD) in the Florida Keys (Fedler 2013) and \$56 million (USD) in Belize (Fedler 2014). Despite the economic value of the fishery, only modest funds have been available for conservation-focused research. Limited data indicate that post-release survival of tarpon in the recreational fishery in Florida ranges from 5 to 28%, depending in part on the presence of predators (Guindon 2011), suggesting that a catch and release fishery can be sustainable if best angling and handling practices are adopted. Despite the importance of the fishery and recent research advances, much remains unknown about tarpon, with insufficient information for management in many locations. For example, satellite tagging shows extensive regional migrations of tarpon within the Gulf of Mexico and along the southeastern US coast (Luo et al. 2019), but there has been only limited tracking in the eastern Caribbean Sea (Luo and Ault 2012a, b) and in other parts of the tarpon's geographic range.

In Brazil, traditional subsistence fishing communities have been catching tarpon with artisanal gears (i.e., hook-and-line, gillnets) for decades, generally supplying families with food and income (Farias et al. 2015; Barletta et al. 2017). Despite the longevity and importance of the artisanal fishery, recent

social changes have created challenges in creating a tarpon fishery management plan. Changes include fishing methods, reduced fishery productivity, human emigration due to lack of employment, decreased incomes, and resistance to management measures (Fernandes and Cunha 2021). In addition, tarpon fishing was prohibited nationwide (Ordinance no. 445 MMA, 2014), with a directive to create species-specific management plans. Thus, we conducted research to obtain appropriate data and community engagement to construct harvest regulations that will inform a new management and governance approach for sustaining the social, economic, and ecological benefits of tarpon fishing in the Parnaíba Delta, northeastern Brazil. Specifically, several research and policy actions were carried out throughout the “Conservation Routes” project (Investment Clauses in Research, Development and Technological Innovation, Shell Brazil). This approach included research on the impacts of fishing (stock production, levels of fishing effort, and stock productivity (i.e., CPUE)), reproduction (spawning season, sexual maturity, fecundity, and oocyte development), movements via satellite pop-up tagging, and a data-limited stock assessment to facilitate development of the management plan proposal.

Methods

Study area

The study occurred between September 2018 and April 2020 in the Parnaíba Delta and adjacent marine area, specifically in Ilha das Canárias in the State of Maranhão (MA), Pedra do Sal in the State of Piauí (PI), and Bitupitá in the State of Ceará (CE), Northeast Brazil (Fig. 1). This region is a designated Environmental Protection Area (Área de Proteção Ambiental, APA) by the Brazilian Legislature as part of the National System of Conservation Reserves, which corresponds to a certain degree of human occupation, endowed with abiotic, aesthetic, or cultural attributes. The Parnaíba River is the border between the states of MA and PI with 1432 km length, draining an area of approximately 344,112 km² (Lucena et al. 2015). In this region, the precipitation ranges between 1300 and 1600 mm year⁻¹, and temperature is typically higher than 26 °C (Alvares et al. 2014). The rainy season is from January to June and the dry season

from July to December. Average monthly rainfall data were provided by the Instituto Nacional de Meteorologia (INMET 2020).

Fishing effort and production

Data on the artisanal fishery of Pedra do Sal Beach (PI) were collected between September 2018 and April 2020. This information included tarpon landings caught with hand lines and longlines by participatory monitoring by local fishers. We recorded catch (kg/day), number of fish captured/day, and biometric data for individual fish: total length (TL) in centimeters, total weight (TW), sex, and gonad weight (GW) in kilograms. Information was also obtained through local ecological knowledge (LEK) from fishers. Estimates of fishery yields and nominal fishing effort (*f*) were calculated and standardized to fishing days per month.

Catch-per-unit effort (CPUE) was computed for each fishing trip as $CPUE = C/f$, where *C* is catch in kg and *f* is nominal fishing effort. Nonparametric Mann–Whitney (U) ($p < 0.05$) tests were applied to test the variation on production, effort, CPUE, length, and weight of the individuals between season and fishing grounds, while Kruskal–Wallis (H) tests were applied to test the variation between production, effort, CPUE, length, and weight of the individuals as a function of seasonality (months).

Reproduction

Gonads were fixed and preserved in a 10% formaldehyde, 70% alcohol, and 20% water solution for future histological processing. Gonads were macroscopically identified to sex and stage according to the stage classification system proposed by Brown-Peterson et al. (2011). To confirm the macroscopic evaluation, histological slides of the gonads prepared by the Bioecology Fishing Lab (Biopesca) of the Federal University of Delta of Parnaíba – UFDPa were further analyzed. The allometric weight dependent on length relationship was estimated by the equation proposed by LeCren (1951), i.e., $W_a = \alpha L_a^\beta$, where W_a is total weight (kg) at age *a*, α is a scalar coefficient, and β is the power coefficient of the weight-length relationship. The gonadosomatic index (GSI) was obtained through the following equation proposed by Flores et al. (2015): $GW/TW \times 100$,

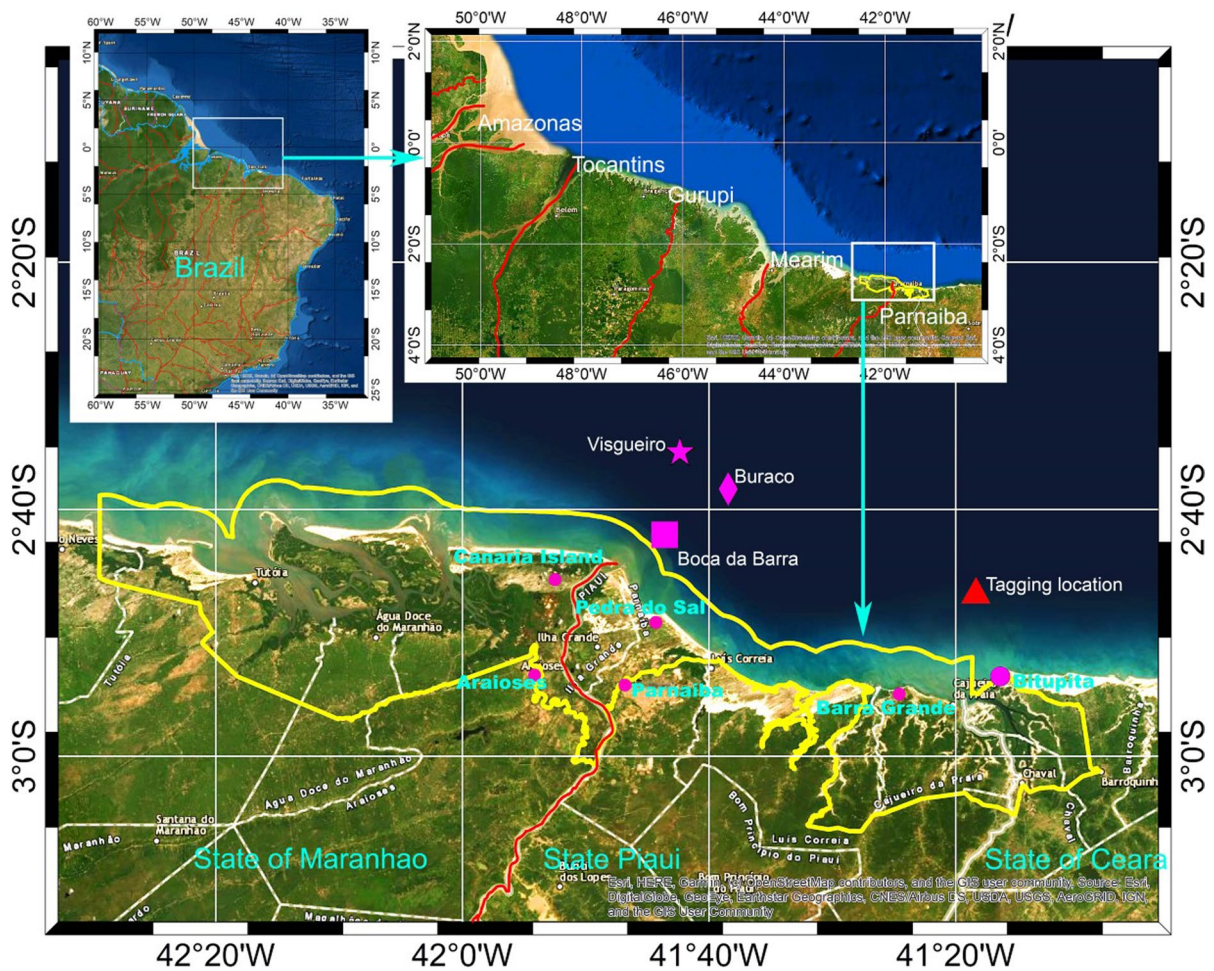


Fig. 1 Map of the study area with insets that show larger geographical surroundings. Red lines in all panels indicate rivers. The yellow polygon indicates the boundary of the Environmental Protection Area (Área de Proteção Ambiental, APA). Pink solid circles indicate towns with place names used in the

