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Marine Insights

Towards a more selective Patagonian toothfish fishery

How measures implemented in Argentina reduced the proportion of juveniles in catches.

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ABSTRACT. The Patagonian toothfish (*Dissostichus eleginoides*) fishery in the South Atlantic Ocean, also known as the Argentine Sea, began in the mid-1980s. It is conducted using two types of demersal fishing gear: bottom trawl and bottom longline. In 2000, a concerning situation was detected that threatened the sustainability of the fishery due to the high proportion of juvenile specimens present in the catches. Given the large size of juvenile fish, which exceeds 80 cm, and the particular shape and size of their mouths, managing selectivity through fishing gear regulations proved to be difficult to implement. Thus, any such regulation was expected to be of limited effectiveness. However, the issue of excessive juvenile Patagonian toothfish in catches was resolved thanks to a particular biological characteristic of the species, which allowed for selectivity to be managed by limiting accessibility to the juvenile fraction of the stock, thereby modifying the exploitation pattern. The species exhibits a differential size distribution by depth: larger and older specimens inhabit depths of up to 2,500 m, while juveniles are predominantly found in shallower waters, typically ranging from 600 to 800 m. Regulating the depth at which both fleets could target the species proved to be a management measure easily accepted by the fleet, as it did not entail additional costs or gear modifications and also facilitated control by national fishery authorities. A series of complementary measures were established between 2001 and 2002, including management elements addressing various aspects of the fishery. The result of this strategy was almost immediate, with juvenile catches in the following years dropping significantly, generally remaining below the established threshold. In general, CCAMLR-managed fisheries lack specific measures to avoid or minimize juvenile catches. The increasing number of immature fish in South Georgia Islands *D. eleginoides* fishery catches has drawn special attention from CCAMLR since 2021. The impact of fishing on the juvenile fraction of a population is a critical factor for both resource sustainability and fishery yield. The practical implementation of measures to reduce juvenile mortality, within a precautionary and ecosystem-based approach, is essential for ensuring the long-term productivity and sustainability of the resource and its fishery.
Key words: Fish juveniles, fishery management, sustainability.

Hacia una pesquería más selectiva de merluza negra

RESUMEN. La pesquería de merluza negra (*Dissostichus eleginoides*) en el Océano Atlántico Sur, también conocido como Mar Argentino, comenzó a mediados de la década de 1980. Se realiza utilizando dos tipos de artes de pesca demersales: arrastre de fondo y palangre de fondo. En el año 2000, se detectó una situación preocupante que amenazaba la sostenibilidad de la pesquería debido a la alta proporción de ejemplares juveniles presentes en las capturas. Dado el gran tamaño de los juveniles, que supera los 80 cm, y la particular forma y tamaño de sus bocas, la gestión de la selectividad mediante la regulación de las artes de pesca resultó difícil de implementar. Por lo tanto, se preveía que dicha regulación tendría una eficacia limitada. Sin embargo, el problema del exceso de juveniles de merluza negra en las capturas se resolvió gracias a una característica biológica particular de la especie, que permitió gestionar la selectividad limitando el acceso a la fracción juvenil del *stock*, modificando así el patrón de explotación. La especie presenta una distribución diferencial de tallas según la profundidad: los ejemplares de mayor tamaño y edad habitan profundidades de hasta 2.500 m, mientras que los juveniles se encuentran predominantemente en aguas someras, que suelen oscilar entre los 600 y los 800 m. Regular la profundidad a la que ambas flotas podían capturar la especie resultó ser una medida de gestión fácilmente aceptada por la flota, ya que no implicaba costes adicionales ni modificaciones de las artes de pesca, y además facilitaba el control por parte de las autoridades pesqueras nacionales. Entre 2001 y 2002 se establecieron una serie de medidas complementarias, que incluían elementos de gestión que abordaban diversos aspectos de la pesquería. El resultado de esta estrategia fue casi inmediato: las capturas de juveniles en los años siguientes disminuyeron significativamente, manteniéndose generalmente por debajo del umbral establecido. En general, las pesquerías de *D. eleginoides* gestionadas por la CCAMLR carecen de medidas específicas para evitar o minimizar las capturas de juveniles. El creciente número de peces inmaduros en las capturas pesqueras de las Islas Georgias del Sur ha atraído la atención especial de la CCAMLR desde 2021. El impacto de

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la pesca en la fracción juvenil de una población es un factor crítico tanto para la sostenibilidad de los recursos como para el rendimiento pesquero. La implementación práctica de medidas para reducir la mortalidad juvenil, dentro de un enfoque precautorio y ecosistémico, es esencial para asegurar la productividad y sostenibilidad a largo plazo del recurso y su pesquería.
Palabras clave: Juveniles de peces, manejo pesquero, sustentabilidad.

INTRODUCTION

The Patagonian toothfish (*Dissostichus eleginoides*) is a demersal-benthic notothenioid species with strong site fidelity (Lee et al. 2022; Troccoli et al. 2023). It has a wide distribution across the Atlantic, Pacific, and Indian oceans, and the northern margin of the Antarctic Convergence (Hureau 1985; Oyarzún et al. 1988). The Malvinas Current influences its distribution in Argentine maritime waters, which ranges from 37° S to 56° S latitude and includes the slope and continental shelf (Otero et al. 1982; Inada 1986). Highest concentrations of the species in the Argentine Sea are found on the slope between Isla de los Estados and the Burdwood Bank and south of it (Wöhler et al. 2024). This area has been the site of Argentina's main industrial fishery for the species since the late 1990s, with catches reaching up to 18,000 t annually in 1995. However, due to more conservative management measures implemented thereafter, these figures have remained steady at around 3,700 t year^{-1} for the last decade (Martínez et al. 2023a).

At the beginning of the 2000s, a concern regarding the sustainability of the fishery was identified, due to both excessive catches and a high percentage of juveniles in the catch. At that time, roughly 40 vessels, including longliners and trawlers, operated in the fishery, with catches consisting of about 90% immature specimens by weight (Wöhler and Martínez 2002a). The minimum length at which 50% of the fish population reaches sexual maturity, known as length at first maturity, is a critical parameter for sustainable management, especially for designing and regulating fishing gear. The 82 cm value estimated as the length at first sexual maturity for both sexes combined in Patagonian toothfish in the Argentine Sea (Prenski and Almeyda 1997) was adopted into regulations as the 'length at first capture'. This is the minimum length from which an individual is considered an adult in the Argentine Patagonian toothfish fishery (SAGPyA Resolution 19/2002). In response to the alarming state of the stock, the national fisheries administration issued numerous administrative measures to create a regulatory framework to address and resolve the problem. These included innovative management tools, such as the creation of an Advisory Commission comprised of representatives from the industry, science, and fisheries administration, and more conventional measures, such as setting a maximum allowed percentage of juvenile Patagonian toothfish per haul and requiring vessels to move a certain distance if that percentage is exceeded (move-on rule), as well as the specification of hook size and shape for longline vessels, among others.

This article describes Argentina's efforts to regulate the Patagonian toothfish fishery, highlighting how the country addressed the concerning capture of juvenile specimens that threatened the fishery's long-term viability in the early 2000s. It was based on catch information obtained from official fishery statistics as well as data collected by on-board observers from the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP) Biological-Fishery and Environmental Information Acquisition Program. The aim was to compare the proportion of juvenile Patagonian toothfish in the total catch of the species over years. A total of 704 fishing trips conducted since 1993 by trawl and longline vessels with INIDEP scientific observers on board were examined. Patagonian toothfish catches were divided into 100-m depth intervals, up to and including those deeper than 800 m. Information regarding the development of the fishery was also analysed, particularly legal regulations issued by the Consejo Federal Pesquero (CFP) (https://cfp.gob.ar/actas-cfp/; https://cfp.gob.ar/resoluciones-cfp/) and resolutions and provisions issued by the Secretaría de Agricultura, Ganadería y Pesca and the Subsecretaría de Recursos Acuáticos y Pesca (https://www.boletinoficial.gob.ar/).

