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Shrimp up, fish down, and vice-versa: Fishers' strategies and long-term changes in small-scale fisheries landings at two spatial levels in Southern Brazil

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ABSTRACT

Fisheries are complex adaptive systems, requiring due consideration of temporal and spatial scales for their understanding and management. In this study, seemingly contrasting long-term fish and shrimp production trends at two spatial levels prompted us to analyze 50 years of small-scale fisheries landing data in Southern Brazil. We applied time-series analyses and mixed-effect models to identify interannual fishing trends at the regional and local levels. Results confirmed an overall decrease in fish landings and an increase in shrimp landings at the regional level. However, a contrasting trend was observed at the local level, with fish landings increasing while shrimp landings decreased. Such patterns suggest that fishers responded differently to the constant changes in the institutional environment. Therefore, in order to identify and discuss possible drivers of change, other than stock availability, we reviewed the literature and institutional documents (laws, government programs, etc.) as well as qualitative information from almost 30 years of research on the local and regional fisheries. The following drivers were found: technical change and innovation; changes in legal restrictions to fishing and resource protection; asymmetrical access and use of government incentives, particularly financial credit, to foster the fish supply chain; market conditions; and local culture and ecological knowledge. The analysis stresses the importance of a more comprehensive, interdisciplinary approach to fisheries science and management. Fishing landings data integrated to human dimensions of fishing (e.g., social organization, laws, and institutions) provide a better means to understanding the complex dynamics of fishery systems.

1. Introduction

Fishery systems encompass a complex dynamic of change and adaptation through the interactions of ecosystems and societies in space and time. This leads to surprises and uncertainties that make fisheries complex adaptive systems [1]. Crafting management in this context is challenging and requires innovative thinking and decision-making [2]. One such challenge is to properly address the different scales (spatial, temporal, and institutional) and organizational levels (e.g., local and regional in the spatial scale) in a given system [3]. For example, scale mismatches between ecosystem dynamics (reproductive cycles of target fish) and institutions (closed seasons) can lead to overexploitation and fishers' distrust of governance mechanisms [4]. Understanding how social-ecological systems evolve at the appropriate scales and levels helps managers build more robust management [5] and foster resilient systems [6].

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An important indicator that helps to understand how fishery systems evolve and respond to change is landings. Fishery landings change in composition and abundance over time, influenced by drivers such as climate change, markets, policy, and overfishing [7–9]. In particular, over the last 50 years, qualitative and quantitative changes in fishing landings have resulted from increased fishing capacity, for both industrial and small-scale fisheries (SSF) worldwide [10].

In Southern Brazil, fishery modernization occurred from the 1960s onwards. Increased engine power in small-scale shrimp fisheries led to the development of otter trawling along the coast, replacing manual or sail trawling [10]. Shrimp trawlers mostly target the Atlantic seabob, *Xiphopenaeus kroyeri* (Heller, 1862), the most captured crustacean species in Brazilian waters. Seabob catches increased from 5 to 50,000 t/year worldwide during 1960–2010 [11]. In Brazil, however, from 1977 to 2003, total production decreased by up to 70%, from 14,000 t/year to 4500 t/year [12]. In the later years of 2009–2011, landings reached approximately 15,500 t/year [13], marking a recovery in catches and surpassing historical values. In a somewhat contrasting pattern, and mirroring global trajectories, Brazilian total marine fishing landings increased to 700,000 tons in the mid-1980s, decreasing thereafter to 500,000 tons by the end of the 20th century, where it approximately remains today, with many fisheries and fish stocks having collapsed or been overexploited [14].

One emblematic case is portrayed on the coast of Paraná, a central region for seabob fishing in Southern Brazil. Seabob is intensely exploited from the Espírito Santo coast, 20°S, to the Santa Catarina coast, 28°S [12]. Southern Brazil small-scale fisheries catch the species at shallow depths of 6–15 m for at least 9 months in a year. Furthermore, in addition to local fishers, trawlers from surrounding regions migrate throughout the year and seasonally overlap in Paraná's coastal waters [15]. In the 1990s, the total landings of crustaceans, fish, and mollusks on the Paraná coast oscillated between 500 and 2500 t/year [16]. Seabob landings were low from 1981 to 1992 but later increased so the species became the main exploited resource, corresponding to 30% of all fishing production by the end of the 20th century [17]. Maintaining that status, seabob participation in total landings has further increased to become greater than that of fish, doubling to more than 60% [18]. In contrast, following the overall national pattern, the reported local fish landings are declining, with some exceptions [19], a situation also referred to by local fishers. However, contrary to regional landing trends, the community of Matinhos has experienced decreasing seabob landings, while some fish landings, particularly the Serra Spanish mackerel, *Scomberomorus brasiliensis* Collette, Russo & Zavala-Camin, 1978, have increased.

What drives the differing trends at different spatial levels in the same region? Taking into consideration that fishery dynamics is influenced by societal and ecosystem drivers, and assuming that both regional (Paraná) and local (Matinhos) levels are subject to similar ecological conditions, this paper explores potential human dimensions that may affect the observed pattern.

We first describe and analyze historical landing data over the last 50 years at the regional and local levels, respectively, the total landings of Paraná state, and the total landings in the Matinhos community in particular. We apply techniques aligned to time series analyses and mixed-effect models to identify time trends and ascertain the observed variations in landings. We then proceed to survey the available literature on the regional and local fishery systems to search for explanations for the observed landing trends in Paraná, other than stock availability. The analysis focuses on the relationship between seabob and fish landings, particularly on how contrasting trends in fish and shrimp landings help to explain and gain an understanding of the current scenario of the local and regional fishery systems.

2. Material and methods

2.1. Study area

The Paraná coast is short, approximately 80 km in length. However, it includes two large estuaries bordered by mangrove forests, Paranaguá and Guaratuba (Fig. 1), which house the early life cycle phases of marine fish, crustaceans, and mollusks, and drain organic detritus towards the adjacent sea [20]. The inner continental shelf presents variable salinities (<35) and temperatures, and it places most small-scale fisheries at depths of up to 30 m.

This region houses around 60 fishing communities, most of which originate from agricultural activities, where a wide variety of practices assembled in different fishery systems can be recognized inside the estuaries and on the continental shelf [21,22]. Landings in these communities take place at many sites, formally recorded according to the six municipalities where fishing is performed (Guaraqueçaba, Antonina, Paranaguá, Pontal do Paraná, Matinhos, and Guaratuba), whose production is added to make up the state landings [18].

2.2. Landings data

2.2.1. Data acquisition

Data on seabob and fish landings on the Paraná coast were extracted from four sources: (i) scientific literature, landings 1970–1975 [23]; seabob landings 1975–1999 [24]; (ii) original federal government statistics from the former Superintendence for Fisheries Development – SUDEPE (landings 1975–1989) and the Brazilian Ministry of Environment – MMA (landings 1993–2000); iii) published MMA data [25–29], landings 2001, 2002, 2003, 2004, and 2005; and (iv) landings 2017–2020 from the fishing monitoring program in Paraná State [18]. Landings on the Paraná coast were considered as a whole, but those of the Matinhos community (25°82′ S, 48°32′ W – Fig. 1) were considered separately in view of the recent reports [19] of increasing catches of the Serra Spanish mackerel, *Scomberomorus brasiliensis*.

2.2.2. Data analysis

We restricted the analyses to the available datasets. Datasets for Paraná were from three time periods: 1970–1989, 1993–2005, and 2017–2020; and for Matinhos from four time periods: 1970–1974, 1983–1984, 1986–1994, and 2017–2020. 'Fish' refers to elasmobranchs and finfish; 'crustaceans' refers to shrimp and crabs. Landings of individual resources – seabob, elasmobranchs, and the most representative finfish – consider, in Paraná as a whole, two periods: 1970–2005 and 2017–2020, with a few gaps; and in Matinhos, the four periods mentioned above.

Catch data were graphically analyzed using the total weight (TW, kg) as well as the fish/crustacean ratio (F/C):

$$\frac{F}{C} = \frac{TW_{fish}}{TW_{crustaceans}}$$

F/C ratio was adopted to evidence contrasting trends between seabob and fish landings. Subsequently, the volume effect was removed by calculating the percentage of the maximum value (PMV), dividing the total weight value of each year by the highest value over the time series for fish and crustaceans separately [30]. PMV values were used to estimate the F/C PMV for time series analysis [31] and modelling [32], for detecting patterns, verifying significances, and for forecasting trends. Whenever possible, missing data were included in the analyses; they are representative of the Brazilian problems related to fisheries statistics and must be modeled as well. To characterize the data for further analyses, the empirical distribution function (EDF) test (Anderson-Darling) was used to assess the individual distribution of each PMV series considering a continuous distribution and Box-Cox and Johnson transformations [33,34]. The significance level was set at $\alpha = 0.05$ for all statistical procedures.

