Progress in Oceanography 87 (2010) 320–330

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Priceless prices and marine food webs: Long-term patterns of change and fishing impacts in the South Brazil Bight as reflected by the seafood market

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ARTICLE INFO

Article history:
Available online 18 November 2010

ABSTRACT

The lack of market variables in fishery systems (i.e., prices and quantities) has often been cited as one reason for the particular difficulty of understanding whole marine ecosystem change and its management under a broader ecosystem perspective. This paper shows the results of efforts to tackle this problem in the South Brazil Bight by compiling and analyzing in-depth an unprecedented 40-year database from the region's largest wholesale seafood market, based in the megacity of São Paulo. Fishery landings and market values for the period 1968–2007 were analyzed primarily by updated trophic level classes and multispecies indicators including the (1) marine trophic index (MTI), (2) weighted price, and (3) log relative price index (LRPI) which relates prices and trophic levels. Moreover, an inferential analysis of major seafood category statistical trends in market prices and quantities and their positive and negative correlations was undertaken. In general, these market trends contributed substantially to identifying and clarifying the changes that occurred. Considerations of the behavior of demand, supply and markets are included. In particular, while the MTI did not support a "fishing down the marine food web" hypothesis, other indicators did show the continued scarcity of major high trophic level categories and fisheries target species. Overall, the results indicate that the analysis of fishery landings, or of certain other indicators alone, can mask real changes. Rather, a joint ecological–econometric analysis provides better evidence of the direction of ecosystem pressures and stock health. This method for detecting market changes across the food web may be particularly helpful for systems considered data-poor but where fish market data have been archived. This study further elucidates historical changes and fishing impacts in the South Brazil Bight ecosystem.

1. Introduction

The assessment and understanding of ecosystem change is a key issue in the context of ecosystem-based fisheries management (EBFM) (FAO, 2003). Multispecies analyses are required to detect changes in the structure of marine ecosystems over time, and several indicators focusing on key ecological aspects are often applied in such analyses (Garcia and Staples, 2000; Cury et al., 2005; Methratta and Link, 2006; Sumaila et al., 2007; Shannon et al., 2009). In this context, the scope of assessment should include not only fishery target species, but also dependent or competing non-target species, covering the broadest possible multispecies scenarios, and should encompass ecological, economic, social, technological, and governance aspects (Cury and Christensen, 2005). Markets also constitute an important aspect linking the natural (seafood resources) and human (consumers) dimensions that drive demand (Sumaila, 1998b; Failler and Pan, 2007). On the other hand, multispecies indicators should be easily parameterized and based on accessible data while communicating a variety of complex processes occurring within an ecosystem through single numerical values (Pauly and Watson, 2005), which seems to be both a challenge and a contradiction (Daan, 2005). Thus, new analyses that track ecosystem change and propose useful pressure indicators are still necessary to contribute to a pragmatic ecosystem approach to fisheries management and oceanography (Daan, 2005).

A first multispecies diagnosis can be performed by assessing time-series of fishery landings associated with species' bio-ecological characteristics, such as abundance, maximum length (Sumaila, 1998a), and trophic levels (Pauly et al., 1998; Vasconcellos and Gasalla, 2001; Milessi et al., 2005; Pauly and Palomares, 2005; Bhathal and Pauly, 2008). The main constraint of such a study seems to be knowledge availability; bio-ecological data are often absent for many species, especially those of lesser economic interest (Jennings et al., 1999), and several ocean ecosystems throughout the world remain data-poor.

A widely used multispecies indicator is the mean trophic level of the catches (Pauly et al., 1998), which has been applied in both

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doi:10.1016/j.pocean.2010.08.006

global analyses (Pauly et al., 1998) and at regional scales [e.g., Gulf of Thailand (Christensen, 1998), west coast of Canada (Pauly et al., 2001), Brazil (Vasconcellos and Gasalla, 2001), Argentinean–Uruguayan common fishing zone (Milessi et al., 2005), Mexico (Pérez-España et al., 2006), India (Bhathal and Pauly, 2008), and Portugal (Baeta et al., 2009). This indicator was termed the marine trophic index (MTI) when it was selected by the convention on biological diversity (CBD) to assess progress towards the reduction of biodiversity loss (CBD, 2004).

This metric is based on the fact that fish trophic levels (TL) relate to hierarchical niches within the marine food chain. Thus, a declining MTI can reflect an intense capture of top predators and their consequent depletion which reduces the trophic level of the fishery – the "fishing down the marine food web" phenomenon (Pauly et al., 1998). An alternative interpretation for a decline of the mean trophic level of the catch was given by Essington et al. (2006), who referred to "fishing through marine food webs". In this case, there is a sequential addition of intermediate trophic level taxa, which drives a decline in the mean trophic level of the catch, although fisheries of high trophic level are maintained or increased (Essington et al., 2006).

Another recommended, but not often used, approach is based on seafood economic data (Liu et al., 2005). Since the economy can directly and indirectly affect the fishery as well as both the resources and the ecosystem (Pinnegar et al., 2006; Sumaila et al., 2007), a market-based data series can also show signals of change across the marine food web (Sumaila, 1998a,b; Pinnegar et al., 2002, 2006), considering that fishing pressure directly relates to marine seafood demand. However, market databases of prices and quantities of fishery resources are usually scattered, incomplete, and unavailable to marine researchers. This has often been cited by economists, as an important gap toward both the understanding of marine ecosystem change and fisheries management (Gudmundsson et al., 2006; Sumaila et al., 2007). Moreover, it was suggested that the analysis of catch alone could mask, for instance, the "fishing down the marine food web" phenomenon (Sumaila, 1998b).

Considering these issues, this paper analyzes whether the trophic levels of marine fishery landings and market values in South Brazil have shifted as a function of time and whether such changes are reflected in both price and volumes of fishery resources across a 40-year period. The hypothesis considered was that market databases can provide useful variables to track changes across the marine food web. The results are expected to further elucidate ecosystem changes and fishing impacts in the South Brazil Bight.

1.1. Study area

The South Brazil Bight (SBB), located between 23° and 28°S, is a crescent shaped area of the South Brazil Large Marine Ecosystem (SBLME) (**Supplementary Fig. S1**). This LME can be considered the most productive coast of the Brazil Current region with moderately high productivity (150–300 g cm^{-2} yr^{-1}) associated with the Brazil–Malvinas confluence system and significant estuarine outflows (Heileman and Gasalla, 2008).

The SBB was considered a proper biogeographic unit defined by a stretch of coast cut by cliffs, small bays and many islands, with isobaths almost parallel to the coastline (Castro and Miranda, 1998) and oceanographic features including the occurrence of meso-scale eddies from the Brazil Current (to the east) and seasonal upwelling (Silveira et al., 2000). These features boost the regional primary productivity and, therefore, some fisheries, including the Brazilian sardine fishery (Castro et al., 1987; Gasalla and Rossi-Wongtschowski, 2004). In addition, numerous taxa are biogeographically limited by the northern and southern boundaries of this region (Lamardo et al., 2000). This region is also influenced by the largest Brazilian cities.