"In response to the alarming state of the stock, the national fisheries administration issued numerous administrative measures to create a regulatory framework to address and resolve the problem"

Selectivity in the Argentine Patagonian toothfish fishery

Since its beginning in the 1990s, the Patagonian toothfish fishery in the Argentine Sea has employed two different types of fishing gear: bottom trawl nets and bottom longlines. The fishery has evolved over time, with periods when one form of gear predominated over another (Table 1). At the beginning of the 2000s, nearly 90% of the trawler fleet's catches were immature specimens, while longliners had slightly more than 60%. This situation posed a threat to the sustainability of the fishery, given the species' biological characteristics, such as slow growth and large size and age at sexual maturity, which make it highly vulnerable to overfishing (Wöhler and Martínez 2002a; Martínez and Wöhler 2017). The large size (82 cm) at which half of the fish acheve reproductive maturity, made it difficult to implement a solution based on mesh size regulations to reduce juvenile catch by bottom trawlers. According to Ercoli (1995), despite the fact that the Patagonian toothfish's body is fusiform, a mesh size greater than 180 mm (current standard for demersal species in Argentine fisheries is 120 mm) is required to allow 50% of 85-cm-long fish to escape. This would also result in the total escape of other target species, including longtail hake (*Macruronus magellanicus*) and southern blue whiting (*Micromesistius australis*), making this solution unfeasible.

Bottom longlines yield a higher proportion of adult specimens than trawls (Martínez et al. 2001, 2002; Wöhler and Martínez 2002a) but did not entirely prevent the catch of juveniles. Patagonian toothfish have flattened heads and large mouths extending beyond the midpoint of the eye (Dewitt et al. 1990). These traits, particularly the size and shape of the mouth, enable even juveniles to ingest large prey and hooks. Prenski and Almeyda (1997) analysed stomach contents of Patagonian toothfish and found regulation-sized hooks in immature fish, which were likely ingested after escaping from longlines. As a result, longline selectivity tends to be limited and relatively ineffective, particularly for large-mouthed fish species (Lokkeborg and Bjordal 1992).

An analysis of both the trawl and longline fisheries revealed that reducing the proportion of juveniles through gear regulations was either operationally unfeasible or met with strong resistance from vessel crews. It was thus deemed a measure of limited effectiveness. However, aside from gear selectivity (retention), other key factors influence

Table 1. Patagonian toothfish catches (t) by gear type reported by the Argentine fleet during the period 1993-2024.

Year	Longline	Trawl	Year	Longline	Trawl
1993	547	3,805	2009	1,760	648
1994	6,969	7,049	2010	2,109	916
1995	14,465	3,760	2011	1,724	1,011
1996	11,878	3,033	2012	1,588	1,687
1997	6,655	2,150	2013	1,730	1,770
1998	7,730	3,155	2014	556	3,340
1999	5,181	4,456	2015	960	2,759
2000	3,737	5,697	2016	824	2,845
2001	2,625	3,704	2017	300	3,370
2002	2,046	6,146	2018	121	3,580
2003	1,514	4,180	2019	74	3,845
2004	765	1,334	2020	14	3,766
2005	883	373	2021	8	3,710
2006	612	474	2022	3	3,635
2007	945	436	2023	4	3,469
2008	1,120	768	2024	3	3,663

"Regulating fleet access to specific fractions of the population by establishing a minimum depth limit for targeted fishing has proven to be an easy-to-monitor management strategy that was well accepted by the fleet because it did not require additional costs or fishing gear modifications"

the proportion of fish effectively captured, such as the ability to locate fish (vulnerability) and the possibility of operating in fish-rich areas (accessibility). The latter played a particularly important role in fishery management.

Establishing a minimum permissible depth for target fishing

A potential solution to the problem of excessive juvenile Patagonian toothfish catches in the early 2000s was found in a particular biological trait of the species, which allowed the regulation of fishery selectivity through restrictions on fleet accessibility to the resource, thereby modifying the exploitation pattern. The species exhibits a spatially size-segregated distribution by depth (Cotrina 1981; Cassia and Perrotta 1996; Prenski and Almeyda 2000; Wöhler et al. 2001; Collins et al. 2010). Larger individuals inhabit depths of up to 2,500 m, whereas juveniles are mainly distributed on the shelf and upper slope, down to 600-800 m. Regulating fleet access to specific fractions of the population by establishing a minimum depth limit for targeted fishing has proven to be an easy-to-monitor management strategy that was well accepted by the fleet because it did not require additional costs or fishing gear modifications. To prevent excessive juvenile catch and ensure rational fishery management, measures were implemented in 2001 to limit the depth at which directed fishing for Patagonian toothfish may take place. The most effective regulation limited Patagonian toothfish fishing (by bottom trawl or longline) to depths greater than 800 m south of 54° S and more than 1,000 m north of that latitude (SAGPyA Resolution 68/2001). Additionally, a series of complementary measures and actions were established to effectively minimize the presence of immature specimens in catches while protecting the integrity of the fishery.

Additional measures aimed at effectively limiting the capture of juvenile Patagonian toothfish

Limiting the proportion of incidental catch. Definition of a fishing trip targeting the species

One of the first management measures established by the Argentine fisheries administration to regulate the fishery was to define when a fishing trip was considered as targeting the species. In the early 2000s, some fishing trips conducted by trawlers were identified as targeting Patagonian toothfish, even though the primary objective of these trips was to capture other species present in the area, such as longtail hake (*M. magellanicus*) or southern blue whiting (*M. australis*). Throughout the history of the Patagonian toothfish fishery, the amount of incidental catch, i.e. not targeted, relative to total catch has been debated and modified (Martínez and Wöhler 2005). Initially, the maximum allowable percentage of Patagonian toothfish catch per fishing trip that may be considered incidental was set at 3% of the total catch (SAGPyA Resolution 19/2002). This value was later reduced to 1.5% (CFP Resolution 21/2012). This percentage was significantly lower than standards generally established in other fisheries in the Argentine Sea (10%). The difference is mainly due to the notable hold capacity of factory-freezer and surimi vessels involved in southern fish fisheries, as well as the fact that catches of Patagonian toothfish by these fleets, which originate from hauls targeting other species and are conducted at depths shal-

lower than 800 m, contain a high proportion of juvenile fish. In 2023, existing regulations were complemented by a restriction stating that the catch of Patagonian toothfish in non-targeted operations and by vessels without Individual and Transferable Catch Quota (ITQ) cannot exceed 1.5% of the total catch or 5 t of the species per trip, whichever is less (CFP Resolution 9/2023).

Establishing the Juvenile Patagonian Toothfish Protection Area (APJMN)

The national fisheries authority established the Juvenile Patagonian Toothfish Protection Area (APJMN) in the main juvenile concentration zone and fishing ground for the species, which constituted another key element in the development of the fishery (Wöhler and Martínez 2002a). Initially, the APJMN consisted of two 1° latitude by 1° longitude grid squares, with a third grid added a year later (CFP Resolution 20/2003) (Figure 1). Once directed fishing was defined and limited, the establishment of a special care area for juveniles led to the implementation of a series of measures aimed primarily at minimizing the presence of immature fish in catches. Although it does not have the same characteristics as a fishing closure (since fishing activity is still allowed), certain requirements must be met to operate within it, which will be detailed later.

