Rev Fish Biol Fisheries
https://doi.org/10.1007/s11160-022-09752-5

ORIGINAL RESEARCH

Implications of utilization shifts of marine fish in India: a macro-level empirical analysis

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Received: 19 June 2022 / Accepted: 25 December 2022

Abstract Fish drying is a traditional method of preserving and utilizing fish in India. Small-scale women processors play a dominant role in production and marketing of dried fish. This paper analyzes the changes in the profile of India's fish processing industry over time focusing on the dried fish segment. We postulate that structural changes in fish production, including the rapid surge in aquaculture production, are closely linked to changes in fish processing and utilization in India. In particular, surge in demand for fishmeal and fish oil (FMFO) as an ingredient in aquaculture feeds has tilted fish utilization from direct human consumption towards feed. We pool data on India's fish production, utilization, and trade to describe these changes and their implications through

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Published online: 09 January 2023

descriptive analysis and regression modeling. Results from the regression analysis show that the FMFO segment gains market share mostly at the expense of the dried fish segment.

Keywords Dried fish · Fishmeal · Small-scale fisheries · Structural change · Compositional data · Dynamic simulations · Utilization shift · Food security · India

Introduction

Dried fish in India are consumed more by poorer households (Siddhnath et al. 2020), making greater contribution in their dietary nutritional requirements[1]. Salted-dried products and sun-dried products are the two most popular dried fish items in India, with much of the products prepared from fish of marine capture fisheries origin. Affordability, rich and diverse nutritional profile, and the utilities offered by dried fish in terms of the form, place, and time of product use make them important dietary components in terms of enhancing food and nutritional security (Siddhnath et al. 2020; Berenji et al. 2021). Compared to industrial fish preservation technologies such as freezing and canning, dried fish can be easily produced, stored, and transported- thus making fish available to consumers even in distant markets and in all seasons. Their easy divisibility into smaller portions allows for affordability to poorer consumers who otherwise may not be able to purchase, for example, a large whole fresh fish. Moreover, dried fish are less expensive than fresh fish in terms of cost per nutrient unit (Belton et al. 2022). Thus, dried fish play a key role in improving the contribution of fish to four fundamental dimensions of food security: availability, accessibility, stability, and utilization.

However, the role played by the dried fish segment in India has mostly been underappreciated by policymakers as well as academics. Development of seafood value chains in India has come to mean setting up of cold chains, i.e., ice-making plants, freezing plants, cold storages, and refrigerated vehicles. For example, the official document on the Pradhan Mantri Matsya Sampada Yojana (PMMSY)[2], a ₹ 20,050 crore (USD 2.628 billion) project of the Government of India aimed at *sustainable and responsible development of fisheries sector*, does not directly mention the dried fish segment even once in the project document. The "Infrastructure and Post-harvest Management" section of the document shows not only the neglect for traditional fish processing technologies such as drying, but also the overwhelming importance attached by the government to the development of cold chains in the country to facilitate value chain of fresh and frozen seafood for exports and domestic market.

This bias is not new, and has been around ever since export potential of fresh/frozen seafood was realized around the time of the third Five-Year Plan (FYP) in 1961–1966. The first and the second FYPs acknowledged the contributions of dried fish processing sector. For example, the first FYP notes that abolition of excise duty on salt encouraged drying of fish in private yards, and there was a proposal for subsidizing the salt and to encourage fishers to use government yards which were supposedly more suitable for producing dried fish of improved quality[3]. The second FYP notes that India exported 27,000 tons of fish to neighboring countries, most of which was dried/dry-salted/wet-salted fish. Some of the inedible fish were made into fishmeal and manure[4]. From the third FYP onwards, government policies began shifting towards promotion of fresh and frozen seafood, even as the efforts on capitalization and modernization of fishing fleets in the country that had begun with the first FYP continued. In fact, the fourth FYP notes the development of exports of frozen prawns in place of cured fish during the third FYP period[5].