From 1980 to 1994, the industrial fleet that operated in this continental shelf contributed 36.8% of the total Brazilian catch (Paiva, 1997). Its fisheries were opportunistic (multispecies), mainly due to the over-exploitation of some target species (i.e., sardines, shrimps and some demersal fish) that can be attributed to strong fishing effort supported by fishing incentives policies since 1970, such as tax deductions for investment in fishing ventures (Valentini and Pezzuto, 2006; Abdallah and Sumaila, 2007). Trawling was the main type of fishing activity, although the presence of small pelagic stocks (particularly sardines) led to the development of an important purse-seine fishery, especially since 1950 (Vasconcellos and Gasalla, 2001). The sardine fishery catch dropped from 228,000 metric tons in 1973 to 17,000 in 2000, while the pink-shrimp trawl fishery declined from 16,629 in 1972 to 1166 in 2001 (Dias Neto and Marrul Filho, 2003).

Conversely, the pole-and-line based fishery for skipjack tuna (*Katsuwonus pelamis*) increased during the 1980s as a consequence of the regional expansion of industrial fisheries offshore (Valentini and Pezzuto, 2006). Other fleets that operated in this region included longliners in oceanic zones and gillnetters in the shelf area (Rossi-Wongtschowski, 2007; Haimovici et al., 2008). Historically, an important part of the regional seafood daily landings supplied the São Paulo Seafood Wholesale Market (SPSWM), regionally named as Companhia de Entrepostos e Armazéns Gerais de São Paulo.

Therefore, this marine ecosystem and its most representative seafood market were considered appropriate units for fisheries management under an ecosystem approach (Matsuura, 1995; Gasalla and Tomás, 1998; Gasalla and Rossi-Wongtschowski, 2004). The large marine ecosystem shows distinct environmental and oceanographic characteristics, as well as particular ecological and socio-economic aspects (Heileman and Gasalla, 2008).

2. Materials and methods

2.1. The data

An unprecedented compilation of monthly seafood market data for the period 1968–2007, including prices in Brazilian currency (R$ kg^{-1}) and quantities (in kg) per seafood category, was undertaken from the São Paulo Seafood Wholesale Market (SPSWM). The digitization of all available reports (CEAGESP, 1968–2007) resulted in a matrix of 223 seafood categories over 480 months, totaling 107,040 records. This fresh fish market is the largest in the region (Sonoda et al., 2002) and retails more than 250,000 metric tons of food and flowers every month (CEAGESP, 2009). Seafood corresponds to categories originating mainly from the SBB and adjacent areas of the SBLME. Most of the seafood categories coincide with the species level, however, some categories aggregate organisms of different species. The correspondence between popular names and scientific species made here was primarily based on technical reports from IBAMA (2007) and the Instituto de Pesca (2004). Moreover, in order to confirm the taxonomic identification of some categories, a visit with a team of experts was performed during market time at night.

Long-term analysis of an unstable economy requires the adoption of an index that considers inflation rates. The consumer price index (CPI) was chosen as a deflator, because it reflects the retail prices of basic, locally consumed products. This index is appropriate because seafood from the SPSWM primarily supplies the consumer market of the city of São Paulo.

Landing values for the entire SBLME region from 1968–1985 were obtained from the Sea Around Us (2007). Values for the period 1986–2004 were obtained from a detailed review of Valentini and Pezzuto (2006). Other publications (SUDEPE, 1969, 1978; Araújo, 1979; Nakatani et al., 1980; Krug and Haimovici, 1991;

Valentini and Cardoso, 1991; Valentini et al., 1991a,b; IBAMA, 1993a,b, 1994; Paiva, 1997) were used to complement the database.

2.2. The methods

Firstly, the marine trophic index (Pauly and Watson, 2005) was estimated for both the catch and market time-series. This index was proposed as the mean trophic level of the catch (Pauly et al., 1998) to reflect whether fisheries remove large, slower-growing fishes first, and thus tend to continually reduce the mean trophic level of the fish remaining in an ecosystem. The MTI is defined as:

$$\mathrm{MTI} = \frac{\sum \mathrm{TL}_{ij} Y_{ij}}{\sum Y_{ij}},$$

where Y_{ij} is the catch (or market quantity) of species i in year j and TL_{ij} is its trophic level.

It was possible to classify 135 seafood categories to trophic level (see **Appendix 1 in the Supplementary information**) based on local research on fish feeding habits, modeling, and stable isotopes, and by using data from FishBase (Froese and Pauly, 2000), which provides trophic level estimates from food items for many fish species. For 37 categories, trophic level was not available from local or regional studies; in these cases, we used references from the closest area possible. When several values were found from different sources, mean values were adopted.

Secondly, the annual price of each seafood market category weighted by its commercial quantity was used as an indicator, since the price should be linearly correlated with the quantity (Sumaila, 1998a; Pinnegar et al. 2002, 2006). Here, the indicator "weighted price" (P_m) followed the definition:

$$P_m = \frac{\sum P_{ij} Y_{ij}}{\sum Y_{ij}},$$

where Y_{ij} is the commercial quantity of seafood category i in year j, and P_{ij} is its price in year. For this analysis, the 135 available seafood categories marketed in the SPSWM from 1968 to 2007 were classified into four trophic level classes: high-TL (TL > 4), intermediate-TL (4 > TL > 3.3), low-TL (TL < 3.3), and invertebrates.

Thirdly, the logarithm relative price index (LRPI), proposed by Pinnegar et al. (2002, 2006) and based on Sumaila (1998b), was calculated by fitting annual linear regressions of price *versus* trophic level. The concept is based on the fact that high-TL species generally obtain higher market prices than do low-TL species (Pinnegar et al., 2002, 2006). The LRPI represents the slope (b) of the linear regression between log price (in this case, in R$ kg^{-1}) in a particular year, and the trophic levels of each seafood category, accordingly:

$$b = \frac{\mathrm{TL} + a}{\mathrm{Log\ RPI}},$$

where b is the index, the Log RPI is the logarithm of the relative price of all seafood categories for that particular year, and TL, the trophic level of all single-categories. The logarithm is used because inflation acts non-linearly and results in larger absolute increases in the price of high-value categories compared to lower-value categories (Pinnegar et al., 2006).

Two different time-series were used in applying this indicator: (i) the complete original time-series and (ii) a larger interpolated data series. In the first case (i), only categories without missing values in the original time-series, including invertebrates, were considered. In order to improve the analyses by considering as many categories as possible, the period was split into two: 1968–1989 (with 42 categories) and 1992–2007 (with 38 categories). The second time-series (ii) was based on 99 categories in which the missing values were interpolated following criteria suggested by Sumaila et al. (2007): (1) trends were assumed to follow those of similar categories; (2) the weighted mean was used when just a few years were missing; and (3) when data were missing from the beginning or end of the period, the last data available was considered to remain constant.

Fourthly, high market prices relate to the scarcity of seafood supplies (quantities) (Clark, 2006). Although changes in consumer tastes and preferences and substitution can influence the relationship between price and quantity, these may be in fact used to detect a "scarcity effect" for each seafood category, which can also be considered as a pressure indicator or even a signal of over-exploitation. In order to understand the changes underlying the multispecies indicators and verify whether they show real change, a detailed analysis was performed for 44 major seafood categories of the SPSWM (Table 1), including a detailed inferential analysis (see Section **2.3**). These market categories made up 62–90% (in kg) of the yearly total market volume and had the most complete time-series (<10% missing data) from the period 1968–2007. The relative importance of the different market categories, based on their quantities, was analyzed yearly. Market categories were also classified into the four different trophic level classes already described.

