

Life history and stock synthesis assessment of *Prionotus punctatus* (Teleostei, Triglididae) in southern Brazil

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Funding information

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil; National Council for Scientific and Technological Development - CNPq; Ministry of Fisheries and Aquaculture

Abstract

Age, growth, and maturity of the bluewing searobin *Prionotus punctatus* were studied to assess its stock status in southern Brazil. Total length compositions, weight, sex, and maturity stage were recorded from commercial landings, and ages were estimated from transverse sections of the sagittal otolith. The oldest observed specimen was a 12-year-old female. Females grew to a larger asymptotic length ($L_{\infty} = 384.4$ mm) than males ($L_{\infty} = 311.7$ mm) but at a slower instantaneous rate ($k_{\text{females}} = 0.41 \text{ year}^{-1}$, $k_{\text{males}} = 0.75 \text{ year}^{-1}$). Reproduction occurred from spring to early fall. Females size- and age-at-maturity was estimated at 246.8 mm and 1.66 years, while males were at 237.2 mm and 1.38 years. Based on a statistical catch-at-age stock assessment, the spawning biomass declined 84% from 1976 to 2000 being classified as overfished and suffering from overfishing ($B/B_{\text{msy}} = 0.62$; $F/F_{\text{msy}} > 1$). *P. punctatus* was regularly discarded by industrial fisheries before 2000 but suffered from high exploitation in the last decades. These results highlight the need for the species to be included in Brazil's fishery management plans.

KEYWORDS

age, bluewing searobin, growth, reproduction, southern Brazil, stock assessment

1 | INTRODUCTION

Knowledge of life history traits is critical to assess population dynamics of commercially exploited fish stocks and for formulating fishery management measures (Dowling et al., 2015; Kirkwood et al., 1994). Age information is needed for calculating growth rates, mortality rates, and productivity, thereby making age among the most influential biological variables (Campana, 2001). Generally, species that grow fast and mature at a young age support higher fishing mortality than species that grow slow and mature at an old age (Reynolds et al., 2001). Furthermore, several management measures, such as minimum size of fish catches and limited fishing seasons, depend on knowledge of reproductive characteristics of the fish stock (Morgan, 2008).

In general, knowledge on such life history traits and population processes are commonly available for species that drive fisheries

(known as target-species), which are also the main (or sole) focus of fishing management regimes. But in multispecies fisheries (e.g. bottom trawl fisheries), particularly in subtropical regions, a variety of species are caught, with variable fractions being retained and commercialized, usually complementing the total income of fishing operations. Their exploitation may be continuous and significant for long periods but often neglected under a target-species management regime. In that sense, these species (a) rarely motivate data collection and populations analysis, (b) are subject to unknown mortality impacts, and (c) may become highly vulnerable to overfishing (e.g. Stobutzki et al., 2001, 2002). Assessing fishing impacts on non-target species tends to allow for more inclusive management regimes and has become a critical step toward the current "Ecosystem Approach to Fisheries Management" (EAFM; Zhou et al., 2011).

Demersal fisheries off southern Brazil have historically targeted sciaenid species and few penaeid shrimps, which became the main focus of management regimes (Pezzuto & Mastella-Benincá, 2015).

Yet a considerable number of demersal fish and shellfish species have made up important fractions of total landings, often without any formal control (Dias, 2020). The searobin *Prionotus punctatus* (Bloch 1793) is one of them. It is a demersal species from the Triglidae family, commonly named searobins or gurnards in English and *cabrinhas* in Portuguese. This species is distributed along the western Atlantic between Nova Scotia and northern Argentina (Figueiredo & Menezes, 1980). On the continental shelf of Southern Brazil, *P. punctatus* is one of the most frequent demersal species caught in bottom trawl surveys (Haimovici et al., 1996). In the early years of the industrial bottom trawl fishery in the 1950s, *P. punctatus* was discarded on board, and only in the early 1980s, larger specimens were landed for filleting (Teixeira & Haimovici, 1989). Intense fishing in the region that led to decreased landings of primary target-species (Cardoso & Haimovici, 2011; Haimovici et al., 2021; Haimovici & Cardoso, 2017) led to greater interest in less-abundant and less-valuable species such as *P. punctatus*.

By the end of the 1990s, part of the trawling fleet, mainly double-rig trawlers, began targeting slow-moving flatfishes (Paralichthyidae), Brazilian codlings (*Urophycis brasiliensis*), and bluewing searobins (Haimovici & Mendonça, 1996; Perez et al., 1998). In the early 2000s the species figured amongst the five most abundantly landed in Santa Catarina State by the multi-species double-rig trawl fisheries (UNIVALI-CTTMAR, 2010). In recent years, some bottom trawlers targeted *P. punctatus* at depths of 80–140m (Fiedler et al., 2021). Landings, however, decreased considerably in the last decade (Figure 10). Catch data from monitoring programs in southeastern and southern Brazil indicate that *P. punctatus* suffers from increasing fishing pressure (FURG/SEMA, 2020; Souza, 2012; UNIVALI, 2020; UNIVALI/EMCT/LEMA, 2020).

In southern Brazil, *P. punctatus* inhabits sandy and muddy substrates of the continental shelf (Haimovici et al., 1996, 2008). Smaller specimens feed on benthic prey, primarily crustaceans as small cumaceans, before shifting to penaeid and braquiurid and small fish. The species is a multiple-spawner between late spring and fall (Teixeira & Haimovici, 1989). Size-at-maturity was 262mm in southern Brazil (Teixeira & Haimovici, 1989) and 295mm and 283mm respectively in southeastern Brazil (Andrade et al., 2005; Souza, 2012). The single age and growth study that counted otolith annual bands estimated an age-at-maturity (A_{50}) of 8 years (Andrade, 2004), which is much older than the ages estimated for other triglid species (1.5–3.2 years; Colloca et al., 2003; McCarthy et al., 2018; McCarthy & Marriott, 2018; Rodrigues et al., 2019; Wong, 1968).

It is possible, however, that such a delay in the maturity schedule of *P. punctatus*, as estimated by Andrade (2004), may have resulted from counting false rings as annual bands. Identification of the first annulus on otoliths can be difficult due to false bands or “checks” that are frequent throughout the first year of life on otoliths of many fish species (Panfili et al., 2002). Checks can be caused by habitat changes or environmental stress (Law, 2000) and are often sources of inconsistencies in age estimates from otoliths (Morales-Nin, 2000). Difficulty in differentiating annual marks from checks on otoliths can lead to age overestimation and

growth underestimation (Cavole & Haimovici, 2015). For example, although analysis of edge types on otolith sections suggested the formation of annual marks, counting additional marks produced by other drivers resulted in underestimation of growth and overestimation of longevity of the Brazilian codling *Urophycis brasiliensis* (Cavole et al., 2018). We hypothesized that the same artifact affected Andrade's (2004) *P. punctatus* age estimates and growth and maturity parameters.

This study quantifies the impact of fishing on and stock status of *P. punctatus*, as an effort to include the species among the management process of multispecies demersal fisheries in southern Brazil. We start by validating otolith ring deposition by both checking annual periodicity of seasonal opaque and translucent bands deposition in otolith sections and counting micro-increments in the microstructure of otoliths of young-of-the-year (<230mm total length) *P. punctatus*. After age readings, we used size-at-age data to estimate the von Bertalanffy growth parameters, length and age-at-maturity, as well as natural mortality. Finally, we incorporated new estimates of life history parameters, catch data, length compositions, and abundance indices into an age-structured model.

2 | METHODS

2.1 | Sampling and data collection

Monthly samples of *P. punctatus* were collected between January and December 2019 from landings of the industrial trawl and bottom gillnet fleets that operated on the continental shelf in extreme southern Brazil. Total length (TL=mm), total weight (g), gonad weight (g), sex, and sexual maturation stage of each specimen were recorded, and *sagittae* otoliths were preserved dry for age estimation.