text. Red triangle indicates the location of arrowhead trap 41, where tarpon were tagged. Pink square indicates the location of the Boca da Barra fishery, the diamond indicates the Buraco fishery, and the star indicates the Visgueiro fishery

where GW = gonad weight (kg) and TW = weight of the fish (kg). The distribution of oocyte diameters was analyzed according to the method proposed by Hunter and Macewicz (1985), selecting only individuals in spawning capable and actively spawning phases. Fecundity was determined by the gravimetric method of Hunter and Macewicz (1985) and Murua and Saborido-Rey (2003). Fecundity (Fec) calculated by $Fec = (N/GP) \times GW$, where N is the number of oocytes counted and GP is the weight of the proportion of the gonad measured (g). Mann–Whitney (U) ($p < 0.05$) nonparametric tests were used to test the variation of gonad weight by fishing grounds and GSI

by season, while the Kruskal–Wallis (H) tests were used to test the variation between GSI and months and by lunar phase in the fishing grounds.

Pop-up satellite tagging

Individual adult tarpon > 30 kg were fitted with pop-up and SPOT-6 satellite tags (Wildlife Computers, Inc.) at Bitupitá Beach, Barroquinha municipality, State of Ceará, during October and November 2019. Tarpon were captured in Arrowhead fixed trap number 41 by local fishers (Fig. 2). Once trapped, the fish were retained and had a very low escape rate.



Fig. 2 Arrowhead fishing traps (i.e., pound nets) used in the artisanal Atlantic tarpon fishery of the Bitupita region of Brazil

Tarpon were obtained from traps daily with the help of fishing nets. For this study, tarpon in the trap were surrounded using a net, carried near the edge of the vessel, and immobilized by holding the jaw. Before tagging, the total length and total girth in centimeters were measured for each individual. Tagging was done by the researchers and tarpon fishers previously trained to tag tarpon. The transmitter was attached with stainless wire to a titanium anchor dart, which was sanitized and immersed in anesthetic solution before the tagging.

Tag anchors were inserted in the anterior dorsal part of the tarpon, and after tagging, the behavior of each individual was monitored before release. The tags were programmed for a transmission period of more than 365 days, according to the battery's maintenance capacity. Then the tagged individuals were monitored using software (Tag Agent) provided by Wildlife Computers. Subsequently, the data were analyzed to verify the spatial distribution of the species

along the Parnaíba Delta, distance traveled per day, and monitored path, in addition to the length of stay.

Local ecological knowledge

This research also involved the acquisition and evaluation of traditional knowledge by fishers, which in Brazil is considered a national heritage, and its access is governed by federal legislation. As such, this project was registered with the Biodiversity and Conservation System (SISBIO) and approved by the Research Ethics Committee of the State University of Piauí (UESPI). Ethno-ichthyology seeks to strengthen the cultural values and political power of the community that becomes part of the process of management of natural resources. The Informed Consent Form (TCLE) was used and signed by all participants. Data collection was performed through direct observation by scientists and with the aid of a standardized form with open and closed questions, with semi-structured interviews using the sampling method known as

“snowball,” where key informants from the community who had greater knowledge on the subject are indicated. During the interview, recordings and photographs were made using a cellular device. While one researcher was in dialogue with the interviewee, the other assisted with the collection of photographs and filled out the forms: Informed Consent Form (TCLE) and Identification Form of the Interviewee and Authorization of Use of Personality Right. The questionnaires were applied to fishers over 18 years of age, addressing general aspects of fishing, socio-economic information, fishing time, fishing gear and fishing strategies used, perceptions about the environment, and aspects of reproduction, feeding, and spatial distribution of tarpon. Twenty professional fishers experienced in camurupim fishing (using hook and line) were interviewed representing the community of Pedra do Sal Beach, Parnaíba (PI), and Ilha das Canárias (MA), which are part of the APA Delta region of Parnaíba. These communities catch tarpon using hook and line. The other community that participated in the research were the fishers of Bitupitá beach, Barroquinha (CE). This community captures tarpon through arrowhead fixed fishing traps, known locally as “curral,” where 29 professional fishers were interviewed. The information was collected because it is essential for informing new regulatory measures on fisheries. However, perhaps most importantly, the process provides a return for artisanal fishers and strengthens the cultural values and political power of the community that becomes part of the process of management of natural resources.

Data-limited stock assessment

The length-based risk analysis (LBRA) methodology of Ault et al. (2019, 2022) was used to evaluate the sustainability status of the Atlantic tarpon fishery in Brazil at a relatively local scale. We used fishery-dependent data (i.e., length composition) combined with novel estimates of population demographic parameters. The LBRA framework allows generation of fishery sustainability metrics from a probabilistic perspective and facilitates the probabilistic representation of spawning and exploitable biomass relative to gear selectivity and fishing intensity patterns over the entire length range at a given time (Ault et al. 2022).

Length composition data were obtained from the artisanal tarpon fishery in the Pedra do Sal (PI) area.

These data were used to estimate length-based population indicator parameters. Population dynamic data were adapted from Ault (2007) and estimates using published data in FishBase (Froese and Pauly 2022):

- (1) Asymptotic length (L_{∞}) from observed maximum length (L_{max})
- (2) Length at first maturity (L_m) from L_{∞}
- (3) Length at maximum possible yield (L_{opt})
- (4) L_{opt} from von Bertalanffy growth function
- (5) Length L_{mega} for mega-spawners
- (6) K from age and size at first maturity
- (7) Estimate age for any given length from the von Bertalanffy equation
- (8) α parameter of weight-length relationship
- (9) β parameter of the allometric weight-length relationship
- (10) t_0 and M obtained from published data (Ault 2007; FishBase) and fitted in the equation of mean length ($\bar{L}(t)$)

Total mortality rate (Z) was described by the statistical properties of the average length estimated as a normally distributed variable; consequently, a normal $N(\mu, \sigma^2)$ probability density function was parameterized by setting $\mu = \bar{L}(t)$ and $\sigma^2 = [SE(\bar{L}(t))]^2$, and then these were used to generate random deviates of average length $\bar{L}(t)$. Random deviates of Z were computed from the average length deviates. In a similar manner, probability distributions of natural mortality rate M were computed from corresponding probability distributions for maximum age a_{λ} described in Ault et al. (2019). The above procedures were used to generate a pair of Z and M random deviates, from which a random deviate for fishing mortality F was computed ($F = Z - M$). This provided the input mortality rates for a single run of the numerical population model. In our applications, to achieve the asymptotic properties of the selected probability distributions, $n = 10,000$ trial runs were carried out. Using an estimate of natural mortality rate (M), fishing mortality rate (F) was then calculated as $F = Z - M$ (Ault et al. 2019, 2022).