Lastly, total annual values of market quantities and their relative importance were calculated for the period 1968–2007 in order to verify whether the maximum yield of the fishery corresponds to the maximum marketed and landed amounts. The total annual value corresponds to the sum of each total value of the market quantity (price × quantity, in Brazilian currency) by taxonomic groups and by year. Seafood market categories from the SPSWM database were aggregated into larger groups following the classification in the Sea Around Us (2007), related to the SBLME (Heileman and Gasalla, 2008) (i.e., crustaceans, perch-like fish, herring-like fish, cod-like fish, tuna and billfishes, anchovies, sharks and rays, flatfishes, mollusks, and other fish and invertebrates) in order to allow for comparisons between the two different and above mentioned sources.

2.3. Statistics

To test for significant long-term trends, the non-parametric Cox–Stuart test was applied (Conover, 1980) on the time-series of MTI, LRPI and the weighted price. A significance level of 5% was adopted for all tests. In order to test the market law economic theory as applied to the SPSWM database, the following issues were tested statistically: (i) the correlation between the price and quantity of each category using Pearson's linear coefficients; (ii) the significance of Pearson's correlations; and (iii) the significance of the trends of prices and quantities using the Cox–Stuart non-parametric test (Conover, 1980; Bussab and Morettin, 2006).

3. Results

3.1. Multispecies indicators

3.1.1. The marine trophic index

The MTI for both fishery landings (SBLME) and market amounts (SPSWM) over 40 years is shown in Fig. 1, exhibiting smooth upward trends. The MTI of fishery landings significantly increased from 3.05 to 3.47 (p-value < 0.05), and the MTI of the market increased from 3.09 to 3.6 (p-value < 0.05). When Brazilian sardines, shrimps and tuna-like fish were excluded from the analysis the upward trend became smoother (Fig. 1), ranging from 3.42 to 3.62 for market quantities and from 3.26 to 3.53 for fishery landings. The index showed no significant variation over time for the market data (p-value > 0.05).

Table 1
Statistical significance of both linear correlations and variation trends of price and quantities time-series. (*P* indicates a positive trend, *N* indicates a negative trend, *P–N* indicates an initially positive trend followed by a negative trend, and "–" indicates no statistical significance).

Seafood category	Species	Price × quantity Pearson's coefficient (*p*-value)	Price trend (Cox–Stuart *p*-value)	Quantity trend (Cox–Stuart *p*-value)
Billfish	*Tetrapturus pfluegeri, Makaira nigricans, Istiophorus* spp.	–	–	*N* (0.0004)
Stripped weakfish	*Cynoscion guatucupa*	–	*P* (<0.0001)	–
Jamaica weakfish	*Cynoscion jamaicensis*	–	*P* (<0.0001)	–
Black grouper	*Mycteroperca bonaci*	–	*P* (<0.0001)	–
Brazilian guitarfish	*Rhinobatos horkelli*	–	*P* (<0.0001)	–
Yellowtail amberjack	*Seriola lalandi*	–	*P* (<0.0001)	*P* (0.0004)
Hammerhead shark	*Sphyrna* spp.	–	–	*P–N* (0.0414)
Angel-shark	*Squatina* spp.	–	*P* (<0.0001)	–
Pompano	*Trachinotus* spp.	–	*P* (0.0005)	–
Atlantic horse mackerel	*Trachurus lathami*	–	*P* (<0.0001)	–
Sharks	Lamnidae, Carcharhinidae, Triakidae, Odontaspididae, Sphyrnidae, Alopiidae and Squalidae	–	*P* (<0.0001)	–
Flatfish	Paralichthyidae and Bothidae, Achiridae	–	*P* (<0.0001)	–
Rays	Rajidae, Rhinobatidae, Myliobatidae, Gymnuridae, Narcinidae and Dasyatidae	–	*P* (<0.0001)	–
Pink-shrimp	*Farfantepenaeus* spp.	−0.805 (<0.001)	*P* (<0.0001)	*N* (<0.0001)
Brazilian sardine	*Sardinella brasiliensis*	−0.696 (<0.001)	*P* (<0.0001)	*N* (<0.0001)
Spinner shark	*Carcharhinus* spp.	−0.514 (<0.001)	*P* (<0.0001)	*N* (<0.0001)
Sand perch	*Pseudopercis* spp.	−0.434 (<0.001)	*P* (<0.0001)	*N* (0.0001)
Green weakfish	*Cynoscion virescens*	−0.383 (<0.001)	*P* (0.0044)	*N* (<0.0001)
Grouper	*Epinephelus marginatus*	−0.340 (<0.001)	*P* (<0.0001)	*N* (0.0026)
Anchovy	*Anchoa* spp.	−0.268 (<0.001)	*P* (<0.0001)	–
Chub-mackerel	*Scomber japonicus*	−0.255 (<0.001)	*P* (<0.0001)	–
Serra mackerels	*Pristis pectinata*, *Sarda sarda*, *Scomberomorus maculatus*	−0.210 (<0.001)	*P* (<0.0001)	–
Swordfish	*Xiphias gladius*	−0.205 (0.002)	*P* (0.0039)	(0.0075)
Common seabream	*Pagrus pagrus*	−0.202 (<0.001)	*P* (<0.0001)	–
Inshore squid	*Loligo* spp.	−0.177 (<0.001)	*P* (<0.0001)	–
Bluefish	*Pomatomus saltatrix*	−0.155 (0.001)	*P* (<0.0001)	–
Goatfish	*Mullus* spp.	−0.139 (0.006)	*P* (<0.0001)	–
Sea bob shrimp	*Xiphopenaeus kroyeri*	−0.098 (0.045)	–	*N* (<0.0001)
Sharpnose shark	*Rhizoprionodon* spp.	−0.132 (0.004)	*P* (<0.0001)	–
Mullets	*Mugil* spp.	−0.131 (0.004)	*N* (0.0118)	*P* (0.0026)
Atlantic moonfish	*Selene setapinnis*	0.103 (0.043)	*P* (<0.0001)	–
Argentine croaker	*Umbrina canosai*	0.104 (0.037)	*P* (<0.0001)	–
Catfish	*Arius* spp., *Cathorops* spp., *Netuma* spp.	0.126 (0.006)	*P* (<0.0001)	–
Skipjack tuna and other bonitos	*Auxis thazard, Katsuwonus pelamis, Euthynnus alletteratus*	0.166 (<0.001)	*P* (<0.0001)	*P* (0.0118)
Spanish mackerel	*Scomberomorus brasiliensis*	0.185 (0.002)	*P* (<0.0001)	*P* (0.0026)
White mullet	*Mugil* spp.	0.203 (<0.001)	*P* (<0.0001)	*P* (0.0414)
Whitemouth croaker	*Micropogonias furnieri*	0.209 (<0.001)	*P* (<0.0001)	–
Miscelaneous fishes		0.218 (<0.001)	*P* (0.0026)	–
Cutlass fish	*Trichiurus lepturus*	0.269 (<0.001)	*P* (<0.0001)	–
Common snook	*Centropomus* spp.	0.340 (<0.001)	*P* (<0.0001)	*P* (<0.0001)
Bigtooth corvina	*Isopisthus parvipinnis*	0.342 (<0.001)	*P* (<0.0001)	*P* (0.0118)
Tuna	*Thunnus* spp.	0.401 (<0.001)	*P* (0.0001)	*P* (<0.0001)
Kingfish	*Menticirrhus* spp.	0.561 (<0.001)	*P* (<0.0001)	*P* (0.0026)

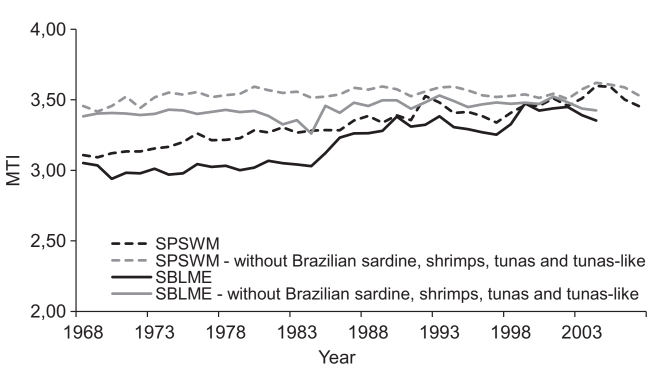

Fig. 1. Marine Trophic Index of fishery landings from the South Brazil Large Marine Ecosystem and of market quantities from the São Paulo Seafood Wholesale Market for the period 1968–2007 (lines in grey exclude the Brazilian sardine, shrimps, tunas and tuna-like categories).