2.2 | Age estimation

Otoliths were embedded in polyester resin and cut through the nucleus using a low-speed rotary saw (Buehler-Isomet). Thin transverse sections (0.20–0.30mm) were fixed on microscopic slides with a xylol base (dimethylbenzene) mounting medium (ENTELAN Merck®). Otoliths of 18 young-of-the-year (YOY) *P. punctatus*, 106–226mm TL, were polished (Cavole & Haimovici, 2015), mounted on slides, and examined using a microscope at 400x magnification with transmitted light. Two readers counted increments along the ventral axis between the core and outer edge of the otolith (Figure 1). Increments were assumed to be daily due to their well-marked appearance and concentric pattern from the focus to the edge of otolith sections, like other species from the region (Cavole et al., 2018).

The macrostructure of 470 otoliths from specimens 173–429mm TL were examined. Otolith sections were observed with a stereoscopic microscope with reflected light over a black background. Digital images of otolith sections were captured using a 10x objective power on a camera with 2048x1536 pixels (Figure 2). Distances

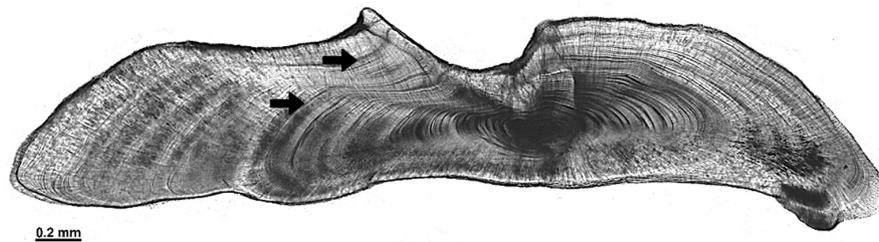
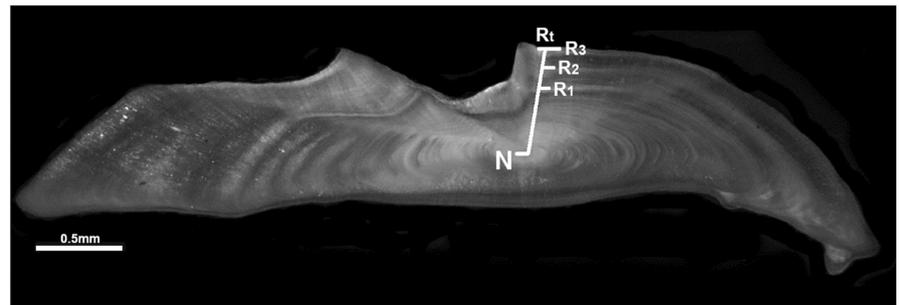


FIGURE 1 A thin section of an otolith from a juvenile specimen of *Prionotus punctatus* (218 mm TL); with 235 microincrements counted (assumed to correspond to days of life) and examined with transmitted light, sampled in southern Brazil on August 2019. Black arrows indicate “checks” within primary increments.

FIGURE 2 A thin section of an otolith from a three-year-old female *Prionotus punctatus* (286 mm TL) examined with reflected light, sampled in southern Brazil on February 2019. Opaque bands appear as white bands and translucent bands as dark bands. N: otolith core, R1, R2, and R3: observed rings.



between the otolith focus to the edge of each opaque band were measured with the free software ImageJ 1.47.

Periodicity of opaque and translucent bands on the edge of otoliths was evaluated by counting monthly opaque and translucent edges. On transverse sections, bands were counted independently by two readers. If counts differed, both readers jointly reexamined otoliths and discarded any from further analyses if a difference persisted.

The mean coefficient of variation (CV; Campana, 2001) was used to quantify precision between readings:

$$CV = 100 \times \frac{\sqrt{\frac{(x-xy)^2 + (y-xy)^2}{R-1}}}{xy}$$

where x is the reading of observer 1, y is the reading of observer 2, xy is the average between both readings, and R is the number of readers. The average CV of a sample was computed as the arithmetic mean of all CV values.

2.3 | Growth

Length at age, in years and fractions of years, were estimated considering the number of annuli and the date of capture, assuming January 1st as the birth date of all specimens. The relationship between age and length was calculated for both sexes using the von Bertalanffy growth model:

$$L_t = L_\infty \left(1 - e^{-K(t-t_0)}\right)$$

where L_t is the total length at age t of a fish, from the tip of the snout to the end of the upper limb of the tail in a normal position; L_∞ is the

asymptotic length; k is the growth coefficient, which represents the instantaneous rate at which fish length approaches L_∞ ; and t_0 is the theoretical age when the fish was length=zero.

The model was fit to the data using a Bayesian approach (Kinas & Andrade, 2010) using the methodology described by Kikuchi et al. (2021). Posterior distributions of parameters were obtained using Monte Carlo Markov chains (MCMC), to easily compare parameters using overlap between posterior probability distributions. Analyses were performed in the software R (R Core Team, 2022), version 4.2.1., using the *OpenBUGS* package and the libraries *R2WinBUGS* (Sturtz et al., 2005) and *BRugs* (Thomas et al., 2006).

2.4 | Weight-length relationship

The weight-length relationship was described using the power model ($Wt = a \times Lt^b$). Linear regression models fitted to log-transformed weight and length data were used to compare relationships between sexes through covariance analysis ($\alpha=0.05$; Zar, 1984).

2.5 | Reproductive period and sexual maturity

Sexual maturity stages were determined based on a macroscopic maturation scale divided into seven stages, based on characteristics of the gonads of fishes of the family Sciaenidae. Sampled individuals were classified as virginal (I), early maturing (II), maturing (III), advanced maturing (IV), spawning (V), recovering (VI), and spawned (VII; Haimovici & Cousin, 1989).

To avoid misidentification between mature and recovering stages, only specimens collected during the reproductive peak were

selected for estimation of maturation ogives. The reproductive cycle was determined through analysis of monthly changes in the gonadosomatic index (GSI):

$$\text{GSI} = 100 \times \text{gonad weight (g)} / \text{total weight (g)}.$$

The mean GSI for each maturation stage was used as criteria to discriminate immature from mature specimens. Females with GSI above 1.5 and males with GSI above 0.3 were considered mature (Figure 3).

Length (L_{50}) at maturity was estimated using a Bayesian approach with the logistic model (Cardoso & Haimovici, 2014; Kinas & Andrade, 2010). The total number (n_i) and number of mature individuals (y_i) were calculated for each sex in 10-mm length classes (i). Where θ_i expresses the probability that an individual in a length class was sexually mature, and was assumed to follow a binomial Bin(n_i , θ_i) distribution. Data were fitted to a logistic model defined by the logit link function, which transforms the parameter θ_i , restricted to the interval [0, 1] to a binomial distribution m between $-\infty$ and $+\infty$ (Kinas & Andrade, 2010):

$$m_i = g(\theta_i) = \log(\theta_i / (1 - \theta_i)).$$

$$m_i = \beta_0 + \beta_1 \cdot X_i$$

where m_i is the probability of maturity for each X_i at each length class. Length at maturity was defined as $L_{50} = -\beta_0/\beta_1$ and $L_{95} = (2.94 - \beta_0)/\beta_1$. The posterior distribution $p(\beta_0, \beta_1 | D)$ was obtained using MCMC (Alves et al., 2020), to compare overlap of distributions, and thereby avoid further statistical analyses (Kinas & Andrade, 2010). Analyses were performed in R (R Core Team, 2022), version 4.2.1., using the *OpenBUGS* package and *R2 WinBUGS* libraries (Sturtz et al., 2005) and *BRugs* (Thomas et al., 2006). The age at sexual maturity (A_{50}) and at 95% maturity (A_{95}) were estimated by inserting the calculated L_{50}

and L_{95} into the Von Bertalanffy growth model following the formula below: as stated below:

$$A_{(50/95)} = -\text{Ln}((L_{\infty} - L_{(50/95)}) / L_{\infty}) / K + t_0.$$

2.6 | Natural mortality

The instantaneous natural mortality coefficient M was estimated as the average of four empirical estimators based on maximum age (t_{max}): $M = 4.899 \times t_{\text{max}}^{-0.916}$; $\log(M) = 1.717 - 1.01 \times \log(t_{\text{max}})$; $M = 5.109/t_{\text{max}}$ (Then et al., 2015); and $M = \exp(1.44 - 0.982 \times \ln(t_{\text{max}}))$ (Hewitt & Hoenig, 2005). Maximum age (t_{max}) was assumed to be the oldest estimated age in this study plus 3 years. This choice was based on an assumption that the number of sampled individuals might not have included the oldest fish, whose frequency might have decreased after more than 70 years of intense fishing in the region (Haimovici & Cardoso, 2017).

