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Long-term changes in the age structure, mortality and biomass of the king weakfish *Macrodon atricauda* (Günther, 1880) in southern Brazil: Is it resilient enough to avoid collapse?

Luís Gustavo Cardoso*, Manuel Haimovici

Laboratório de Recursos Pesqueiros Demersais e Cefalópodes, Instituto de Oceanografia, Universidade Federal do Rio Grande (FURG), Caixa Postal 474, Avenida Itália Km 8, CEP 96201-900 Rio Grande, RS, Brazil

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ABSTRACT

Worldwide overfishing has caused the collapse of populations of excessively exploited marine fish. The coastal demersal sciaenid fish "pescadinha", *Macrodon atricauda*, has been intensely fished since the 1960s along the southern Brazilian coast, resulting not only in decreasing abundance but also in increasing growth rates and decreasing age and length at first maturity. We analyzed the time series of several population indicators, such as catch per unit effort (CPUE), age composition of the stock, total and natural mortality and exploitation rate to investigate the long-term impact of fishing on the mortality, age structure and biomass of *M. atricauda*. Furthermore, we modeled the time-trajectory of the total biomass under an assumption of constant recruitment and discuss the limits of resilience and the risk of collapse of the fishery. The CPUE (kg/day at sea) has decreased almost 50%. Total mortality increased from 0.5 yr^{-1} in the almost unexploited stock in the 1950s to around 1.9 yr^{-1} in the 2000s, while the age structure changed dramatically: fishes in the landings were not older than 9 years old in the 1960s, 7 years old in the 1970s and no fish over 5 years old has been observed since the 1990s. Taking into account the growth changes, a deterministic model estimated a reduction of 67% in total biomass over five decades. In the last 30 years, the stock has withstood high exploitation rates (between 0.5 and 0.7 yr^{-1}) and has suffered a steady decline in biomass but has not collapsed, probably due to life-history traits that favor resilience: early maturation and rapid individual growth. However, the stock is at risk of collapse, taking into consideration the present non-stabilized level of high mortality, changed age structure and life history, low biomass and high exploitation rates. A precautionary approach suggests the need to reduce fishing effort.

1. Introduction

Worldwide overfishing has caused the collapse of excessively exploited marine fish populations (Hutchings, 2000; Worm et al., 2009). By imposing an additional mortality component, fisheries have truncated the age structure by removing old age classes, a fact that, in turn, has increased the relative abundance of the youngest classes (Berkeley et al., 2004; Hsieh et al., 2010). These changes are likely to reduce the capacity fish populations have to withstand environmental variability, besides increasing the risk of commercial extinction (Longhurst, 2002; Marteinsdottir and Thorarinsson, 1998).

The southern king weakfish *Macrodon atricauda* (Günther, 1880) (local names are pescadinha, pescada-foguete, pescadinha-real) is a sciaenid fish that inhabits shallow coastal waters in soft bottom areas near estuaries from Espírito Santo state (Brazil) to northern Argentina. This species was recently discriminated from *Macrodon ancylodon* (Bloch and Schneider, 1801), which can be found from northeastern Brazil to Venezuela (Cardoso et al., 2012; Carvalho-Filho et al., 2010; Santos et al., 2006). Five population groups of *M. atricauda* have been genetically identified (Rodrigues et al., 2014). The largest one occurs between La Plata River (Lat. 36°) estuary and Santa Marta Grande Cape in southern Brazil (Lat. 28°), where it has been one of the major targets of the pair-bottom trawl fishery since the late 1950s (Haimovici, 1998; Valentini et al., 1991; Yamaguti and Moraes, 1965; Yesaki and Bager, 1975).

Prior studies of the long-term impact of the fishery on the population dynamics showed a large increase in growth between the 1970s and 2009 that was interpreted as a density-dependent

* Corresponding author. Tel.: +55 53 32336525.
E-mail addresses: cardosolg15@gmail.com (L.G. Cardoso), docmhm@furg.br (M. Haimovici).

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Table 1
Numbers of sampled fishing trips, length samples, measured individuals and aged specimens per decade.

Decade	Number of landing records	Number of length composition samples	Measured specimens	Aged specimens
1970	314	129	40,151	280
1980	674	297	86,182	308
1990	466	116	29,185	328
2000	133	35	9171	769
2010	43	17	4548	
Total	1630	594	169,237	1685

change in response to decreasing density (Cardoso and Haimovici, 2011). Moreover, age and size at maturation have also decreased. The most plausible explanation is that these changes occurred due to the selective pressure of fishing, and implies lower fitness for individuals that mature at larger sizes. However, there is some evidence that the age at maturation has also been driven by the decrease in population abundance, which mitigates density-dependent effects responsible for delaying maturation (Cardoso and Haimovici, 2014).

