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REVIEW ARTICLE

# Long-term changes in the fisheries in the Patos Lagoon estuary and adjacent coastal waters in Southern Brazil

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**ABSTRACT**
The life cycle, fisheries and management of the main fishing resources of the Patos Lagoon and adjacent coastal waters are reviewed. Over recent decades, fish landings in Rio Grande have decreased by over 60%. The stocks of the large-sized, slow-growing fishes *Genidens barbus* and *G. planifrons*, *Pogonias cromis* and *Rhinobatos horkelii* collapsed in the early 1980s. The pink shrimp *Penaeus paulensis* stock was reduced by intense fishing of subadults in the estuary and of adults at sea. The sciaenid fishes *Micropogonias furnieri*, *Macrodon atricauda*, *Umbrina canosai* and *Cynoscion guatucupa*, which together represent more than half of local marine fish landings, are overexploited. These sciaenids are more resilient to intense fishing when compared with other families because of their early maturation and high fecundity, but high exploitation rates are unsustainable in the long run. The pelagic migrant fishes *Pomatomus saltatrix* and *Mugil liza* and the blue crab *Callinectes sapidus* are at the limit of exploitation. The recovery of these stocks will depend on diminishing the fishing pressure they have suffered in recent decades. Despite legal protection, the present enforcement has proven to be insufficient and intense fishing by a large number of industrial and small-scale fishing boats still goes on. Overall, the future of the estuarine and coastal fishing resources is uncertain and the recovery of the large long-living species of the higher trophic levels is unlikely.

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## Introduction

Coastal lagoons and coastal shelf waters at intermediate latitudes are considered to be among the most productive ecosystems in the world (Perez-Ruzafa & Marcos 2012). Shallow waters, relative isolation and protection from the sea and the presence of boundaries with strong physical and ecological gradients help explain the high productivity of costal lagoons and their importance as nursery grounds for fisheries resources (Cataudella et al. 2015). On the other hand, coastal waters enriched by continental runoff and diverse oceanographic processes are responsible for nearly 10% of world fisheries landings (Pauly & Christensen 1995).

The Patos Lagoon Estuary (PLE) and the large adjacent soft bottom shelf (Figure 1) are among the richest fishing regions of Brazil (Haimovici 1997; MPA 2012). The surface circulation of the coastal waters in southern Brazil, characterized by the northward flow of both the La Plata River runoff and the inner branch of the Malvinas/Falkland current, is responsible for the enhanced primary productivity in the region (Ciotti et al. 1995; Gaeta & Brandini 2006; Moller et al. 2008). On the other hand, the intrusion of marine waters enhances the productivity of the shallow embayments of the lower part of the Patos Lagoon, which are considered important nursery and feeding grounds of diverse species of fishes and invertebrates (Odebrecht et al. 2010). Most of the abundant species fished on the continental shelf spend part of their life cycle in the PLE or adjacent coastal waters (Chao et al. 1985; Haimovici et al. 1996).

Ecological extinction due to overfishing precedes all other pervasive human disturbances to coastal ecosystems, including pollution, degradation of water quality, and anthropogenic climate change (Jackson et al. 2001). Understanding the life cycles of the main target species and providing an historical perspective of the magnitude of the decline of fisheries, including those that have collapsed, is the basis for their sustainability in the future (Jackson et al. 2011). This paper provides an updated review on the life cycle, fishery, exploitation state and management of the main species in the PLE and coastal waters of Southern Brazil fisheries.

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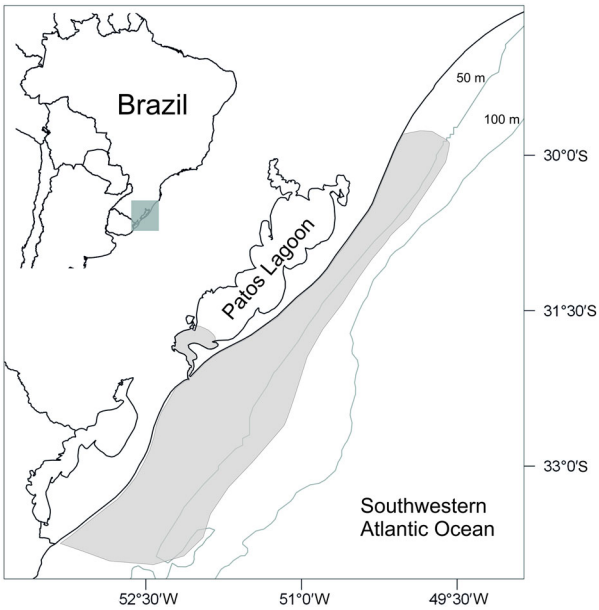


**Figure 1.** The study area in southern Brazil. The fishing regions in the Patos Lagoon Estuary and in coastal waters are shaded in grey.

## Methodological approach

Local landings statistics were recovered from reports of the federal fisheries research centre in Rio Grande for 1945 to 2011 (Silva 1990; Ibama/Ceperg 2001–2011) (Figure 2). Landings from Santa Catarina State, Uruguay and Argentina were obtained from the research group at the University of the Itajaí Valley (Univali/CTTmar 2010, 2011, 2013), the Uruguayan aquatic resources agency (Dinara 2015) and the Argentinean agriculture, livestock and fisheries agency (MAGyP 2015).

The analysis of the life history of each selected species was based on the available information of: (1) latitudinal limits of the stock distribution; (2) spawning, nursery and fishing grounds; (3) larger sizes and maximum ages in commercial catches; (4) von Bertalanffy growth parameters; (5) spawning type and seasons and the order of magnitude of the annual fecundity; and (6) life-history changes, as reduction in the spawning grounds, changes in growth and loss of older ages in the stock.

Assessment criteria depended on available data of total landing of the stocks of each of the main species, including those in other harbours such as Santa Catarina in Brazil and Uruguay and Argentina, catch per unit effort (CPUE), the instantaneous total mortality coefficient and the exploitation rate. CPUE and biological data of the main species landed by industrial fishing in Rio Grande were obtained from a long-term sampling programme conducted by the Institute of Oceanography of the Federal University of Rio Grande (FURG) since 1976 (Haimovici et al. 1989a; Cowx et al. 1998). In the PLE, no consistent series of effort data are available for the artisanal estuarine fisheries.

Based on the reduction of the total landings, the state of exploitation was recorded as fully exploited, overexploited or collapsed if recent landings were respectively more than 50%, less than 50% and less than 10%, respectively, of the maximum in a five-year period (Pauly & Zeller 2015).

Changes in growth, reproduction and instantaneous total mortality coefficient were obtained from published references or estimated following the published methodology (Cardoso & Haimovici 2011, 2014, 2015a).