From the eighth FYP onwards, aquaculture was promoted as a means to achieving food security and to earn export revenues. Aquaculture production quantity in India increased from about 1.02 million metric

[1] The terms fish and seafood are used in this paper in a broader sense to refer to all aquatic animals including shellfish such as crustaceans and mollusks. Also, unless otherwise specified, the term dried fish in this paper refers to a broader range of related products such as cured, salted, smoked, and preserved fish.

[2] https://dof.gov.in/sites/default/files/2020-07/AnnexureFrameworktostatesUT_0.pdf.

[3] https://niti.gov.in/planningcommission.gov.in/docs/plans/planrel/fiveyr/1st/1planch23.html.

[4] https://niti.gov.in/planningcommission.gov.in/docs/plans/planrel/fiveyr/2nd/2planch14.html.

[5] https://niti.gov.in/planningcommission.gov.in/docs/plans/planrel/fiveyr/4th/4planch8.html.

tons (MMT) in 1990 to about 7.80 MMT in 2019, thus increasing by about 667%. India's aquaculture sector is characterized by substantial farm production of carps and shrimp. Expansion of shrimp farming in particular has created a huge derived demand for fishmeal as an ingredient in aquafeeds. However, there is a larger debate around the use of fishmeal and fish oil (FMFO) in aquaculture, and its impacts on food security and ecological impacts (e.g., Naylor et al. 1998; Naylor et al. 2000; Fréon et al. 2014; Scholtens et al. 2020; Shannon and Waller 2021). Small pelagic forage fish, that are excellent sources of nutrition, are mostly used in producing fishmeal. About 64% of all fishmeal produced is through reduction of whole fish that are fit for human consumption, with much of the rest prepared from "unwanted" discards and byproducts (Shannon and Waller 2021). The fish-for-food-versus-feed debate is more relevant for India, a country that lags in many human development indices including malnutrition, and is grappling with depleting freshwater resources and other severe environmental challenges. Developmental programs of the Government of India such as the PMMSY promote aquaculture in marine, coastal, and freshwater environments which would lead to even higher demand for fishmeal. The premise of this paper is that such capital-intensive fisheries and aquaculture have direct and indirect impacts throughout the seafood value chain of India, including the fish utilization patterns.

The dried fish segment of India's seafood value chain has been neglected not only by policymakers, but also researchers. There are only scattered attempts to understand the segment's profile in the country and its contributions to food and nutrition security. Of these limited attempts, a larger emphasis has gone into the technology of production- neglecting the social, cultural, value chain, and governance dimensions (Belton et al. 2022). A driving factor could be the typologies prevalent in the study of fisheries. By classifying fisheries into small-scale and large-scale solely based on the technology of fish harvesting, characteristics of the fisheries at downstream levels of the value chain do not receive the due attention (Smith and Basurto 2019). Processing of fish through salting, drying and smoking is essentially a characteristic associated with small-scale fisheries (Berkes et al. 2001). This also implies that, given substantial presence of women in the dried fish sector and dominance of men in fish harvesting, classification of fisheries based on fishing technology alone tends to obscure the gender dimension of small-scale fisheries.

The goal of this paper is to describe and quantify the changes that have taken place in India's fish processing sector, particularly in the dried fish segment, in view of structural changes in fisheries and aquaculture production in the country. Data on India's fish production, availability (supply), utilization, and trade are assembled from different sources. These are analyzed descriptively using graphs, and also using a regression model. Utilization here refers to the methods of post-harvest processing of fish. We classify India's fish utilization data into three broad categories: (1) FMFO; (2) Dried/Salted/Smoked/Preserved; and, (3) Live/Fresh/Chilled/Frozen. Thus, this study collates the marine fish harvest data with the end-use data to describe the competition between utilization of fish for direct human consumption and for FMFO production. The descriptive analysis focuses on structural changes in marine capture fisheries of India, and the implications of these changes for fish production and utilization patterns. The regression model is based on the compositional data approach, and explains the dynamics of composition of seafood processing industry in India. The model captures the tradeoffs occurring among the three different seafood product categories produced in India as a function of a set of relevant exogenous variables included in the model based on the descriptive analysis.