Spawning potential ratio (SPR), a management benchmark that defines exploited stock reproductive capacity (c.f., Ault et al. 2014), was computed as the ratio of $SSB(t)$ at an $F(t)$ at time t relative to that of an unexploited stock (i.e., $F = 0$),

$$SPR = \frac{SSB_{F(t)}}{SSB_{F=0}}$$

Because of the recruitment assumption, relative spawning biomass and *SPR* are functionally equivalent. *SPR* is a life history indicator parameter that can estimate the effect of fishing mortality of a fishery. By comparing the estimated current *SPR* with a target *SPR* defined by stakeholders, a harvest control rule can be adjusted accordingly (Wallace and Kristen 2001; McDonald et al. 2017; Ault et al. 2022).

The overfishing limit (OFL) was defined as the ratio of current estimated fishing mortality rate relative to the fishing mortality rate at the limit reference point (i.e., $OFL = \hat{F}/F_{LRP}$), where here the F_{LRP} was set equal to 40% *SPR*. This represents the magnitude of difference of mortality relative to the reference point.

The distribution of random deviates of \hat{F} was used to compute likelihood distributions for OFL and *SPR* for the tarpon fishery. The proportion of the distribution of $\hat{F}/F_{LRP} > 1.0$ was defined as the overfishing risk probability from the current estimated fishing mortality rate, and the proportion of the distribution of $SPR < 40\%SPR$ was defined as the population sustainability risk (Ault et al. 2022).

Management plan

Tarpon fisheries in Brazil have been prohibited since Ordinance MMA 445/2014, which listed tarpon in the vulnerable category, prohibiting capture unless it occurs in a protected area. As part of an effort by the management institution (ICMBio/MMA), which has been tasked with creating plans leading to the recovery of the target species, fishers, community leaders, fishery representative entities, NGOs, researchers, and public authorities were gathered to define the Recovery Plan for the conservation and population recovery of the species. Eight steps in the process were established: (1) local meetings to break down social barriers and exchange information, (2) analyses and definition of the fishing rules from research results and LEK, (3) agreement by all members through official meetings, (4) publication of the management plan as federal law, (5) implementation of the action plan, (6) policy, (7) monitoring and evaluation, and (8) review of the plan's effectiveness.

Researchers presented information about Atlantic tarpon ecology and biology, fisheries, and management based on local studies and research from other locations, as well as case studies from other regions. The presentations provided a foundation for discussions about local observations and possible plans for conservation management. Following these meetings, fishers sent a letter to the management institution (ICMBio) requesting the recovery plan for tarpon. Two meetings were held by ICMBio with a majority of the fishers and representatives from NGOs, research institutions, as well as resource managers ($n=31$, 5/10/2018; $n=31$, 12/2/2019). During these meetings, participatory methodologies were used, mainly the elaboration of spoken maps and targeted conversations, to obtain information on fishing sites, fishing gears, boat types, crew, and fishing seasonality. Fishers were also engaged to participate in monitoring (landings), collection of biological samples (gonads), and tagging experiments and to support research and planning. The involvement of the fishers increased the local credibility of the results and invested them in the planning process. The process was further enhanced by an agreement among participants, including NGOs, Research institutions and Higher Education, Secretariat for the Development of Family Agriculture, the fishing community ICMBio. Finally, a smaller group ($n=10$) was formed to build applicable rules based on scientific data and fishers agreements, analyze information, and draft a proposal for the Tarpon Recovery Plan for the Parnaíba Delta APA, with a focus on regulations on catch size, exclusion areas, temporal fishing restrictions, closed seasons, and fishing gear prohibitions.

Results

Fishing effort, production, and stock reproduction

Tarpon fishing in Pedra do Sal is by an artisanal fleet formed by canoes with an average size of 6.67 m in length, with propulsion by sail and 12 hp engine. The vessels operate in fishing grounds located 20–40 km from the coast, at depths between 13 and 30 m. Daily fishing effort is typically 8 h (6 am to 4 pm), with the participation of three fishers per vessel. Fishing is by hand line with monofilament nylon from 1.2 to 1.8 mm in diameter, sinkers, steel cable, and number

15/0 hooks, using fish baits (small Haemulids, sardines, etc.).

Tarpon catches are marketed locally for consumption of their meat and gonads. The average price of meat is R\$15.00/kg, while gonads reach the price of R\$120.00/kg, with higher revenues from gonads in the dry season (R\$265.50) than in the rainy season (R\$99.50). Gonad weight ranged from 0.1 to 4.3 kg (2.2 ± 1.2 SD) in the dry season and from 0.05 to 3.0 kg (0.8 ± 0.6 SD) in the rainy season.

During the study period, 178 specimens of *M. atlanticus* were collected on Pedra do Sal beach, 174 females and 4 males. The total length (TL) of the specimens ranged from 123 to 228 cm (mean TL 190.76 ± 18.48 SD) (Fig. 3). Tarpon length varied by month ($W=18.63$, $p<0.05$), but not between dry and rainy seasons ($U=3045.0$; $p>0.05$).

The total harvest was 7855 kg, with 3066 kg in the dry season (65 individuals) and 4789 kg in the rainy season (113 individuals). The total weight (TW) of the captured individuals varied between 18 and 80 kg; however, the average production varied by month ($H=25.84$, $p<0.01$) and season ($U=2920.00$; $p<0.05$) with the highest average production in the dry period (47.2 ± 13.1 SD) and lower in the rainy season (42.4 ± 12.6) (Fig. 4).

Fishing effort was higher in April, May, and June ($H=134.40$, $p<0.01$) and in the rainy season ($U=1620.0$, $p<0.01$) with 6.46 ± 1.98 fishing days/month versus 4.4 ± 1.11 days/month in the dry season. As a result, the CPUE showed significant variations

between months ($H=92.90$, $p<0.01$) with highest CPUE in August (62.00 ± 0.00) and higher CPUE in the dry season (11.96 ± 7.46) than the rainy season (7.72 ± 5.12) ($U=1646.5$, $p<0.01$) (Fig. 4).

The fisheries took place in two areas with distinct characteristics: (1) the fishery called Buraco occurs approximately 30 km from the coast, has an average depth of 30 m, and a bottom formed by sand and gravel substrate and (2) Boca da Barra which is approximately 20 km from the coast, average depth of 13 m, with muddy substrate. In the Buraco fishery, 75 individuals were captured during the dry season with average weight and length of 47.1 ± 13 kg and 193.6 ± 18.3 cm, respectively. In Boca da Barra, fishing occurred during the rainy season; 103 specimens were captured with average weights and lengths of 42.0 ± 12.5 kg and 188.7 ± 18.4 cm, respectively (Table 1). The total length (TL) of fish caught in the two fishing grounds was similar ($U=3381.0$, $p>0.05$), recording an average of 188 cm $TL \pm 18.39$ SD in Boca da Barra and 193 ± 18.34 SD in Buraco (Fig. 5). Fish weight differed by region ($U=3052.0$, $p<0.05$): 18 to 70 kg (41.97 ± 12.54) in Boca da Barra and 18 to 80 kg (47.09 ± 13.0) in Buraco (Fig. 5, Table 1).