## The fishing history in the Patos Lagoon Estuary and coastal adjacent region

Estuaries and coastal seas have been focal points of human settlement and marine resources use

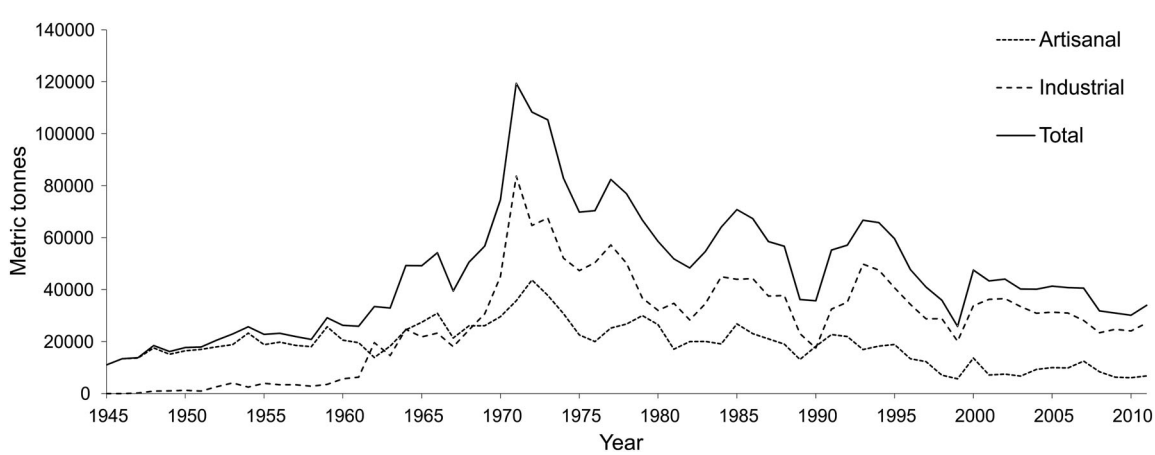


**Figure 2.** Annual recorded landings in Rio Grande by the industrial fishery in shelf waters and the artisanal fishery in the Patos Lagoon Estuary between 1945 and 2011.

throughout history (Lotze et al. 2006). Fishing in the estuarine region of the Patos Lagoon and coastal adjacent areas has taken place since, at least, the last transgression event, 5100 years ago, as seen by the large quantity of fish otoliths and crab shells in shell mounds on sandbanks between the Patos Lagoon and the oceanic coast (Ribeiro & Calippo 2000; Santos & D'Incao 2004).

During the colonial period, fishing took place in the PLE but no specific information is available. During the imperial period, in the second half of the nineteenth century, tax exemptions and financing of public lands were offered to stimulate the installation of fluvial, estuarine and marine fish salting industries (decree 876, 1856) (Paiva 2004). These incentives also stimulated the development of the fisheries in the Patos Lagoon as described by the German naturalist Hermann von Ihering, who lived in Rio Grande from 1884 to 1885, and pointed out that four or five large companies (enterprises, industries) salted fish and shrimp in Rio Grande (Odebrecht 2003). The main species were the black drum *Pogonias cromis* (Linnaeus, 1766), mullet *Mugil liza* (Valenciennes, 1836), marine catfishes (*Genidens* spp.), Atlantic tripletail *Lobotes surinamensis* (Bloch, 1790) and pink shrimp *Penaeus paulensis* (Pérez Farfante, 1967). These products were transported abroad by steam boats to Montevideo and Rio de Janeiro, and by sailboats further north to the states of Bahia and Pernambuco. The canned flatfish *Paralichthys orbignyanus* (Valenciennes, 1839) and mullet, head and viscera fat of marine catfishes and their swim bladders, after being cleaned and dried for glue production, were exported to the USA (Odebrecht 2003).

The development of the industry and commerce of fish caught in the Patos Lagoon may be associated with the salting fish expertise of the nineteenth-century Portuguese immigrant farmers and fishermen who arrived in southern Brazil. In the early twentieth century, several companies salted fish that were sold through commercial chains formerly developed for salted meat. Most sales were sent by steam ships to the northeastern region of Brazil to cater for the increased demand, mainly during Easter time each year.

In the early 1900s, the entrance to the Patos Lagoon was permanently fixed by a pair of 5 km long jetties facilitating the capture of diadromous fish with gillnets along the channel that connects the lagoon to the ocean. In the 1950s and 1960s, several companies invested in the catch, processing and commercialization of fish for export stimulated by road improvements, the expansion of domestic consumption and the expectation of exporting frozen fish, and also by tax incentives according to the Brazilian decree-law no. 221, 1967 (Abdalah & Sumaila 2007).

The main source for the rapid increase of the fish landings in Rio Grande after 1967 was the development of the bottom trawl industrial fishery along south Brazil, Uruguay and Argentina (Yesaki & Bager 1975). At its peak, 28 fish processing plants provided over 17,000 jobs in Rio Grande (Haimovici et al. 2014a). The decline of Rio Grande as a fishing harbour was caused by a combination of factors, the main one being the implementation of the Exclusive Economic Zones of Uruguay and Argentina that gradually excluded Brazilian fishing boats from their waters. The loss of the foreign fishing grounds led to intense fishing over the continental shelf of Rio Grande do Sul and the PLE, resulting in a rapid decrease in catches (Haimovici et al. 1989a, 2006a). Consequently, the fish processing industrial park in Rio Grande, mainly for frozen fish for export, was gradually reduced. At the same time, the city of Itajaí located north of Rio Grande developed as the main fishing harbour of the southern and southeastern Brazilian regions due to its proximity to the large centres of fresh fish consumption and lower dependency on demersal fishes (Haimovici et al. 2014a). Fishing has economic and social importance in the region. A recent census in the Patos Lagoon identified ca. 3500 artisanal fishermen, most of them living in the estuarine region of the lagoon (Vasconcellos & Kalikoksi 2014). Many crew members of the industrial fleets landing in Rio Grande also live in the region and fish processing industries still provide a large number of jobs in Rio Grande (Haimovici et al. 2014a).

## The fisheries

Most of the species fished in the PLE by small-scale fishermen are migrants that spend part of their life cycle in the estuarine region and part in coastal waters: the pink shrimp *Penaeus paulensis*, the whitemouth croaker *Micropogonias furnieri* (Desmarest, 1823), the sea catfishes *Genidens* spp., the mullet *Mugil liza*, the black drum *Pogonias cromis*, the savelha *Brevoortia pectinata* (Jenyns, 1842), the red flatfish *Paralichthys orbignyanus* (Valenciennes, 1839) and the blue crab *Callinectes sapidus* (Rathbun, 1896). Others use shallow coastal waters for spawning and are only occasionally found in the PLE. These species are fished exclusively in shelf waters: the king weakfish *Macrodon atricauda* (Günther, 1880), the Argentine croaker *Umbrina canosai* (Berg, 1895), the striped weakfish *Cynoscion guatucupa* (Cuvier, 1830), the bluefish *Pomatomus*

*saltatrix* (Linnaeus, 1766) and several elasmobranchs, mostly the guitar fish *Rhinobatos horkelii* (Müller & Henle, 1841) and the hammerhead *Sphyrna* spp. (Chao et al. 1985; Haimovici 1997; Vooren & Klippel 2005). Together they represent over 70% of the landings in Rio Grande between 1976 and 2011 (Figure 2).