2.7 | CPUE standardization

Catch and effort data from landings by the commercial trawl (double, single, and pair) and bottom gillnet fleets from Rio Grande during 1976–2019 and Santa Catarina during 1989–2019 were compiled to standardize CPUE for the assessment model (Perez et al., 1998; Perez & Pezzuto, 2006; UNIVALI/EMCT/LEMA, 2020). Data from each fishing trip included: year, season, boat, fishing strategy, and depth range. The fishing strategy was defined by application of cluster methods to explore factors that contributed to patterns and to identify effort groups with similar species composition, and presumably, similar fishing and targeting strategy (Hoyle, 2015; Sant'Ana et al., 2020).

The CPUE standardization was implemented using Bayesian hierarchical models with a latent Gaussian structure to accommodate

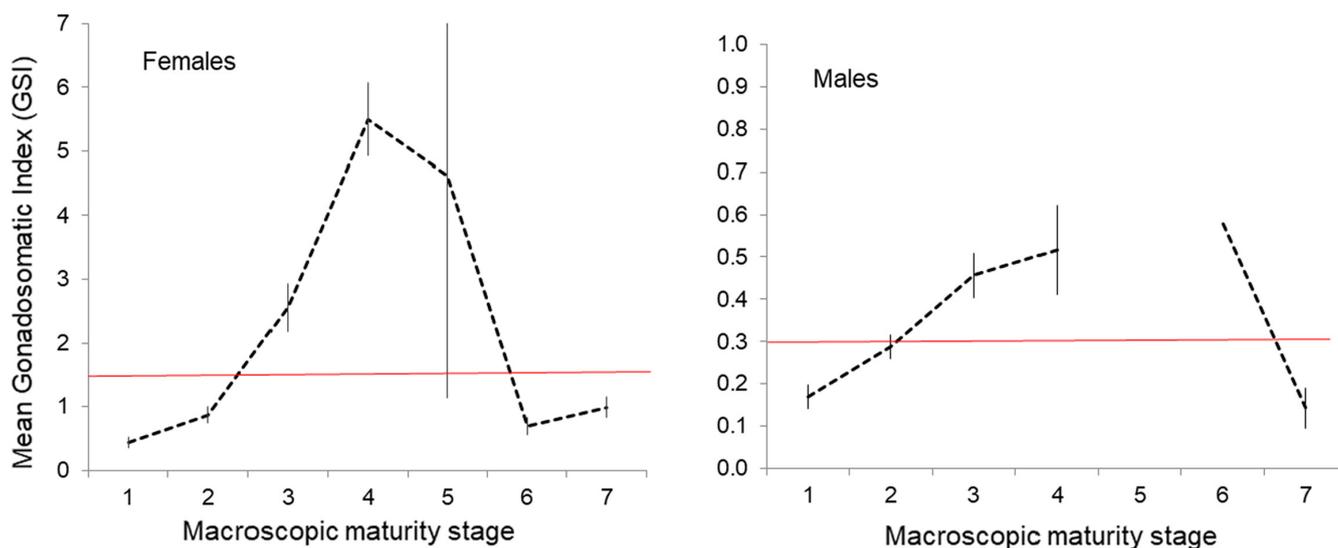


FIGURE 3 Mean gonadosomatic indices for maturation stages of female and male *Prionotus punctatus* sampled in southern Brazil during January–December 2019. Vertical bars indicate confidence intervals ($\alpha=0.05$).

temporal and seasonal effects (Hirota et al., 2022) through the INLA package (Rue et al., 2013; available at www.r-inla.org). Nominal CPUE was defined as a metric kilogram of *P. punctatus* caught per trawling time. As a non-target species of commercial value, the proportion of zero catches was high in all trawling fleets, so the response variable was transformed into logarithms, after adding one to the catch, and was assumed to follow a log-normal distribution.

2.8 | Population dynamics

A temporal series of spawning biomass and stock status indicators were estimated with an age-structured population dynamic model, Stock Synthesis (Methot Jr & Wetzel, 2013). This tool uses input parameters, natural mortality (M), von Bertalanffy growth parameters (L_{∞} , k , and t_0), size at 50% and 95% of maturity (L_{50} and L_{95}), coefficients of weight-length and weight-fecundity relationships, and stock-recruitment parameters (steepness and virginal recruitment $\ln R_0$).

The model was built using life history parameters estimated in this study (Table 4). Due to a lack of quantitative information on fecundity, weight-fecundity coefficients were estimated using the length-weight ratio (i.e., $\text{eggs} = aTL^b$). Steepness was set at 0.75, corresponding to the value estimated for Perciformes using the *FishLife* package (Thorson, 2020; Thorson et al., 2017), the taxonomic group closest to *P. punctatus*, and virginal recruitment was freely estimated in the model.

In addition to life history parameters, available data such as catch time series during 1975–2019, annual size compositions during 2006–2019, and standardized CPUE during 2000–2019 were used (Figure 4). Available data encompassed 43 years from 1976 to 2019, but all years did not have full or available data (Figure 4).

Data were compiled for four fishing fleets: double-rig bottom trawl (fishery 1), bottom pair trawl (fishery 2), single bottom trawl (fishery 3), and bottom gillnet (fishery 4). Selectivity was freely estimated by the Stock Synthesis assuming an initial logistic model (asymptotic selectivity) for fisheries 1, 3, and 4, and a double-normal distribution, with defined initial and final selectivity for fishery 2.

Some of the *P. punctatus* catch fished before 2000 were discarded (Haimovici & Mendonça, 1996). Annual catches of commercial-sized *P. punctatus* were estimated as 4.2% of the sum in each year of the four most important targets of demersal trawls fleets (*Umbrina canosai*, *Micropogonias furnieri*, *Macrodon atricauda*, and *Cynoscion guatucupa*). This factor was calculated from catches in four scientific research cruises with commercial trawls along the Rio Grande do Sul continental shelf between 1981 and 1983, over an area of 58,000 km² and at depths of 10–120 m (Haimovici et al., 1996). These estimates were pooled with recorded landings since 2000.

Model convergence was assessed using the Carvalho et al. (2021) flow chart. The first diagnostic was whether the Hessian matrix (matrix of second derivatives of the likelihood concerning the parameters) was positive and definite. The second diagnostic ensured joint residuals plots were randomly distributed. The third diagnostic

was a retrospective analysis with five-year retrospective peels. The fourth diagnostic analyzed model prediction using a model-based hindcasting. The fifth diagnostic was a jitter analysis of parameter starting values to evaluate whether the model converged to a global solution rather than a local minimum. Starting values of all estimated parameters were randomly perturbed by 10%, for 50 trials of each model run.

Other diagnostics included likelihood profiling of critical parameters (steepness and natural mortality). Likelihood profiles were used to elucidate conflicting information among data sources, determine asymmetry around the likelihood-surface surrounding point estimates, and evaluate precision of parameter estimates. Diagnostic tests for Stock Synthesis were performed with the *r4ss* R package (Taylor et al., 2021; github.com/r4ss/r4ss).

3 | RESULTS

3.1 | Validation of age estimations

Age analysis included a total of 470 specimens ranging in length from 173 to 429 mm. Ages were estimated from 416 otoliths; 54 otoliths (11.5%) were discarded due to difficulties in discerning annuli. After the joint reading, coincidence between independent readers increased from 62.6% to 88.5%, with an average coefficient of variation of 7.6%. Initial divergence was primarily caused by differences in identifying the first annuli, because of frequent checks around the nucleus.