Cashion et al. (2017) analyzed the fish commercial landings data focusing on the taxa to describe the implications of utilizing fish catch for purposes other than direct human consumption including FMFO. We analyze a range of issues related to capture fisheries production and utilization, including trade, domestic consumption, and growth of aquaculture in India. Moreover, we use a more direct approach to characterize shifts in fish utilization patterns, by basing our modeling on the final products rather than landings, to demonstrate the implications of increase in FMFO production on direct human consumption of fish.

Data and methodology

The principal source of data for the analysis in this paper is the *Fisheries and Aquaculture Statistics* platform of the Food and Agricultural Organization

(FAO)[6]. This platform hosts different publicly accessible databases containing annual time-series observations. These databases allow different levels of aggregation over geographies and fish species. India-specific variables were extracted from the following databases:

(a) The *FAO Global Fish Processed Products Production Statistics* database: This database is a collection of statistics on the annual production of processed fishery and aquaculture products by country and product-type in terms of metric tons of net product weight from 1976;
(b) The *FAO Global Fish Trade Statistics* database: This database contains statistics on annual imports and exports (including re-exports) of fishery and aquaculture products by reporting country and product in terms of volume and value from 1976. The export quantities data are measured in tons of net product weight, while export values are given in thousand US dollars;
(c) The *FAO Global Fishery and Aquaculture Production Statistics* database: The Global Capture Production database contains capture fisheries production statistics by country or territory, species item, and FAO Major Fishing Area. The Global Aquaculture Production database contains statistics on production quantity and dollar value by species, country or area, fishing area and culture aquatic environment. The production quantity data are available from 1950 and are expressed in tons of live weight, whereas dollar values are available from 1984 onwards. And,
(d) The *FAO Food Balance Sheets of Fish and Fishery Products* database, which provides country-wise statistics on *apparent consumption* quantities in terms of tons of live weight for fish and fishery products, by broad groups of species, from 1961 to 2017. This database is a *food balance sheet* for fish and fishery products that approximates the fish availability situation in a country. It provides the total supply of fish and fishery products in a country by combining domestic production with imports, and adjusting for stock variations, exports, and non-food uses. It can be used as a measure of "apparent consumption", i.e., not actual consumption as obtained from a typical food/dietary survey, but the availability of fish in a country (Al Hasan et al. 2019).

In addition, we draw on the 2016 round of the Marine Fisheries Census conducted by Central Marine Fisheries Research Institute (CMFRI) to characterize the marine capture fisheries sector of India. We also pooled the data published by Ansell (2020; Appendix Table 5), who re-estimated India's total marine capture fisheries production quantities by accounting for unreported catches in India's official statistics. This dataset captures the changes in India's marine fish catch profile introduced by changes in the intensity of fishing technologies over time.

A caveat is necessary regarding the FAO databases before delving further. Each database comes with a metadata that briefly explains the data dimensions (description of geographical units, species descriptions, etc.) and details about data collection. However, no India-specific information could be found in the *Global Fish Processed Products Production Statistics* database. Therefore, not much detail can be provided here about the origins of the dependent variable used in the regression analysis. For example, how is the data on fish utilization collected in India and who collects it? The processed production quantities are measured in tons of net product weight. It is likely that the India-specific data in the *Global Processed Products Production Statistics* database are derived from one of the official statistical sources of the Government of India. There are some India-specific descriptions available for other databases such as the *Global Fishery and Aquaculture Production Statistics* database.

For the regression modeling, we follow the compositional data approach[7]. A composition is a vector of parts/shares/proportions/components of a whole that contains relative information. By design, the sum of individual components equals unity. For the empirical application, annual category-wise quantities of processed products produced in India (available in

[6] https://www.fao.org/fishery/en/statistics.

[7] Compositional data analysis finds extensive applications in diverse fields such as geology (e.g., composition of sediments, sandstone etc.), biology (e.g., nutritional composition of foods; species composition in different habitats etc.), and economics (market shares, expenditure elasticities etc.).

the FAO *Global Fish Processed Products Production Statistics* database) were transformed into respective proportions or components (i.e., compositional data) out of the total quantities of processed products. In the absence of price data, transforming the quantities data into the respective proportions can give a better insight into the dynamics in trade-offs among the components.