Seasonality of fishing effort differed among regions, occurring January to June in the Boca da Barra fishery and June to December in Buraco, with June the only overlapping month. In the Buraco fishery, lower biomass and number of individuals were captured, and these had gonads with higher weights (2.5 ± 1.1 kg)

Fig. 3 Total weight (TW) dependent on total length (TL) relationship for 178 tarpon collected from the catches of artisanal fishers at Pedra do Sal

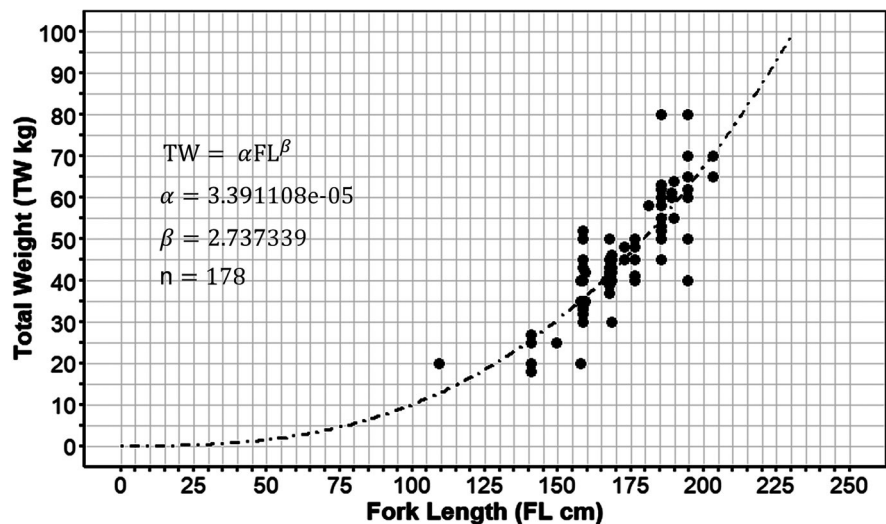
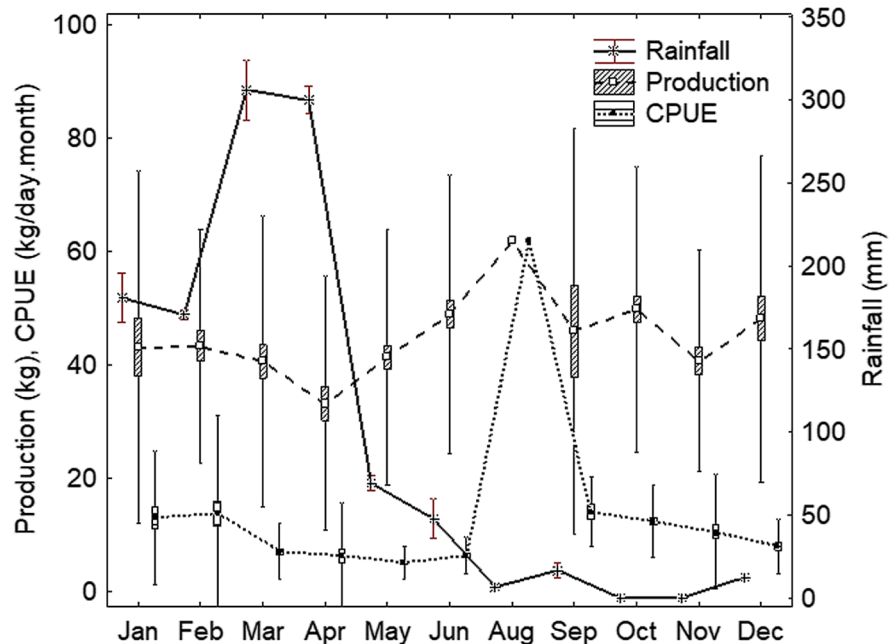


Fig. 4 Monthly box-and-whisker plots of tarpon production, CPUE and rainfall for the Pedra do Sal fishery from September 2018 to June 2020. Box-whisker plots show medians, first and third quartiles, and data range



when compared to the Boca da Barra fishery (0.8 ± 0.7 kg) ($U = 1017.00$, $p < 0.01$) (Table 1).

The highest proportion of spawning capable and actively spawning (hydrated oocytes) individuals were observed between September and December. From February onward, no individuals were observed in the active spawning phase, together with a higher proportion in the regression phase (Fig. 6).

Individuals in all phases of sexual maturity were captured in both fishing regions. However, in the Buraco fishery, the highest proportion of individuals were actively spawning (66.67%) and capable of spawning (16%), while in Boca da Barra, the largest

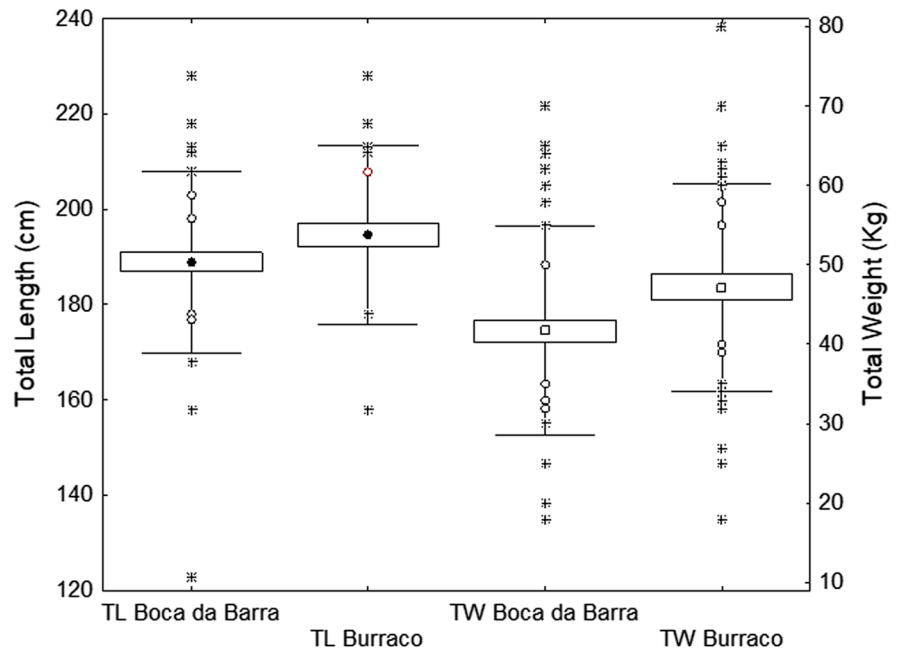
proportion of captured individuals were in the regression (33%) and regeneration (24.27%) phases.

The GSI ranged from 0.22 to 12.50%, with higher values in the dry season ($U = 960.0$, $p < 0.01$) and in the Buraco fisheries ($U = 976.0$, $p < 0.01$) (Fig. 7). The GSI temporal patterns matched spawning seasonality ($H = 90.05$, $p < 0.01$), with higher average values ($> 5\%$) from August to December, reinforcing that spawning occurs in the dry season (Fig. 8). Lunar phase was also important, with highest GSI values in the full moon phase ($H = 12.56$, $p < 0.01$) (Fig. 7). However, the lunar phase effect on GSI only occurred in the Buraco fishery ($H = 9.76$,

Table 1 Tarpon weight (kg), number of individuals (n), and gonad weight (GW) from sampling of the artisanal fishery carried out in two fishing areas as a function of seasonality

Month	NT	BURACO TW \pm SD	Σ TW	GW \pm SD	Month	N	B. BARRA TW \pm SD	Σ TW	WG \pm SD
Jun	10	46.60 \pm 13.00	466.00	2.00 \pm 1.02	Jan	9	43.22 \pm 15.53	389.00	1.87 \pm 0.49
Aug	1	62.00 \pm 0.00	62.00	3.00 \pm 0.00	Feb	15	43.40 \pm 10.28	651.00	1.07 \pm 0.40
Sep	5	46.00 \pm 17.94	230.0	2.26 \pm 1.37	Mar	19	40.74 \pm 12.81	774.00	0.74 \pm 0.38
Oct	29	49.86 \pm 12.61	1446.00	2.86 \pm 1.12	Apr	14	33.28 \pm 11.22	466.00	0.44 \pm 0.39
Nov	16	40.81 \pm 9.82	653.00	1.75 \pm 1.01	May	31	41.39 \pm 11.23	1283.00	0.64 \pm 0.67
Dec	14	48.21 \pm 14.42	675.00	2.82 \pm 0.82	Jun	15	50.67 \pm 11.93	760.00	0.97 \pm 1.04
Total	75	47.09 \pm 13.00	3532.00	2.47 \pm 1.12		103	41.97 \pm 12.54	4323.00	0.85 \pm 0.71

Fig. 5 Total length (TL cm) and total weight (TW kg) of individual tarpon captured in Buraco and Boca da Barra fisheries from September 2018 to June 2020



$P < 0.05$), with no significant differences in Boca da Barra fishery ($H = 4.15$, $p > 0.05$).