Opaque and translucent edges were observed throughout the year; however an annual cycle was observed in the monthly relative frequencies of edge types (Figure 5). The frequency of opaque bands differed significantly among months ($\chi^2 = 38.97$, on 1 DF, $n = 376$; $p = 4.30 \times 10^{-10}$). The proportion of opaque edges was higher in summer (81.3%), December through February, and lower in fall and early winter (50.0%), April through August.

Spawning and opaque band formation on the edge of otoliths occurred most frequently in the austral spring and summer, so we assumed January 1st was a convenient birth date for *P. punctatus*, to calculate age in years and fractions of years of specimens sampled in southern Brazil.

3.2 | Growth

The oldest *P. punctatus* sampled, a 369 mm TL female, was estimated to be 12 years-old, and the oldest male, 347 mm TL, was estimated to be 11 years-old. The largest individual was a 429 mm TL female, of age 7. Females were significantly longer than males at all ages (Table 1).

Length increased from 106 to 226 mm TL as the number of microincrements increased from 81 to 235 for 18 YOY specimens (Figure 6). The effect of the number of microincrements on TL was positive and significant ($R^2 = 0.916$, F -statistic = 175.2, on 1 and 16

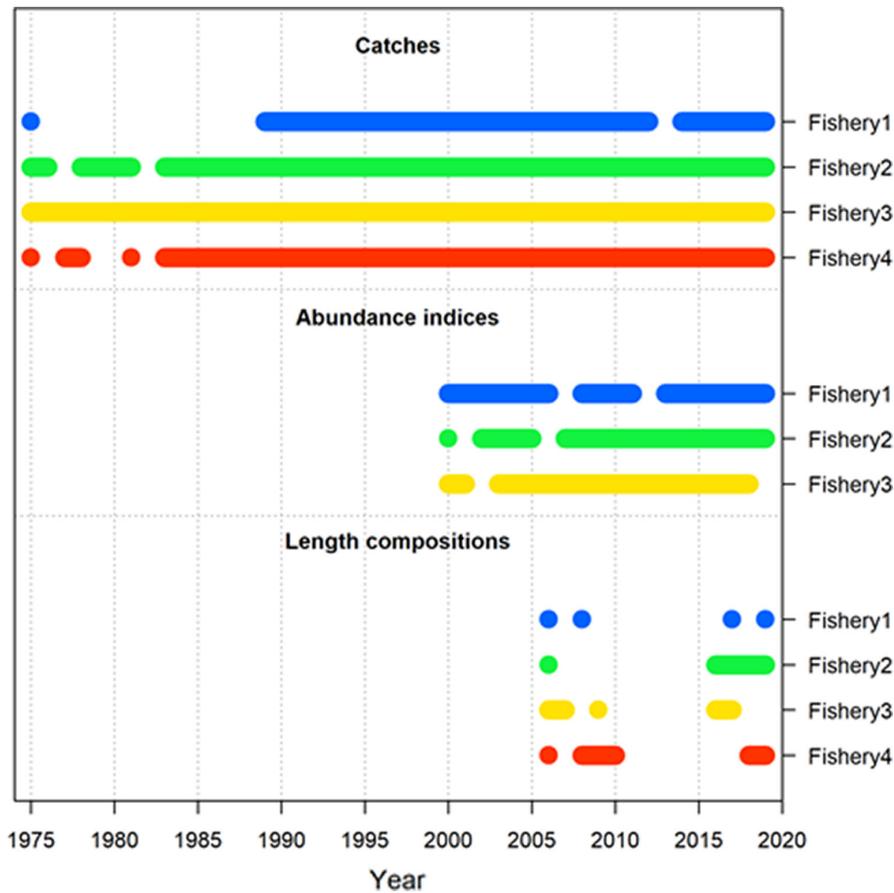


FIGURE 4 Periods covered by each type of data (Catches, Abundance indices, and Length compositions) for *Prionotus punctatus* sampled in commercial landings of trawl and bottom gillnet fleets in southern Brazil during 1976–2019. Fishery 1=Double-rig bottom trawl, Fishery 2=Bottom pair trawl, Fishery 3=Single bottom trawl, and Fishery 4=Bottom gillnet.

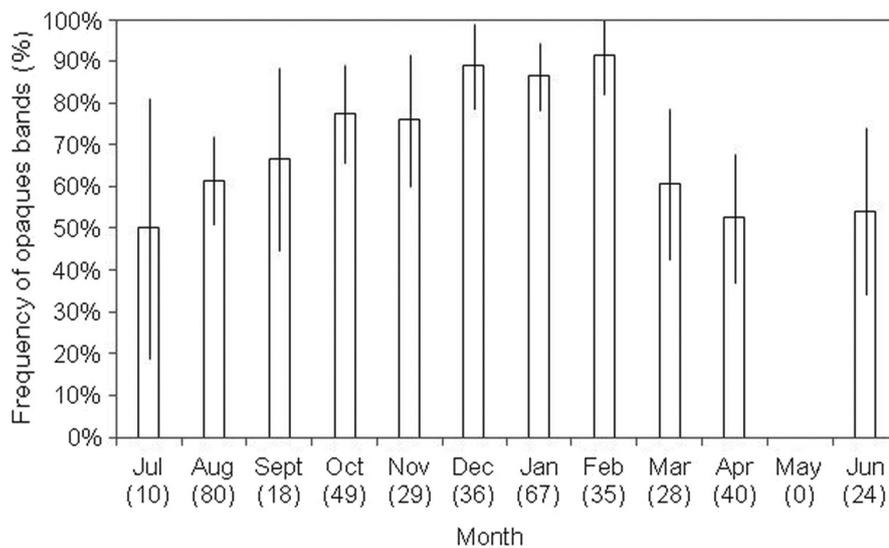


FIGURE 5 Monthly frequency of opaque edges on otolith sections of *Prionotus punctatus* sampled in southern Brazil during January–December 2019. Vertical bars indicate confidence intervals ($\alpha=0.05$). The monthly sample sizes are shown in parentheses.

DF, $p=4.91 \times 10^{-10}$). The length-at-age of YOY were included in growth models for estimating growth parameters for both sexes.

Non-overlapping credible intervals indicated that female *P. punctatus* grew to a larger asymptotic size than males (Table 2). Females grew to a larger asymptotic length ($L_{\infty}=384.4\text{mm}$) than males ($L_{\infty}=311.7\text{mm}$). The instantaneous growth coefficient was significantly larger for males ($k=0.417\text{year}^{-1}$) than females ($k=0.750\text{year}^{-1}$). The theoretical age at length zero do not differ significantly between females ($t_0=-0.80\text{years}$) and males ($t_0=-0.52\text{years}$; Figure 7).

3.3 | Weight-length relationship

Relationships between weight and total length differed significantly between male and female *P. punctatus* (F -statistic=13.1, on 1 and 464 DF, $p=0.0003$), with females heavier than males of the same length (Figure S1). The fit based on the potential model was:

$$Wt_{\text{females}} = 6 \times 10^{-6} \times L^{3.1450} \quad (R^2 = 0.9692; n = 271).$$

$$Wt_{\text{males}} = 9 \times 10^{-6} \times L^{3.062} \quad (R^2 = 0.9596; n = 196).$$

TABLE 1 Mean total lengths by estimated age for pooled sexes, male, and female *Prionotus punctatus* sampled in southern Brazil during January–December 2019, and results of t-tests for comparing sexes.

Age class	Pooled sexes		Male		Female		Comparison between sexes	
	n	Mean TL	n	Mean TL	n	Mean TL	t-score	p value
1	53	240.5	33	232.4	20	253.9	14.040	0.025
2	94	277.4	53	270.7	41	286.2	14.966	<0.001
3	74	306.6	25	296.1	49	312.0	15.585	<0.001
4	90	326.2	24	306.0	66	333.6	15.306	<0.001
5	41	336.5	13	304.5	28	351.4	15.630	<0.001
6	18	364.7	3	319.3	15	373.7	16.196	<0.001*
7	16	384.8	2	295.0	14	397.6		
8	3	399.3			3	399.3		
9	3	377.7	1	334.0	2	399.5		
10	2	352.0	1	314.0	1	390.0		
11	3	379.7	1	347.0	2	396.0		
Total	397		156		241			

*Values calculated for pooled data at ages >6.