Given the objectives of the study, and considering the profile of products produced in India's seafood industry, some product-level aggregations were made before obtaining the composites. Since the original quantity data from FAO are in a common unit, i.e., net product weight in metric tons, aggregation is a simple exercise. The composites used in the regression model are as follows: (1) the categories "Meals" and "Oils" in the original data were grouped into one component, and is referred to as "FMFO"; (2) the categories "Crustaceans and molluscs, prepared or preserved", "Fish, prepared or preserved", and "Fish, dried, salted, or smoked" in the original data were combined into a component referred to as "Dried/Salted/Smoked/Preserved"; and (3) the categories "Crustaceans & Molluscs, live, fresh, chilled, etc." and "Fish, fresh, chilled or frozen" in the original data were combined into another component referred to as "Live/Fresh/Chilled/Frozen". Proportions/shares were calculated for these three categories.

The dependent variable in the regression analysis is the compositional variable, i.e., the category-wise shares or proportions of processed seafood produced in India. By construction, an increase in one of the shares results in a decrease in one or more of the other proportions so that the sum of proportions equals one[8]. Thus, a joint modeling of the shares helps in understanding the trade-offs among seafood categories produced in India. Therefore, we follow the multivariate approach proposed by Philips et al. (2016a and 2016b) and Jung et al. (2020), which has been previously used in analyzing issues such as budgetary allocations (Adolph et al. 2020; Funk and Philips 2019), and dynamics of support for political parties (Philips et al. 2016b).

Mathematically, let the dependent variable be denoted as $\boldsymbol{Y}$ which has J categories (in our case $J = 3$) at any given time t. Individual categories of $\boldsymbol{Y}$ can be represented by y_{jt}, and let the category $j = 1$ be the reference/base category. For any $J > 2$, the log-ratios, s_{jt}, can be calculated for $J - 1$ categories using the base category such that $s_{jt} = ln\left(\frac{y_{jt}}{y_{1t}}\right)\forall j \neq 1$, where ln is the natural logarithm function. The impacts of independent variables on the log-ratios can be analyzed using a regression model of the following form proposed by Jung et al. (2020):

$$s_{jt} = \beta_{j,0} + \varphi_j s_{j,t-1} + \boldsymbol{\beta}_{js}\boldsymbol{X}_t + \in_{jt} \quad (1)$$

where $\beta$and φ are parameters to be estimated, $\boldsymbol{X}$ is a vector of independent variables, and $\in$ is a stochastic disturbance term with possible correlations across the categories. Our regression model captures the impacts of major demand and supply drivers of India's seafood industry on the category-wise seafood utilization patterns in India. The specific explanatory variables included in the regression model were selected based on the descriptive analysis, and will be described in a subsequent section. The model is estimated using the seemingly unrelated regression (SUR) estimator of Zellner (1962), a multivariate approach to account for any cross-equation correlations.

In time-series models, especially those involving lagged variables, there are large number of estimated coefficients that may be difficult to interpret directly. Moreover, in regressions involving compositional data as used in this study, the coefficient of an explanatory variable represents the impact of that variable on the logarithm of the ratio of share of one category over another. A better and direct interpretation is possible by visualizing the impacts of one or more explanatory variables on the shares themselves using model-based simulations. This paper presents dynamic (i.e., time-varying) simulations of the impacts of a 1-standard deviation increase in the major demand and supply shifters on the composition of the processed seafood produced in India[9]. Further details are provided in the "Results" section.

[8] For the empirical analysis, we did not drop any of the fish product categories available in the FAO database. Hence, these shares or proportions do actually sum to one.

[9] Regression modeling and the subsequent simulations in this study are based on the procedure described in Philips et al. (2016a and b). These studies also provide a more detailed exposition on model-based simulations in the context of compositional time-series data. Descriptive analysis in this study were carried out using the open-source software R (R Core Team 2022), and the regression modeling was carried out using the proprietary software Stata (StataCorp. 2013).