3.1.2. Weighted price over time

A marked upward temporal trend (p-value < 0.05) of prices weighted by monthly commercial quantities of 135 seafood categories is shown in Fig. 2a. Prices, ranged from R$0.89 at the start to R$3.76 at the end of the time-series. Seafood categories grouped by trophic level classes showed significantly different increasing trends (p-value < 0.05) (Fig. 2b). Slopes indicate that the high-TL class had increased comparatively more (slope = 0.13) than low-TL (slope = 0.06) and intermediate-TL (slope = 0.10) classes (Fig. 2b). Invertebrates also showed an upward trend of weighted price (Fig. 2c), which ranged from a minimum of R$2.09 to a maximum of R$12.22. This high price corresponds to the pink-shrimp (*Farfantepenaeus brasiliensis*; *F. paulensis*).

3.1.3. Log relative price index (LRPI)

3.1.3.1. Original time-series analysis. Results for the earliest period (1968–1989) showed a significant decreasing trend of LRPI (Fig. 3a and c; p-value < 0.05), ranging from −0.1 to 0.03. The small increase before 1971 can be explained by the fact that the price of some high-TL categories, such as large crevalle jacks, horse-eye jacks, king mackerel and tunas, increased by 58%, 54%, 33%, and 39%, respectively, while most low-TL categories decreased (e.g. crabs, Brazilian sardines, chub mackerels, whitemouth croakers, and catfish (CEAGESP, 1968–1971). This was followed by a decreasing trend for the index, which is explained by an increase

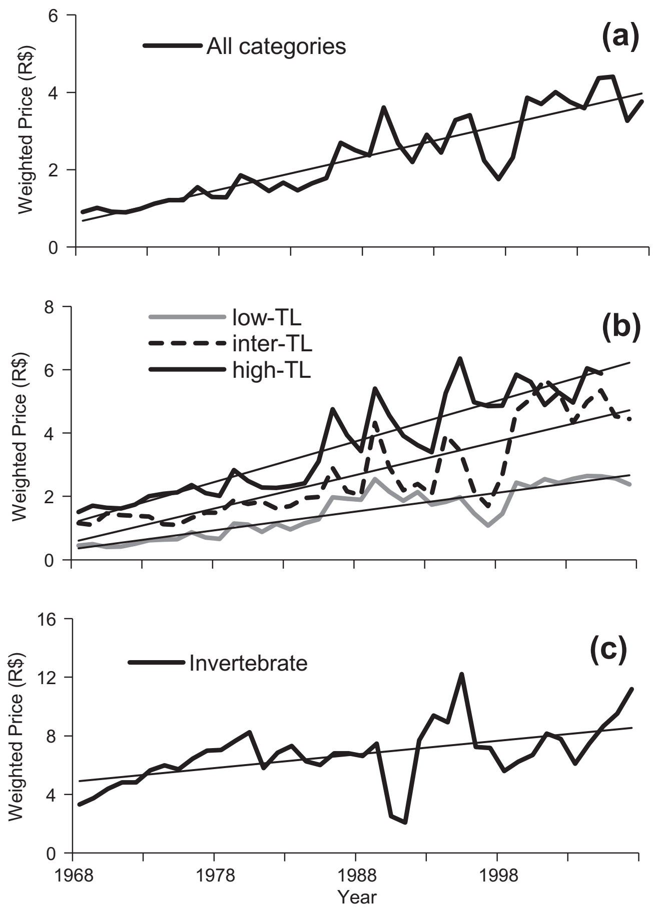

Fig. 2. Weighted price of (a) all 135 market categories, (b) high trophic level, intermediate trophic level, and low trophic level fish, and (c) invertebrates, for the period 1968–2007.

in the prices of all categories that was greater for some low-trophic level taxa (783% for crabs, 694% for Brazilian sardines, and 758% for chub mackerels) (CEAGESP, 1971, 1989).

For the period from 1992 to 2007 (Fig. 3b and d), the LRPI showed greater variation than during the earlier period (1968–1989). The increasing trend of LRPI during 1992–1996 was due to the fact that high-TL categories, such as angel sharks, became more valuable (83% price increase) compared to low-TL categories, such as chub mackerels (CEAGESP, 1992, 1996). Between 1996 and 2003, the index decreased, reflecting an actual increase in the prices of low-TL categories, such as whitemouth croakers (222%), bigtooth corvinas (241%), and Brazilian sardines (269%) (CEAGESP, 1996, 2003). After 2003, low-TL categories declined in value, resulting in an increasing index (CEAGESP, 2003, 2007). However, between 1992 and 2007, the dynamic trend was not statistically significant (p-value < 0.05).

In both periods, when the errors bar are considered (Fig. 3c and d) the LRPI trend seemed smooth since the error is high (~0.03) compared to the variation in the LRPI trend.

3.1.3.2. Interpolated time-series analysis. A significant decreasing trend of LRPI (p-value < 0.05), ranging from 0.09 to −0.06, was observed (Fig. 4). The first decreasing trend (1968–1993) occurred primarily because the price increased 1475% for pink-congers, 1009% for greater amberjacks, 986% for snowy groupers, 969% for yellowtail amberjacks, and generally for high-TL species (CEAGESP, 1968, 1993, with interpolated unpublished data). The observed break between 1993 and 1995 (Fig. 4) is explained by price increases for some low-TL categories, such as 868.7% for the carib, 168.05% for mussels, and 128% for horse-mackerels, and also for some high-TL categories, such as 143.61% for crevalle jacks and 131.99% for Spanish mackerels (CEAGESP, 1993, 1995, with interpolated unpublished data).