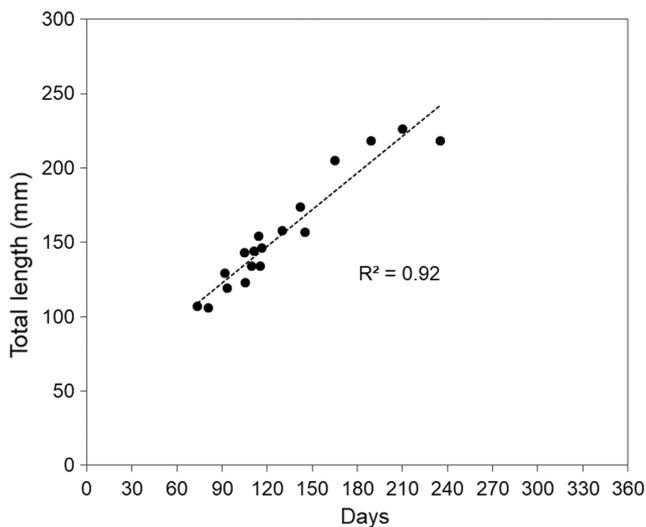


FIGURE 6 Relationship between total length and number of microincrements (assumed = days) counted on otoliths of juvenile *Prionotus punctatus* sampled in southern Brazil during January–December 2019.

$$W_{\text{pooled sex}} = 5 \times 10^{-6} \times L^{3.1561} \quad (R^2 = 0.9717; n = 467).$$

3.4 | Reproductive cycle

Gonadosomatic indices indicated that most of the reproductive activity began in the austral spring, peaked in summer, and decreased in early autumn (Figure 8). Female GSI followed an annual cycle, with values above 1.5 between November and March. Male GSI was above 0.3 between November and June.

TABLE 2 Asymptotic length (L_{∞}), instantaneous growth coefficient (k), and theoretical age at zero length (t_0), and credible confidence intervals (Lower and Upper, $\alpha=0.05$), for male, female, and pooled sexes of *Prionotus punctatus* sampled in southern Brazil during January–December 2019.

Parameter	Female	Male	Pooled sexes
L_{∞}			
Lower	373.1	301.6	363.2
Mean	384.4	311.7	374.7
Upper	396.8	323.0	387.7
k			
Lower	0.368	0.621	0.347
Mean	0.417	0.750	0.398
Upper	0.477	0.897	0.451
t_0			
Lower	-0.94	-0.68	-1.19
Mean	-0.80	-0.52	-1.00
Upper	-0.67	-0.37	-0.84

3.5 | Length and age at maturity

Size at 50% and 95% maturity did not differ significantly between male and female *P. punctatus*, because credible confidence intervals overlapped (Table 3). Mean length at 50% maturity was 76.1% of asymptotic length (237.2 mm) for males and 64.2% of asymptotic length (246.8 mm) for females (Figure 9). Corresponding age at 50% maturity was 1.38 years for males and 1.66 years for females. Mean length at 95% maturity was 306.0 mm for males and 312.7 mm for

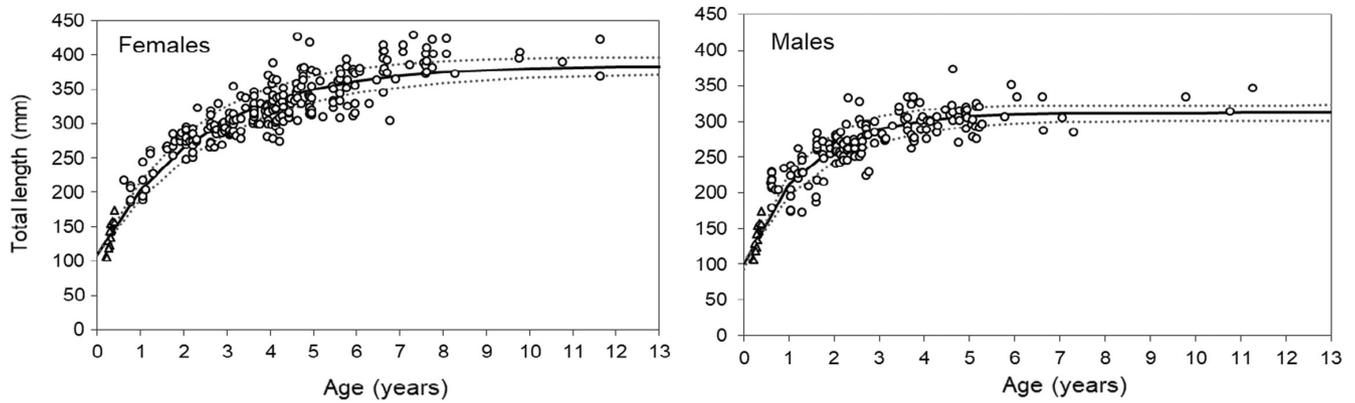


FIGURE 7 Von Bertalanffy growth curves for female and male *Prionotus punctatus* sampled in southern Brazil during January–December 2019. Continuous black lines represent modeled mean length-at-age and dotted lines represent credible intervals. Circles represent estimated ages in years and fractions of years and triangles represent fractions of years of juveniles whose microincrements were counted.

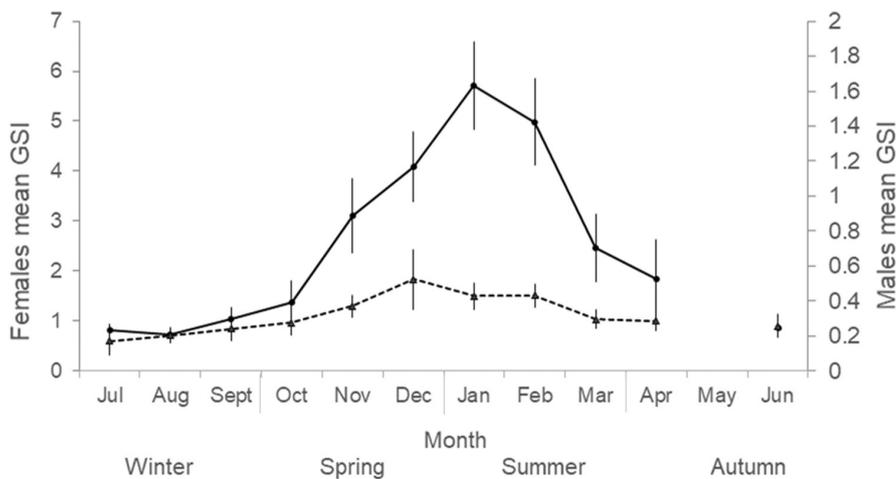


FIGURE 8 Monthly mean gonadosomatic indices (GSI) of female (continuous line) and male (dotted line) *Prionotus punctatus* sampled in southern Brazil during January–December 2019. Vertical bars indicate confidence intervals ($\alpha=0.05$).

TABLE 3 Mean and credible 95% intervals ($\alpha=0.05$) of logistic model parameters (β_1 and β_0), length at 50% maturity (L_{50}), and length at 95% maturity (L_{95}) for female and male *Prionotus punctatus* sampled in southern Brazil during January–December 2019.

Parameters	Female (n = 130)			Male (n = 81)		
	Lower	Mean	Upper	Lower	Mean	Upper
β_1	0.026	0.048	0.072	0.024	0.046	0.072
β_0	-18.591	-11.903	-5.787	-17.695	-11.061	-5.216
L_{50} (mm)	217.0	246.8	264.1	214.2	237.2	252.2
L_{95} (mm)	297.8	312.7	333.8	285.6	306.0	336.0

females. Corresponding age at 95% maturity was 4.82 years for males and 3.23 years for females.

3.6 | Population dynamics

The input parameters used in the Stock Synthesis model and their respective treatments are represented in Table 4. Life history parameters, except natural mortality, were discriminated by sex and weight-based fecundity, which applied only to females.