Results

Marine capture fisheries of India

The FAO Global Fishery and Aquaculture Production Statistics database shows that the total marine capture fisheries production of India in 1950 was about 0.53 MMT, which increased to about 3.69 MMT in 2019. Thus, marine fish production in India has increased by over 600% during the last 70 years. The 2016 round of the Marine Fisheries Census conducted by CMFRI reports that there are 1363 fish landing centers, 3477 fishing villages, 893,258 fisher families, and a total fisherfolk population of 3.77 million in the country. Of these families, 600,890 or 67.3%, are Below Poverty Line (BPL). There are a multitude of livelihood options created by the marine small-scale fisheries sector in India, including fishing, fish seed collection, fish marketing, mending of nets, fish processing and curing, peeling, fish trading and retailing, and laborer. Moreover, women play a dominant role in many of these occupations. For example, according to the Marine Fisheries Census 2016, there are 28,551 men fishers and 181,686 women fishers engaged in fish marketing; 4699 men and 43,623 women fishers are engaged in curing/processing of fish; and 2514 men and 43,643 women are engaged in peeling of fish products. Further, Ramappa et al. (2022) indicate that almost every fisher household in coastal fishing villages of Karnataka is engaged in dried fish processing and retailing, with about 95% of the processors being women. In all likelihood, the overwhelming presence of women in fisheries post-harvest operations is true for even other states of India. Thus, the marine fisheries sector of India plays an important role in sustaining the livelihoods of millions of fishers from the more vulnerable sections of Indian society.

Meenakumari (2014) notes that there were 863 mechanized fishing vessels in the 1951-56 period. According to the 2016 Marine Fisheries Census, there are a total of 166,333 fishing craft (boats/vessels) in the country. Of these, there are 42,985 or about 26% mechanized boats (i.e., boats with engines permanently fixed to the hull for propulsion and fishing); 97,659 or about 59% are motorized boats (i.e., boats fitted with motors for propulsion only); and, 25,689 or about 15% are non-motorized/traditional boats that are maneuvered in the water by paddling, poling or sailing for propulsion and fishing[10]. Of the mechanized boats, there are 30,772 (about 72%) trawlers, 6,548 (about 15%) gillnetters, 3395 (about 8%) bag-netters/dol-netters, 1189 (about 3%) purse-seiners, with the rest being 943 ring-seiners, 49 liners, and 88 other types of craft.

Industrial/mechanized fishing contributes by far the largest share to India's total marine fisheries production. Figure 1 shows the shares of industrial fishing, artisanal fishing (i.e., small-scale commercial), subsistence fishing (small-scale non-commercial), and discards in India's total marine capture fisheries production quantities. The segment-wise catch quantity data are taken from Ansell (2020), who reconstructed India's marine fish catches for the period of 1950 to 2018[11]. There are two inflection points in the increase in share of industrial fishing: the first around late 1960s with a steep increase, attributable to the impacts of initial rounds of fishing fleet modernization; and the second jump around mid-1990s with a more secular increase, which indicates to the impacts of adoption of more powerful fishing vessels such as multiday trawlers. Multiday trawlers, with their high-powered engines and advanced designs, can stay continuously at sea for 9 to 13 days, and have become popular since the late 1990s (Bhathal 2014). Interestingly, the share of discards started increasing only after around 1995, coinciding with increased uptake of multiday trawlers. Trawlers account for over 50% of total marine fish production (Dineshbabu et al. 2013). Ansell (2020) notes that the share of multiday trawling in India's total marine catches reached about 37.5% from 2005 onwards. Thus, the share of mechanized fishing in the total marine fish production has substantially increased over the years in India, even though small-scale fisheries are still important in terms of livelihood creation as shown previously. What Fig. 1 does not reveal is the importance

[10] However, there is substantial regional heterogeneity in the distribution of fishing boat types. For example, only about 2.7% of the total number of fishing craft in Gujarat state is traditional/non-motorized, whereas in Andhra Pradesh it is about 34.4%. Even within a state, individual coastal districts may show great variations in the composition of fishing fleet. For example, in 2016 the share of traditional boats in Uttara Kannada district of Karnataka state was about 78% whereas in Dakshina Kannada district it was about 37%.

[11] We extrapolated the data for the year 2019 based on Ansell (2020).