Fig. 1. Paraná coast, Southern Brazil, where small-scale fisheries take place. The six main landing localities are shown (circles = municipalities), as well as the estuarine systems of Paranaguá (north) and Guaratuba (south).

Trend analysis (overall and by period) was performed for Paraná and Matinhos landings independently (PMV transformed) using the Mann–Kendall test [35]. It is a non-parametric test in which the missing values are deleted, and the number of observations is adjusted accordingly. To verify the relationships between fish and crustacean PMVs (x and y variables, respectively), a cross-correlation analysis was performed [31], and its significance was tested (*t*-test - [36]) for the entire period and for periods with at least five data points. Previously, each time series was tested to verify autocorrelation patterns. A standard number of lags was adopted (from $-\sqrt{N}+10$ to $+\sqrt{N}+10$, where N is the number of observations). Time series analyses were performed by observing their premises (e.g., chronological sequence, regular interval, seasonal effect, and others) [31,35].

The landing data from Paraná and Matinhos were also analyzed based on the following categories: seabob *Xiphopenaeus kroyeri*, sharks and rays, primarily *Rhizoprionodon lalandii* (Müller & Henle, 1839), *Sphyrna zygaena* (Linnaeus, 1758), *Zapteryx brevirostris* (Müller & Henle, 1841), and *Pseudobatos percellens* (Walbaum, 1792), whitemouth croaker *Micropogonias furnieri* (Desmarest, 1823), weakfish *Cynoscion* spp. and *Isopisthus parvipinnis* (Cuvier, 1830), and Serra Spanish mackerel *Scomberomorus brasiliensis*. The PMV data were $asin\sqrt{PMV}$ transformed [36] and analyzed using a mixed-effect model [37] after some simulations, considering 'year' (nested in 'quinquennium'), 'quinquennium' (nested in 'decade'), and 'decade' as fixed factors and 'species' as an aleatory factor. These time intervals were used to ascertain different temporal scales. Based on a normal distribution, the restricted maximum likelihood method (RELM) with 999 iterations was used, and the *p*-values were calculated using the Satterthwaite approximations. The best model was evaluated based on its premises, numerical indicators, and residue analysis. Multiple comparisons were performed using

Tukey's test [36]. The overall procedures followed those of Zuur [37], Thorson and Minto [32], Luke [38] and Schielzeth [39]. In that way, we endeavored to tailor the methodology to our data sets, to ensure consistency, robustness and accuracy in the analysis.

2.3. Human aspects

Information on human aspects was retrieved from the published scientific literature and legislation. When necessary, additional information was obtained from theses, technical reports and government reports. The information was reviewed in order to describe and analyze the main historical events, as well as social and economic processes related to local and regional fishery dynamics, and relevant for explaining the observed changes in landings. Information included, but was not limited to fleet and gear development, institutional changes (laws, incentives, organizational and authority changes), conflicts and fishers' perceptions. In addition, the authors have relied on unpublished information from their own previous research practice (field notes, community workshops, scientific events, interviews) since they have been privileged observers of fisheries in the study area over the last 30 years. Such information provided insights on fishers' perceptions, as well as descriptions of events that could help towards understanding trends, drivers, and any other factors related to the evolution of fisheries in the region.

3. Observed patterns in landings

Time series analysis is designed to evidence temporal trends [42] and mixed-effect models are versatile enough to be applied in different datasets [37]. Analysis of fishing landings is a crucial aspect of fisheries management and, historically, it dates back to the beginning of the 20th century and, notably, to the models of Thompson & Bell (1934) and Graham (1935) (*apud* [40], facsimile of the original edition from 1957). Since then, methodological advances and new techniques have been developed, most of them based on standardized catch per unit effort (CPUE) or landing per unit effort (LPUE) data [41] either coupled to general linear and additive models [42,43] or to time series methods [44,45]. In our case, modeling of historical data evidenced contrasting

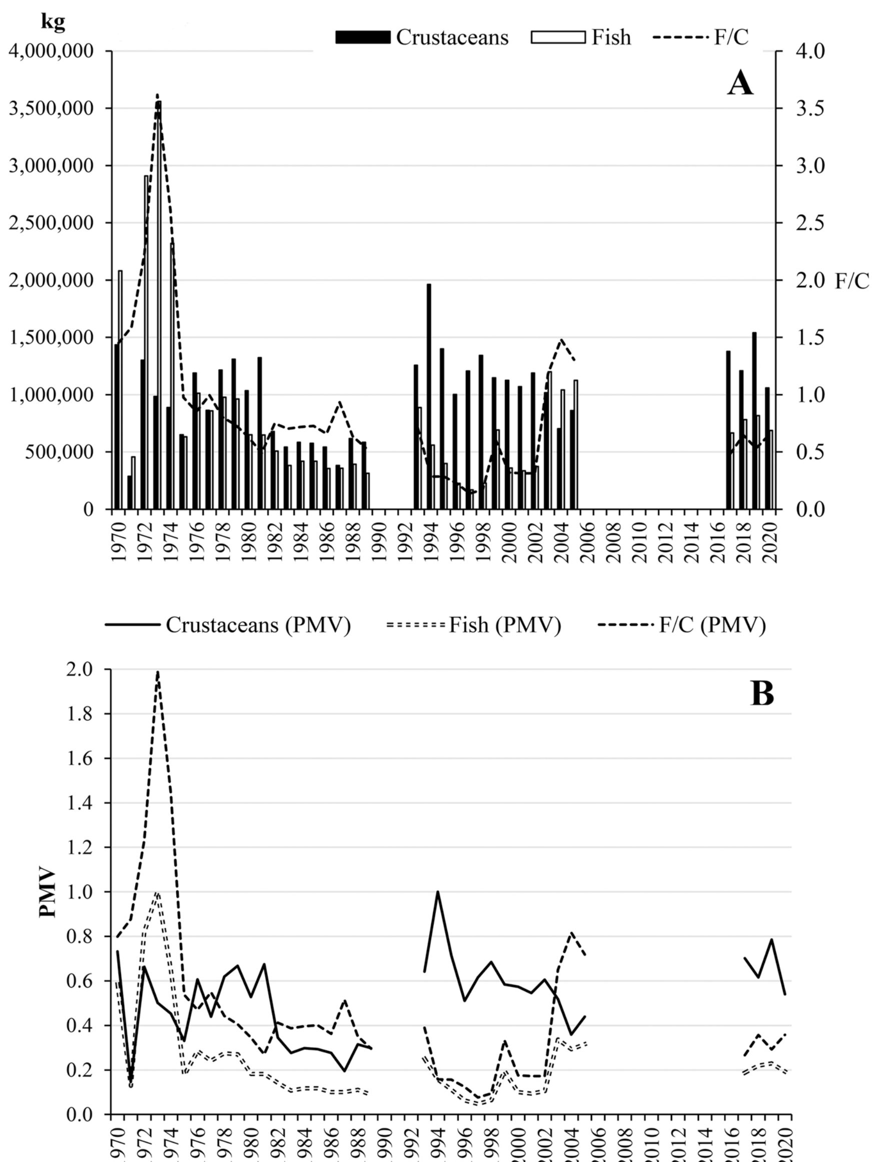

Fig. 2. (A) Total weight of crustaceans and fish landed by small-scale fisheries on the Paraná coast, Brazil, including Matinhos, and fish-crustaceans ratio (F/C), in three periods, 1970–1989, 1993–2005 and 2017–2020. Landings data sources: [34], government original databases (1975–2000), [29], and MMA [36–40]. (B) Percentage of maximum value (PMV) for crustaceans, fishes and the fish-crustacean ratio.

patterns of fishery landings for fish and crustaceans at regional (Paraná) and local (Matinhos) levels, as described below.