Oocyte diameter varied between 46.05 and 895.53 μm , and the simultaneous presence of oocytes

in different stages of development, mainly for females in spawning capable and actively spawning phase, indicates asynchronous development of oocytes, multiple spawning events, and indeterminate fecundity.

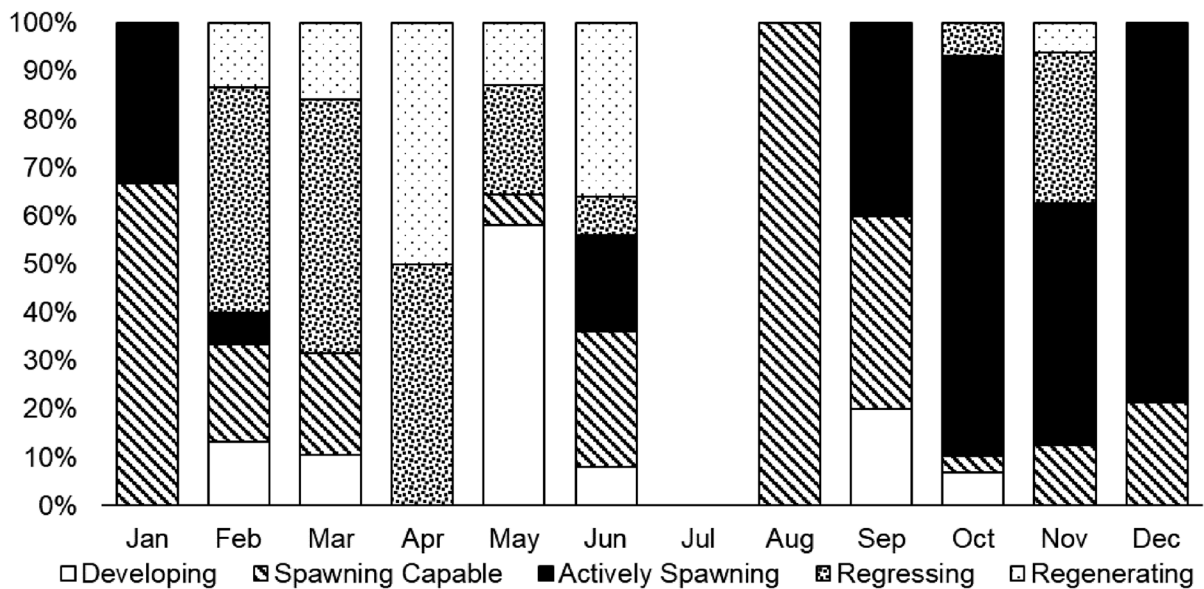


Fig. 6 Spawning phases by month for mature tarpon captured in the Pedra do Sal fishery from September 2018 to June 2020

Fig. 7 Gonadosomatic index (GSI) of tarpon captured from September 2018 to June 2020 in the Buraco and Boca da Barra fisheries during lunar phases and season

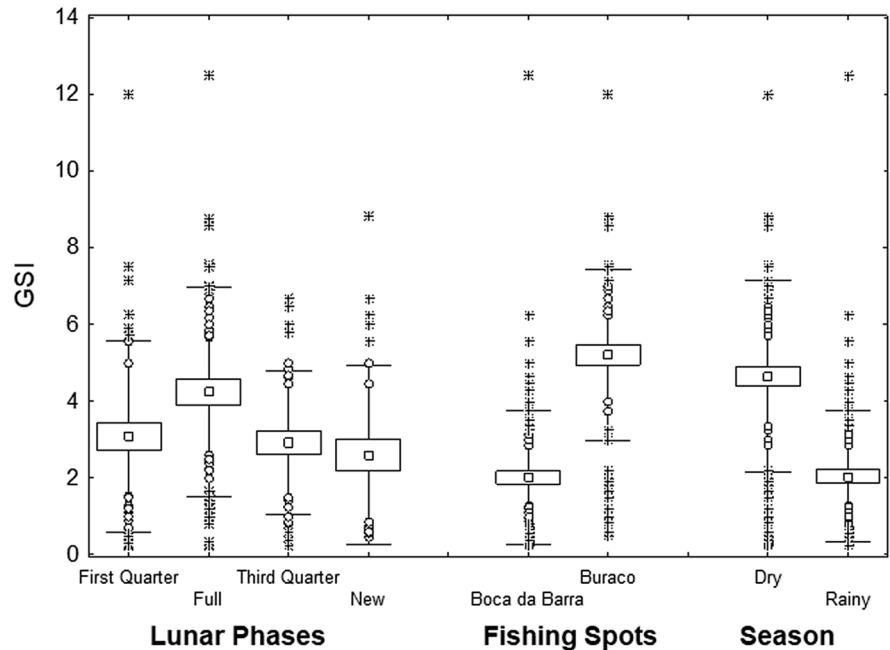
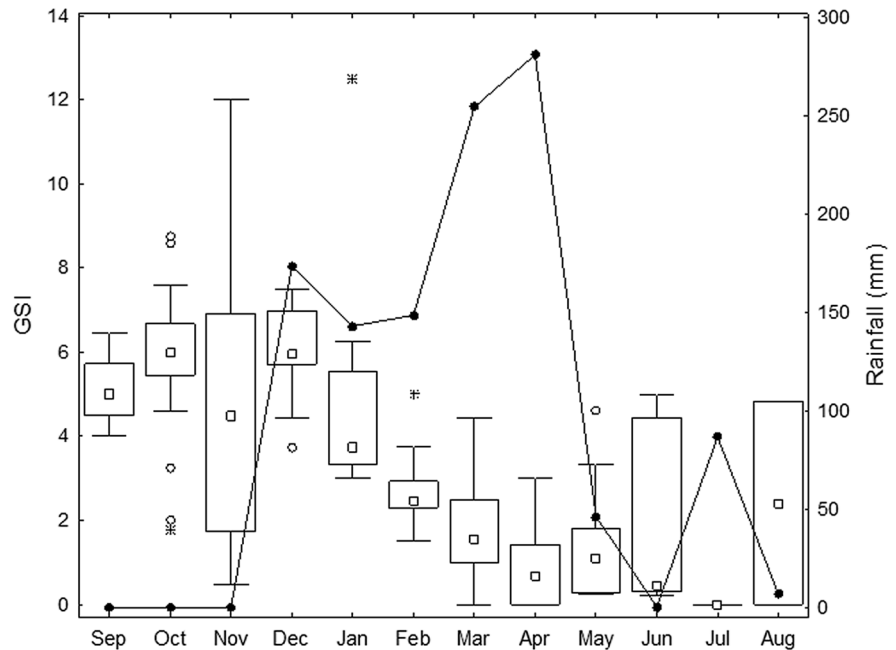


Fig. 8 Monthly gonadosomatic index (GSI, left axis) from tarpon collected in the Pedra do Sal fishery from September 2018 to June 2020 (open circles are medians, lower and upper lines are 1st and 3rd quartiles, circles outside the box are outliers, and asterisks are extremes). Black dots and line indicate rainfall volumes in mm per month (right axis)



Preliminary tags observation for tarpon movements and habitat use

Six specimens were tagged with SPOT-6 satellite telemetry devices between October and November 2019 in Bitupitá (Table 2). Data were received

from four tags: 17U2661, 17U2666, 17U2674, and 17U2670, and the data were obtained via satellite through the specific software on an online access basis (Wildlife Computers). Only one tag has been recovered to date (17U2661). Duration of tracking data was from five to 12 days.