Residuals for the abundance index were randomly distributed, with no outliers, no autocorrelation, and no temporal pattern (Figure S3). The final gradient of the model was small (0.00000096), the Hessian matrix for parameter estimates was positive definite, and the model ran relatively fast (~1 min) with good convergence properties. The model was not sensitive to natural mortality, and recruitment was the most informative parameter (Figure S4). Similarly, the model was not sensitive to steepness, being recruitment and length composition the most informative parameters (Figure S5). In both cases, gradients of likelihood profiles for fleets supported by

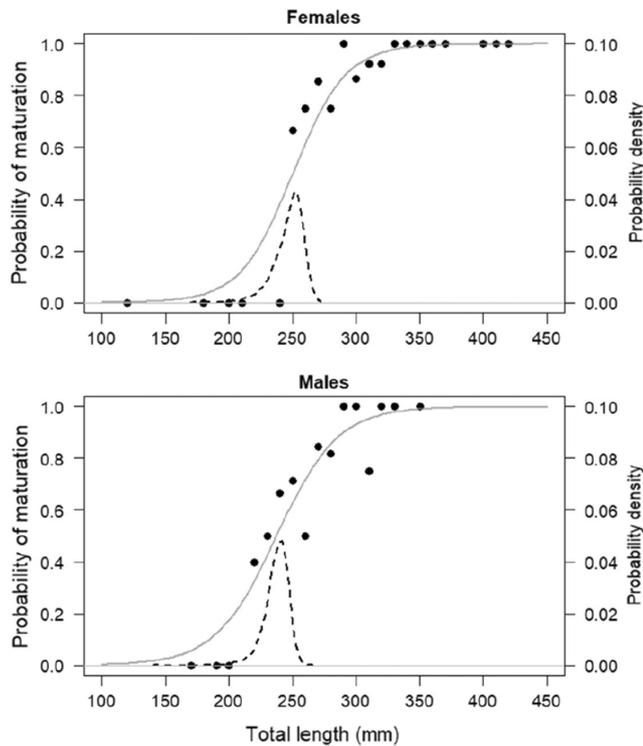


FIGURE 9 Length at maturity (continuous line = fitted logistic curve; dots = observed data; dashed lines = probability density for L_{50}) for female and male *Prionotus punctatus* sampled in southern Brazil during January–December 2019.

length-composition and CPUE data were low, with CPUE being the least informative for variability of natural mortality and steepness, which indicated no apparent conflicts between these parameters and fisheries data. Retrospective analyses indicated a small retrospective bias, mainly in the trend for 2014. However, the value of ρ (rho) for spawning biomass was still acceptable for the species (−0.22 to 0.30). For exploitation (F/F_{msy}), a negative ρ indicated consistent model behavior as data were peeled off from sequential years (Figure S6). Hindcasting analyses to measure predictive skill of the model (Figure S7) were acceptable for fitting abundance indices ($MASE < 1$), except for bottom pair trawlers (Fishery 2, $MASE > 1$). For fish length compositions, the model exhibited low predictive skill ($MASE \gg 1$), except for bottom gillnets (Fishery 4). The model was stable to variation in starting values, because all 50 jitter model runs converged, with 47 converging at the same total likelihood as the base model, and only three converging at higher total likelihoods (Figure S8).

Landings were initially dominated by the single bottom trawl (Fishery 3), bottom pair trawling (Fishery 2) remained more or less constant, and landings by the bottom gillnet fleet (Fishery 4) increased during 2004–2010, before decreasing again. After 2000, increased landings were attributed to the double-rig bottom trawl fleet (Fishery 1; Figure 10).

Length selectivity curves better fitted to length composition data with double normal curve for the bottom pair trawling (fishery 2) and asymptotic for the other fleets since larger individuals (>TL

40 cm) were frequent caught by gears used in the fisheries 1, 3, and 4 (Figure 11a, Figure S2). Fish length composition data was available for all fleets for only a few years after 2006. These data are essential for estimating the current stock status by length-based stock assessment methods integrated into the overall model. Abundance index for the three trawl fleets (Figure 11b) varied greatly without temporal trends for single and double trawlers during 2000–2019, but declined for pair trawlers after 2007.

Spawning biomass decreased steadily from 1976 until 2003, with a slight increase in 2009, followed by a continued decrease through 2019 (Figure 12a). Current biomass ($B = 1132.7$ mt) was less than the biomass that sustain maximum yield ($B_{msy} = 1813.84$ mt), so stock status was classified as overfished ($B/B_{msy} = 0.625$; Figure 12b). Recruitment in the 2000s was dynamic, when abundance index data series began, with a very large positive recruitment event in 2005 and relative large negative recruitment events in 2008, 2014, and 2017 (Figure 12c). Fishing mortality varied erratically during 2000–2010, declined until 2015, and increased thereafter (Figure 12d).

4 | DISCUSSION

We found that *P. punctatus* was relatively fast-growing, with females growing to larger sizes than males, and both sexes maturing between the first and second year of life, like other species of the same family. The species reproduced in warm months, in warm subtropical and temperate waters of southern Brazil, which confirms an earlier study (Teixeira & Haimovici, 1989). Similar life history traits seem to be common in the Triglidae family with relatively short lifespans: age-8 for *Chelidonichthys lucerna* (McCarthy & Marriott, 2018; Rodrigues et al., 2019), age-11 for *Aspitrigla cuculus* (Wong, 1968), and age-7 years for *Eutrigla gurnardus* (McCarthy et al., 2018). Our estimates of the early onset on sexual maturation of *P. punctatus* are also similar to other species of the Triglidae family: 1.5 years for *Aspitrigla cuculus* (Colloca et al., 2003), 2–3 years for *Prionotus carolinus* (Wong, 1968), 0.71 years (Rodrigues et al., 2019) and 2.8 years for *Chelidonichthys lucerna* (McCarthy & Marriott, 2018), and 3.2 years for *Eutrigla gurnardus* (McCarthy et al., 2018).

We observed seasonally alternating opaque and translucent bands on *P. punctatus* otoliths, with highest frequencies of opaque ones in austral summer months, December to February, unlike an earlier study of *P. punctatus* in southern Brazil (25°S–33°S) that found highest frequencies (53–56%) of translucent edges on transverse otolith sections in January–February and lowest frequencies (33–42%) in April–June (Andrade, 2004). The small difference in timing of band deposition may have been observational, because thickness of slices and mounting media differed, although both studies found a seasonal pattern of otolith edge types.

We counted 1–12 annuli, whereas Andrade (2004) counted 1–19 annuli, which led to different growth estimates in the two studies. In a subsequent study, mean length was 29.50 cm and age at sexual maturity was 8 years for both sexes of *P. punctatus* (Andrade et al., 2005; Table S1). Several other lines of evidence suggest that

Parameter	Female	Male	Treatment
L_{∞} (cm)	38.4	31.1	Fixed
k_{yr}^{-1}	0.417	0.750	Fixed
t_0	-0.802	-0.520	Fixed
L_{50} (cm)	24.68	23.72	Fixed
L_{95} (cm)	31.27	30.60	Fixed
Natural Mortality	0.38	0.38	Fixed
Weight (g)-length (cm) alpha	0.000008	0.00001	Fixed
Weight (g)-length (cm) beta	3.15	3.06	Fixed
Weight-based fecundity coefficient	0.000008		Fixed
Weight-based fecundity exponent			Fixed
Steepness	0.75	0.75	Fixed
Initial recruitment (ln R_0)	9.96 (0.055)	9.96 (0.055)	Estimated
Fleet 1 selectivity inflection size (cm)	23.065 (0.513)	23.065 (0.513)	Estimated
Fleet 1 Amplitude at 95% selectivity (logit)	4.418 (1.184)	4.418 (1.184)	Estimated
Fleet 2 peak selectivity (cm)	27.656 (0.873)	27.656 (0.873)	Estimated
Fleet 2 selectivity first bin (ln units)	-10.005 (70.347)	-10.005 (70.347)	Estimated
Fleet 2 ascending width (ln units)	2.862 (0.347)	2.862 (0.347)	Estimated
Fleet 2 descending width (ln units)	3.810 (0.421)	3.810 (0.421)	Estimated
Fleet 2 selectivity final bin (ln units)	-4.907 (2.766)	-4.907 (2.766)	Estimated
Fleet 3 selectivity inflection size (cm)	29.928 (0.475)	29.928 (0.475)	Estimated
Fleet 3 Amplitude at 95% selectivity (logit)	5.284 (0.397)	5.284 (0.397)	Estimated
Fleet 4 selectivity inflection size (cm)	26.701 (0.812)	26.701 (0.812)	Estimated
Fleet 4 Amplitude at 95% selectivity (logit)	5.633 (0.852)	5.663 (0.852)	Estimated

TABLE 4 Input parameters and their treatments in the Stock Synthesis reference model for *Prionotus punctatus* sampled in southern Brazil during January–December 2019. The asymptotic standard deviation of the estimated parameters is included in parentheses next to the parameter value.