3.1. Paraná landings

Landings of small-scale fisheries in Paraná presented two patterns: in the first one, landings of fish surpassed those of crustaceans; this refers to the periods 1970–1974 and 2003–2005 when the fish: crustacean ratio ranged between 1.18 and 3.62; in the second pattern, landings of crustaceans surpassed those of fish; this refers to the periods 1976–1989, 1993–2002, and 2017–2020, when F/C ranged between 0.14 and 0.85 (Fig. 2A). Similar landings of fish and crustaceans occurred in 1975 and 1977 (F/C 0.98–1.00). After volume effect removal, the same trends were observed in the PMV series for the crustaceans (normal distribution, $A^2 = 0.498$, $p = 0.198$), fish (normal distribution Johnson transformed, $A^2 = 0.289$, $p = 0.596$), and F/C (normal distribution Johnson transformed, $A^2 = 0.409$, $p = 0.329$), corroborating the two diagnoses (Fig. 2B).

Over the last 50 years, the absolute production and PMV values have presented inverse patterns among crustaceans and fish. Crustacean landings have consisted mostly of shrimp: the seabob *X. kroyeri*, with 70–80% of catches, and secondarily, the white-shrimp *Litopenaeus schmitti* (Burkenroad, 1836), and the prawn *Artemesia longinaris* (Bate, 1888) known locally as 'barba-ruça' or 'ferrinho'. Crustacean landings have shown an overall increase ($S_{crustacean} = +78$, $p = 0.3139$) and fish landings, an overall decline ($S_{fish} = -150$, $p = 0.0513$) despite different trends when considering each period individually (Table 1). Thus, 'shrimp up and fish down'.

In the 1970–1989 period, annual landings of crustaceans surpassed 1000 t in 6 years, in the 1993–2005 period in 10 years, and in the 2017–2020 period in 4 years. This corresponds to 30%, 75%, and 100% of each period, respectively. The general volume reduction in the landings caused negative trends (Fig. 2, Table 1). In contrast, annual fish landings declined from over 2000 t in 4 years of the 1970–1974 period, to < 500 t in most years of 1982–2020, with a maximum of 1350 t (Fig. 2). Even considering the remarkable initial increase (1970–1974), the subsequent decrease explains the negative trend of that period. The following periods (1993–2005 and 2017–2020) experienced a positive but not significant trend due to rising fish landings (Fig. 2, Table 1).

The overall value of F/C PMV statistics ($S_{F/C} = -278$, $p = 0.0003$) highlighted the crustacean rise and fish decline, and the variations by period can be explained in the same way as those of crustaceans and fish PMV analyzed separately. Cross-correlations in Paraná landings were significant only for the period 1970–1989 (Fig. 3A), specifically in the lag times − 6 (r = 0.703, $p = 0.005$) and − 7 (r = 0.647, $p = 0.017$). These values show that a reduction in fish landings will reflect an increase in crustacean landings after 6–7 years. This result matches with the variation in production and the diagnosis of fish up in 1970–1974 and crustaceans up in 1976–1989, when the fish catch diminished (Fig. 2). There was no significant cross-correlation in the 1993–2005 period (Fig. 3B).

Table 1
Results of the Mann-Kendall trend test for PMV of crustaceans and fish landed by small-scale fisheries on the Paraná coast (including Matinhos) and in Matinhos, Brazil (PMV = percentage of maximum value, F/C = fish-crustaceans ratio, S = test statistic, *p* = probability values, plus (+) = increase, minus (-) = decrease, bold = significant results).

Category	Crustaceans PMV		Fish PMV		F/C PMV	
	S	*p*-value	S	*p*-value	S	*p*-value
Paraná						
Overall	+ 78	0.3139	-150	0.0513	-278	**0.0003**
1970–1989	-70	**0.0252**	-132	**< 0.0001**	-114	**0.0002**
1993–2005	-48	**0.0041**	+ 20	0.2464	+ 30	0.0769
2017–2020	-2	0.3750	+ 2	0.3750	+ 4	0.1670
Matinhos						
Overall	-46	0.1439	+ 7	0.8454	+ 94	**0.0026**
1970–1974	-6	0.1170	-2	0.4080	+ 4	0.2420
1986–1994	+ 6	0.3060	-1	0.4600	-6	0.3060

The data attested that Paraná's landings underwent a shift in target resources in the 50 years prior to 2021. The annual landings of seabob *X. kroyeri*, the most captured crustacean species on the Paraná coast, strongly increased, from 400 to 1200 t in 50% of the years in the period 1970–1981, to 600–1800 t in 50% of the years in the period 1994–2020 (Fig. 4A). However, conversely, a decline was observed in captures of the most important fish resources: landings of sharks and rays declined from over 250 t/year in 1970–1973, to < 20 t/year in 2017–2020 (Fig. 4B); of whitemouth croaker, from 26.1 to 262.0 t/year in 1970–1974, to 13.3–34.3 t/year in 2017–2020 (Fig. 4C); and weakfish, from > 500 t in 1970–1974, to < 100 t in most years since the 1980 s (Fig. 4E). Exceptions were observed with respect to mullet and the Serra Spanish mackerel, for which landings in 2017–2020 remained > 50 t/year, similar to the 1970s (Fig. 4D).

The mixed-effect model satisfactorily explained (coefficient of determination $r^2 = 0.8724$, standard error SE = 0.1373) the variations in PMV values for the species analyzed in Paraná's landings (Table 2), supported by the residue analysis in terms of randomness, normality, and temporal independence. Species composition by itself did not affect the landings (17.45% of variance, Z = 0.8769, $p = 0.190$), but its temporal interaction did, in relation to both decadal (36.15% of variance, Z = 1.7768, $p = 0.038$), and quinquennial changes (17.21% of variance, Z = 1.7753, $p = 0.038$). Isolated decadal variation was not significant (F = 2.79, $p = 0.064$), whereas variations with respect to quinquennium (F = 3.09, $p = 0.048$), and year (F = 5.79, $p < 0.001$) were significant. Constant significances (Table 2) and multiple comparisons (Tukey tests) showed that changing patterns of PMV (observed in Fig. 4) were significant, primarily because of the landing data from the 1970s.

3.2. Matinhos landings

The Matinhos community presented a different scenario, since the landings of fish surpassed those of crustaceans in all periods considered, 1970–1974, 1983–1984, 1986–1994, and 2017–2020. Moreover, the fish-crustacean ratio in landings increased from 1.82 to 3.77 in the first and second periods, to 2.35–4.17 in the third period, and 5.83–8.97 in the last 4 analyzed years (Fig. 5A). The transformed values of PMV enhanced the observed tendency of absolute landings, mainly for F/C in the most recent period (Fig. 5B). The three PMV data series showed a Johnson transformation normal distribution ($A^2 = 0.505$, $p = 0.179$ for crustaceans; $A^2 = 0.237$, $p = 0.754$ for fish; and $A^2 = 0.177$, $p = 0.909$ for F/C).

The main target resources accessed by Matinhos community have shifted in a different way from that shown by communities in Paraná as a whole. Overall trend analysis (Table 1) confirmed that crustaceans decreased ($S_{crustacean} = -46$, p = 0.1439) and fish increased (S = +7, p= 0.8454). Only the increase in F/C presented a high level of statistical significance (S_F/C = +94, p = 0.0026), reinforcing 'fish up'. With respect to time periods, only 1970–1974 and 1986–1994 were analyzed, when the relative constancy of crustaceans and fish down (at the end of both periods) caused the 'neutral' trend for the former group (S values −6 and +6) and an incipient decrease for the latter (S values –2 and –1, nearly zero). Cross-correlation at lag zero for 1970–1974 (Fig. 3C) indicates no dominance of fish or crustaceans, and for 1986–1994, fish landings increased in relation to a crustacean decrease that occurred in an interval of 2 years (Fig. 3D).