The main fishing gear used in the PLE are trawl nets, gillnets and fyke nets deployed by around 2500 artisanal open-deck fishing vessels less than 12 m long, constructed of plank wood; about 60% are motorized by internal (mostly diesel) motors of 9–32 HP (Kalikoski & Vasconcellos 2012). Until the 1980s, most of the artisanal fishery followed a calendar with well-defined fishing seasons for most species (Kalikoski et al. 2002). More recently, due to the collapse of the black drum, catfishes and red flatfish fisheries in the PLE, only the pink shrimp, the mullet and young whitemouth croakers are targeted by the artisanal fishery. Part of the artisanal fishery migrated to the coastal area in the early 1980s, forming the so-called semi-industrial fleet with closed-deck boats initially measuring 12–15 m long (Reis et al. 1994) but more recently measuring 17–22 m, converging towards the industrial gillnet fleet (Vasconcellos et al. 2014). These boats target whitemouth croaker in spring and summer with bottom gillnets; for the rest of the year, they initially targeted sharks and more recently other species such as bluefish, Argentine croaker and striped weakfish (Vasconcellos et al. 2014).

In the coastal region the industrial fleet, typically 18–30 m long wooden or steel hull boats powered by 200–400 HP engines, fish with bottom trawls, seines and gillnets. Stern bottom trawling (single and paired) target mainly the Argentine and whitemouth croakers, and king and striped weakfishes (Haimovici et al. 1989; Cowx et al. 1998). Double-rig trawling began in the mid 1980s (Barcellos et al. 1991), targeting the shrimps *Artemesia longinaris* (Spence Bate, 1888) and *Pleoticus muelleri* (Spence Bate, 1888) in summer and autumn, the angel shark *Squatina* spp. in winter and spring, and later on the flatfish *Paralichthys patagonicus* (Jordan, 1889) (Haimovici & Mendonça 1996).

Landing records are classified for artisanal small-scale fisheries inland, estuarine and marine waters, and industrial including semi-industrial larger boats fishing exclusively in the ocean. Despite some doubts regarding their coverage, they represent the general trend of the landings in Rio Grande (Reis 1993). Artisanal landings evolved from 11,000 t in 1945 to a maximum of 43,700 t in 1972 and decreased to a mean of 6300 t since 2001 (Figure 2). Industrial fishing started in 1947 with the arrival of several trawlers from northern Europe (Yesaki & Bager 1975). Landings from the industrial fishery attained a maximum of 83,000 t in 1971 and decreased to around 30,000 t in the last decade (Figure 2). In 1966, artisanal catches accounted for more than 80% of the total catch in southern Brazil and their relative importance decreased to less than 25% in the last decade. Bottom trawling attained a maximum of 42,700 t in 1986 with a mean of 11,000 t from 2000 to 2011. Semi-industrial and industrial gillnet fishing increased in relative importance in the last decade, together attaining mean annual landings of 13,500 t. Industrial purse-seining is highly variable; larger annual landings were of around 10,000 t in 1975 and 1991, and the mean in the last decade was of 2000 t (Figure 2). It should be noted that part of the decrease in the industrial demersal landings after 1985 was because the number of fishing boats landing formerly in Rio Grande moved to other ports in Santa Catarina (Haimovici et al. 2014a).

## The main species

The information on life-history parameters and stock assessment based on peer review publications, reports and theses of the main species fished in the PLE and adjacent shelf waters is summarized in Table I. Individual catch per unit of effort (CPUE) series for demersal species caught in coastal waters by pairs of trawlers between 1976 and 2011 in kg per day at sea are presented in Figure 3. All species show a decreasing trend up to the 1990s and stabilization in former years. No increase in the size or power of the boats was observed in the last 45 years, but their fishing power may have increased due to gear improvements; therefore, the observed trends may underestimate the decrease of the abundances.

## The pink shrimp

*Penaeus paulensis* is a penaeid shrimp with a 2–3 year life cycle. A single migratory stock occurs in the region, reproducing at sea along southern and southeastern Brazil and growing in estuaries in southern Brazil and Uruguay (D'Incao 1991).

Post-larvae recruit to the Patos Lagoon Estuary (PLE) in spring and grow in shallow bays where they find food and protection against currents and predators in the submerged *Ruppia maritima* (Linnaeus, 1753) seagrass meadows (Ruas et al. 2014). High recruitments and large catches are associated with low rainfall in the previous winter in the Patos-Mirim basin and the prevailing southwest winds in spring (Möller et al. 2009; Pereira & D'Incao 2012). Poor recruitment

**Table I.** Life-history parameters, stock assessment and management of the main fishing resources from the Patos Lagoon Estuary and adjacent coast.