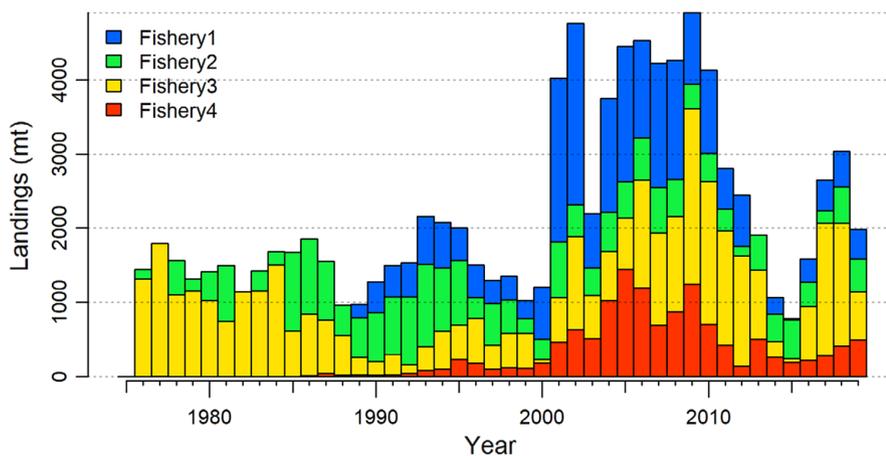


FIGURE 10 Landings by double-rig bottom trawl (Fishery 1), bottom pair trawl (Fishery 2), single bottom trawl (Fishery 3), and bottom gillnet (Fishery 4) fishing fleets for *Prionotus punctatus* in southern Brazil during 1976–2019.

the first 3–4 assumed annuli counted by Andrade (2004) were false rings. First, Andrade (2004) observed no fewer than four annuli and all specimens over 220 mm TL had more than six opaque bands. At this length, many mid-sized marine teleosts in Southern Brazil were

at most 2 years old (Haimovici & Cardoso, 2017). Second, Andrade et al. (2005) estimated the age at maturity to be 8 years, based on the growth curve of Andrade (2004), which is three to four times older than the age at maturity we estimated for teleosts of similar sizes

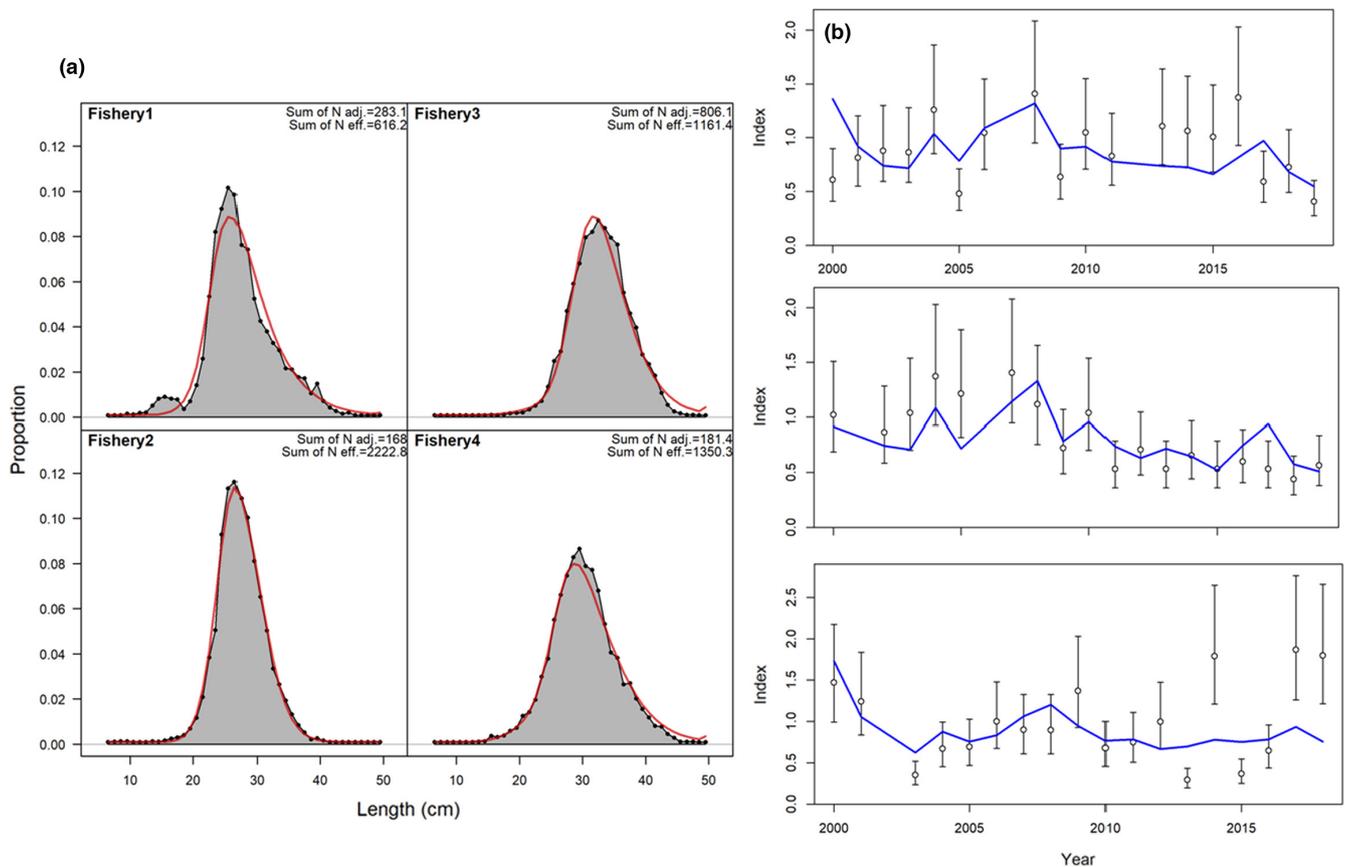


FIGURE 11 Length composition (a) and relative abundance indices (b) of *Prionotus punctatus* harvested by double-rig bottom trawl (Fishery 1), bottom pair trawl (Fishery 2), single bottom trawl (Fishery 3), and bottom gillnet (Fishery 4) fleets in southern Brazil during 2000–2019. Red lines in (a) indicate modeled length composition fit to observed data. Blue lines in (b) indicate modeled abundance indices fit to observed data for trawl fisheries in southern Brazil (top panel = Fishery 1; middle panel = Fishery 2, and bottom panel = Fishery 3).

in the region (Cardoso & Haimovici, 2015; Haimovici et al., 2021; Haimovici & Cardoso, 2017). Third, the demersal shelf fish community along southern Brazil has been heavily fished by bottom trawlers since the 1950s, so if *P. punctatus* grew as slow and matured as old as estimated by Andrade (2004), the stock should have been depleted, which was not true. Therefore, we believe that results presented by Andrade (2004) underestimated growth and overestimated longevity of *P. punctatus* in southern Brazil.

A difference in interpretation of band patterns can be seen in figure 2 of Andrade (2004), in which the author counted 11 annuli and we counted no more than seven or eight annuli, while considering the first three or four bands to be false annuli formed in the first year of life. False annuli can be caused by habitat changes or environmental stress (Cavole et al., 2018; Green et al., 2009; Panfili et al., 2002) and are often responsible for differences in age estimates from otoliths (Cavole & Haimovici, 2015; Law, 2000; Morales-Nin, 2000). For example, juvenile rings formed in the first year of life of the triglid fish *Aspitrigla cuculus* (Colloca et al., 2003).