Establishing a maximum allowed percentage of juvenile specimens in catches

Another measure implemented by fishery authorities to reduce the presence of juvenile Patagonian toothfish in catches was the establishment of a maximum allowable percentage of juveniles in the total catch during fishing trips targeting the species. In 2002, it was decided that the proportion of juveniles in fishing trips targeting Patagonian toothfish should not exceed 15% of the total number of individuals caught (SAGPyA Resolution 19/2002). However, because this threshold was set in a very different fishery context than what exists today, it was recently revised. The previous limit was considered overly restrictive, requiring a large propor-

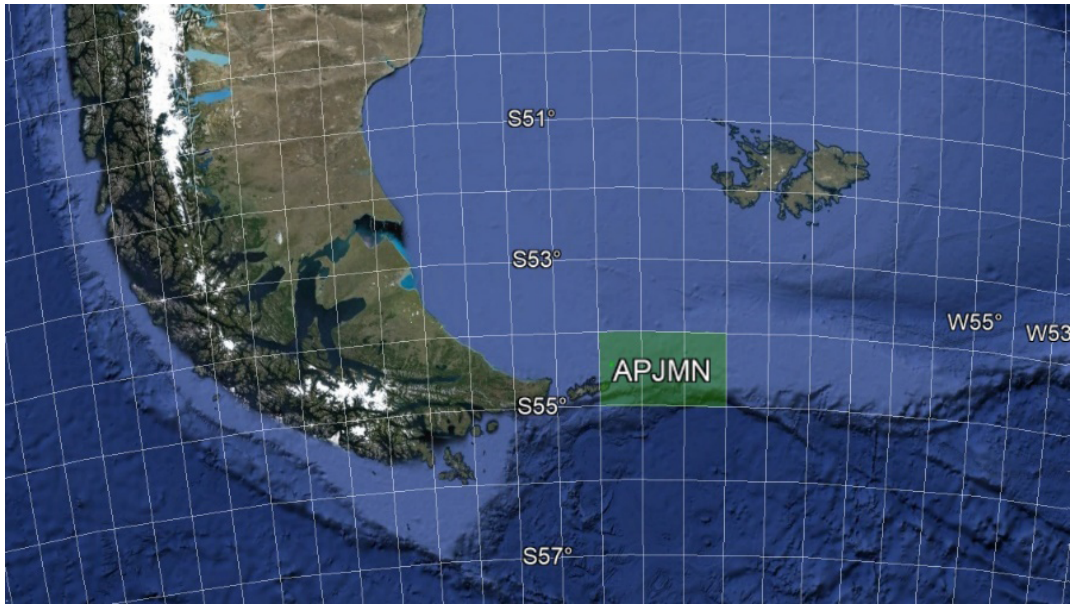

Figure 1. Juvenile Patagonian Toothfish Protection Area (APJMN) initially established by SAGPyA Resolution 19/2002 and expanded by CFP Resolution 20/2003.

tion of adult fish to cover the quota (Martínez et al. 2019). Consequently, in 2019, the allowable limit was increased to 20% for the proportion of juveniles in catch (Table 2) (CFP Resolution 12/2019).

Control of landings

The establishment the Advisory Commission for the Monitoring of Patagonian Toothfish Fishing Activity (CASPMeN) (SSP Provision 18/2002; SSPyA Provision 15/2023) marked a key milestone in the history of the Patagonian toothfish fishery. The commission, comprised of representatives from industry, science, and fisheries administration, introduced a collaborative and participatory approach to fisheries management. As an advisory body, CASPMeN's primary role is to provide recommendations for the development of the fishery and propose new regulations or modifications to existing ones, with the goal of improving management efficiency. This platform has proven to be highly effective, positively impacting the long-term sustainability and governance of the fishery. At the same time, the Mixed Sub-commission for Landing Control (SCMD) was established, which was a novel mechanism in the context of Argentine fisheries (SSP Provision 18/2002). The major goal of the group, which includes fisheries administration inspectors and representatives from participating companies (serving as observers), is to verify landings, including total catches and the proportion of juveniles. The effectiveness of this sub-commission lies in its specific procedures, which includes a mandatory 72-h advance notification of port arrival for all vessels landing Patagonian toothfish, as well as dockside monitoring with the presence of representatives from competing companies. To ensure transparent and accountable monitoring of landings, official landing reports were introduced, co-signed by regulatory inspectors and company observers. In addition to routine inspections, this cross-check system encouraged a culture of self-regulation among companies, as failure to comply could be noticed by competitors, creating a strong incentive for compliance.

Estimating conversion factors for trunks and fillets to monitor landings

One of the initial challenges for SMCD inspectors was that Patagonian toothfish are generally landed already processed, primarily as trunks (headed and gutted, HG). This made it difficult to verify compliance with minimum landing lengths and juvenile proportion limits. To address this, Wöhler and Martínez (2002b) conducted an

Table 2. Percentage of total and per gear type of immature fish from 2000 to 2023.

Year	2000	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Total	87	37	38	32	28	16	13	12	9	3	16
Trawl	87	44	57	71	45	20	2	13	10	1	16
Longline	61	17	17	10	18	12	13	12	8	7	12
Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Total	6	11	9	15	25	14	12	17	9	13	12
Trawl	12	12	8	15	25	14	12	17	9	13	12
Longline	6	10	10	15	0.8	-	13	13	5	-	5

"As an advisory body, CASPMeN's primary role is to provide recommendations for the development of the fishery and propose new regulations or modifications to existing ones, with the goal of improving management efficiency"

analysis to correlate trunk length with total length. Results showed that the trunk represents approximately 52-53% of the total length of whole fish between 45-105 cm total length (TL). Based on this, a minimum trunk length of 43 cm was legally established, corresponding to a whole fish of at least 82 cm TL (SSPyA Provision 597/2004; SSPyA Provision 15/2023). Additionally, correlations were established between total length and the base lengths of the second dorsal and second anal fins, which were incorporated into regulations as alternative methods to indirectly determine total fish length at the time of landing (Martínez 2003). More recently, as some vessels began landing Patagonian toothfish as fillets processed onboard, the weight of each fillet was estimated relative to the fish's total length (Troccoli et al. 2020). According to this analysis, the average minimum weight of a skin-on fillet corresponding to a fish measuring at least 82 cm TL is 1.27 kg, whereas a skinless fillet is 1.16 kg. The same study showed no statistically significant difference between fresh and frozen fillet weights.

Determining regulatory hook type for Patagonian toothfish fishing

Bottom longline fishing for Patagonian toothfish enables a more selective harvest because it targets the species specifically and provides access to seafloor areas not suitable for trawling, such as deeper submarine canyons where large adult specimens dwell (Cotrina 1981; Cassia and Perrotta 1996; Prenski and Almeyda 2000). As previously noted, the species' largemouth allows it to consume large prey items, including juveniles. However, considering that hook size could influence selectivity toward smaller individuals, Prenski (2000) recommended using hooks with a 4 cm gape. He also advocated for circular hooks, which are considered more effective in retaining the catch. As a result, in 2002, regulations were introduced specifying the size and type of hooks permitted in longlines targeting Patagonian toothfish (SAGPyA Resolution 19/2002). Hooks must be round in shape, with a minimum gape of 4 cm (Wöhler and Martínez 2002b).