Considering the species composition, the annual catches of seabob were > 150 t at four instances in 1970–1984 and were < 50 t in all years but one in 1986–1994, and in all years in 2017–2020 (Fig. 6A). An inverse trend was seen with respect to fish: sharks and rays declined in Matinhos from > 60 t in 1970–1973 to < 20 t/year in 2017–2020 (Fig. 6B). Similar declines were observed with the whitemouth croaker, from > 100 t in 1970–1974, to < 20 t in 2017–2020 (Fig. 6C); and

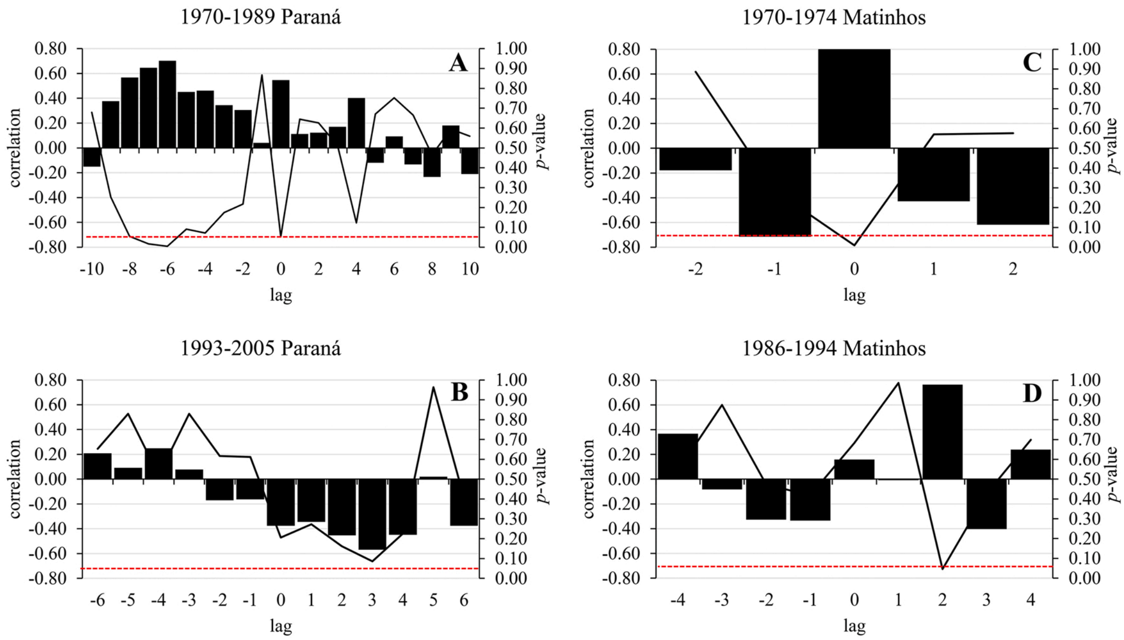

Fig. 3. Correlograms between fish PMV (percentage of maximum value) and crustacean PMV for the following periods and spatial levels: (A) 1970–1989, Paraná, (B) 1993–2005, Paraná, (C) 1970–1974, Matinhos, and (D) 1986–1994, Matinhos. Significant negative lags indicate fish PMV leading and positive lags indicate crustacean PMV leading. Bars = correlation, black line = p-value, dashed line = 0.05 p value. *p*-values below the dashed line are significant (right axis scale).

weakfish, from > 150 t in 1972–1973, to < 50 t in most years since the 1980 s (Fig. 6E). Conversely, landings of the Serra Spanish mackerel have substantially increased: in 1970–1973 they ranged from 5.5 to 74.7 t, while in recent years, the annual catches have varied from 45.5 to 89.2 t (Fig. 6D). Thus, 'fish up and shrimp down'.

Modelling PMV values for the Matinhos landings presented a satisfactory explanation (coefficient of determination $r^2 = 0.8759$, standard error SE = 0.0911, residue analysis). In the same way as Paraná landings, species composition by itself did not affect the landings (9.33% of variance, $Z = 0.4636$, $p = 0.321$), only its decadal interaction did (63.90% of variance, $Z = 2.1732$, $p = 0.015$). The effect of fixed factors endorsed this diagnosis ('decade'): $F = 3.59$, $p = 0.048$), with the 'year' effect being the most pronounced ($F = 8.60$, $p < 0.001$). The main constants (Table 3) and multiple comparisons (Tukey tests) revealed that PMV patterns (observed in Fig. 6) showed the same tendency in 1970–1974 and 2017–2020, differing from those in 1983–1984 and 1986–1994. Although explained by different secondary data than that of Paraná, the main differences were also due to the 1970s and the model error (26.77% of variance, $Z = 5.2849$, $p < 0.001$) (see the following section).

4. Human dimensions explain patterns and trends in landings

Fishery landings provide an important 'onboard' understanding of the dynamics of fishery systems. However, an investigation of 'on land' information reveals how institutional aspects such as laws, fishing regulations, and incentives influence fishery dynamics [46]. In addition, exploring information at the local level helps towards understanding how fishers respond to such contrasting patterns [47]. Local and regional events selected from the literature review have shaped a timeline of drivers and outcomes over the last 50 years (Fig. 7). Such events may call attention to potential aspects that can help to explain the observed patterns in fishing landings.

4.1. Long-term changes and trends at regional and national levels

Seabob landings in Paraná showed a general growth trend between 1970 and 2020, following the global pattern of increasing production in 1960–2016, from 5 t to > 40 thousand t/year [48]. However, in Southern Brazil as a whole, an opposite scenario occurred because of the drastic reduction registered in 1977–2003, from 14 to 4.5 thousand t/year [12]. Between the 1972–1987 and 1990–1999 periods, the maximum sustainable yield and catch per unit effort (CPUE) of seabob in Brazil decreased by 47.5% and 39.3%, respectively, showing that fishing efforts exceeded the levels recommended by regional production models [24]. Recently, the Instituto Chico Mendes [49] warned of the possible reduction in Brazilian seabob stocks and recommended their monitoring along the coast. Brazilian small-scale and commercial fisheries are experiencing trends similar to the global decline in CPUE [50]. Except for the seabob fishery, small-scale fisheries on the Paraná coast have presented the same patterns.

Similarly, the decline of sharks and rays and whitemouth croaker has been observed in Southern Brazil [51]. Small chondrichthyans are captured during shrimp trawling, but large individuals are caught by gillnets targeting demersal finfish, such as whitemouth croaker and flatfish in Paraná, and hakes in Argentina [52]. The capture of sharks and rays as targets in pelagic fisheries and as bycatch in others (e.g., trawling) helps explain such a decrease in landings globally and locally [53,54].

Such production patterns can be explained, in part, by the modernization in fisheries technology (Fig. 7). Brazilian fisheries rapidly expanded during the 1960–1980 period through government incentives (National Plan for Fisheries Development – PNPD; Fisheries Development Plan - PDP) and regulations to support the development of the fish supply chain. For example, bordering the state of Paraná, the states of São Paulo and Santa Catarina increased their fishing capacity to support the demand for fish marketing and consumption. The industrial bottom long-line was disseminated in the 1990s from the state of São Paulo [55]. The neighboring fishing port of Itajaí (Santa Catarina state) showed an increase in the number of fishing vessels from 38 to 122, and an increase in the mean engine power from 152 to 227 HP in the 1967–1971 period [56]. With poor regulation of fisheries, the shrimp trawl fisheries (primarily the pink shrimp *Farfantepenaeus* spp.) collapsed abruptly. Consequently, the fishing fleets expanded their range of targeted species, including fish and seabob in shallower waters.

Our results showed significant changes in landings during the 1970s.