We analyze the time-series of several population indicators, such as catch per unit effort (CPUE), total and natural mortality, exploitation rate and the age composition of the landings to investigate the long-term impact of fishing on the mortality, age structure and biomass of *M. atricauda* and to evaluate the risks of the collapse of the fishery. We calculated the yearly mean CPUE for pair-trawler fishing trips – whose main target was pescadinha – landing in Rio Grande. We also estimated the mean yearly instantaneous coefficient of total mortality (Z) based on available information on the length frequencies and age-length keys. We also estimated natural mortalities and, then, used them to calculate yearly exploitation rates. The landing records of marine fisheries in southern Brazil have gaps and biases over time. The lack of consistent landing statistics for *M. atricauda* prevents the analysis of the long-term impact of fishing on the biomass of the stock through the application of stock assessment models. However, the consistent estimates of the age structure of the catches enabled us to build a simple deterministic model which integrates total mortality and changes in growth to show the evolution of the total biomass over the last five decades. We discuss the limits of resilience and the risk of collapse of the fishery.

2. Materials and methods

2.1. Data source and analysis

Data for the assessment of *M. atricauda* were obtained from a long-term sampling program of the coastal demersal fisheries on the Southern Brazilian shelf (28°40′–34°S). It has been carried out in Rio Grande by the Oceanography Institute of the University of Rio Grande since 1976 (Haimovici, 1987, 1998). Data on several periods representing five different decades are available (Table 1). Overall, data have included the landing records of 1630 fishing trips of pair-bottom trawlers and 594 length samples, totaling 169,000 measured individuals and 1685 aged specimens (Table 1). Haimovici (1987) described the length composition sampling strategy and Cardoso and Haimovici (2011) reported age-length keys.

2.2. Catch per unit effort (CPUE)

The quality of the commercial landing and of effort statistics in Rio Grande has not been homogeneous over the last decades. In addition, long-term changes in the CPUE based on these data are not reliable estimators of changes in abundance. Therefore, we analyzed data obtained by samplers in dockside interviews collected between 1977 and 2011. These data comprise the number of days at sea, fishing depths, total and pescadinha catch information and the size and power of the boats from 710 pair-trawler fishing trips. CPUE is expressed as kg/day at sea, because neither the size nor the power-type of nets of the pair trawlers has changed substantially since the 1970s (Haimovici et al., 1989; Vasconcellos et al., 2006).

Pescadinha represents less than 20% of the landings of the industrial multispecific pair-trawl fishery off southern Brazil (Haimovici, 1998). To better associate catches with the effort that targets pescadinha, only trips in which it represented 30% or more of the catch ($n = 413$ and), or 40% or more ($n = 297$), were included in the analysis of the changes in CPUE (Chikuni, 1975). In each category, we calculated the mean CPUE values and 95% confidence intervals per year. A linear model was fitted to annual CPUEs and an analysis of variance (Zar, 1984) were used to analyze the statistical significance of the CPUE trend.

2.3. Age composition, mortality data and analysis

The smallest sizes of *M. atricauda* are poorly selected by the mesh and also discarded when caught, since specimens under 20 cm were usually landed in small numbers (Haimovici and Maceira, 1981; Cardoso and Haimovici, 2014). Thus, ages 0 and 1 are under-represented in the landings. Therefore, we calculated the percentage of individuals aged two or older for each five-year period between 1975 and 2010 to examine changes over time in the age composition of the stock.

We used two sources of data to estimate the long-term changes in the instantaneous total mortality coefficients ($Z\,\mathrm{yr}^{-1}$). The age composition of the landings in the 1950s and 1960s was obtained by relative CPUE data at different ages: ages 6 to 8 born from 1953 to 1955, landed in 1961, represented the 1950s and ages 3 to 6 born between 1958 and 1961, landed in 1963 and 1964, represented the 1960s (Table 2). These catches were landed by pair trawlers in Santos (southeastern Brazil). These pair trawlers fished mostly along the coast of Rio Grande do Sul, as shown by Yamaguti (1968). We reduced Yamaguti's readings on whole otoliths by one year,

Table 2
Relative catch per effort by age according to Yamaguti (1968)* and relative catches by age of *Macrodon atricauda* in pair trawl landings in southern Brazil.

Year	Age						
	2	3	4	5	6	7	8
1955*			0.85	0.09	0.04	4.00	
1963*	0.68	0.22	0.10	0.01	0.01		
1964*	0.49	0.46	0.05	0.01	0.01		
1976	0.74	0.19	0.04	0.03	0.01		
1977	0.72	0.19	0.05	0.03	0.00		
1978	0.64	0.24	0.07	0.04	0.00		
1979	0.72	0.20	0.05	0.03	0.01		
1984	0.56	0.31	0.09	0.03	0.01		
1985	0.60	0.29	0.09	0.02	0.01		
1986	0.54	0.32	0.09	0.03	0.01		
1987	0.54	0.32	0.10	0.03	0.01		
1989	0.63	0.27	0.08	0.02	0.01		
1997	0.69	0.27	0.03	0.01			
2006	0.73	0.22	0.05	0.00			
2007	0.82	0.15	0.03	0.00			
2009	0.83	0.15	0.02	0.00			