Impact of the new management and control scheme

The primary effect, mainly resulting from the implementation of the minimum depth restriction for fishing operations and the strategy aimed at minimizing juvenile catch, was almost immediate. In subsequent years, juvenile catch gradually decreased until it stabilized at or below the authorized level. The initial conflict surrounding the implementation of the measure also progressively diminished, leading to a decrease in sanctions for noncompliance. As mentioned earlier, in 2000, the length distribution of fish caught by trawling indicated that nearly 90% of the individuals captured were under 82 cm TL and therefore could be considered juveniles (Martínez et al. 2001). During the 2003-2006 period, although the proportion of juveniles remained high, it showed a decreasing trend in both trawl and bottom longline fisheries (Martínez et al. 2023a) (Table 3). It is worth noting that during 2000-2003, the INIDEP Biological-Fishery and Environmental Information Acquisition Program was not operating as it is today. The funds available at that time were insufficient to cover the entire fleet and collect reliable biolog-

Table 3. Percentages of Patagonian toothfish catches by year and depth (m). Higher values for each year are highlighted. Period: 1993-2023.

Depth (m)	1993	1994	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
< 100	0.00	0.00	3.20	0.00	0.05	1.14	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
100-199	0.00	0.00	1.02	0.17	3.80	3.51	0.06	0.53	0.78	0.19	0.27	0.06	0.16	0.36
200-299	0.00	0.08	5.64	3.75	1.93	6.15	3.08	3.52	3.55	3.94	1.48	1.70	2.62	4.34
300-399	100.00	0.17	19.12	6.69	16.28	1.04	0.78	1.20	3.84	13.70	5.01	4.06	4.92	6.74
400-499	0.00	0.17	65.55	87.64	73.81	4.88	3.05	1.43	2.10	31.26	5.22	0.72	10.05	20.06
500-599	0.00	0.04	5.47	1.74	1.11	27.56	4.79	1.33	2.53	0.17	0.46	0.04	4.14	8.17
600-699	0.00	45.55	0.00	0.00	3.02	54.66	80.47	3.30	0.70	0.00	0.04	0.00	4.65	27.01
700-799	0.00	48.99	0.00	0.00	0.00	0.00	0.34	1.68	0.86	0.00	3.20	0.00	2.24	5.60
> 800	0.00	4.99	0.00	0.00	0.00	1.07	7.44	87.00	85.63	50.74	84.31	93.41	71.22	27.72

Depth (m)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
< 100	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00
100-199	0.12	0.25	0.03	0.01	0.02	0.10	0.00	0.06	0.03	0.04	0.01	0.01	0.00	0.01
200-299	0.82	1.45	0.65	0.05	0.15	0.40	0.17	0.69	0.69	0.28	0.13	0.13	0.09	0.38
300-399	2.54	4.21	0.78	0.19	0.51	0.55	0.33	1.17	1.50	0.22	0.07	0.07	0.20	0.23
400-499	8.62	8.49	1.00	0.21	0.24	0.40	0.40	0.48	0.81	0.22	0.11	0.03	0.07	0.52
500-599	3.44	2.08	2.40	0.07	0.13	0.52	0.86	1.53	0.68	0.90	0.96	0.19	0.05	0.04
600-699	0.24	0.17	1.82	0.03	0.01	0.57	0.93	5.10	2.37	1.99	2.07	3.43	1.40	0.20
700-799	0.00	0.10	1.32	0.00	0.10	0.00	0.20	3.17	6.76	28.82	1.30	12.32	2.95	0.05
> 800	84.21	83.25	92.01	99.45	98.85	97.46	97.10	87.8	87.16	67.53	95.34	83.77	95.24	98.57

ical-fishery data. However, beginning in 2003, the deployment of observers became mandatory for the fleet targeting Patagonian toothfish. Additionally, a minimum fishing depth of 800 m was officially established (Resolution SAGPyA 19/2002). In the following years and up to the present, the proportion of juveniles in has decreased progressively and significantly in the catch, generally remaining well below the allowable annual average values (15% or 20%) established in current regulations.

Patagonian toothfish catches were examined by depth to evaluate whether the decrease in juvenile catch was primarily due to effective enforcement of the target species' minimum fishing depth limit. Nine depth strata were considered, ranging from less than 100 m to more than 800 m (Table 3). It was observed that, at the beginning of the analysed period, most catches occurred at depths of 300-500 m, and therefore contained high percentages of immature specimens, as confirmed by the length frequency distributions of those years (Figure 2). Since 2003, most catches occurred at depths greater than 800 m, coinciding with the establishment of the minimum fishing depth for targeting Patagonian toothfish. As a result, the catches were largely composed of adult specimens (Table 3; Figure 2).

Proportion of juveniles in Patagonian toothfish catches in other fisheries

The genuine concern for minimizing the capture of juvenile Patagonian toothfish in the Argentine

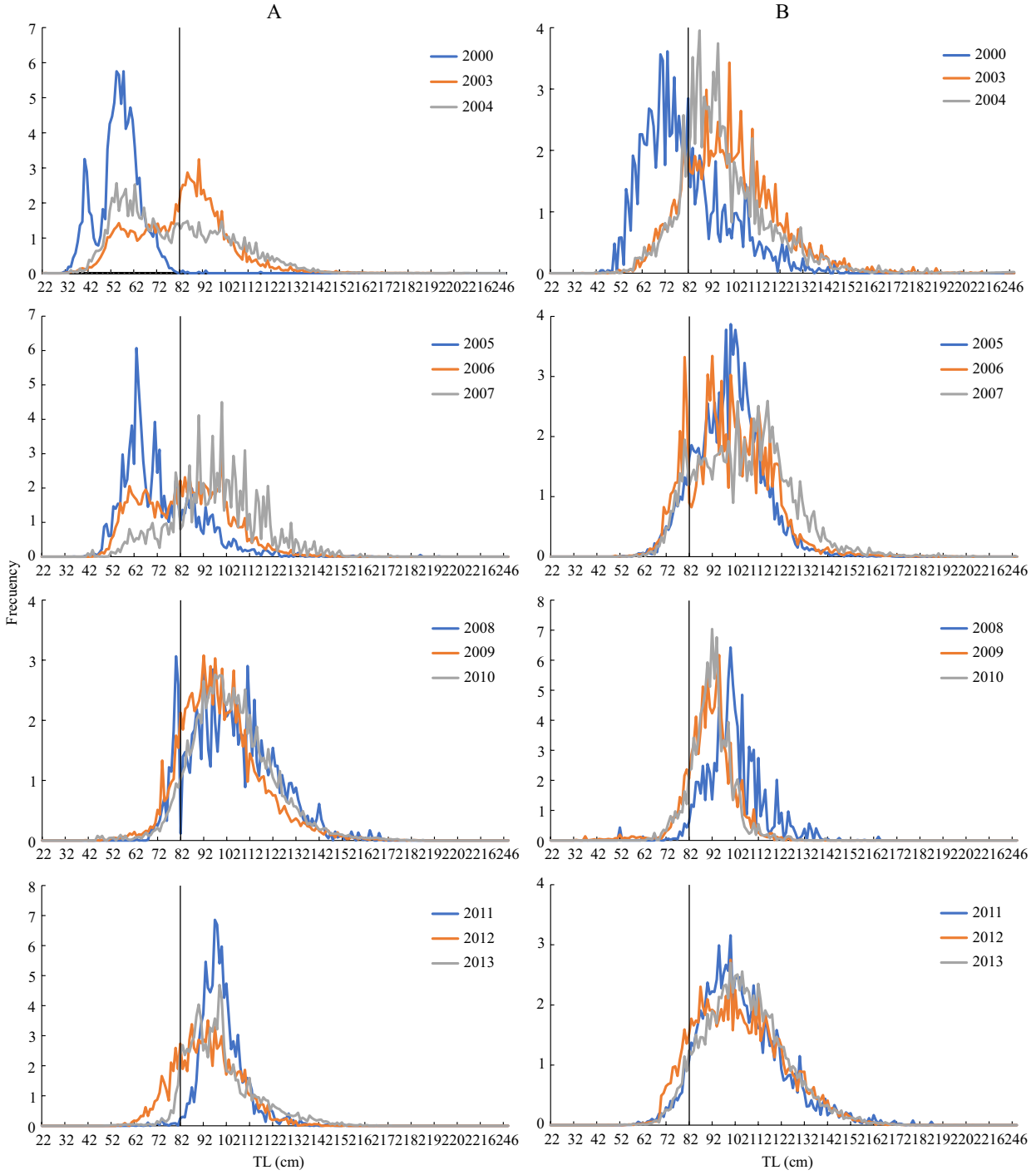

Figure 2. Frequency distributions of Patagonian toothfish lengths weighted by total catch by the trawl fleet (A) and longline fleet (B). Years 2000 and 2003-2023. The vertical line indicates the minimum catch length established by regulations based on the species' length at first sexual maturity (TL50%: 82 cm).