| | *Penaeus paulensis* (Pérez Farfante, 1967) | *Micropogonias furnieri* (Desmarest, 1823) | *Mugil liza* (Valenciennes, 1836) | *Callinectes sapidus* (Rathbun, 1896) | *Genidens* spp. | *Pogonias cromis* (Linnaeus, 1766) | *Macrodon atricauda* (Günther, 1880) | *Umbrina canosai* (Berg, 1895) | *Cynoscion guatucupa* (Cuvier, 1830) | *Pomatomus saltatrix* (Linnaeus, 1766) | *Rhinobatos horkelli* (Müller & Henle, 1841) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fished unit stock distribution | Uruguay – SE Brazil | Argentina – south Brazil | Argentina – SE Brazil | South Brazil | South Brazil | Argentina – SE Brazil | Southern Brazil | Argentina – SE Brazil | Argentina – SE Brazil | Argentina – SE Brazil | Argentina – SE Brazil |
| Spawning environment | Shelf 40–80 m | Shelf < 50 m | Shelf < 50 m | Surf zone | Estuarine | Coastal < 20 m | Coastal < 20 m | Shelf < 150 m | Shelf < 60 m | Shelf < 60 m | Coastal < 20 m |
| Nursery grounds | PLE | PLE and shelf | PLE | PLE | PLE | PLE | Coastal < 20 m | Shelf < 60 m | Shelf < 60 m | Coastal < 20 m | Coastal < 20 m |
| Fishing areas | PLE and shelf | PLE and shelf | PLE and shelf | PLE | PLE and shelf | PLE and shelf | Shelf < 60 m | Shelf < 180 m | Shelf < 180 m | Shelf < 180 m | Shelf < 180 m |
| Maximum ages (years) | 2–3 | > 35 (1977) 10 (2010) | 11 (2013) | | > 35 (1978) | > 50 (1978) 3–4 (2013) | 9 (1966) 5 (2010) | 22 (1978) 15 (2013) | 18 (1980) 12 (2002) | 10 (1990) | 28 (1980) |
| Larger size (mm) | 300 TL | 700 TL | 650 TL | CW > 150 | 980 TL | 1400 TL | 450 TL | 450 TL | 600 TL | 700 TL | 1270 TL |
| von Bertalanffy growth parameters ($L_\infty$ (mm), k (year$^{-1}$), $t_0$) | | 545, 0.170, −2.72 (1978) 661, 0.30, −0.02 (2007–2010)* | 662, 0.168, −1.7 (2013) | | 638, 0.1287, 0.195 (1986)** | 1226, 0.171, −0.177 (1979) | 333, 1.1, 0.1 (1976–1979) 410, 0.61, −0.05 (2006–2009) | 356, 0.31, −1.14 (1976) 420, 0.30, −1.13 (2011)* | 516, 0.24, −0.97 (1976–1980) 566, 0.21, −0.95 (1997–2002) | 662, 0.387, −0.321 (1989) | 1355, 0.194, −1.078 (1982) |
| Type of spawning | Total | Multiple, broadcast | Multiple, broadcast | Multiple, broadcast | Mouth-breeder | Multiple, broadcast | Multiple, broadcast | Multiple, broadcast | Multiple, broadcast | Multiple, broadcast | Total |
| Spawning season | Year-round with a peak in spring | Spring and summer | Autumn and winter | Summer and early autumn | Summer | Late spring to early autumn | Late spring to early autumn | Winter and spring | Spring to autumn | Spring and summer | Summer |
| Intraovaric fecundity | > $10^6$ | > $10^6$ | 0.8–3 × $10^6$ | 2.5 × $10^6$ | 65–230 | > $10^8$ (1979) | $10^5$–$10^6$ | $10^5$–$10^6$ | $10^5$–$10^6$ | $10^5$–$10^6$ | 3–12 viviparous |
| Size at 50% maturuity (mm) | | 340 TL (f) | 400 TL (m) 422 TL (f) | 108 CW m) 115 CW (f) | 450 TL (1986) | <700 TL (1980) <500 TL (2013) | 230 TL (1979) 200 TL (2011) | 220 TL (1980) 200 TL (2011) | 320 TL (1984) 320 TL (2002) | 350 TL (1987) | *1100 (1980) |
| Female age at 50% maturity (years) | < 2 | 2–3 | 5–6 | | 8–9 | 4 (1980) 3 (2013)* | 2–3 (1976) 1–2 (2011) | | | | 5–8 |
| Exploitation status | Overexploited | Overexploited | Fully exploited | Fully exploited | Collapsed | Collapsed | Overexploited | Overexploited | Overexploited | Fully exploited | Collapsed |
| Assessment criteria | Reduced total catches and CPUE | E = 0.72* Reduced CPUE | E = 0.56–0.77 Reduced CPUE | | Reduced landings | Reduced landings and CPUE | Reduced CPUE E > 0.7 (2011) | Reduced CPUE E > 0.7 (2010)* | Reduced CPUE E > 0.7 (2002) | | Reduced landings and CPUE |
| Life-history changes | | Increased growth | | | | Smaller $TL_{50\%}$ and $A_{50\%}$* | Increased growth, smaller $TL_{50\%}$ and $A_{50\%}$ | Increased growth, maller $TL_{50\%}$* | Increased growth | | |
| Main management tools and enforcement | Seasonal closures, gear restrictions, minimum size, poorly enforced | Licences and gear restrictions, poorly enforced | Licences, seasonal and spatial restrictions | Minimum size, protected spawning grounds | Fishery banned in 2014 | Fishery banned in 2014 | Licences, minimum size, poorly enforced | Licences, minimum size, poorly enforced | Licences, minimum size, poorly enforced | Licences, minimum size, poorly enforced | Fishery banned in 2005 |

References in the text. CW, carapace width (mm); TL, total length (mm); f, females; m, males; maximum observed age, age reached by less than 1% of the sampled specimens; larger size (mm), size reached by less than 1% of the sampled specimens; maximum recent age, age reached by less than 1% of the sampled specimens in the last decade; CPUE, catch per unit effort. *Manuel Haimovici, 2016, unpublished data; ***Genidens barbus*

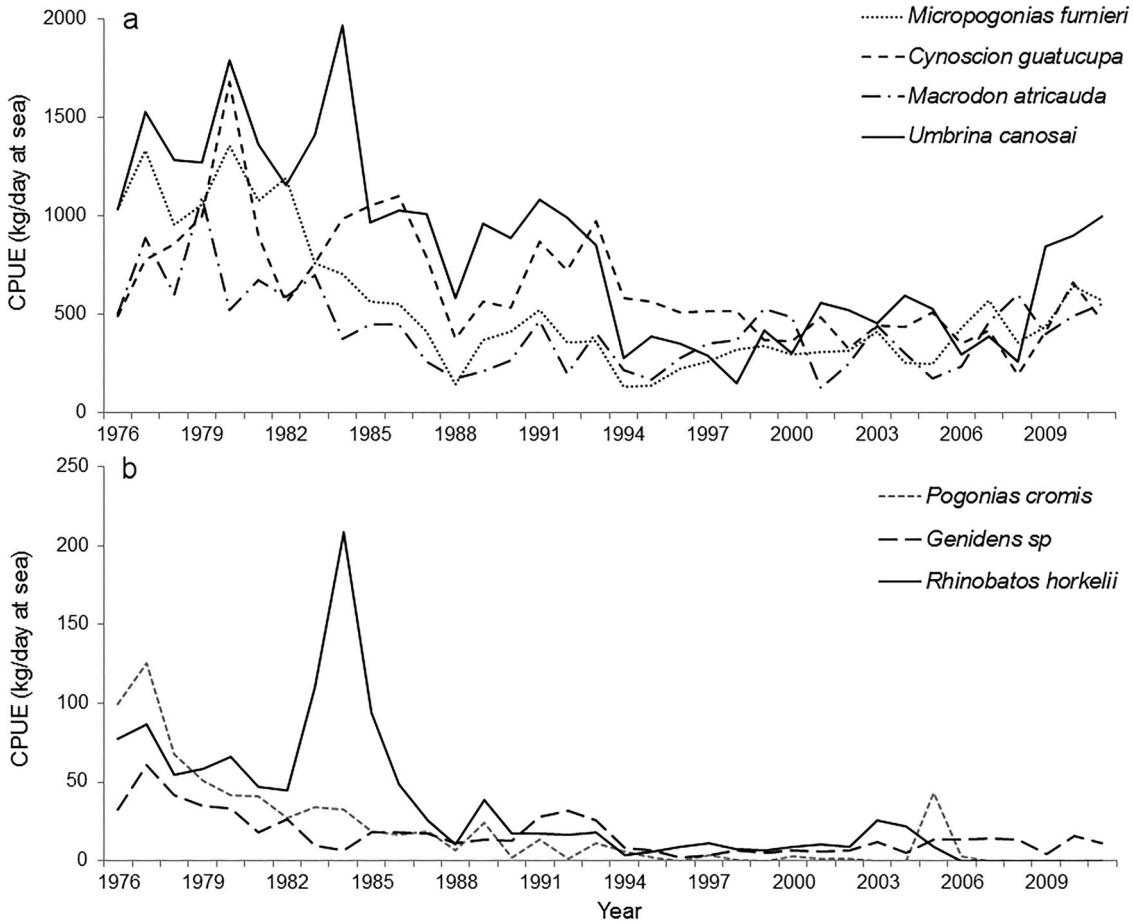


**Figure 3.** Catch per unit effort (CPUE, in tonnes per day) by pair trawlers fishing in coastal waters of Southern Brazil. (a) Target species. (b) Incidentally caught species.