More recently, between 1995 and 2007, the observed LRPI trend was driven more by high-TL species, such as dolphinfish and amberjacks (*Seriola dumerili* and *S. lalandi*), that became more

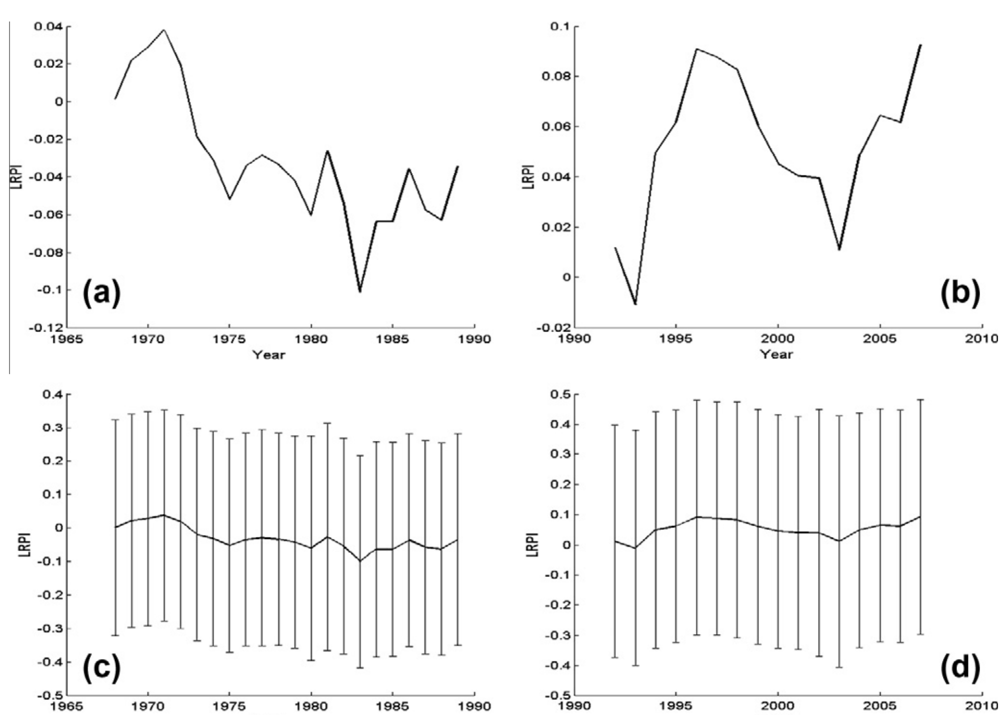

Fig. 3. Annual Logarithm Relative Price Index trends for (a) 1968-1989, (b) 1992-2007, followed by the respective annual standard errors (ca. ±0.35) for 1968-1989 (c), and 1992–2007 (d).

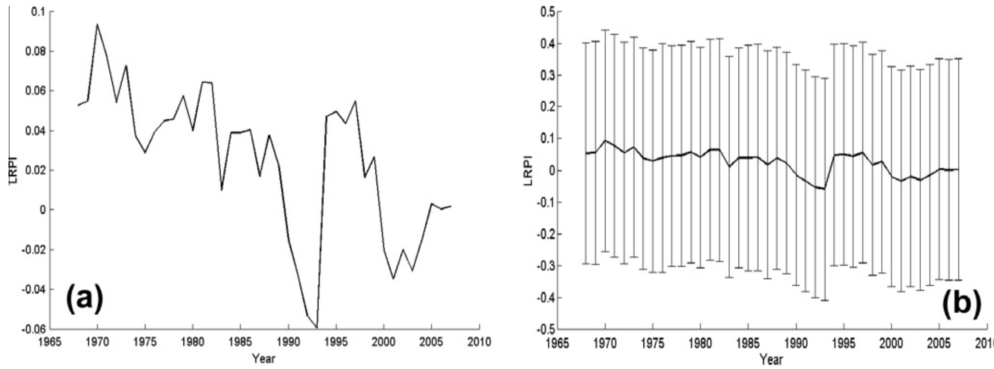

Fig. 4. Annual interpolated Logarithm Relative Price Index trends for the period 1968–2007 (a) and standard errors (ca. ±0.35) (b).

valuable than low-TL categories, in spite of the increased price of goatfish and of some shrimp (both from the low-TL class) (CEAG-ESP, 1995, 1997, with interpolated unpublished data).

3.2. Market-series analysis of major seafood category

3.2.1. Market quantities

The composition of the total market quantity sorted by the four different trophic level classes changed over time (Fig. 5; **Supplementary Fig. S2–S4**). In the earlier period, market quantities were dominated by low-TL species (∼60%), especially by Brazilian sardines (**Supplementary Fig. S4**), whose quantities changed abruptly, especially since 1992. In 2007, market quantities were dominated instead by intermediate-TL species (∼50%), such as the triggerfish *Balistes capriscus*, and also by some high-TL species (∼10%), such as tunas (*Thunnus* spp.), skipjack tunas, and other bonitos (*K. pelamis*, *Auxis thazard* and *Euthynnus alletteratus*) (**Supplementary Fig. S2**).

3.2.2. Inferential analysis of the behavior of major seafood category

Fig. 6 and **Supplementary Fig. S5–S8** show trend plots of market prices *versus* market quantities for seafood categories representing the four TL classes. Table 1 shows the statistical significance of both linear correlations and variations in the trends of the price and quantity time-series. Of the 44 categories included in the analyses, 31 showed significant linear correlations (*p*-value of Pearson's coefficient < 0.05) between trends of prices *versus* commercial quantities (Table 1).

Seventeen categories showed negative correlations between market prices and quantities (i.e., increasing price with decreasing quantity) (Table 1; see Fig. 6 and Suplementary Figs. S5-S8). Note the trends of spinner shark, mackerels, Brazilian sardine and pink-shrimp in Fig. 6 (see also sharpnose shark, swordfish and sand perch in **Supplementary Fig. S5**; grouper, common seabream, green weakfish in **Supplementary Fig. S6**; chub mackerel, anchovy, mullets, goatfish in **Supplementary Fig. S7**; and seabob-shrimp and squids in **Supplementary Fig. S8**). Assuming a constant demand, this price-quantity relation is at most determined by the supply, since marine seafood supply depends greatly on the stocks availability and environmental variability (Bakun, 1996), The negative correlation was particularly stronger for high-TL categories (especially piscivorous fish, such as spinner sharks (−0.51) and sand perches (−0.43) (Fig. 6b and **Supplementary Fig. S5d**) and also for some fisheries target and commercially important low-TL species, such as sardines (−0.69) (Fig. 6e) and pink-shrimp (−0.80) (Fig. 6f).

Significant positive correlations between market prices and quantities were found for 13 categories (see Fig. 6a and d, **Supplementary Figs. S5c, e, S6a, b, d, e, h, i and S7a, d, e**), particularly for tunas and tuna-like fish (Fig. 6a and **Supplementary Fig. S5b**).

Price trends for 40 out of 44 categories showed statistical significance (Table 1). However, only 19 seafood categories showed a significant variation in the trend of market quantities (Table 1). Categories that did not show significant trends in quantities, such as mackerels (Fig. 6c), flatfish (**Supplementary Fig. S6k**) and sharks (**Supplementary Fig. S5c**), showed an early increase followed by a decrease in the later period, while prices always increased.

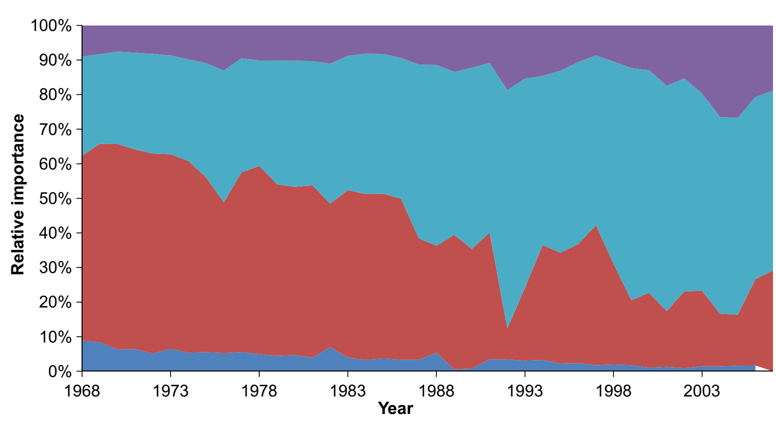

Fig. 5. Annual relative importance of trophic level classes (high, intermediate, low trophic level species and invertebrates) in the total market composition between 1968 and 2007.