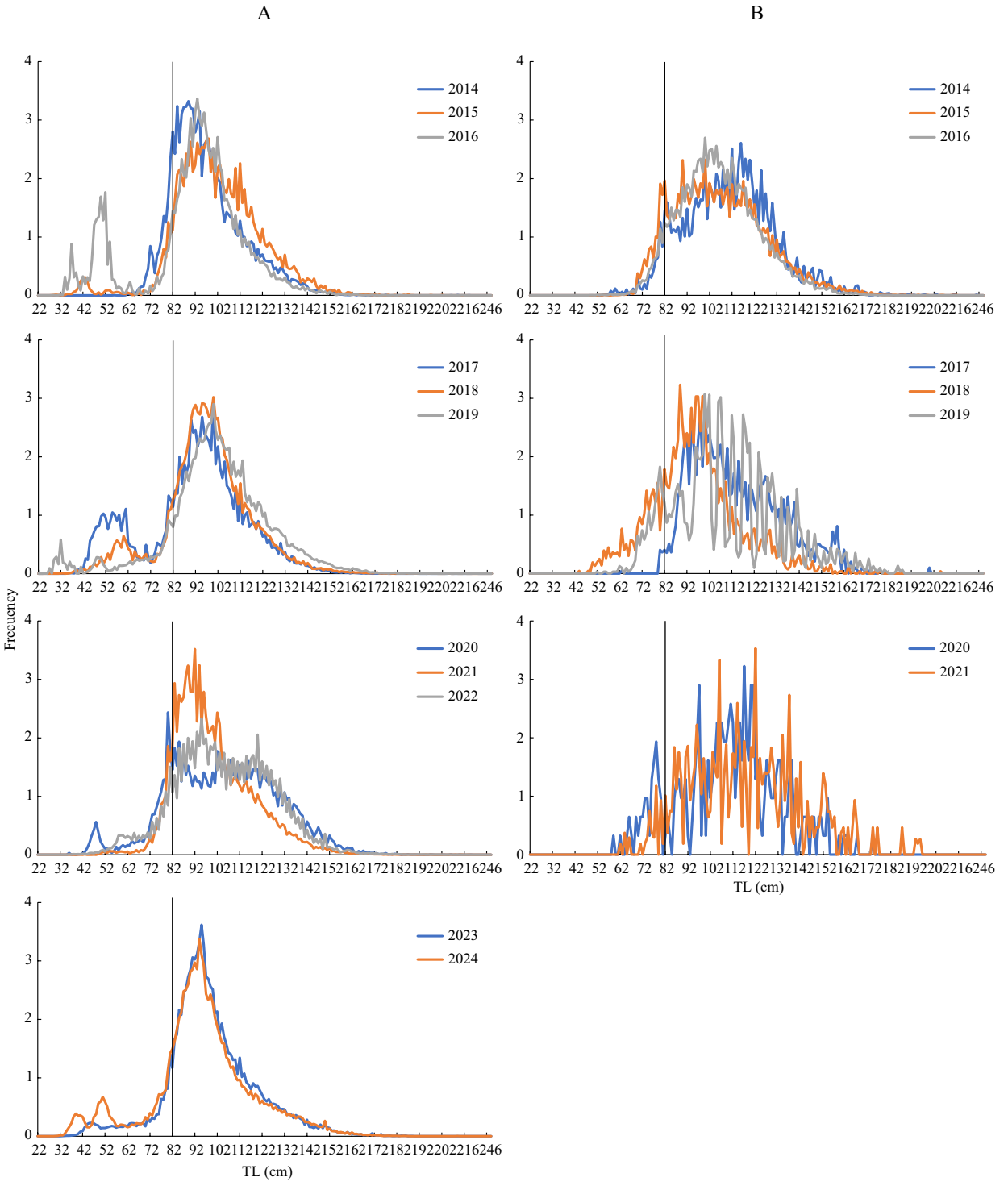

Figure 2. Continued.

fishery, given its potential impact on the health of the stock, has not been mirrored in nearby fisheries. In Chile, the industrial fleet catches a similar proportion to the Argentine fleet (Céspedes et al. 2019). However, there is currently a very high proportion of juveniles being caught in the artisanal fishery operating north of 47° S (CCT-RDAP 2020; SPA 2023), even when considering the lower estimated length at first maturity for both sexes (Arana 2009, 85 cm TL) (Figure 3). Nonetheless, other estimates suggest that the length at first sexual maturity for females in the Chilean Pacific could be considerably higher, up to 128.7 cm TL (Moreno et al. 1997; Young et al. 1999; Oyarzún et al. 2003).

In the fishery operating around the Malvinas Islands, high proportions of juveniles in the catch are also regularly recorded, with annual total catch exceeding 500 t (trawl + longline), depending on the contribution of bycatch to the total catch of the species (Figure 4). In this case, the estimated age at maturity is relatively similar to those made for the rest of the Argentine Patagonian shelf. Since the by-

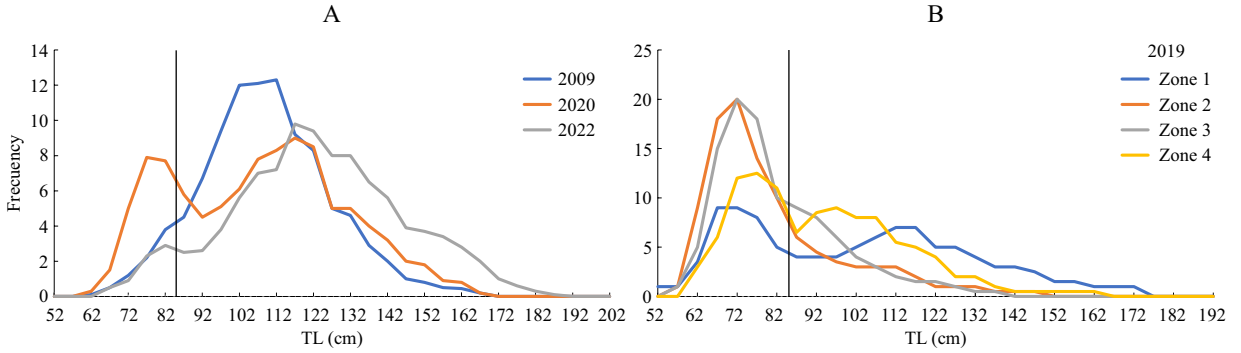

Figure 3. Length frequency distributions of Patagonian toothfish caught by industrial (A) and artisanal (B) longline fleets in the Chilean Patagonian toothfish fishery. Adapted from Céspedes et al. (2019), CCT-RDAP (2022) (industrial longline fleet) and CCT-RDAP (2020) (artisanal longline fleet). Zone 1: north of the 30° S, Zone 2: 30° 01′ S-41° S, Zone 3: 41° 01′ S-47° S, Zone 4: 47° 01′ S-57° S. The bar indicates the estimated length at maturity for the species in Chile (85 cm TL for both sexes combined).