Validated daily formation of microincrements can contribute to identification of the first annulus (Brophy, 2014; Campana, 2001; Morales-Nin, 2000). Daily periodicity of microincrement formation we observed in otoliths of juvenile *P. punctatus* (age-0) was not experimentally validated, so further age validation is needed

(Campana, 2001). However, daily periodicity of microincrement formation was validated for marked otoliths of juvenile *Prionotus carolinus* and *P. evolans* (McBride, 2002), which supports a similar pattern of daily microincrement formation we observed for *P. punctatus* otoliths. Further, we observed a good fit of estimated ages (in fractions of years) at length to the von Bertalanffy growth model for small juveniles estimated from microincrement counts on otolith annuli.

Available data on landings, length composition, and abundance, combined with life history parameters estimated in this study, allowed us to assess the exploitation status of *P. punctatus* stocks in southern Brazil. Overall, the assessment model exhibited relatively good diagnostic performance and convergence properties, and satisfactory fit to available data. Therefore, we interpreted our results as being representative of *P. punctatus* stock status in southern Brazil, which was classified as suffering from overfishing because current biomass was below the level that would sustain maximum yield and current fishing mortality was above F_{msy} . Therefore, we recommend a precautionary approach for management of its fishery.

The *P. punctatus* stock was not initially a target of fishing fleets in southern Brazil, but by the end of the 1990s, in the face of depletion of other fished species (Haimovici & Cardoso, 2017) part of trawling fleets began focusing on other commercially valuable species,

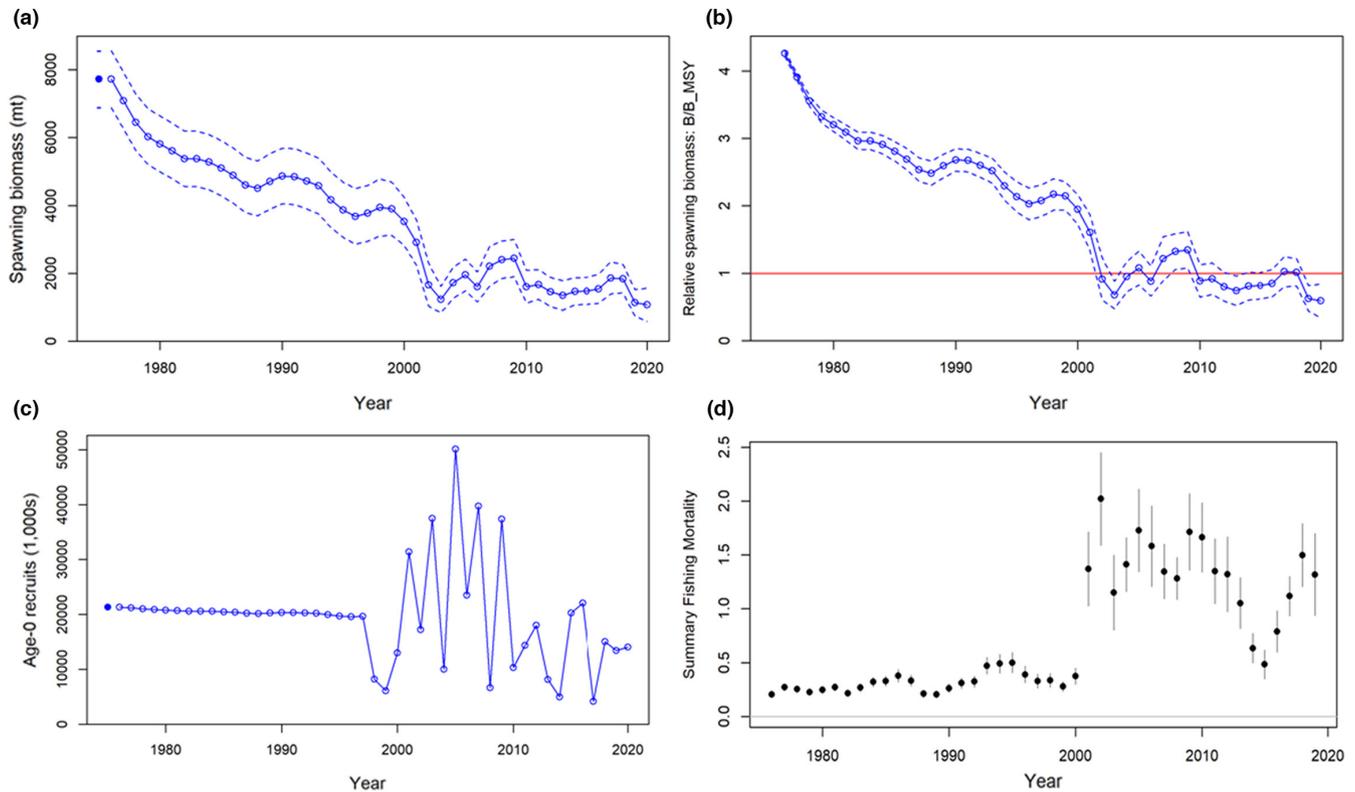


FIGURE 12 Relative spawning biomass (a); ratio of observed biomass to biomass that would sustain maximum yield ($b = B/B_{MSY}$); age-0 recruitment (c); and fishing mortality (d) estimated for *Prionotus punctatus* in southern Brazil during 1976–2019.

such *P. punctatus* (Perez et al., 1998, 2009). In addition to compensation measures adopted by trawl fleets since 1999, *P. punctatus* was a target species by masters of vessels in this region in a follow-up study of these fleets in the southern region during 2015–2017, in which information from three fishing trips of the single-trawl fleet targeting *P. punctatus* recorded a total catch of 245,885 t, with 27% discarded (Fiedler et al., 2021). Further, the frequency of *P. punctatus* was 47.7% for pair trawl and 66.9% for double trawl, reported mostly as discarded. This confirms that *P. punctatus* has always been important as bycatch (Cardoso et al., 2021), often retained and landed, and that *P. punctatus* was a target species for these fishing fleets several years ago.

According to the results obtained by the statistical catch at age modeling, if the fishing effort continues to follow the current trajectory, the *P. punctatus* fishery could collapse in southern Brazil. It is a good example of the negative consequences of neglecting bycatch species in management regimes of little-selective multi-species fisheries. Therefore, we recommend the inclusion of *P. punctatus* as a priority for eventual Brazilian fisheries management plans and that similar approaches are extended to several other demersal species affected by demersal fisheries off southern Brazil. Life history studies enable stock assessments as a fundamental step in any management strategy. All the steps performed in this work, i.e., life-history parameter re-estimations, the data gathering, and the stock assessment, can be used as an example for other stocks elsewhere. The absence of any assessment of

the stock status prevents the development of harvest strategies, increasing the probability of fishery collapses. In turn, this brings several ecological and socio-economic issues worldwide, hence the importance of this kind of study. It is also a fundamental limitation to the implementation of an ecosystem approach to fisheries management (Dolan et al., 2016).

ACKNOWLEDGMENTS

We are grateful to the fishing industries of southern Brazil that allowed us to collect the data. Additionally, we thank the technicians for collecting the samples and the colleagues of the Laboratório de Recursos Pesqueiros Demersais e Cefalópodes from FURG for collaborating in the processing of the samples.

FUNDING INFORMATION

This article was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil. This research was also funded by the National Council for Scientific and Technological Development – CNPq and the Ministry of Fisheries and Aquaculture – MPA within the scope of the Call MCTI/MPA/ CNPq No. 22/2015 – *Ordenamento da Pesca Marinha Brasileira*.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Rodriguez, A. R., Haimovici, M., Kikuchi, E., Sant'Ana, R., Mourato, B. L., Alvarez Perez, J. A. & Cardoso, L. G. (2023). Life history and stock synthesis assessment of *Prionotus punctatus* (Teleostei, Triglidae) in southern Brazil. *Fisheries Management and Ecology*, 00, 1–14. <https://doi.org/10.1111/fme.12631>