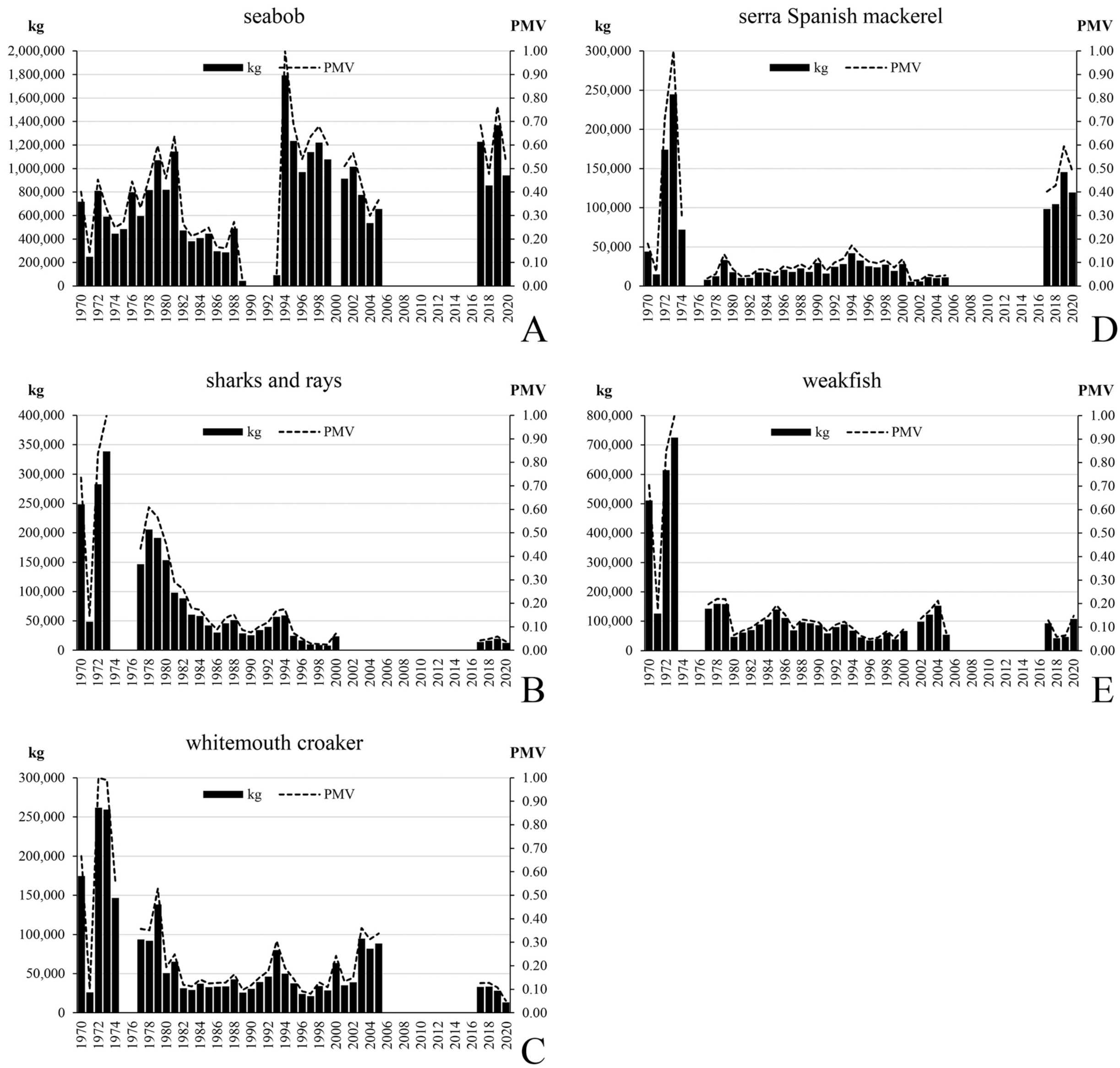

Fig. 4. Total weight of seabob, chondrichthyans, and three of the main finfish resources landed by small-scale fisheries on the Paraná coast, Brazil: 1970–1989, 1993–1999, 2001–2005, and 2017–2020 for seabob (A); 1970–1973 and 2017–2020 for sharks and rays (B); 1970–1974, 1977–2005, and 2017–2020 for Whitemouth croaker (C) and Serra Spanish mackerel (D); and 1970–1974, 1977–2005 and 2017–2020 for weakfish (E). Landings data sources: [34], government original databases (1975–2000), [35], MMA [36–40,52]), and [29].

Not surprisingly, the period from 1965 to 1975 was marked by the appearance in Paraná of a 'technological package' for the modernization and intensification of fisheries, consisting of inboard fishing engines, ice technology, synthetic fibers, and wooden plank boats [57,58]. Slow at first, its diffusion surged from 1976 to the 1980s, on account of strong technical assistance from the state government fishing extension service combined with credit availability [14]. This input stratified the local trawling fleet into three levels based on distinct types of vessels (canoes, *botes*, and *barcos*). *Barcos* are larger, decked, and appeared later, starting in 1982. Accordingly, the fishing effort increased sharply during that period, with the fleet strength peaking in 1987 [32] (Fig S1 - ESM).

During the 1990s, at least four factors prevented further expansion of the fleets [14]: (i) government emphasis shifted from intensification and expansion of fishing to resource protection, (ii) credit and financial conditions deteriorated, (iii) oil and maintenance costs increased, and (iv) increased effort led to diminishing returns. According to some of the respondents interviewed by Andriguetto-Filho et al. [14], a true crisis was established after 1988. In the 1990s, for example, a 5 cm mesh driftnet, targeting white shrimp in shallow waters close to the surf zone, was introduced in the central and southern portions of the coast, where Matinhos is located. Driftnetting partially replaced trawling in response to closed-season legislation, which prohibited trawling but not other practices. However, in 1996, a federal government credit program for family agriculture named PRONAF was established, with adequate funding after 2000 [14,59], when fishers were also considered as part of the family agriculture sector. Thus, during the last two decades, credit has regularly been available [59], allowing for continuous expansion and modernization of vessels and equipment, albeit not as intensely as in the first period. In particular, and relevant to this study, gillnets increased in size, and wooden canoes began to be replaced by fiberglass ones [60], while shrimp trawling gear, requiring less capital, remained both the entry-level option for new fishers and the staple for poorer fishers.

This second 'cycle' of credits offered a more diversified portfolio of funding for the small-scale fisheries sector, including support for improving and/or expanding the fish supply chain. However, such

Table 2
Main estimated coefficients for the mixed-effect model to the transformed PMV (percentage of maximum values) (dependent variable) obtained for Paraná landings (SE = standard error, df = degree of freedom, *t*-test = statistic values, *p* = probability values, bold = significant results).

Factor	coefficient	SE	df	*t*-test	*p*-value
Constant	0.4969	0.06033	4.11	8.236	**0.001**
Decade					
1970	0.2320	0.07331	14.91	3.164	**0.006**
1980	-0.1026	0.07128	13.35	-1.439	0.173
1990	-0.0616	0.07153	13.54	-0.861	0.404
2000	-0.0749	0.07792	17.98	-0.961	0.349
Quinquennium					
1970	0.1463	0.04440	18.9	3.296	**0.004**
1980	0.0375	0.03858	11.41	0.972	0.351
1985	0.0295	0.03932	12.17	0.751	0.467
1990	0.0053	0.05275	27.71	0.100	0.921
Year					
1970	-0.0545	0.05601	106.61	-0.973	0.333
1971	-0.5210	0.05601	106.61	-9.301	**< 0.001**
1972	0.2514	0.05601	106.61	4.488	**< 0.001**
1973	0.4840	0.05601	106.61	8.640	**< 0.001**
1974 ... 2019	–	–	–	–	> 0.05

benefits were available only to fishing communities formally instituted and regularized; those under informal status could not get access to them. Fishers' organizations historically struggled to keep their activities and legal situation consistent and coherent with their primary role (to legitimately represent fishers). The 2000s period provided several opportunities, including conflicting situations, for fishers to diversify their forms of organizations. Prior to that period, the so-called *Colônias de Pesca* – a legacy from the military period of 1964–1985 in Brazil – were mostly the main and sole organizations. From local ideological-political conflicts to Regional and National Conferences, fishers' organizations diversified into social movements, cooperatives, associations and unions [61]. However, fishers were empowered asymmetrically, as in the case of Matinhos, and only accessed the credits when more organized.

Thus, the state-wide development of fleet and gear possibly led to general fish stock depletion and the corresponding drop in fish landings but was sustained by the seabob, despite some studies pointing to local overexploitation on other places, such as the Rio de Janeiro coast 21°37′S [62], as well as on the Santa Catarina coast [63]. On the other hand, Kolling and Ávila-da-Silva [64] concluded that the species had been harvested at stable levels on the coast of São Paulo state from 1990 to 2009, and it has recently been shown that the seabob shrimp is not yet overexploited in Northeastern Brazil, where fishing effort is equally heavy [65].

The government's shift to resource protection needs to be highlighted because of its differential effect on fleets [14]. Although the first rule dates back to the 1970s, it was only after 1992, with the creation of new environmental agencies at the federal and state levels, that enforcement and sanctions took place, including the application of fines. Three types of control apply to Paraná: vessel permits, shrimp closed seasons (see [66]), and trawl exclusion zones delimited by distance from the shore according to vessel size. As expected, various conflicts over legislation pit distinct groups of fishers against each other, depending on the type of fishing they practice. In the 1990s, canoe and gillnet fishers demanded limitations to the trawl fleet of larger plank vessels, including boats from other states. Andriguetto-Filho et al. [14] considered that, overall, the canoe fleet in particular, and fishers with small boats in general, were favored by the exclusion zone legislation, as this restricted the action of large boats in areas close to the shore. The ban on trawling creates the conditions for driftnetting practices that target white shrimp. In the early 1990s, permission for 5-cm mesh driftnetting was offered as a bargaining tool by IBAMA, a federal environmental agency, which understood that the practice was acceptable as it generated low proportions of discards. In the opinion of officials and fishers interviewed by the aforementioned authors, the driftnetting permission favored canoe fishers. In addition, enforcement generally tolerates smaller vessels, especially canoes, that trawl within the first mile, which is against the norm.