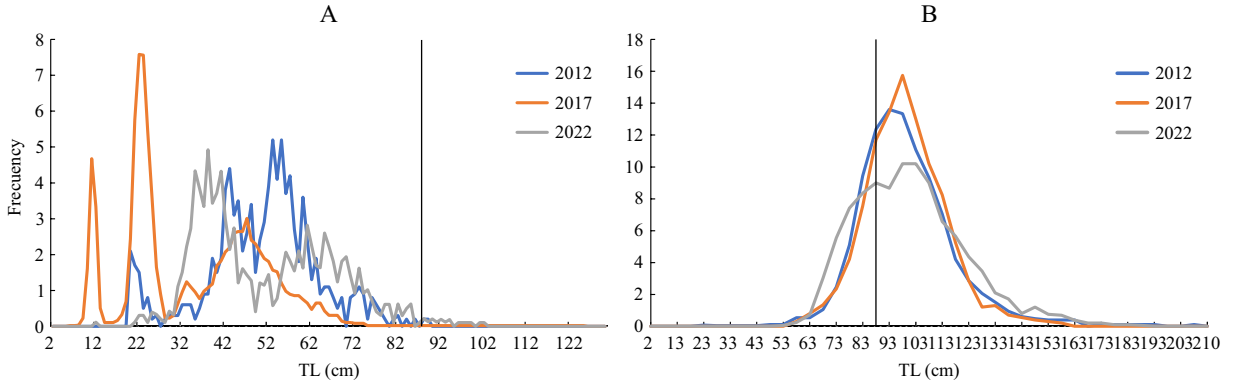

Figure 4. Length frequency distributions of Patagonian toothfish obtained by trawl (A) and longline (B) fleets operating around Malvinas Islands. Adapted from FIFD (2013, 2018, 2023). Vertical lines indicate the estimated length at first maturity (88 cm TL) for both sexes combined based on macroscopic observations reported by Laptikhovsky and Brickle (2005), for the purpose of comparison with the estimates by Prenski and Almeyda (2000) and Arana (2009) for the Patagonian shelf from the Atlantic and Pacific oceans, respectively.

catch consists almost entirely of juvenile specimens, and its share in the total catch of the species often reaches up to 35% of all individuals caught, the addition of juveniles caught by longline can bring the total proportion of juveniles in the catch to 40% or more by weight (FIFD 2013, 2018, 2023). This analysis is based on maturity lengths reported by Laptikhovsky and Brickle (2005), based on macroscopic observations -86 cm for males and 90 cm for females- although Boucher (2018) indicates that the length at maturity for females, based on microscopic analyses, would be 79.1 cm.

There is no specific conservation measure in place to reduce the prevalence of juveniles in Patagonian toothfish fisheries controlled by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Although a high proportion of juveniles in the catches is acknowledged, it has been noted that the CCAMLR's management approach takes the maturation stage into consideration (SC-CAMLR 2019, paragraphs 3.61 to 3.65; SC-CAMLR 2021, paragraph 3.29). However, in some fisheries that have been awarded the sustainability certification by the Marine Stewardship Council (MSC), or are pursuing it, management measures with an indirect positive effect on toothfish populations have been implemented. This is the case of the fishery around South Georgia Islands (CCAMLR Subarea 48.3), where since 2013, a set of management tools designed to protect the ecosystem more broadly has been in place. At the same time, the sustainable use of fisheries is promoted, such as restricting longline operations to depths between 700 m and 2,250 m (CCAMLR 2022).

"There is no specific conservation measure in place to reduce the prevalence of juveniles in Patagonian toothfish fisheries controlled by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)"

The frequency distribution of length of catches from the fishery operating around the South Georgia Islands and Aurora Islets (Shag and Black Rocks) indicates that most of the individuals caught would correspond to juveniles ($TL_{50\%}$: 92.5 cm, based on the average lengths of sexual maturity reported by Agnew et al. (1999) -75 cm for males and 110 cm for females) (Figure 5). These values are largely consistent with a comprehensive review of maturity estimates conducted by CCAMLR for Subarea 48.3, using data from 1996 to 2018, resulting in $LT_{50\%}$ values ranging from 68.8 to 78.8 cm TL for males and 96.7 to 106.1 cm TL for females.

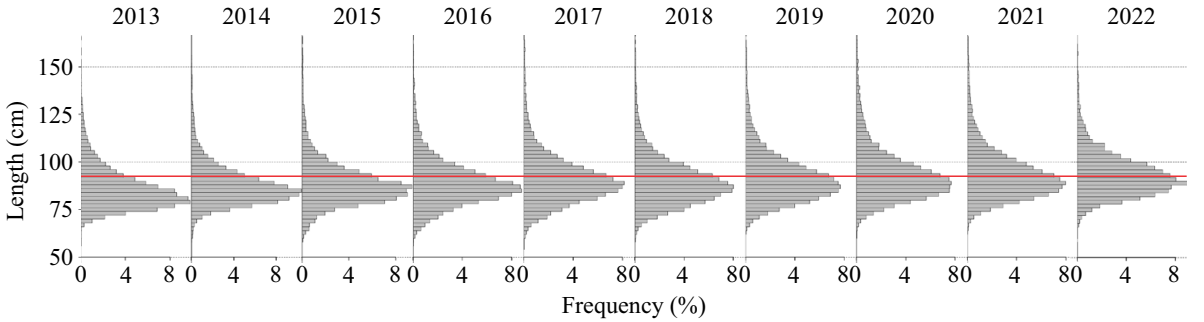

Figure 5. Annual total length frequency distributions of Patagonian toothfish catches in CCAMLR Subarea 48.3 (South Georgia Islands and Aurora Islets (Shag and Black Rocks)). The red line indicates the reference length at sexual maturity, determined as the average for males and females in this area (92.5 cm TL) derived from Agnew et al. (1999). Adapted from CCAMLR (2023a, 2024).

In the case of the Kerguelen Islands (France's EEZ, Division 58.5.1, CCAMLR), a six-year management plan was adopted in 2019 with the general objective of ensuring optimal and sustainable exploitation conditions for Patagonian toothfish. To minimize the capture of immature individuals, several conservation and fisheries management measures have been implemented, such as the 'move-on rule', which requires vessels to relocate 5 nm for a minimum of 5 days if Patagonian toothfish under 60 cm TL are caught in any haul (CCAMLR 2023b). Despite this, considering the estimated lengths at sexual maturity reported by Lord et al. (2006) for the region (63 cm TL for males and 85 cm TL for females), a significant number of juveniles are caught annually in the fishery, reaching values close to 40% each year (Figure 6).

Fish are caught by bottom trawling and longlining in the Patagonian toothfish fishery operating in the Heard and McDonald Islands and the Kerguelen Plateau (CCAMLR Division 58.5.2), which covers depths ranging from shallow waters to nearly 3,000 m. In general, the trawl fishery captures smaller specimens (Figure 7), consisting almost entirely of juveniles, while bottom longlining yields larger fish with approximately 60% to 70% being adults (Figure 8). Despite the existence of a trawl fishery, no measures have been established to minimize juvenile catch, such as those implemented in Argentina (CCAMLR 2023c).