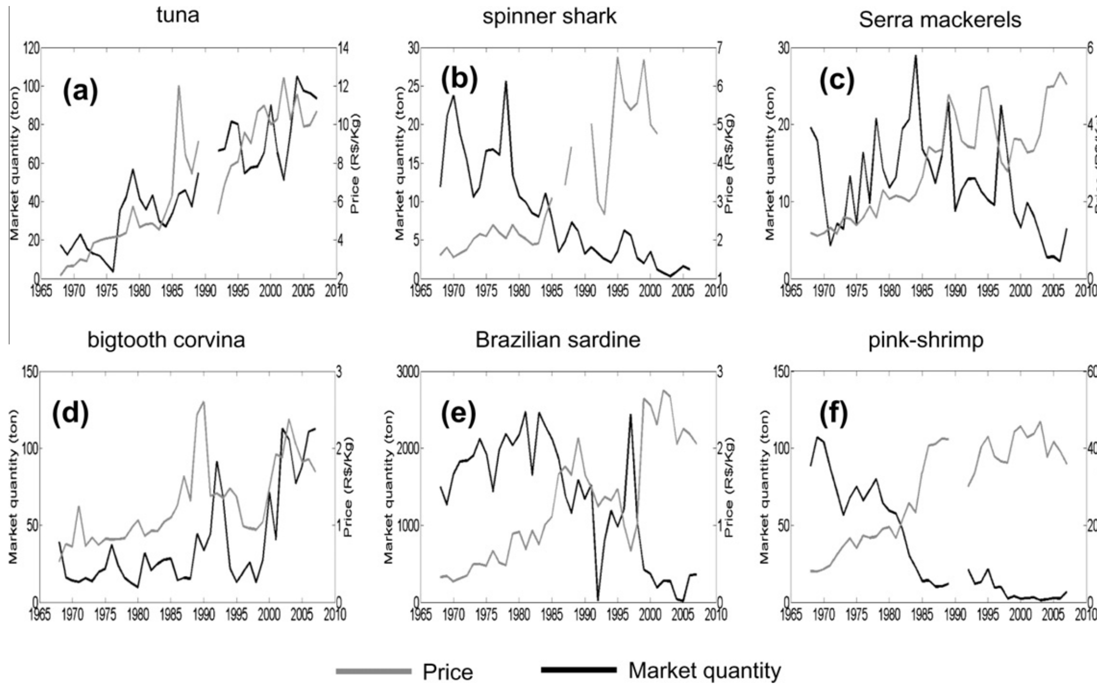

Fig. 6. Trends of market prices and quantities from 1968–2007 for: (a) tuna, (b) spinner shark, (c) Serra mackerels, (d) bigtooth corvina, (e) Brazilian sardine and (f) pink-shrimp.

3.2.3. Total value of the market quantities

The history of the total commercial value of seafood of the SPSWM (Fig. 7) showed an upward trend from 1968 to 1989, reaching R$150 million, and a predominantly decreasing trend after 1989. This decline was accompanied by changes in the relative importance of some categories, such as crustaceans and herring-like fishes. From 1968 to 2007, the total value of herring-like fish and crustaceans declined 10% and 25%, respectively, while that of perch-like fish increased by 20%.

Moreover, it is important to note that the maximum total value (∼R$200 million, reached in 1989) did not occur in the same period as the maximum total Brazilian landings (∼350,000 metric tons, reached in 1972), nor at the same time as the maximum commercial quantity (∼85,000 metric tons, reached in 1984) (Fig. 8). Another important point is that the trend of total seafood market quantities over time apparently correlated with the trend of total Brazilian fishery statistics (Fig. 8), in spite of their different spatial scales.

4. Discussion

Our findings demonstrate the value of economic data for interpreting the dynamics of exploited populations and their fisheries that can be used to investigate changes across the food web.

The MTI analysis conducted did not support the expected "fishing down the marine food web" process (Pauly et al., 1998). However, signals of change in this direction (i.e., heavy decline of high-TL categories) were verified by the additional market analysis. Moreover, this study illustrates the continuous "scarcity effect"

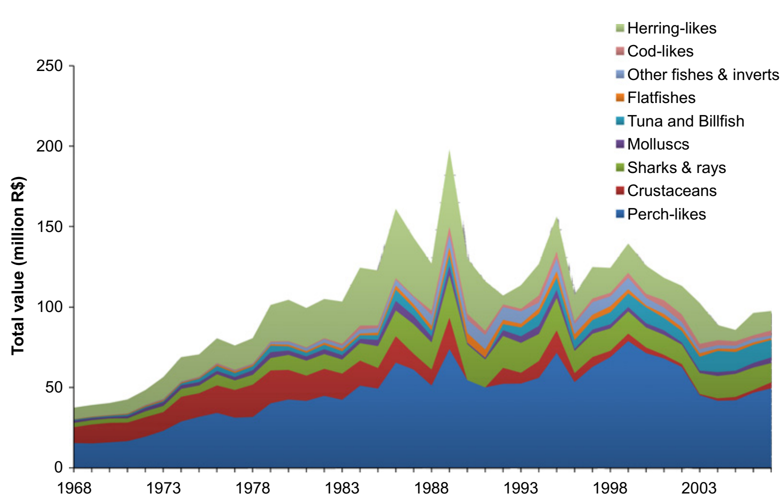

Fig. 7. Seafood values (in R$) from the São Paulo Seafood Wholesale Market for the period 1968–2007.

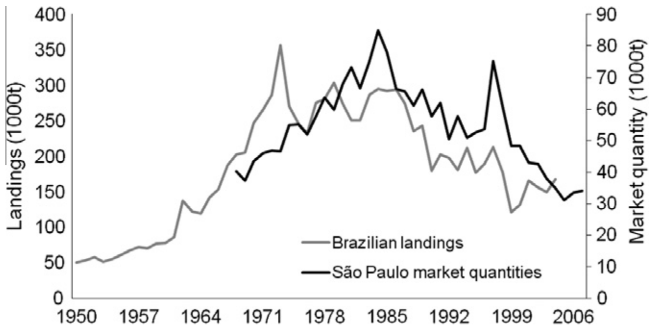

Fig. 8. Total Brazilian landings and total São Paulo Seafood Wholesale Market quantities, in metric tons (source: Sea Around Us; CEAGESP).

of some high-TL market categories in the SBB over 40 years, as well as of the main target species in the fishery. Nevertheless, the analysis of each multispecies indicator was able to demonstrate different aspects of change and non-linearities, as indicated below.

4.1. Marine trophic index

The light upward trend of MTI found in this study, which indicates that the mean trophic level of both landings and market quantities has increased slightly over 40 years, seems to be explained in part by the decline in landings of the low-TL Brazilian sardine and shrimps, which have historically been the most important fishery resources of the region (Matsuura, 1981; Vasconcellos and Gasalla, 2001; Rossi-Wongtschowski, 2007) (Fig. 6e and f). Also, although most high-TL categories declined over time (e.g., sharks) for both market data (**Supplementary Fig. S2**) and landing volumes (Valentini and Pezzuto, 2006), there was an increase of tuna-like fish in the later period which contributed to the total MTI increase. This seems consistent with both the expansion of pelagic offshore fishing (i.e., longlining for tunas and pole-and-lining for skipjack) together with the increasing demand for these species to supply the local Japanese restaurants that became fashionable in the city of São Paulo (Teixeira et al., 2004; Germano and Soares, 2004).