Despite modernization through government incentives, Paraná's fish supply chain did not develop as much as that of the neighboring states and did not reach an industrial scale. The state coast is an important fishing zone for several outsiders, including industrial and small-scale fishing boats, which include trawlers, purse seiners, and gillnetters [15]. Therefore, competition with more aggressive fishers, with more powerful boats and fishing gear and no attachment to the fishing grounds (outsiders), greatly influences local fishers' interest in safeguarding their activities [67].

As noted, part of the first period of fisheries development was mediated by the fishing extension service. In the early period of modernization, extension agents had important roles in supporting fishers' engagement in the pursuit of credit. They also had roles in enforcement and collecting data on landings. However, institutional decadence in fisheries policy also affected extension. As of 2000, the fishing extension carried out by state government agencies was resumed but restricted to the mediation of the credit process. Keeping their historical narrow perspective of extension, the agencies have a limited participation in fisheries development and management.

4.2. How the Matinhos fishery system responded: Shifts in technology and fishing strategies at the local level

Technological advancement was more intense in, and in some cases restricted to the central and southern coast of Paraná, partly because, starting in the 1960s, those areas received a large migratory contingent of fishers from the neighboring southern state of Santa Catarina (the so-called 'Catarina legacy') and they were important in the formation of Matinhos fisher communities [58]. The historical influence of Santa Catarina's fishers on Paraná's professional fishers is recognized in the literature since the former brought with them a more open mindset about technological innovation and market economy [22].

Moreover, Matinhos fishers have actively participated in these developments owing to the prominent level of organization of their association, thus making it easier to obtain credit and leading to more effective innovations in this community. Fishers replaced the heavy, multifilament polyamide and cotton gillnets in shark fishery with light polyamide monofilament driftnets. By 2010, they also developed another innovation to the driftnet used to catch fish (mainly mullets and the Serra Spanish mackerel). They increased the driftnet height to work as an encircling gillnet in deeper waters, closer to the coastal islands in the proximity. Unpublished reports from community workshops also showed fishers' perceptions of their higher catches after the changes that occurred between 2016 and 2020.

Fishers use the adapted gillnet as an encircling gillnet (locally named *rede alta*) and as a driftnet as well. They successfully exploit a large variety of resources, including at least eleven chondrichthyans and thirty-four finfish species [68], promoting less bycatch than shrimp trawling, which is recognized by fishers. Compared to certain finfish species, such as the Serra Spanish mackerel, seabobs are sold at similar prices. However, while a single gillnet deployment can catch > 80 kg of fish, a similar volume of shrimp requires many hours of trawling and a larger volume of fuel [68]. That seems to be an important reason why, in Matinhos, seabob trawling plays a secondary role, and fishers use a 5-cm mesh size driftnet to catch the white shrimp [68]. Twenty years ago, the Serra Spanish mackerel was barely mentioned among the main resources in Southeast marine fisheries [69], but in recent years it has played a key role in Matinhos landings [19], revealing itself as a more resilient resource. In fact, *Scomberomorus brasiliensis* is a finfish normally caught with a total length of 40–60 cm and is a new, promising boon for small-scale fisheries in Southern Brazil. Its fecundity is high, up to 390, 000 oocytes; the size at first maturity is approximately 45 cm and is

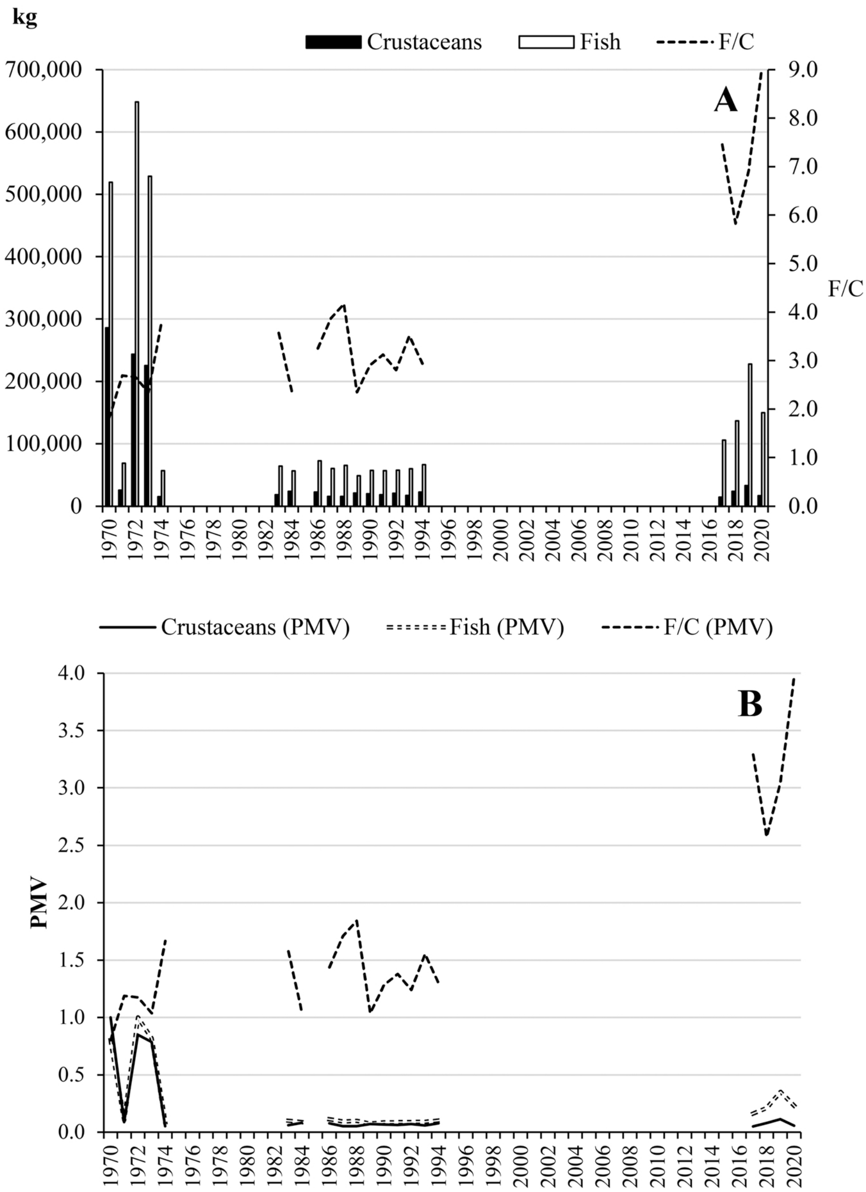

Fig. 5. (A) Total weight of crustaceans and fish landed by small-scale fisheries in Matinhos, Brazil, and fish/crustacean relationship (F/C) in four periods, 1970–1974, 1983–1985, 1986–1994, and 2017–2020. Landings data sources: [34], government original databases (1975–2000), and [29]. (B) Percentage of maximum value (PMV) for crustaceans, fishes and fish-crustacean ratio.

attained rather early, at 1.4 years of age. Also, the size range in catches is influenced by gillnet selectivity, which explains the low incidence of individuals smaller than 30 cm [70].

Thus, Matinhos fishers may have succeeded by diversifying the fish targets in combination with the increase in engine power and size of the new fiberglass canoes. In 2004, 55–60% of the fishing boats in Paraná were motorized, but in Matinhos, the proportion of motorized boats, in relation to the paddle-propelled boats, was greater than 80% [71], and almost 90% of the canoes in Matinhos were engaged in bottom trawling [71] while in recent years most canoes operate driftnets or both types of gear [68]. A recent survey showed the predominance of trawling nets and driftnets in Matinhos compared to Paraná as a whole [29] (Fig S2 - ESM). Gillnets reach 25 m in height and are 400 m to 4000 m long [68]. It must be noted that, contrary to the general state trend, plank boats were not adopted in Matinhos because the community is located on an open beach, with large waves and no mooring infrastructure. Under these conditions, the canoe is still the most suitable vessel for navigating the surf zone, allowing the beach to be used as a port. In addition, as noted in the previous section, the evolution of resource protection favored canoes and the fisheries practiced in Matinhos. However, plank boats are still more productive for shrimp trawling than canoes. For example, Kolling and Ávila-da-Silva [64] have found that the most powerful vessels were up to 3.5 times more efficient at trawling seabob on the coast of the neighboring state of São Paulo, in conditions quite similar to those found in Paraná.