The Patagonian toothfish fishery around the Crozet Islands (France's EEZ-Subarea 58.6),

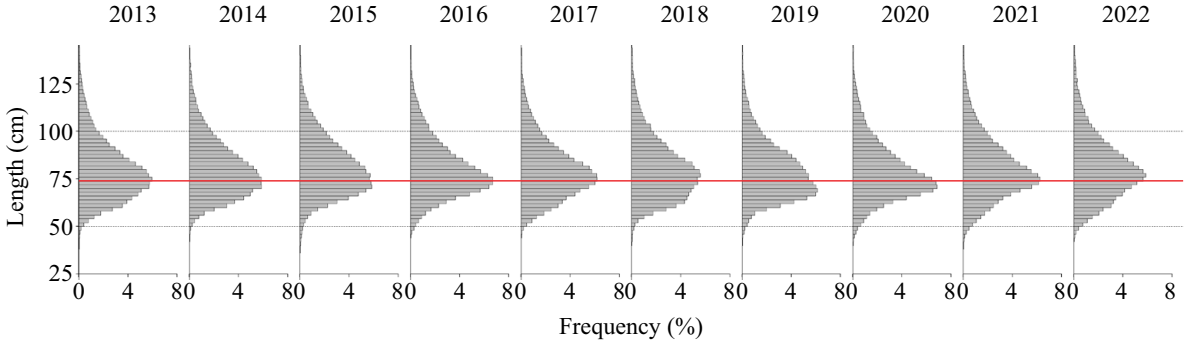

Figure 6. Annual length frequency distributions of Patagonian toothfish caught by longline in CCAMLR Division 58.5.1 (Kerguelen Islands). The red line indicates the reference length at first sexual maturity, determined as the average for males and females in this area (74 cm TL) (Lord et al. 2006). Adapted from CCAMLR (2023b).

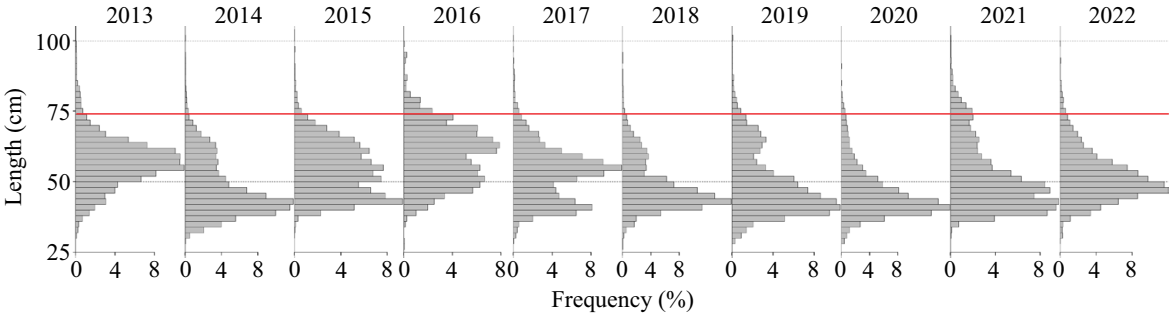

Figure 7. Annual length frequency distributions of Patagonian toothfish caught with bottom trawl nets in the fishery of the Heard and McDonald Islands and the Kerguelen Plateau (CCAMLR Division 58.5.2). The red line indicates the reference length at first sexual maturity, determined as the average for males and females in this area (74 cm TL) (Lord et al. 2006). Adapted from CCAMLR (2023c).

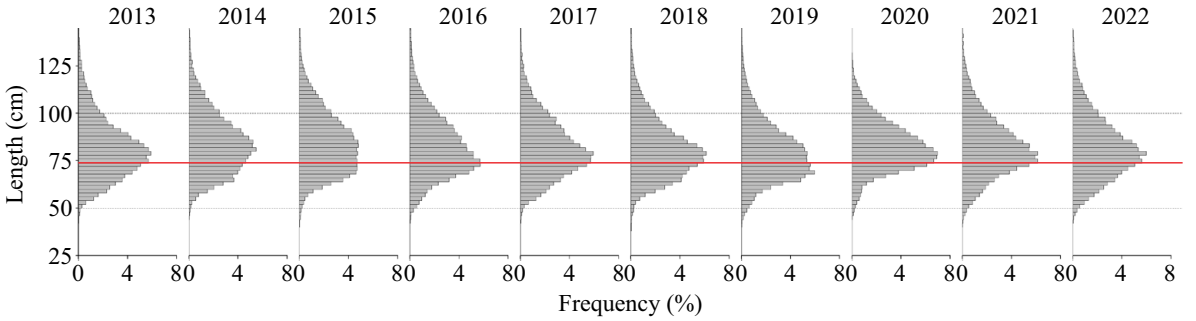

Figure 8. Annual length frequency distributions of Patagonian toothfish caught with bottom longlines in the fishery of the Heard and McDonald Islands and the Kerguelen Plateau (CCAMLR Division 58.5.2). The red line indicates the reference length at first sexual maturity, determined as the average for males and females in this area (74 cm TL) (Lord et al. 2006). Adapted from CCAMLR (2023c).

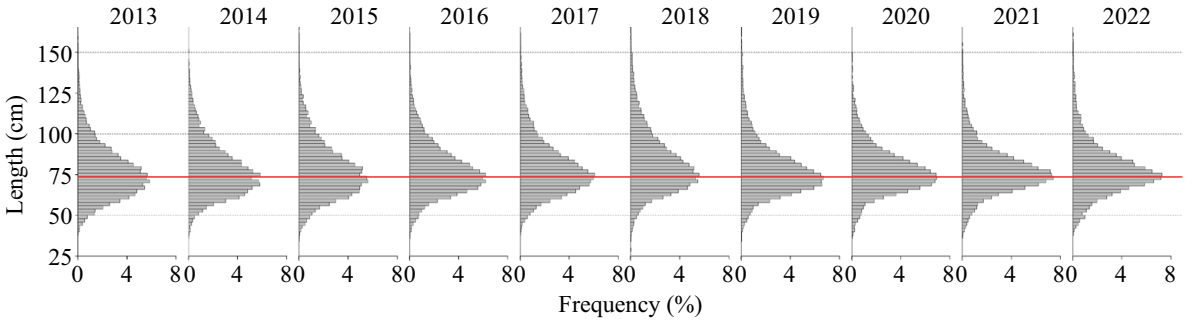

Figure 9. Annual length frequency distributions of Patagonian toothfish caught with bottom longlines in the fishery around the Crozet Islands (CCAMLR Subarea 58.6). The red line indicates the reference length at first sexual maturity, determined as the average for males and females (74 cm TL). There were no TL50% values available for this area, so estimates by Lord (2006) were assumed as it is geographically the closest. Adapted from CCAMLR (2023d).

which reports annual catches of around 700-800 t, prohibits catching specimens smaller than 60 cm TL. As in the Kerguelen Islands, this involves the previously mentioned 'move-on' rule (CCAMLR 2023d). However, the capture of juveniles remains significant, accounting for between 40% and 50% of the total catch (Figure 9).

One of the most widespread CCAMLR measures aimed at protecting juvenile Patagonian toothfish (the so called 'move-on' rule) has proven to be ineffective in reducing the capture of immature fish, both in the Argentine fishery and in other fisheries where it is mandatory (Crozet and Kerguelen Islands). Similarly, the prohibition of targeted Patagonian toothfish fishing in exploratory fisheries at depths shallower than 550 m (CCAMLR 2009) does not prevent juvenile catches in commercial fisheries. This measure is primarily intended to protect benthic communities, not juvenile toothfish.