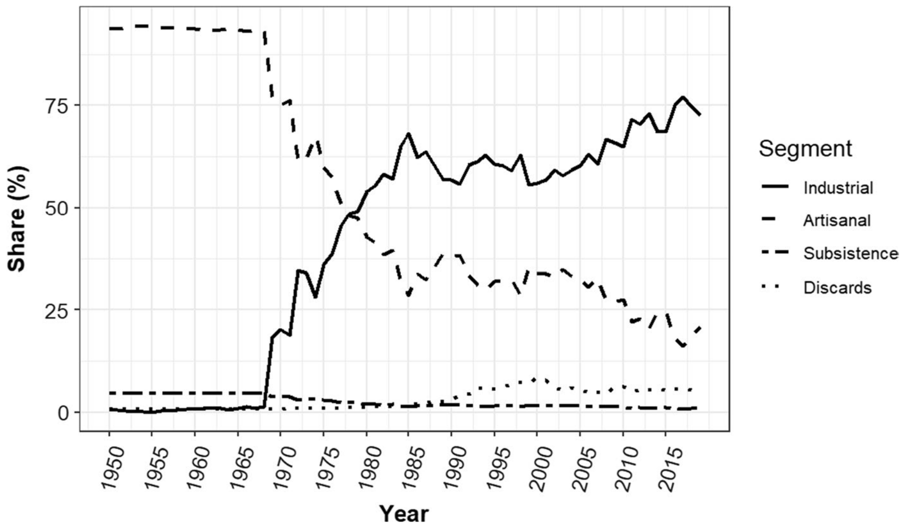


Fig. 1 Share of different fishing segments in India's total marine capture fisheries production quantities: 1950–2019. Data source: Harvest quantities taken from Ansell (2020), transformed into shares and plotted by authors

of small-scale artisanal and subsistence fisheries in terms of commercial value and livelihood- as their catches are more often valued higher than harvests of industrial fishing. Moreover, even though the share of artisanal fishing in India's total marine fisheries production has declined, landings from artisanal fishing over the years have increased albeit slowly. This also indicates to the resilience of India's small-scale fisheries in the face of policy apathy and other challenges (Jadhav 2018).

Post-harvest practices in India's Fisheries Sector

Changes in the technology of fishery exploitation and the transformations in India's post-harvest utilization and marketing patterns are closely linked. The increasing importance of exports in India's seafood industry, and expansion of the of FMFO industry, are two of the most significant changes in recent decades enabled by increased uptake of mechanized fishing. Increasing dominance of exports in the seafood industry of India is evident from Fig. 2. The figure plots the total quantity of seafood exported from India expressed as a share of the total quantity of processed seafood produced in India. The figure clearly shows that the share of seafood exports has increased dramatically since the mid-1990s. The average share of exports during the 1976–1995 period is 25.59%, whereas the respective figure for the 1996–2019 period is 50.47%- coinciding with the increased adoption of multiday trawlers in India[12]. The figure also shows that the share of exports in the years 2017 to 2019 has consistently been over 60% of total processed seafood production. The "Merchandise Exports from India Scheme" (MEIS) made effective from 1st April 2015 under the Foreign Trade Policy has increased the incentives to export seafood.

The second major change, i.e., increased production of FMFO, is also an offshoot of dominance of mechanized fishing in India's marine fisheries sector. Mechanized fishing in general, and multiday trawling in particular, are notorious for hauling non-target species, called trash fish, discards, or bycatch depending on their utility[13]. Hornby et al. (2015) estimate that about 33% of trash fish caught in India during 1950 to 2010 was the discard variety. The proportion of discards has decreased since 2000, as the price of even low-value bycatch increased by 300 to 600% between 2000 and 2011 (Aswathy et al. 2012; Dineshbabu et al. 2013). Dineshbabu et al. (2013) find that the shares of bycatch in total trawl landings in 2011 were 33% in Veraval, 26% each in Mangaluru and Calicut, 17% in Chennai, and 21% in Vishakhapatnam. Bycatch are mostly reduced to FMFO. FMFO

12 There are other factors, such as the liberalization of the Indian economy in 1991 and export promotion programs under various FYPs of the Government of India, that facilitated the growth of seafood exports.