occurs in the years of high rainfall that prevail under El Niño events (Grimm et al. 1998) in which a physical barrier prevents the entrance of oceanic water and the post-larval recruitment (Möller et al. 2009; Pereira & D'Incao 2012). Pre-adults are fished in summer and autumn in the PLE before most leave the estuary and migrate northward, where they spawn at depths between 40 and 80 m year-round but mainly in spring (D'Incao & Dumont 2010).

In the PLE the pink shrimp is caught with both fixed and trawled gear (passive and active gear). Fyke nets are fixed in shallow areas of the lagoon attracting shrimp with light, in the 1950s produced by carbide lamps, later replaced by gas lamps and more recently by LED lamps. Trawled nets include bag nets (coca), hand trawls (birimbau) and motorized otter board bottom trawls. Stow nets are the only legal fishing gear of pink shrimp, but bag beach and hand nets are widely used in embayments and otter boards trawl in deeper areas (Benedet et al. 2010).

The recorded mean annual pink shrimp production in the PLE between 1945 and 2011 was 2637 t, but attained around ca. 8000 t in 1972, 1979 and 1985 (Figure 4). The adult pink shrimp fishery in southeastern Brazil attained over 7000 t annually in the late 1960s (D'Incao et al. 2002) and decreased steadily to less than 1000 t in the 2000s, indicating overexploitation. Low catches in the spawning grounds suggest a strongly reduced spawning stock that led to lower mean annual catches and reduced frequency of large recruitments in the PLE in the last decades (D'Incao & Dumont 2010).

The management of the pink shrimp fishery in the PLE is regulated by seasonal closures and restricted fishing to a maximum of 10 fyke nets per fisherman. However, enforcement is poor and higher numbers of fyke nets and other gear are routinely used whenever larger-size pink shrimps are available.

### *The whitemouth croaker*

*Micropogonias furnieri*, locally called corvina, is a demersal sciaenid fish associated with soft bottoms of coastal and estuarine regions from the Caribbean (20°N) to northern Argentina (41°S). It sustains the most important demersal coastal fishery of the southwestern Atlantic. A common stock is fished in

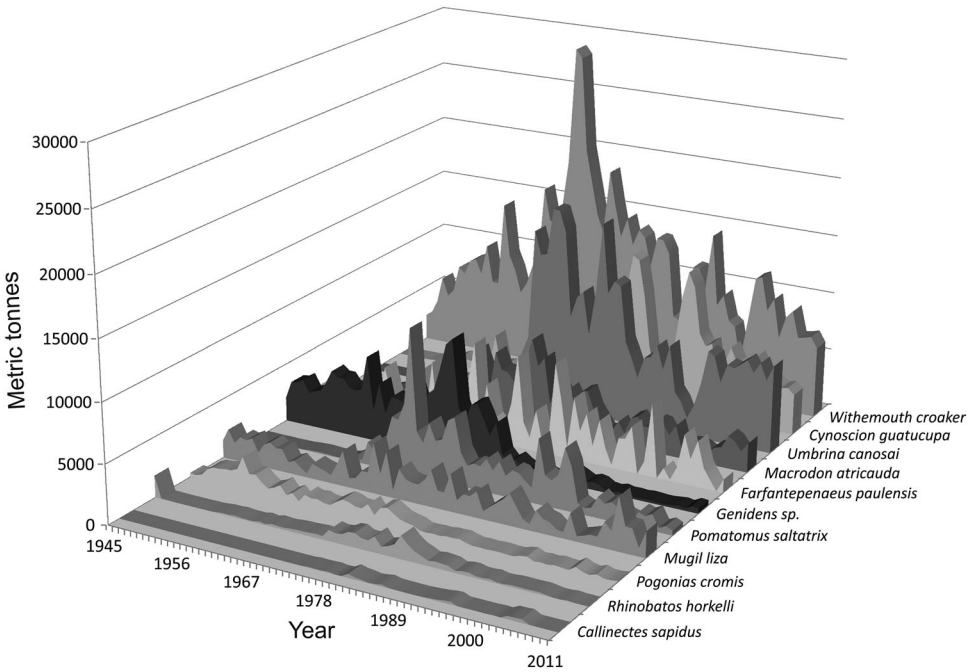


**Figure 4.** Annual recorded landings in Rio Grande of the main species caught in the Patos Lagoon Estuary and coastal waters of Southern Brazil (sources in the text).

southern Brazil, Uruguay and northern Argentina (Haimovici & Umpierre 1996; Haimovici & Ignacio 2005; Norbis & Verocai 2005; Vasconcellos & Haimovici 2006; Galli & Norbis 2013; Vasconcellos et al. 2015). It is a long-lived species that matures in 2–3 years and reaches 250–350 mm total length (TL) and can grow to over 38 years old and over 700 mm TL. It spawns from November to April in coastal waters near freshwater runoffs, the most important being the Rio de la Plata frontal zone (Jaureguizar et al. 2003; Macchi et al. 2003) and the mouth of the Patos Lagoon. Pelagic eggs and larvae are carried passively to the estuarine region of the Patos Lagoon (Muelbert & Weiss 1991; Sinque & Muelbert 1997) and pelagic larvae of 20–30 mm recruit to the bottom where they actively feed on infauna and epifauna organisms (Gonçalves et al. 1999). Juveniles remain in the central and lower Patos Lagoon where they find adequate conditions for fast growth (Garcia & Vieira 1997; Costa et al. 2014) until attaining a TL of 150–300 mm. Young specimens (1–3 years old) are found in the coastal region and adults throughout the inner shelf (Haimovici et al. 1996).

In the PLE, juveniles smaller than 300 mm TL have been and are still fished with small trawls, gillnets and encircling gillnets for many decades. Since the early 1980s, adults are fished almost exclusively in coastal waters with gillnets in spring and summer targeting pre-spawning aggregations, and both young and adults are fished using pairs of trawlers year-round (Reis et al. 1994; Vasconcellos et al. 2014).