There were other changes reflected by the market-series that could explain part of the MTI trend. During some periods, intermediate-TL species increased in market quantities (**Supplementary Fig. S3**) and landings (Valentini and Pezzuto, 2006), including the triggerfish *B. capriscus* and some sciaenid fish (e.g., *Menticirrhus* spp.). These categories are part of the by-catch of the pink-shrimp and seabob-shrimp fisheries (Rossi-Wongtschowski, 2007), and became valuable when other target species became scarce.

Moreover, there seem to be a number of reasons why the MTI may not vary significantly. It may be due to the non-linearities and eventual ecological replacement of overexploited species by others within the same trophic level or below, often called "ecological compensation" (Jackson, 2001; Jackson et al., 2001). On the other hand, it may be because of the high biodiversity and life history patterns of these tropical fish (Pauly, 1998; Pérez-España et al., 2006). The SBB is located in a transition zone of the sub-tropical Atlantic Ocean which is characterized by oceanographic features that are somewhat different from those of typical tropical regions. Nevertheless, the system is highly diverse, which can certainly increase resilience (Holling, 1973). Overall, this may make it more difficult to detect and record structural changes in the marine ecosystem over time by the use of one single indicator. Previous studies from marine fisheries of Brazil, using other databases and different spatial scales, have found an increasing trend in MTI (Vasconcellos and Gasalla, 2001; Sea Around Us, 2007 (after Heileman and Gasalla, 2008)).

Therefore, an important point is that the MTI incorporated both the behavior of the fishery and exploited populations and may provide a simplistic interpretation of the processes causing change in marine populations.

4.2. Market database analysis and economic indicators

Our study demonstrates that prices can be relevant variables for the study of structural change in marine ecosystems, especially for data-poor situations (i.e., when time-series of marine population biomass or abundance are missing).

Market prices and quantities of the SPSWM usually followed the supply–demand law, as indicated by a simple price and quantity analysis (Table 1). The positive and negative correlations between price and market quantity for specific species or categories reflected key issues.

An increase in the price of some high-TL categories and also for fishery target and commercially important low-TL species (i.e., sardines and pink-shrimp) (Figs. 6e and f) and a decrease in their market quantities reflect their poor supply in the marine ecosystem. It can be observed from the significant negative correlations between market prices and quantities (Table 1; Fig. 6b, c, e, f and **Supplementary Fig. S5c, d, f, S6c, e, f, S7b, c, g, h and S8**), assuming a constant demand. This is based on the fact that prices tend to increase when available quantities are decreasing due to a supply restriction, especially in the case of seafood that is a natural resource and dependent on unpredictable environmental issues.

On the order hand, for some other categories, such as tuna-like fish (Fig. 6a and **Supplementary Fig. S5b**), demand cannot be considered constant, since local demand seems to exceed supply, as indicated by positive correlations between prices and market quantities (Table 1). As mentioned previously, the increasing offshore fishing effort (Teixeira et al., 2004) and the demand for local Japanese food (Germano and Soares, 2004) may explain this.

Some categories, such as mackerels (Fig. 6c), flatfish (**Supplementary Fig. S6k**) and sharpnose shark (**Supplementary Fig. S5c**) showed an earlier increase followed by a decreasing trend in quantities, while the price always increased. This seems to reflect the fisheries development phases from expansion through over-exploitation (Jennings et al., 2001). In the former phase, the increasing demand is greater than the supply due to fisheries development, while the price increases. In the later phase, the quantity decreases while the price increases, reflecting the fishing pressure (assuming a constant demand).

In general, seafood prices can be influenced by particular changes in consumer income, current tastes or preferences or by the price of substitutes on the market. They can also be influenced by the availability of suppliers (fishing fleets) to land desirable fish, which in turn is reliant upon the availability of target species in the environment, technological innovations as well as the weather (Ludicello et al., 1999).

In terms of multispecies economic indicators, both weighted price over time and LRPI, showed signs of fishing pressure and over-exploitation. The increase in prices of high-TL species (except for tunas) and fleets' target species as a consequence of their supply limitation could have forced the prices of other species of intermediate-TL to increase while the target species became commercially extinct. This can be corroborated by the fact that while the target species of the main shrimp trawl fishery were in decline, some intermediate-TL categories, such as the triggerfish and some Sciaenidae (e.g., *Umbrina canosai* and *Menticirrhus* spp.) became more important as bycatch (Vianna and Almeida, 2005). A similar pattern was observed for the sea-bob shrimp fishery, since the market quantity of this target species decreased over time while that of bycatch species, such as the sciaenid fish *Isopisthus parvipinnis* (**Supplementary Fig. S3**), increased.

This phenomenon has also been observed by Pinnegar et al. (2002, 2006), and was described by Sumaila (1998a) as "pricing down the food web", based on the fact that markets shift to previously undesirable seafood when target species become unavailable (Sumaila, 1998a, 1998b). These patterns are reinforced by the LRPI analysis (but see restrictions in Section **4.3**), in which the significant decreasing trends over time correspond only to the later portion of the conceptual model proposed by Pinnegar et al. (2006). A decreasing trend in the LRPI possibly reflects a period of substitution within seafood markets whereby high-TL categories began to become "commercially extinct" and were replaced by lower-TL (low and intermediate-TL) categories which attained a higher value. In our study case, the pricing of lower trophic level species can be due to their high-TL replacement or their scarcity (e.g., for Brazilian sardine). This situation contrasts the increasing trend of LRPI when high-TL species became relatively more expensive than low-TL species, as shown in the analyses from the Celtic Sea (Pinnegar et al., 2002, 2006) and Portugal (Baeta et al., 2009).

In addition, the historical trend of total market value (Fig. 7) shows a relevant point: the maximum value reached by the seafood market in 1989 corresponded to a period of declining fishery landings (Fig. 8). This lack of synchrony between the peak value and the peak volume of fishery landings suggests a typical case of economic overfishing, where the scarcity corresponds to the maximum of yield (Clark, 2006).

Moreover, evidence of change in the relative importance of market and landing categories as a consequence of the decline of some target species, such as pink-shrimp, Brazilian sardines, and demersal fishes (Valentini and Pezzuto, 2006), appeared to be clear. Although the prices of both target species and some high-TL increased (Fig. 6b, c, e, f and **Supplementary Figs. S5c, d, f, g and S8a2–S4**), the total market value did not maintain its earlier maximum (Fig. 7).

Considering the total market values of grouped categories (commercial groups) (Fig. 7), the participation of the main groups appeared to be different than in the Sea Around Us (2007) (Heileman and Gasalla, 2008, p. 726). In SPWSM trends, the participation of perch-like fish was greater, while crustaceans were of lesser importance.