Market conditions may also have played a role in Matinhos fishers' choices. Matinhos is one of the most urbanized municipalities on the coast of Paraná with intense sun-and-beach tourism, high second housing indices, and good road infrastructure. This offers fishers strategic advantages for the flow and marketing of their catch, such as direct sales to restaurants and the final consumer, as well as to the closest cities. In their study on the sustainability of fishing systems on the coast of Paraná, Andriguetto-Filho et al. [22] conclude that the south coast canoe system appears to attain economic efficiency even on a relatively small scale of operation. Their analysis revealed that, based on work relationships determined by the traditional logic of camaraderie,

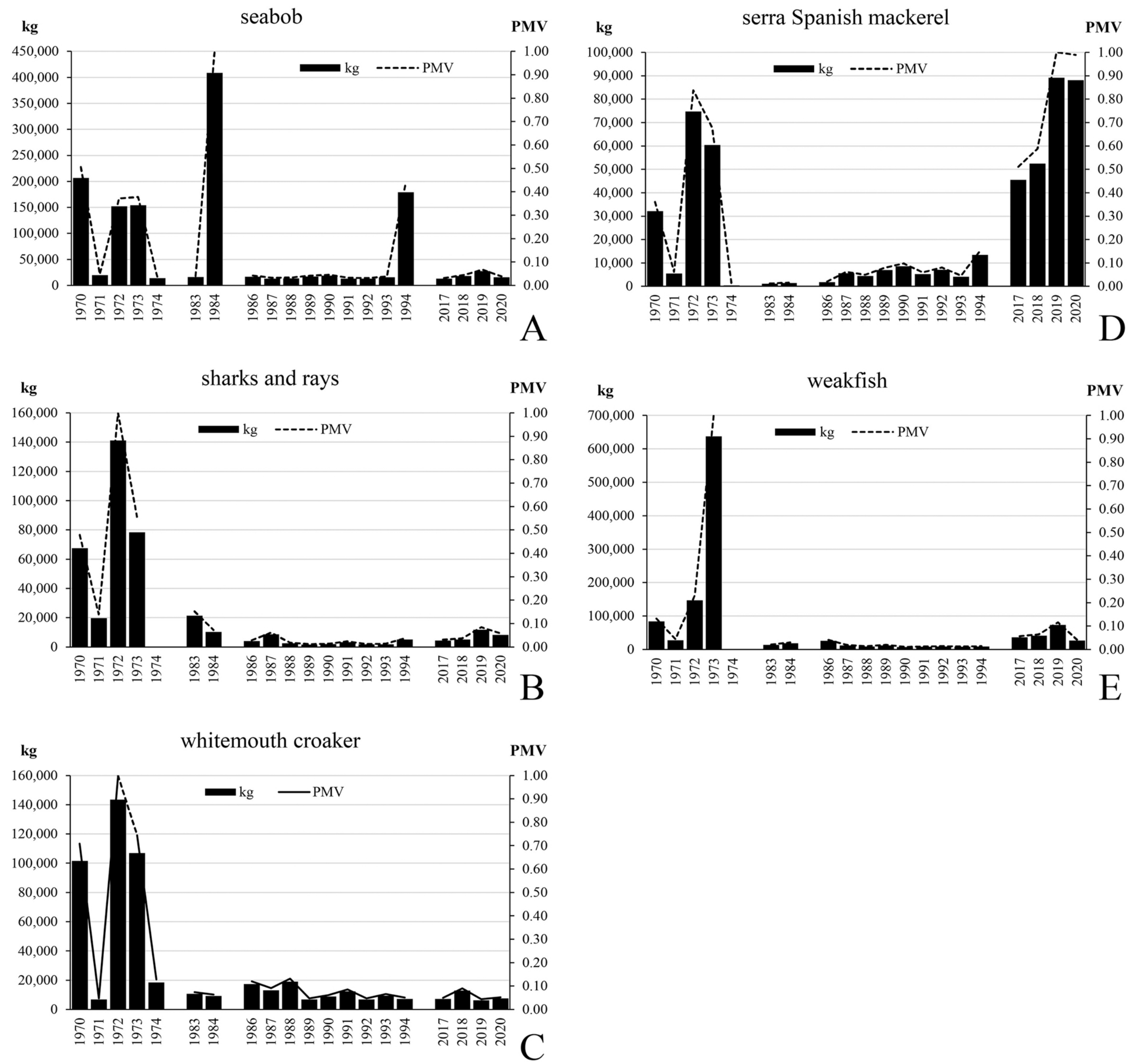

Fig. 6. Total weight of seabob, chondrichthyans, and three of the main finfish resources landed by small-scale fisheries in Matinhos, Brazil, in: 1970–1974, 1983–1984, 1986–1994, and 2017–2020 for seabob (A), sharks and rays (B), whitemouth croaker (C), and Serra Spanish mackerel (D); and 1970–1074, 1977–2000, and 2017–2020 for weakfish (E).
Landings data sources: [34], government original databases (1975–2000), [29,35–40].

Table 3
Main estimated coefficients for the mixed-effect model to the transformed PMV (percentage of maximum values) (dependent variable) obtained for Matinhos landings (SE = standard error, df = degree of freedom, *t*-test = statistic values, *p* = probability values, bold = significant results).

Factor	coefficient	SE	df	*t*-test	*p*-value
Constant	0.1521	0.0409	4.01	3.722	**0.020**
Decade					
1970	0.1652	0.0575	11.74	2.871	**0.014**
1980	-0.1026	0.0570	11.29	-1.802	0.098
1990	-0.0925	0.0569	11.25	-1.624	0.132
Quinquennium					
1980	0.0014	0.0185	55.99	0.077	0.939
Year					
1970	0.1196	0.0383	56.16	3.121	**0.003**
1971	-0.2495	0.0383	56.16	-6.512	**< 0.001**
1972	0.2186	0.0484	57.42	4.516	**< 0.001**
1973	0.2242	0.0423	56.82	5.301	**< 0.001**
1983 ... 2019	–	–	–	–	> 0.05

friendship, and family ties, the canoe system is a reasonable social success in which small-scale activities and moderate technological levels show economic viability under current market conditions.

The history of strong ties within the community is relevant for sustaining successful fishers' organizations. This was reflected in effective access to credit, as mentioned, and rapid organization to claim their rights. In 2012, two landmark regulations witnessed this capability. First, a national regulation that restricted the use of gillnets to reduce incidental catch. Second, the creation of the Ilha dos Currais Marine National Park (similar to IUCN category II), a no-take marine protected area that excluded an important fishing ground for pelagic fishes, especially *Scomberomorus brasiliensis*. Fishers claimed the right to access the fishing grounds within the Marine Park, a condition legally assured to traditional people (such as fisherfolk) dependent on the area, through fishing agreements (the so-called terms of commitment – TC). It was the only TC signed by the federal protected area management agency (ICMBIO) in southern Brazil until 2021. It is too soon to assess biological outcomes from the newly created MPA. On the other hand, fishers' empowerment, resulting from their enrollment in the decision-making