Annual recorded landings in Rio Grande attained a mean of over 22,500 t (1970–1974) and decreased steadily to ca. 7000 t (2007–2011) (Figure 4). These statistics do not include the significant illegal fishing of young individuals in the PLE. The pink shrimp fyke nets fishery catch and discard a large number of juveniles (Vieira et al. 1996).

The whitemouth croaker abundance in southern Brazil decreased for decades (Haimovici & Ignacio 2005; Vasconcellos & Haimovici 2006). The age of older fishes in the catch of industrial pair trawlers decreased from 30 years in 1978–79 to 8 years in 2011–12 and the total instantaneous mortality coefficient increased steadily from 0.13 in the 1960s to 0.72 in the late 2000s (Table I). The species is overexploited and the high recent exploitation rate may lead to a strong catch reduction in the near future. Despite some formal regulations limiting the fleet size and trawling in the PLE, the fishery is of free access in practice, except for some local fishing restrictions for industrial purse seiners on spawning concentrations in coastal water near the Patos Lagoon access channel.

## *The mullet*

*Mugil liza* is a catadromous fish distributed along the Atlantic coast of South America, from Venezuela to Argentina (Siccha-Ramirez et al. 2014). A single stock

occurs in Argentina and southern Brazil (Mai et al. 2014), where it grows to around 650 mm TL and 11 years old (Garbin et al. 2014). Mean age at first maturity is 5 years and mean size at first maturity is 400 mm for males and 420 mm for females. This species is an autumn and winter total broadcast spawner with high fecundity, producing 0.8–3 × $10^6$ oocytes (Lemos et al. 2014).

A northward reproductive migration occurs in autumn to coastal waters at latitudes between 24°S and 26°S (northern Santa Catarina and Paraná) where it spawns from April to July (Lemos et al. 2014). Marine currents carry the juveniles south to enter the estuaries, including the PLE, which is considered to be one of the main nursery and feeding ground for *M. liza* in the region (Vieira et al. 2008).

Fishing of *M. liza* is culturally and historically important and occurs mainly on its migratory aggregations. In the last two decades, fishing pressure increased because of the high value of the roes. In the PLE, artisanal fishing with gillnets occurs at the beginning of the reproductive migrations and is followed in coastal waters with gillnets and purse seiners. Landings in Rio Grande and Santa Catarina peaked, respectively, at 4500 t and 6400 t in 2007 and decreased to 2200 t and 3000 t in 2011 (Sant'Ana & Kinas 2015).

Based on the age structure of the catches, Garbin et al. (2014) estimated the total instantaneous mortality of *M. liza* at 0.77 and an exploitation rate of over 0.5. Sant'Ana & Kinas (2015) formulated a spatially structured Schaefer model based on the CPUE data from 1970 to 2011 discriminated by fleets and landing harbours that shows a consistent decreasing trend in the abundance of *M. liza* and a high exploitation rate. Both approaches suggest the stock is at least fully exploited.

### *The blue crab*

Widely distributed in the northwestern and southwestern Atlantic, the blue crab *Callinectes sapidus* is estuary-dependent with marine larval stages and eurythermic and euryhaline juveniles and adults (Kennedy & Le Cronin 2007). It is the most abundant crab in the PLE and the only estuary-dependent fish resource with its life cycle in the lagoon and nearby coastal waters. Copulation occurs in winter in the mid estuary where males remain while females move to nearby coastal waters for spawning from spring to early autumn (Rodrigues & D'Incao 2014). Post-larvae are carried back to the estuary and settle in low-salinity embayments with preference for submerged seagrass meadows where they find protection and adequate growth conditions as young juveniles (Ruas et al. 2014). Larger females attain a carapace width (CW) of over 150 mm. Mean CW at first maturity is 108 mm for males and 115 mm for females, and fecundity is around 2.5 × $10^6$ eggs (Rodrigues et al. 2011; Rodrigues & D'Incao 2014). Spawning females are highly vulnerable to fishing when they concentrate near the jetties and channel at the lagoon entrance. Post-larvae from the PLE and from other neighbouring estuaries are carried inwards through the entrance channel during periods of low freshwater discharge and southwestern winds (Lacerda et al. 2016).

In the PLE, the blue crab is fished with otter trawls, fishing dredges, gillnets, stow nets and hookless baited longlines (Ferreira 2007), and as by-catch of pink shrimp with artisanal trawling and fyke nets in summer. Profitability of the crab fishing is low and only the poorer or less well-equipped fishermen target them year-round and during periods of poor shrimp catches. The crab is processed by the fishermen and their families and sold locally or by small-scale middlemen and, therefore, landing statistics are poor. For a short period between 2004 and 2006, 200–300 t of blue carb were canned for export, but supply soon collapsed. The failure to provide sustainable catches indicates that it has a low potential of sustainable production and is consequently of low interest for large-scale fishing.

Management includes a minimum carapace width (CW) of 120 mm. Most crabs under this size are discarded alive because of their low meat yield. Fishing on reproductive concentrations nearby the Patos Lagoon entrance channel is illegal; however, otter trawls and beach nets are indeed used in the lower estuary and shallow coastal waters (Kalikovski & Vasconcellos 2012).

### *The catfishes*

The two marine catfishes are *Genidens barbus* (Lacepède, 1803), which ranges from northeastern Brazil to northern Argentina (17°S to 40°S), and *G. planifrons* (Higuchi, Reis & Araújo, 1982) (Higuchi et al. 1982), with a narrower distribution that is restricted to Uruguay and southern Brazil. The first is far more abundant than the second, and both species are pooled in the landings statistics (Reis 1986a). The catfishes are fished in the PLE and adjacent coastal waters, and their juveniles are common in the neighbouring oceanic beach surf zone.

*Genidens barbus* is a long-lived and slow-growing species that reaches around 1000 mm in length and 36 years of age (Reis 1986b). Fifty percent of sexual

maturation is attained at 405 mm by females and 430 mm by males, both at 8–9 years; 100% females over 730 mm and males over 630 mm were mature (Reis 1986c). Their life cycle includes entering the Patos Lagoon in August and September where sexual maturation takes place and spawning in November and December. Females return to the sea and the males, which are mouth-breeders, remain, carrying small numbers (32–320) of large eggs, between 12 and 14 mm diameter, until the release of the juveniles in January and February. Adults disperse on the shelf for feeding mainly on fish, polychaetes, molluscs and crustaceans (Reis 1986b). Little is known of *G. planifrons*, but it is assumed that its life strategy is similar to that of *G. barbus*.

Marine catfishes were intensely fished in the PLE from 1945 to 1981, with a mean annual recorded landing of 4502 t (Figure 4). Most of the catches were salted and only a small part was commercially frozen (Reis 1986a).