Another important point is the similar trend between the total seafood market quantities over time and the total Brazilian fishery statistics (Fig. 8), in spite of their different spatial scales. This indicates that trends in the local market relate more to the fisheries themselves, i.e. to the supply curve, than to a particular local demand, even though this intrinsic relationship may exist. The period of increase until the mid-1980s (Fig. 8) can be largely explained by government fiscal incentives implemented in the 1970s that resulted in a significant increase of total fishing effort (Abdallah and Sumaila, 2007). More recently, while total Brazilian landings have remained stable due to the introduction of new fisheries in other parts of the country, the total seafood market volume in São Paulo has decreased (Fig. 8). This is consistent with regional trends in total landings (Instituto de Pesca, 2004), but may also be due to external factors such as middleman competition by supermarkets (Sonoda et al., 2002).

4.3. Constraints and pitfalls

There are some potential limitations to be considered when evaluating the results of this kind of analysis. First, the trophic level of categories may incorporate some uncertainty, because they are estimated from data based on different methods and areas and from some gray literature. Unfortunately, this cannot be overcome until new trophic studies are performed in the study area.

Concerning LRPI, there was an additional constraint, since the statistical standard error associated with the index was much larger than the signal itself (Figs. 3 and 4; ca. ±0.3). A positive linear correlation between price and trophic level is assumed for the interpretation of such an index, but for some high-TL categories (e.g., some sharks, snappers, cutlass fishes and cobias) a pattern of high prices was not always found, resulting in some weak yearly correlations. However, since the correlations between price and trophic levels followed positive trends, the interpretation of the index behavior can be based on the slopes over time rather than just on absolute values.

Additionally, considering other aspects that influence the market price time-series, such as changes in fishing preferences or consumer tastes (Sumaila, 1998b), the SPWSM database seems to be very consistent with the behavior of local fisheries and availability rather than being primarily demand-oriented. However, improved interpolation processes could be used to track such subjective variables, including uncertainties that may be underestimated (Maunder and Deriso, 2010). Other improvements to the present analysis may include models of substitution elasticity between seafood categories (Asche et al., 2007).

4.4. Implications for the understanding of ecosystem change and management

One of the study's main findings, following the market law, was that the price increase of high-TL categories (with the exception of tuna-like fish) was possibly due to the scarcity of their supply. This can be reflected by the decrease in market quantity and increase in prices, assuming a constant demand situation. The same pattern was observed for the most important target species, sardine and shrimps, that are both from low-TLs. Their scarcity can also be emphasized by the fact that intermediate-TL bycatch categories increased in quantity and prices.

These findings highlight possible fishing impacts mainly at the top (high-TL) and close to the bottom of the food web (i.e., sardines, from the pelagic pathway, and shrimps, from the detritus-based pathway).

Changes over time at the top of the food web may eventually drive a cascading process in the ecosystem. This top-down trophic control occurs because top predators exert considerable effects on their prey that can cascade through marine communities (Daskalov, 2002; Worm and Myers, 2003; Heithaus et al., 2009). Thus, a decrease in the abundance of trophic level 4 leads to a decrease in the rate of predation mortality on trophic level 3 and thus an increase in its biomass, and so on.

In the SBB area, previous studies have demonstrated and simulated top-down control of the marine food web (Gasalla et al., 2003; Gasalla, 2004a; Gasalla and Rossi-Wongtschowski, 2004). The reduction of piscivore fish populations has been shown in this area by studies that have reconstructed past scientific surveys conducted before the expansion of industrial fisheries (Gasalla, 2004a) and those that have assessed fishers' knowledge (Gasalla, 2004a,c). Both fishery-dependent and independent data (based on scientific surveys) suggest the decline of large piscivorous fish and changes in species composition. The testimonies of older fishermen also indicate that sharks were considered to have "disappeared" during the last 50 years in the SBB (Gasalla et al., 2003, 2007). The pre-fished coastal ecosystem used to support larger populations of sharks, large carangids, serranids, and lutjanids and larger stocks of sardines and mullets (Gasalla, 2004b). Following those trends, some of the evidence found in this present market analysis seems to corroborate these previous findings, such as spinner shark (Fig. 6b), mackerels (Fig. 6c), swordfish (**Supplementary Fig. S5f**) and sand perch (**Supplementary Fig. S5d**) that showed clearly a decrease in market quantity and an increase in price.

Such top-down effects in marine food webs have been widely discussed in the literature (Jackson, 2001; Vasconcellos and

Gasalla, 2001; Baum et al., 2003; Worm and Myers, 2003; Gasalla and Rossi-Wongtschowski, 2004; Myers et al., 2007). There are several potential ecosystem effects of fishery-induced removal of large predators. Not only the extinction of populations, but also the reduction of fish biomass to low levels, may compromise the sustainability of fisheries, which may eventually produce only small economic yields (Myers and Worm, 2003). Conversely, the intense removal of resources close to the bottom of the food web can eventually trigger bottom-up alterations (Menge, 1992).

One mechanism that could compensate for the effects of fishing is the increases in non-target species due to release from predation or competition (Worm and Myers, 2003). In our analyses, signs of species compensation can be raised, for example, in the case of triggerfish or some Sciaenidae increases, both of which are bycatch in the pink-shrimp fishery. However, accurate prediction of the ecological consequences of past and potential future declines is critical for fisheries and ocean ecosystem management (Heithaus et al., 2009) but hard to achieve, especially when scientific surveys that monitor population changes are missing. In terms of a fishery management perspective, our findings are a useful contribution to the implementation of Ecosystem Approach to Fisheries practices, such as ecolabeling and modeling techniques. Overall, this study contributes to further elucidating ecosystem changes and fishing impacts in the SBB.

5. Conclusions

The unprecedented 40-year fish market time-series analyses presented here showed valuable signals of fishing impacts across the marine food web. The MTI did not show the "fishing down the marine food web" phenomenon, but, alternatively, the indicators weighted price over time and LRPI and, especially, the inferential analysis of single seafood categories demonstrated the continued scarcity of high-TL species. Changes across trophic levels became clearer through in-depth market analysis.

The behavior of the LRPI was generally related to the scarcity of overexploited species. Seafood market prices increased during 1968–2007, with the strongest trends shown by the high and intermediate-TL categories. These trends demonstrate the "pricing down the marine food web" phenomenon.

The use of a single indicator, such as MTI or landings, can mask some changes, while price-related multiple analyses over time can make these changes more explicit. The study demonstrates that one single indicator can show simplistic or controversial interpretations while representing, with a single number, a complex system (i.e. the behavior of both the fishery and the exploited populations).

Inferential analysis and correlations between trends in prices and quantities of individual categories appear to be extremely useful as indicators. A negative correlation between price and quantity can suggest fishing pressure or over-exploitation and a positive correlation can indicate increasing seafood demand.

Economic indicators for fisheries (such as seafood prices) can reveal changes in the marine ecosystem over time that cannot be shown by surveys of ordinary fishery landings databases. Therefore, price databases proved to be priceless to understand fishery dynamics from an ecosystem perspective, especially for data-poor marine systems.

Acknowledgements

We are particularly grateful to FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for financial support and to CEAGESP for data availability. We greatly thank Manuel Barange, Ian Perry, and two anonymous reviewers for valuable inputs and Rashid U. Sumaila (University of British Columbia) for providing ideas while kindly receiving us as visitors in the Fisheries Centre (Canada). Also, we thank A. Alencar, C. Toloi, and H. Lee of the University of São Paulo Center of Applied Statistics (IME-USP) for assistance. M.A.G. acknowledges the productivity grant from CNPq (Brazilian Scientific Research Council). Support from the University of São Paulo Graduate Dean (PRPG–USP) and GLOBEC-IPO is also recognized.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pocean.2010.08.006.

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