Table 2 Summary data from Atlantic tarpon satellite tagging

TAG S/N	17U2661	17U2666	17U2670	17U2674
Deployment date	22/Oct	27/Oct	07/Oct	28/Oct
Total length (cm)	183	198	172	212
Girth (cm)	-	88	77	113
Weight (kg)	60	55	40	70
Number of signals with no locale	2	33	17	13
Date of 1° signal	23 Oct	03 Nov	10 Nov	31 Oct
Date of last signal	25 Oct	08 Jan	05 Jan	04 Jan
Signals with localization	10	1	2	3
Date of 1° signal with localization	25 Oct	04 Nov	10 Nov	31 Oct
Date of last signal with localization	25 Oct	04 Nov	10 Nov	01 Nov

The length of the tagged individuals ranged from 1.73 to 2 m TL and the weight between 40 and 70 kg and the circumference between 77 and 113 cm TL. Tag-derived location data suggest the individuals follow the current toward Maranhão (Fig. 9). However, the displacement amplitude varied between 50.13 and 261.44 km, with a mean daily displacement of 21.75 km, and permanence and reception of the signal between 5 and 12 days, prohibiting determination of fine-scale movements. Tagged tarpon remained close to coast and near the estuarine and coastal complex that covers the Parnaíba Delta area, between the regions of Maranhão and Piauí. The lowest displacement observed between each point was approximately 5 km, which also indicates a behavior of permanence during the period of data analysis.

Local ecological knowledge

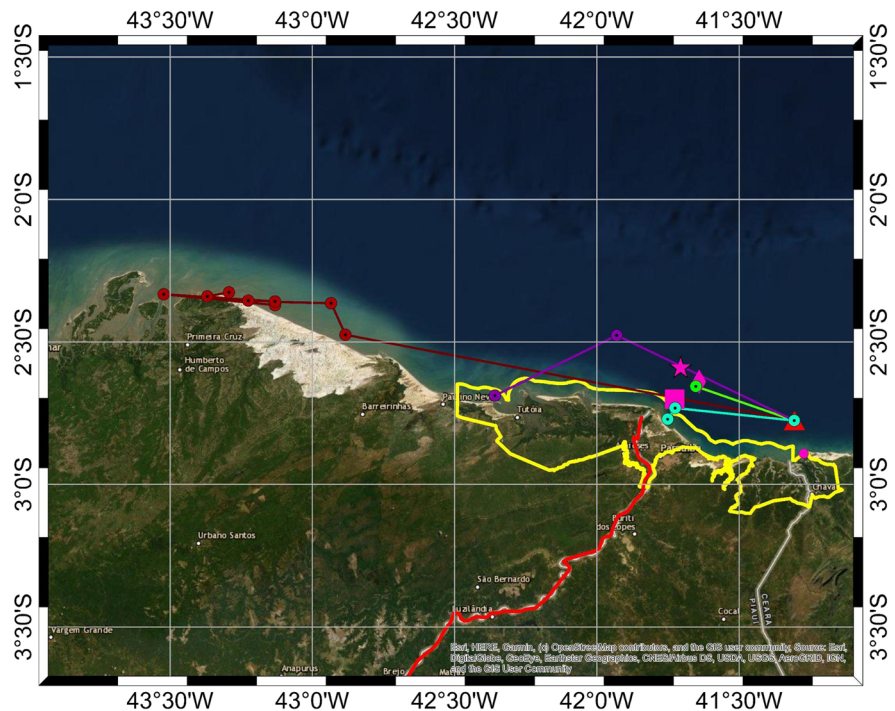
The 38 fishers interviewed demonstrate a good understanding of the behavior, patterns, and variations of natural phenomena in the environment. These fishers reported that environmental variables such as tide, wind, and rain conditions, as well as moon phase influenced catch rates. The reports of fishers from the community of Bitupitá suggest that tarpon move to the coastal region to feed or reproduce, resulting in a higher incidence of capture between the months of May and September. Fishers from fishing communities in the states of Maranhão and Piauí reported a higher incidence of captures between August

and December (dry season), corroborating the data obtained from the histological analysis of the gonads collected in this study. CPUE analysis showed significant differences between seasons, with higher productivity in the dry season and lower in the rainy season.

Fishers cited the moon as a factor that directly influences their fisheries. Of the 38 fishers, 12 reported believing that the best moon is full moon due to greater luminosity and proximity of the largest fish to the surface to feed. The reproductive biology data obtained here showed that gonad weight (2.01 ± 1.35 kg), total weight (45.75 ± 13.93 kg), and total length (193.52 ± 20.74 cm) were higher at full moon. Eleven fishers answered that the crescent moon is the best period for fishing, eight fishers answered that the waning moon is the best moon, and five fishers believe that the new moon is the best period. However, the new moon was considered by 28 fishers the lunar phase less prone to fishing due to low light, as they believe that fish hide in deeper waters. Only two fishers believe that the moon has no influence on fisheries.

All fishers stated that there has been a reduction in the abundance of fish due to trawling, which has a negative impact on the fishing region. They believe that trawling caused a reduction in tarpon prey, resulting in movement to other areas in search of food. Fishers in Maranhão and Piauí also showed great concern about the mortality of young tarpon, which are found in bays and lagoons in the region. During the dry period, it was reported that most of the lagoons dried up, causing the death of young fish.

Fig. 9 Map with spatial distribution of four tagged tarpon that provided good signals along Delta do Parnaíba and adjacent areas. Small colored (green, wine-red, purple, and blue) circles and lines represent the tracks of individual tarpon. Red triangle indicates the location of arrowhead trap 41, where tarpon were tagged. Pink square indicates the location of the Boca da Barra fishery, the pink diamond indicates the Buraco fishery, and the pink star indicates the Visgueiro fishery



Data-limited stock assessment

The LBRA sustainability analyses methods were applied to Atlantic tarpon fishery of Pedra do Sal, Brazil. Life history demographic parameters for species are provided in Tables 3 and 4. From the fishery-dependent data, average length in the exploited phase (\bar{L}) was 169.97 cm FL and minimum length at first capture L_c was 145 cm FL, estimated from the artisanal fishery length composition data for the period 2018–2020 (Fig. 10). LBRA indicated that the risk of exceeding the overfishing limit (OFL) was 22.05%; and further, the risk of falling below the limit reference point of 40% SPR was also 22.05% (Fig. 11). These findings suggest that at present, there is a moderate to low sustainability risk for this fishery.

Toward sustainable management of the local artisanal tarpon fishery

To determine an effective management plan for the local artisanal tarpon fishery, a number of population dynamics, stock assessment, and ecological and socio-economic concepts were integrated. The primary aim

was to regulate fishing mortality across the range of species' life stages to maintain a sufficient reproductive population size that ensures sustained reproduction and recruitment into the indefinite future (Ault et al. 2014, 2022). For consideration of the potential aspects of a viable management plan, several management controls were considered, namely minimum size of capture, areas that prohibit fishing, temporal fishing restrictions, closed seasons, and gear prohibitions.

Fishers supported the inclusion of a minimum size of capture (> 100 cm FL), derived from the minimum length at maturity L_m estimation, as an initial management application. Fish size was also considered for fisheries for juveniles in the lagoon and stream. The fishers also asked for transport of juveniles trapped in the lagoons due to the reductions in rainfall and isolation of these areas that prevented juvenile tarpon from escaping.

The majority of the scientific group agreed that closed areas to protect juveniles, regulations on the spawning grounds, and bag limits based on F would be difficult to apply. Consensus was that minimum length restrictions were most appropriate. However, the group indicated concerns about fishing on the spawning grounds based on the reproduction data. Since the landings are centralized at Pedra do Sal,

Table 3 Provisional estimates of Atlantic tarpon population demographic parameters using the equations proposed by Froese and Binohlan (2000)

Parameter	Description	Equation	Units
L_{∞}	Asymptotic length	$\ln(L_{\infty}) = 0.044 + 0.9841 \times \ln(L_{max})$	cm FL
FL	Conversion of TL to FL	$FL = 1.062607 + 0.896584 \times TL$	cm FL
L_m	Length at first maturity	$\ln(L_m) = 0.8979 \times \ln(L_{\infty}) - 0.0782$	cm FL
L_{opt}	Optimum length	$L_{opt} = L_{\infty} \times \frac{\beta}{\beta + \frac{M}{K}}$	Cm FL
K	Brody growth coefficient	$K = \ln\left(1 - \frac{L_m}{L_{\infty}}\right) / t_m$	yr ⁻¹
t	Estimate of age from von Bertalanffy equation	$t = \frac{\ln\left(1 - \frac{L_t}{L_{\infty}}\right)}{K} + t_0$	yr
L_{mega}	Size of mega-spawners	$L_{mega} = 1.1 \times L_{opt}$	cm FL
M	Natural mortality rate	$\hat{M} = \frac{\ln(S_A(0.015))}{t_A}$	yr ⁻¹

size limits can be monitored. The group also discussed the feasibility of future protections of early life stages, combined with gear restriction. Finally, sex-specific regulations were deemed not feasible because of the value of the gonads for the fish community.