In the late 1970s, most fishing was with trammel nets formed by three layers with a central netting of small mesh sandwiched between two large-mesh nets, which caught a wide variety of fish sizes. These nets were fixed along the estuary channel or used floats with boats up to 40 miles along the coast (Reis 1986a). Most *G. barbus* and *G. planifrons* were fished in the PLE with gillnets and measured between 400 and 500 mm TL, which indicates that larger and older fishes had been fished out before the late 1970s (Reis 1986a).

Since the collapse of the stock in the 1980s, catfishes have been caught as by-catch in the bottom trawl and gillnet fisheries and, in recent years, have been targeted by a few bottom longliners. No significant recovery of the fishery was observed; landings between 1982 and 2011 were 427 t. The local stock of the *G. barbus* catfishes is considered endangered and *G. planifrons* as critically endangered (Cardoso & Haimovici 2015b) and fishing has been banned in Rio Grande do Sul since 2014.

## The black drum

*Pogonias cromis* is a large sciaenid fish widely distributed along the western Atlantic from north of Cape Hatteras (35°N) to the San Matías Gulf (42°S) in Argentina. In southern Brazil, adults are found in estuaries and the coastal region up to 40 m depth. This species can attain over 1400 mm TL, 40 kg in weight and can live for over 55 years. The first maturity occurs at 4–5 years at around 650–700 mm TL, and spawning takes place between spring and summer in the PLE and adjacent coast (Haimovici et al. 2006a).

Because of its large size, *P. cromis* is very vulnerable to gillnet fishing in the entrance channel of PLE, beach seines in the adjacent coastal region, and also when feeding on crabs and molluscs in the shallow waters of the Patos Lagoon and tributaries.

Mean annual landing records from 1945 to 1980 were 996 t and most catches were salted (Figure 4). In the 1970s most fished specimens measured 900–1400 mm TL and later they were only occasionally caught by beach-seines, industrial paired trawlers and purse seiners. Mean landings decreased to 129 t between 1981 and 2011. The local stock of *P. cromis* is considered endangered (Chao et al. 2015). Since 2013, small black drums have been fished in the PLE (Santos et al. 2016); most were 1–3 years old and specimens in their third year of life measuring over 450 mm TL were already mature.

The gradual decrease of its abundance was not reflected in the landings because most fishing was in the narrow channel entrance to the PLE where the species was easily targeted along its reproductive migration. The sudden collapse of the fishery occurred when most of the adults of the stock were fished out. Only after 35 years of the collapse of the fishery have significant recruitments to the PLE been observed. Earlier maturity at a smaller size suggests a possible adaptation to the fishing pressure on the larger ones.

## The Argentine croaker

*Umbrina canosai* is a demersal sciaenid fish endemic in the southwestern Atlantic between Rio de Janeiro, Brazil (22°S) and the Gulf of San Matías, Argentina (41°30′S). A single stock is fished from northern Argentina to southern Brazil (Gonzalez-Alberdi & Nani 1967). Maximum landings in the southwestern Atlantic attained up to 26,700 t in 1973, of which 20,200 t was caught in Brazil. Annual landings in Brazil decreased to less than 5000 t in the late 1990s and recovered to around 15,000 t in the 2000s (Figure 4).

*Umbrina canosai* reaches over 450 mm TL and over 25 years of age (Haimovici & Reis 1984). It feeds on epibenthic fauna (Haimovici et al. 1989b) and matures at 2 years of age and 200 mm TL (Haimovici & Cousin 1989). It spawns in winter and spring on the continental shelf of southern Brazil, where it spends the first 2 years of life (Haimovici et al. 1996) before undertaking seasonal southward summer migrations to feeding grounds in Uruguay and northern Argentina.

It is one of the main targets of the semi-industrial and industrial gillnet fisheries in coastal waters in

winter and spring, and of industrial trawlers year-round. The intense fishing through recent decades has resulted in decreasing abundance and increasing total mortality rate, which led the stock to reach over-exploited status (Haimovici et al. 2006b). In recent years, highly efficient mid-water trawlers targeting reproductive aggregations of older fishes along the outer shelf led to the risk of collapse of the stock (Haimovici & Cardoso 2016).

### The king weakfish

*Macrodon atricauda* is a sciaenid fish endemic in the southwestern Atlantic between Rio de Janeiro, Brazil (22°S) and the Gulf of San Matías, Argentina (41°30′S). Fishing in southern Brazil occurs on a genetically distinct stock (Yamaguti 1979; Rodrigues et al. 2014). The king weakfish has been fished since the 1950s mainly by industrial paired trawlers with annual landings peaking at over 11,000 t in the 1970s and decreasing steadily to around 3000 t in the 2000s (Figure 4).

It is a coastal species that feeds on shrimp, squid and fishes (Juras & Yamaguti 1985). It is a multiple spawner during spring and summer (Juras & Yamaguti 1989). Juveniles grow in estuarine and coastal areas. Older weakfishes attained 9 years of age in the 1960s (Yamaguti & Santos 1966) and matured at 2–3 years (Juras & Yamaguti 1989; Cardoso & Haimovici 2014). However, fishing-induced life-history changes led to the following scenario: in the 2000s no king weakfishes over 6 years old were fished, growth increased, age and size at maturation decreased, mortality increased and the stock was reduced to one-third of its abundance in the 1960s (Cardoso & Haimovici 2011, 2014, 2015a). A precautionary approach to avoid further decrease requires the reduction of the fishing effort.

### The striped weakfish

*Cynoscion guatucupa* is a sciaenid fish endemic in the southwestern Atlantic between Rio de Janeiro, Brazil (22°S) and the Gulf of San Matías, Argentina (41°30′S). A common stock occurs in northern Argentina, Uruguay and southern Brazil. At least part of the adult stock moves northward in autumn and spring to the coastal waters of southern Brazil and back southward in summer. The main nursery grounds for the first 2–3 years of life is the inner shelf (> 50 m depth) off Uruguay and southern Brazil (Haimovici et al. 1996). As a multiple spawner, the species presents two distinct peaks in spring and early autumn. It is a relatively slow-growing fish that matures around 3 years of age and reaches over 15 years of age (Vieira & Haimovici 1993, 1997). Intensely fished in the three countries, total annual landings oscillated around 30,000 t in the 2000s. It is fished year-round by the industrial bottom trawlers and from autumn to spring by the semi-industrial and industrial gillnet fleets. In recent decades a growth increase was observed, a decrease in the mean size and age in the landings in Rio Grande, and an increase in the instantaneous mortality rate leading to a high exploitation rate of circa 0.7 in 2002 (Miranda & Haimovici 2007). A precautionary approach in the entire distribution range in the three countries is necessary to reduce fishing effort and avoid further decrease in the stock.

### The bluefish

*Pomatomus saltatrix* has a worldwide distribution, generally in temperate and warm temperate continental shelf waters (Briggs 1960). A single migratory stock is fished in northern Argentina and southern Brazil (Haimovici & Krug 1996). Landings peaked at ca. 15,000 t in 1971, but decreased steadily and oscillated between 1000 t and 5000 t in the 2000s (Figure 4).