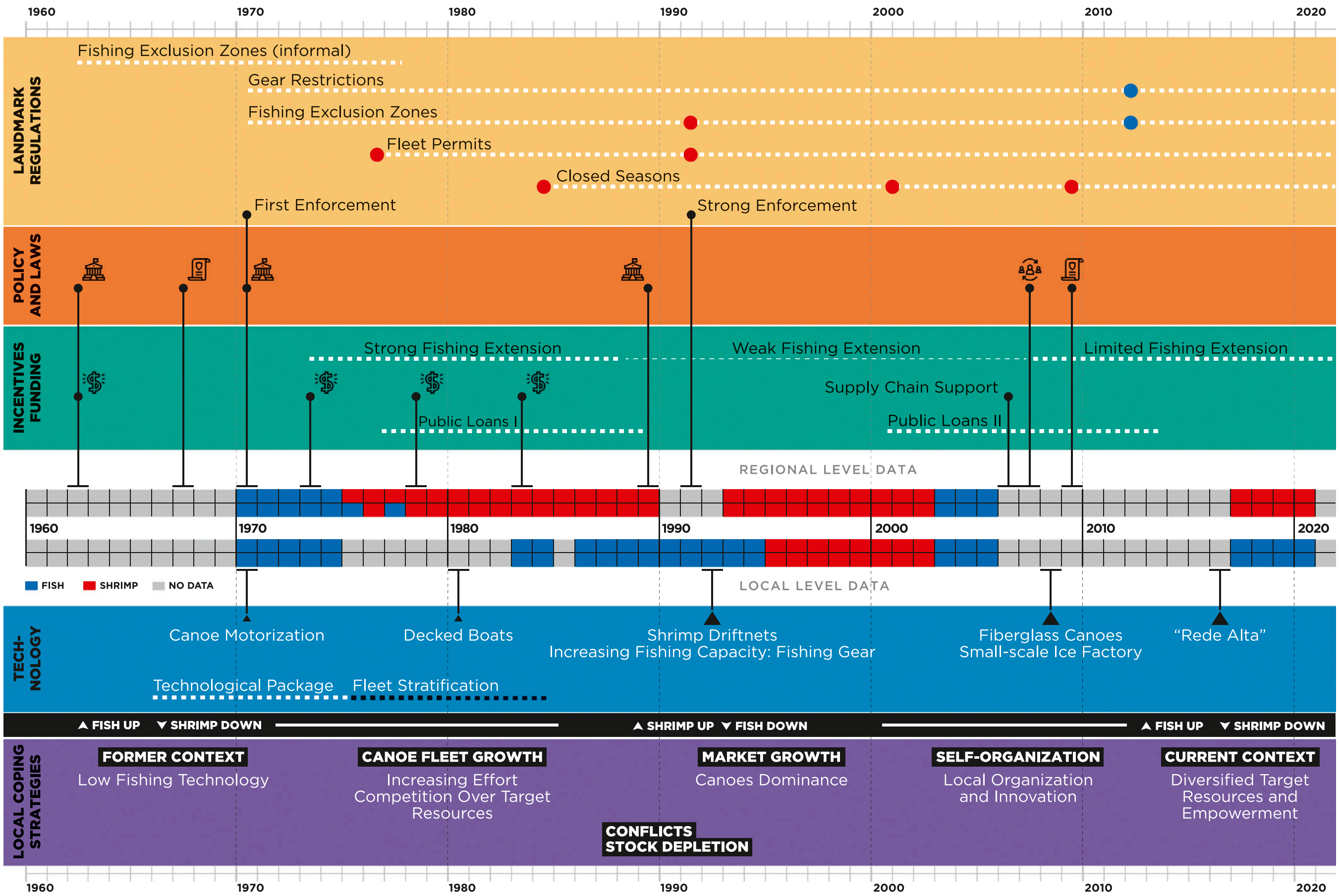

Fig. 7. Timeline with the main landmarks, dynamics and factors of change in the development of marine fisheries in the state of Paraná and the Matinhos community, in southern Brazil. Throughout the figure, horizontal lines represent time frames, while symbols represent important moments in time. From top to bottom, tiers are as follows. "Landmark regulations" are those with particular influence on local and regional fisheries. Blue and red circles mark important revisions of regulations applying to fish and shrimp, respectively. "Policy and laws" shows major policies and organizations created over the researched period at national and state level, as well as the advent of fishers conferences . "Incentives/funding" shows starting years of laws and programs that supported fisheries modernization and development at federal and state level. The "brick lines" in the middle of the figure indicate the relation between fish and shrimp landings per year at state level (upper line) and Matinhos (lower line), red for F/C < 1 and blue for F/C > 1; gray means no data. "Technology" highlights main technological changes and advances in fisheries. Decked boats are trawlers; large triangles indicate changes particularly important to Matinhos' fisheries context and fishers' responses. The black tier highlights main shifting trends in landings in Matinhos. Finally, the bottom tier summarizes the dynamic of the local fishery systems, as a response to the events described in the upper tiers, including drivers, outcomes and strategies perceived/conducted by fishers in Matinhos.

process, is an important outcome of fisheries management when human dimensions are taken into consideration [72]. Fisher empowerment allowed local fishers to keep their traditional fishing grounds, as a strategy to diversify fishing areas, and, potentially, to reduce the impact of fishing on habitats.

Such strategies help to explain the significant differences in landing patterns and their historical trends between Matinhos and Paraná as a whole, particularly with respect to the relationship between fish and crustaceans in landings. The increase in fishing effort, combined with a larger range in mesh size, 5–45 cm, led to increased catches of fish with high market value, such as mullet, flatfish, and the Serra Spanish mackerel [68,70]. In addition, the installation of an ice factory in the Matinhos community contributes to fish storage, as fish need larger refrigerated compartments than shrimp.

4.3. Fish down, shrimp up, and vice-versa: Shifting trends and implications for fisheries management

Fisheries landings are sensitive to stock availability and fishers' behaviors and choices. Such behaviors are poorly addressed in fisheries management. The first reason for that may be the usually high spatial level of landing data aggregation and analysis. The FAO fishing areas and their subdivisions are organized at different spatial levels based on political, geographic, and environmental features [48]. The Southwestern Atlantic (FAO Major Fishing Area 41) encompasses the coasts of French Guiana, Uruguay, Brazil, and Argentina, where there are many fisheries resources, including shared stocks [73]. Brazil has the largest and the most heterogeneous coast, where the most productive fishing area corresponds to the FAO division 41.2.1 (20–29°S), referred to as Southern Brazil in the literature. An analysis at such a macro-scale may not accurately reflect landing trends due to: (i) the use of different sampling units and the limitations of using catch per unit effort data [74], (ii) fish landing data available from census or from sampling [75], and (iii) data gaps, including overlooking small-scale fisheries [76].

Two main aspects are relevant for supporting management at multiple scales and levels. First, adopting interdisciplinary and comprehensive perspectives, such as the ecosystem approach to fisheries (EAF) [77]. The EAF supports the understanding that complexity is a part of fisheries dynamics and goes beyond fishery landings [78]. Second, due consideration of the human dimensions of fisheries [79]. In this paper, we advocate that the human dimensions encompass social and economic aspects, such as fishers' organization, traditional knowledge, and social benefits, which can help explain trends in landings [72].

Long-term data series for target fish and bycatch are crucial to support EAF, yet information on fishery landings in Brazil is inconsistent, particularly for SSF. Small-scale fisheries around the world share some 'universal' common features: (i) they are multi-gear and multispecies, demanding alternative methods to evaluate multiple factors; (ii) there are no standardized methods to evaluate them; and (iii) they are still neglected [80–83]. SSF systems require a particular analytical design in order to encompass such complexity. In addition, when available, the use of scenario analysis, for example, can provide insights on how different fisheries could respond to changes in biomass and/or resource management [84].

The estuarine environments of Paranaguá and Guaratuba promote favorable conditions for high levels of productivity on the continental shelf where the Matinhos fisheries take place [71]. Therefore, different proportions of seabob and fish in the catch are more dependent on fishers' strategies, and on the technology available to them, than on the availability of resources (for example, the described adoption of the *rede alta* by Matinhos' fishers and their choice of fishing grounds specifically to target the Serra Spanish mackerel). Evidently, fish stocks must be monitored to avoid overfishing. As Rousseau et al. [50] have cautioned, although small-scale fleets have total engine power comparable to large-scale ones, this sector is not properly restricted and monitored.

Limited interpretations of which factors drive fishing strategies under the umbrella of Hardin's 'tragedy of the commons' [85] have led to narrow approaches to fisheries management [86]. Missing social and ecosystem dynamics at the community level undermine our ability to effectively manage resources at multiple levels (from the regional to community level) [87]. Fisheries management in Brazil faces historical challenges when managing fisheries at different scales and levels [4,88]. For example, successful fisheries management within marine protected areas (MPAs) contrasts with the absence of effective management outside the MPAs in the same region [89].

5. Conclusion

Most fishing stocks in Brazil are managed regionally, with generic rules in the context of multiple dynamics. This perspective of 'one size fits all' is grounded in a 'tunnel vision' of the problems, leading to narrow 'fixes' [2]. Complex adaptive systems require a more comprehensive understanding of how fisheries systems evolve at all pertinent scales and levels. Andriguetto-Filho et al. [21] reported that Paraná fishers are not usually specialized but employ opportunistic strategies for changing gear or mesh sizes in response to variations in the availability of resources, especially those of a seasonal nature. Our results suggest that, at least in the case of the Matinhos' *rede alta*, operating as an encircling gillnet, a better interpretation is that fishers are quick to adapt to new circumstances and specialize when it is advantageous. Their decisions actually integrate not only their particular societal circumstances but also their particular history of coping with social and technical change.

CRediT authorship contribution statement

J.M. Andriguetto-Filho: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **R.P. Medeiros:** Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **A.M. Vaz-dos-Santos:** Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **P.T.C. Chaves:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105184.

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