After discussion with both groups, ICMBio prepared the management plan, with size restrictions (fish > 100 cm FL can be harvested) and prohibition of fisheries in the lagoon and streams (scheduled for the rainy season) where juveniles occur. From this stage, the plan still needs to be voted on and an agreement reached in the deliberative council, for later publication in the official journal of the union through an ordinance dispatch.

Discussion

Fishery management in Brazil is extremely difficult to execute, due to the influence of different groups during the implementation process, mainly for artisanal fishing (e.g., Too Big To Ignore), in which socio-economic issues gain a greater weight in the final decision-making by managers. In addition, fishery management is often suppressed by other government interests that deconstruct regulations, often resulting in the loss of biodiversity and the collapse of fish stocks (Dario et al. 2015).

Currently, Brazil lacks direction for application of fishery statistics and data generation to management strategy and fishery plans (Barros et al. 2021; Freire et al. 2021). Another hindrance to effective management is that fisheries are shared by different

ministries. Artisanal fishing and environmental management in conservation areas are under the Ministry of the Environment (MMA), while artisanal fishing outside conservation areas and industrial fishing are the responsibility of the Ministry of Agriculture, Livestock and Supply (MAPA). This management disparity underscores the need for collaborations involving fishers, researchers, and managers.

Tarpon in the Parnaíba Delta exhibit a relatively wide distribution and use of different habitats throughout their ontogeny. Adults occupy the marine-coastal zone and use offshore waters for spawning, much of this outside of the protected area. Early life stages inhabit lagoons and tributaries within the conservation area (Fernandes et al. 2017; Silva et al. 2021). The ontogenetic shifts and migrations make the species more vulnerable to being caught by multiple fishing gears throughout the life cycle. Currently, the management plans do not consider these spatial and temporal factors, in part because the protected area and adjacent unprotected area are managed by different government institutions.

The fishing data in Pedra do Sal show that the fishing fleet is of artisanal character with low catch rates, which indicates a low impact on the stock. However, the aggregate value of the gonads implies a greater selectivity for the larger and heavier females of the population. The LBRA suggested a low to moderate sustainability risk, but this should not confer a lack of sense of urgency to development strategic management plans to sustain this resource. Because tarpon are long-lived and grow to large sizes, they

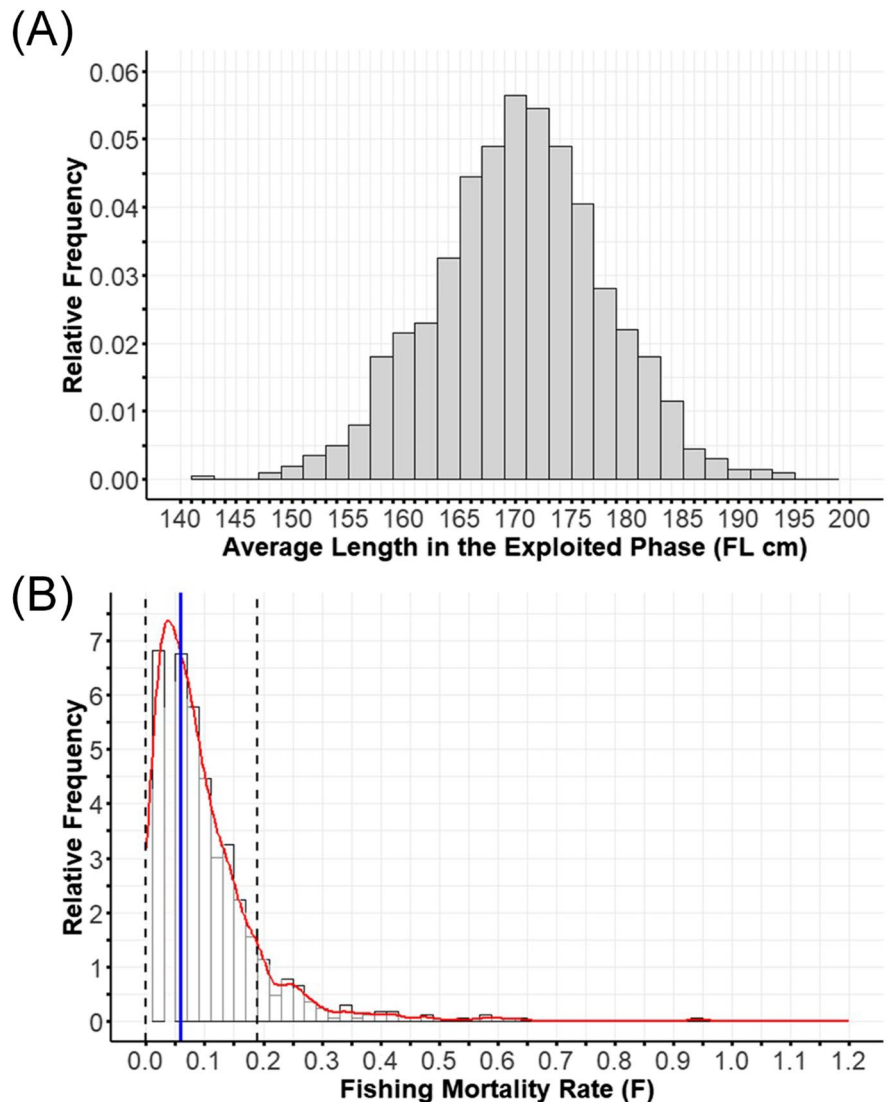
Table 4 Parameter symbols, definitions, values, and units for demographic relationships used in the LBRA estimation-simulation analysis of the Brazilian tarpon population

Symbol	Definition	Value	Units
a	Cohort age class ($a = 0, \dots, a_\lambda$)		Months
$Z(a, t)$	Total mortality rate at age a at time t		Per year
$M(a, t)$	Natural mortality rate at age a at time t		Per year
$F(a, t)$	Fishing mortality rate at age a at time t		Per year
$N(a, t)$	Numbers (abundance) at age $a + \Delta a$ at time $t + \Delta t$		Number of fish
$L(a, t)$	Length at age a and time t		mm FL
$W(a, t)$	Weight at age a and time t		kg
$B(a, t)$	Biomass at age a and time t		kg
L_∞	Asymptotic length	195.29	mm FL
K	Brody growth coefficient	0.1019	Per year
a_0	Age at which length equals zero	0.0	Years
W_∞	Asymptotic weight	73.70	kg
α	Scalar coefficient of weight-length function	3.3911e-05	Dimensionless
β	Power coefficient of weight-length function	2.7373	Dimensionless
a_λ	Maximum observed age (under exploitation)	55	Years
S_λ	Average survivorship probability to a_λ		Dimensionless
L_m	Length at 50% maturity	128.50	mm FL
\bar{L}	Average length in the exploited phase	169.97	cm FL
L_c	Minimum length at first capture	145.00	cm FL
L_λ	Mean length at maximum age	194.57	mm FL
W_λ	Mean weight at maximum age	72.97	kg
\hat{M}	Natural mortality rate estimated from \hat{a}_λ	0.07636	Per year
\hat{F}	Fishing mortality rate estimated from \hat{Z} and \hat{M}		Per year
$\hat{\bar{L}}$	\bar{L} estimated from numerical model		mm FL
F_{med}	Median of fishing mortality rate distribution		Per year
f	Nominal fishing effort		Numbers
$\theta(a)$	Sex ratio at age a		Dimensionless
$\phi(L)$	Selectivity at length L		Dimensionless
$\bar{N}(t)$	Average population abundance at time t		Numbers
$\bar{B}_{EX}(L_c, t)$	Average exploitable population biomass		mt
$\bar{N}(L, t)$	Average abundance (numbers) at length at time t		Numbers
$\bar{B}(L, t)$	Average population biomass at length at time t		mt
$Y_n(t)$	Yield in numbers at time t		Numbers
$Y_w(t)$	Yield in weight at time t		mt
SSB	Spawning (mature) stock biomass		mt
SPR	Spawning potential ratio		Dimensionless
F_{LRP}	Fishing mortality rate at limit reference 40% SPR		Per year
F/F_{LRP}	Current F to reference F (overfishing limit, OFL)		Dimensionless
B/B_{LRP}	Current to reference spawning biomass		Dimensionless