Off southern Brazil, the bluefish is a multiple spawner from mid spring to late summer and first maturity is attained in the third year of life at TL 350–400 mm (Haimovici & Krug 1992). Adult bluefish move northward in winter toward lower latitudes and most catches along the coast of southern Brazil with purse seine and gillnets occur in winter on subadults (Haimovici & Krug 1996). Landings in Rio Grande show sporadic higher peaks and a general decreasing trend; however, it cannot be associated with fishing as the number of purse seiners fishing has decreased over the years in the region. In the eastern USA, *P. saltatrix* shows a large short-term and a long-term variability, not associated with fishing (Fahay et al. 1999).

### The guitar shark

*Rhinobatos horkelli* is a benthic shark endemic to the southwestern Atlantic between São Paulo state, Brazil (23°S) and Buenos Aires province, Argentina (39°S). It is a slow-growing species that reaches 28 years of age and up to 125 cm TL (Lessa 1982). Along the southern coast of Brazil, higher densities occur on the outer shelf in winter and in spring adults migrate towards coastal waters, where females copulate and give birth in summer; in autumn the population returns to deeper water (Vooren et al. 2005). It is a viviparous species that matures at between 5 and 8 years of age at 105 cm TL and gives birth to an average of six

(3–12) neonates (Lessa 1982). The species was fished along southern Brazil mainly in summer with artisanal beach nets. Recorded landings reached 1803 t in 1987 and decreased to less than 200 t in 2000 (Miranda & Vooren 2003), prior to the closure of the fishery in 2005 (Figure 4). The overall abundance of elasmobranchs between the 1970s and 2000s decreased more than 10-fold (Vooren & Klippel 2005) and at present the stock of several species, including *R. horkelli*, is critically endangered following the IUCN criteria. Despite protection procedures, some illegal fishing as by-catch in the paired trawl industrial fishery takes place and compromises the recovery of the stock.

## Discussion

Fishing is clearly responsible for the alteration and impoverishment of estuarine and coastal fish communities worldwide (Jackson et al. 2001), and southern Brazil is no exception. Intense fishing since the 1960s decreased the landings of the estuarine and coastal species and among the main ones, three collapsed, six are overexploited and three are fully exploited in the PLE and the adjacent coast (Table I).

Life-cycle traits are determinant for the resilience to fishery exploitation (King & McFarlane 2003). High vulnerability to fishing can be associated with large size, long living, late maturing, low fecundity, small distribution ranges and spawning in estuaries or shallow waters (Cheung et al. 2005). Elasmobranchs such as *Rhynobatos horkelli*, large sciaenid fishes such as *Pogonias cromis* and mouth-breeding catfishes such as *Genidens barbus* and *G. planifrons* share at least some of those traits, which make them highly vulnerable to fishery and prone to local extinctions (Dulvy et al. 2003; Vooren & Klippel 2005; Wang et al. 2009). Their recovery in the PLE and adjacent coastal waters depends on strongly decreasing the fishing pressure.

Since the 1970s, the bulk of the coastal catches were of *Micropogonias furnieri*, *Cynoscion guatucupa*, *Macrodon atricauda* and *Umbrina canosai*. These sciaenid fishes are relatively resilient, when compared with other fish families, because of their early maturation, high fecundity and plasticity in their growth and first maturity age in response to decreased density (Miranda & Haimovici 2007; Cardoso & Haimovici 2011, 2014). However, due to a high exploitation rate (Table I), their abundance and catches are expected to decrease if fishing effort is not reduced (Vasconcellos & Haimovici 2006; Cardoso & Haimovici 2015a).

As with many other estuarine and coastal shrimps, *Penaeus paulensis* is overexploited due to intense fishing of both the pre-adults in the PLE and the adults on the continental shelf by industrial fishing (D'Incao et al. 2002). Due to the relatively high fecundity, fast growth and short life cycle, the pink shrimp stock will recover if fishing intensity is reduced and adequately managed to prevent recruitment overfishing. The medium-sized *Mugil liza* and *Pomatomus saltatrix* are at a lower level of vulnerability. Both are high-fecundity broadcast spawners and form pelagic schools that migrate seasonally to their marine spawning grounds. However, both are vulnerable to the large gillnet fishing fleets and the highly efficient purse-seine fishery. In this group can be included the blue crab, that probably is the least-affected fishing resource of the Patos Lagoon due to its high fecundity and low value, which prevented the development of an intense fishery. Mature spawning females, which concentrate adjacent to the PLE entrance, are highly vulnerable to illegal fishing, but spawners from other estuaries in the region may contribute to local recruitment (Lacerda et al. 2016).

Apart from the impact of capture, the indirect impact of fyke nets in the shrimp fishery in the Patos Lagoon estuary on juveniles of other important commercial species is not a negligible factor affecting the fishery potential of some important species in the region. In the 1990s, although representing only 6% of the total catch, estimated annual discard in numbers was of 4.2 and 2.7 millions of small *M. furnieri* and *G. barbus*, respectively (Vieira et al. 1996). On the other hand, the trawl fishery in the 2010s caught 6 kg of by-catch for each kg of pink shrimp, composed of 61 species of fish and macroinvertebrates, most of which were small-sized commercially important fish such as *M. furnieri*, *G. barbus* and *Paralichthys orbignyanus* and the blue crab *Callinectes sapidus* (Rezende 2016).

Overall fishing resources in the PLE and coastal areas are intensely exploited and their recovery depends on the release of the fishing pressure that they have been suffering in recent decades. Marine fisheries are under national jurisdictions of federal agencies, which historically have shown to be more efficient in stimulating the development of the fisheries than in their control and focusing on sustainability (Haimovici et al. 2014b). Despite this mostly top-down approach, some initiatives of local management are in place in the PLE. As an example, since 1996 the 'Forum da Lagoa' has worked effectively to limit the seasonal migration of artisanal fishermen from other states and discusses other issues such as the fishing season of the pink

shrimp (Reis & D'Incao 2000; Kalikoski et al. 2002; Reis & Rodrigues 2003; Kalikoski & Vasconcellos 2012).

The future of the coastal and Patos Lagoon estuary fishing resources is uncertain. The recovery requires efficient local, national and international management to reduce fishing, as all important stocks are shared with industrial fisheries based both in Rio Grande do Sul and Santa Catarina states in Brazil and some stocks such as those of bluefish, whitemouth croaker and Argentinean croaker and striped weakfish are shared internationally. In the cases where management rules exist in Brazil, enforcement has proven to be insufficient and fishing continues to be intense. Even in the best scenario, the recovery of the large, long-living species of the higher trophic levels is unlikely in estuarine and coastal environments (Lotze et al. 2006). In particular are the cases of *G. barbus*, *G. planifrons*, *R. horkelli* and *P. cromis*, species that are vulnerable in their spawning grounds and accessible to a large number of industrial and small-scale fishing boats.

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