Fishing activity often has various effects on the structural components of a population, with the juvenile fraction being particularly vulnerable in many fisheries. This vulnerability arises from a combination of biological and operational factors: juveniles typically inhabit coastal or shallow areas where fishing pressure is high, and fishing gear with low selectivity, such as bottom trawls, tends to capture individuals of all sizes, including those that have not yet reached sexual maturity, unless restrictions are in place. Excessive juvenile catch can severely compromise population performance by reducing effective recruitment rates,

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disrupting age structure, diminishing resilience to environmental disturbances, and impacting future exploitation. Therefore, the protection of juveniles plays a key role in fisheries management. The use of fishing gears or methods that ensure selectivity –retaining larger fish while allowing juveniles to escape– tends to support sustainable exploitation (Armstrong et al. 1990). Fish stocks are generally more resilient to intensive fishing pressure when juveniles are protected (Vasilakopoulos et al. 2012).

Typically, fisheries management measures to avoid excessive juvenile catch include mandating the use of selective gear (with specific retention or selectivity rates), restricting access through closed areas or seasons (geographical areas or fishing periods where access is prohibited or limited), or implementing specific move-on rules. In Argentina, the excessive presence of juveniles in catches has generally been addressed through the development of selective devices incorporated into the net or modifications to its design or panels. In the hake (*Merluccius hubbsi*) fishery, for example, devices aimed at minimizing juvenile bycatch include metal grids or flexible grids inserted in the gear, or changes in mesh type (square or diamond) in the upper panel of the trawl (Larsen and Isaksen 1993; Ehrhardt et al. 1996; Erikson et al. 1996; Ercoli et al. 1998; Roth et al. 2022). However, none of these have been widely and consistently adopted by the fleet. On the contrary, their use has been questioned for a variety of reasons, including difficulties in onboard implementation, limitations during handling procedures and catch operations, net clogging with mud, and even safety concerns (Roth and Rubio 2021). Additionally, using any of these devices reduces catches and thus economic losses, which is why the extractive sector avoids them. Furthermore, fisheries authorities frequently implement these restrictions unilaterally, without sufficient consultation or consensus among stakeholders, resulting in resistance and difficulty in practical enforcement (Roth 2019; Roth and Pisano 2020; Roth et al. 2022). In contrast, in the case of the Argentine Patagonian toothfish fishery, we believe that the success in rapidly reducing juvenile catch was mainly due to an innovative real-time dynamic fishery management approach, implemented in the early 2000s, in which administrators, industry stakeholders, and scientists worked collaboratively. The set of measures designed and agreed upon to reduce juvenile proportions in catches proved effective in this synergistic context, where collaborative action yielded greater results than individual efforts. The main measure consisted of allowing a maximum of 15% juvenile proportion in landings, monitored through the SCMD and associated monitoring tools. The implementation of a bycatch threshold significantly lower than in other fisheries forced vessels to focus their efforts on the adult fraction of the population. In most cases, the catch of immature individuals was minimal and unavoidable, accompanying other southern species in shallower waters.

CONCLUSIONS

Based on the analysis conducted, it is evident that the Argentine Patagonian toothfish fishery is among the most strongly regulated in terms of ju-

"Accordingly, the impact of fishing on the juvenile fraction of Patagonian toothfish in the Southwest Atlantic is a key concern for the sustainability of this high-value fishery"

venile protection, not only compared to other domestic fisheries but also compared to Patagonian toothfish fisheries in other parts of the world. As we have seen, Argentina's regulations specifically aim to limit the capture of immature fish, thereby increasing the likelihood that adults contribute to the reproductive stock. These regulations are far more restrictive and effective than those implemented in other regions.

As a result of this pragmatic approach, the proportion of juveniles in the Argentine fleet's catches has averaged only 12.2% every year over the last 15 years, even though most of them were caught by trawling. In contrast, the lack of effective measures specifically targeting juvenile Patagonian toothfish in various fisheries, both within and outside of CCAMLR, has certainly contributed to annual juvenile catches ranging from 30% to 50%. In general, CCAMLR-managed fisheries lack specific measures to prevent or minimize juvenile catches. The 'move-on' rule, which specifies how far vessels must travel (or how long they must wait) before returning to a certain area, is a widely used method to reduce juvenile bycatch or non-target species. Unfortunately, no empirical approaches exist to determine effective move-on distances or waiting times for reducing juvenile Patagonian toothfish catches. Instead, move-on rules in CCAMLR appear to be based on borrowed values from other fisheries (Dunn et al. 2015), therefore their effectiveness remains uncertain.

The increasing number of immature fish in South Georgia Islands fishery catches has drawn special attention from CCAMLR since 2021, when Russia warned that the repeated removal of juveniles under 100 cm by the longline fleet could negatively affect the fishery's sustainability. Russia even recommended suspending fishing to prevent the excessive removal of juveniles (SC-CAMLR 2019, paragraph 3.63). This issue led to a lack of consensus regarding the setting of annual quotas for Patagonian toothfish in Subarea 48.3 of CCAMLR (SC-CAMLR 2021) since that year. Special attention should also be paid to bottom trawl fisheries around Malvinas Islands and the Heard, McDonald, and Kerguelen Plateau. In the former, juvenile Patagonian toothfish catches (Figure 4) averaged approximately 210 t between 2013 and 2022 (FIFD 2023), but peaked at nearly 490 t in some years, accounting for up to one-third of total catches. In the latter, bottom trawl fisheries in Division 58.5.2 of CCAMLR are also characterized by very high juvenile proportions –over 90% (Figure 7)– with average catches around 150 t annually during the survey period (2013-2022), though showing a clear downward trend in recent years (CCAMLR 2023c). To minimize juvenile catch and promote the sustainability of both fisheries, specific measures could be implemented.

From a fishery yield perspective, juvenile catch represents a loss in growth and reproductive potential. A fundamental concept in exploited population dynamics (yield per recruit) can be severely affected when individuals are removed before reaching reproductive age. The classic Beverton and Holt (1957) model predicts an optimal capture size that maximizes yield per recruit, and removing individuals below this threshold substantially reduces the stock's potential yield. In populations facing high fishing mortality from early ages, the spawning biomass may be compromised, which reduces future recruitment and leads to recruitment overfishing and potentially dangerous abundance declines (Myers and Mertz 1998). However, capturing immature fish does not always threaten the sustainability of a resource or fishery, as it largely

depends on the level of fishing pressure. Nevertheless, it is always advisable for fish to reproduce at least once before being harvested. Therefore, minimizing juvenile catch in long-lived, slow-growing, and relatively low-fecundity species, such as Patagonian toothfish, is always recommended. Juvenile protection not only conserves reproductive potential but also allows for somatic growth, increasing average weight at capture and thereby improving economic yield.

Finally, the impact of fishing on the juvenile fraction of a population is a critical factor for both resource sustainability and fishery yield. Implementing management measures aimed at juvenile protection is thus a fundamental strategy for achieving more sustainable and productive fisheries. Accordingly, the impact of fishing on the juvenile fraction of Patagonian toothfish in the Southwest Atlantic is a key concern for the sustainability of this high-value fishery. The practical implementation of measures to reduce juvenile mortality, within a precautionary and ecosystem-based approach, is essential for ensuring the long-term productivity and sustainability of the resource and its fishery.

INIDEP contribution no 2483.

Author contributions. Otto C. Wöhler: conceptualization; investigation; project administration; writing-original draft. Patricia A. Martínez: conceptualization; investigation; writing- original draft and editing. Gonzalo H. Troccoli: investigation; data curation; visualization; writing-review and editing. Germán Lukaszewicz: investigation; data curation; visualization; writing-review and editing. Emiliano J. Di Marco: investigation; data curation; visualization.

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