are exceptionally vulnerable to even low levels of exploitation. The two principal management interventions of LBRA (size and effort limits) clearly suggest that a minimally effective management strategy would include setting the minimum size of capture L_c

greater than the minimum size of sexual maturity L_m to ensure that fish have at least one spawning event in their lifetime. However, this will not be sufficient in the long term to ensure stock sustainability. While this fishery does not appear to affect the youngest age

Fig. 10 Distributions of **A** average size in the exploited phase; **B** estimates of fishing mortality rate. Solid blue vertical line in **B** is the median rate, and dashed vertical lines are 1st and 3rd quartiles



classes per se, other fisheries in the region do catch many immature individuals (Tarrafa, in lagoons) or sub adults by arrowhead fishing traps (Fernandes et al. 2017; Silva et al. 2021). Even though the regional fishery is still a relatively artisanal, significant attention to the collection of accurate and precise fishery statistics is paramount to ensuring that exploitation rates are maintained at low levels that minimize resource sustainability risks and produce maximum benefits for the constituency (e.g., Ault et al. 2022).

Satellite tagging data showed a migration flow in the East–West direction of the Parnaíba Delta during the study period, but conclusions on overall movement patterns are not possible with the limited data

available. However, tracking data, in combination with GSI data, suggest that individuals remain in the Buraco area for spawning, making this area especially important for management consideration. More satellite tagging studies are needed for this region to determine long-term migration pattern.

The likelihood of spawning in the Buraco region during the dry season is further supported by GSI data and LEK. The greater lengths and weights of individuals captured in the dry season and high values for GSI in the new and full moon phases in Buraco suggest reproductive behavior. Luo and Ault (2012a, b) and Luo et al. (2019) found correlation between the lunar phase and deep dives (~ 100 m), which indicates

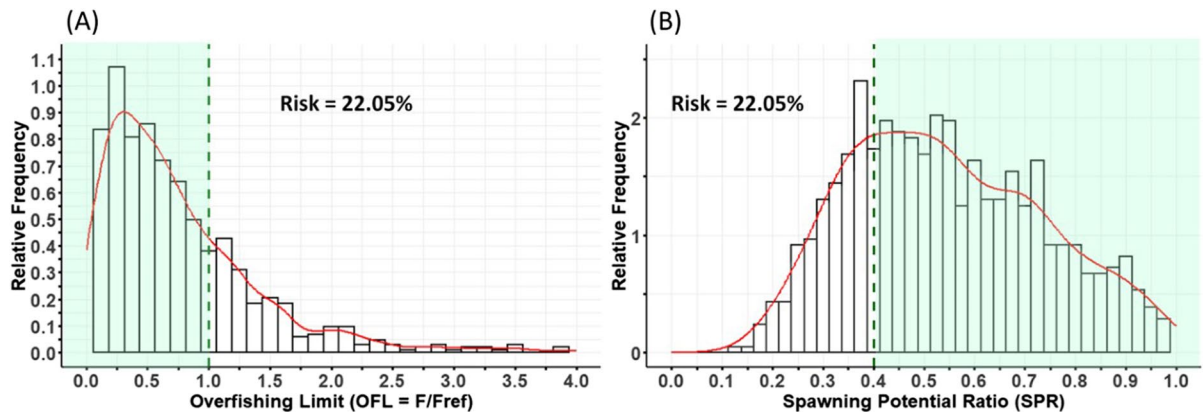


Fig. 11 Sustainability risk distributions for Atlantic tarpon in Brazil for **A** overfishing limit (OFL) and **B** spawning potential ratio (SPR). Green-shaded areas denote sustainable population sizes

spawning. Previous research in Florida (Crabtree et al. 1992) also reported offshore migrations that were likely for spawning, a movement pattern we also observed near the Parnaíba Delta. Further, the asynchronous oocyte development indicates batch spawning and indeterminate fecundity for the species over a prolonged spawning season. The presence of females in the spawning phase in the dry period and in the regression and regeneration phases in the rainy season helped to understand the spatial-temporal distribution of the species in the Parnaíba Delta.

Our findings may also reflect a resident or temporary resident population, as has been documented elsewhere (Griffin et al. 2018; Luo et al. 2019). Residency may reflect locally favorable feeding conditions in years of high rainfall, as occurred during this study. This possibility is supported by LEK, which indicated that high catches during rainy season is not common (Fernandes et al. 2017).

To the extent that seasonality of fishing effort reflects seasonal residency of tarpon in the study regions, the seasonality of tarpon occurrence in Brazil differs from seasonality in more northern latitudes. For example, peak abundance of tarpon in the Florida Keys is April through June (Griffin et al. 2022), with seasonal migrations northward to the northern Gulf of Mexico and mid-Atlantic region of the USA east coast from summer through early fall (Luo et al. 2019) and extremely low abundance during winter months. In contrast, tarpon abundance, and even spawning readiness, appear to be relatively even throughout the year in Costa Rica (Crabtree et al. 1997), which is more

similar to the findings in this study. Thus, it may be that adult tarpon are resident in coastal waters of Brazil throughout the year and change locations associated with peak spawning. If so, regulations should consider that fishing harvest is affecting a regional population with relatively local movements.

Although the information obtained through LEK was useful for understanding the ecology of tarpon in the study area, the interaction with fishers also revealed additional challenges to implementing a management plan. The lack of information at the community level is a major barrier, as is the concern of fishers afraid of losing their livelihoods. This is best addressed by initiating an environmental education program focused on achieving sustainability of fisheries for tarpon and other species in the region.

The process of education was, in a sense, initiated by the collaborative process reported here and by the publication of the management plan of the Parnaíba Delta. The fishing community recognizes the benefits of fishery management and has started in a subtle way the process of discussing possible rules for local fishing planning, with an eye toward sustainability. As ICMBio engages in the task of complying with the legislation that prohibits tarpon fishing in Brazil, and creating a plan to allow artisanal fisheries in Pedra do Sal (PI), they will further this education process.

Although progress was made during this process, and initial steps toward effective management were taken, much more needs to be done. For example, there are still concerns about the focus of the fishery on mature females, a high level of non-compliance

with regulations, and illegal fisheries. Nonetheless, the proposal to adopt a minimum harvest size of 145 cm FL is a good start, as is consideration of spatial protections for juvenile areas. That the different multiple methods used here (biological data, tracking, data-limited stock assessment, LEK) all had similar findings is encouraging and provides a guide for continued research, monitoring, and revision of management plans.

Although we know more about the regional tarpon fishery than before this study, additional research is needed to improve management decision-making. This includes better population demographic data that covers the juvenile through adult life stages, better sampling of the fishery size structure, more tagging studies to understand habitat-use and long-term migration for the species, and a continuous program to evaluate population status and fishery performance. It will also be important to continue the engagement of fishers in the process and to continue the multi-partner collaboration to ensure that agreements are maintained, enforcement is implemented, and management plans are improved.

Data availability The data that support the findings of this study are not openly available due to reasons of sensitivity, e.g., human data, and are available from the corresponding author upon reasonable request (include information on the data's location, e.g., in a controlled access repository where relevant).

Declarations

Conflict of interest The authors declare no competing interests.

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