13 Usually, discards are the non-target fish species caught, but are discarded in the sea itself. Bycatch is the portion of non-target species caught that is hauled onto the fishing harbor.

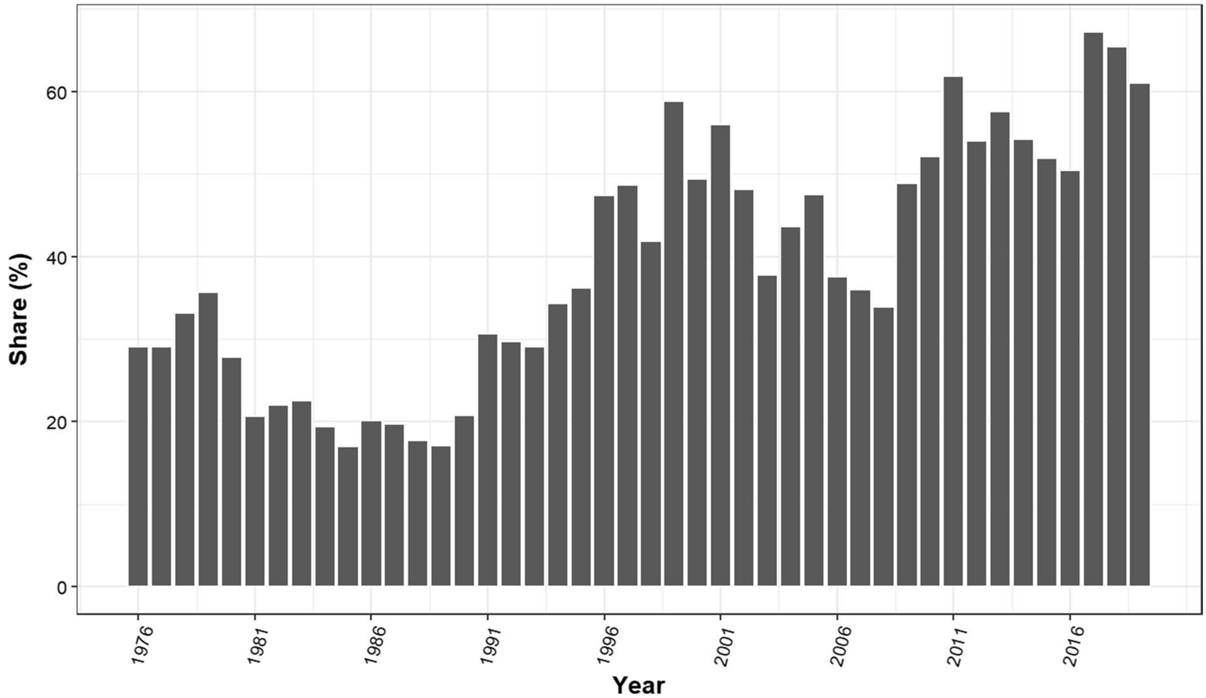


Fig. 2 Exported seafood quantities as a share of total quantities of processed seafood produced in India: 1976–2019. Data source: Exported seafood quantities obtained from the FAO Global Fish Trade Statistics; Processed seafood production quantities taken from the FAO Global Fish Processed Products Production Statistics

production has become a prominent commercial activity in coastal towns of Karnataka and Kerala, catering to the increased demand for fishmeal as an ingredient in livestock and aquaculture feeds in the global and domestic feed industry. This has increased the derived demand for even low-value bycatch[14].

Figure 3 shows the annual total quantities of processed seafood produced in India for the 1976–2019 period (Panel A), the respective annual quantities of fishmeal production (Panel B), and the prices of exported fishmeal where price denotes the unit value, i.e., total export value divided by total export quantity (Panel C). There is a clear increase in FMFO production since around 2005. There are reasons to believe that the increase in fishmeal production has increased the incentives for industrial fishing vessels to engage in unsustainable fishing practices. For example, Dineshbabu et al. (2013) analyzed harbor-wise trawler catches for the 2007–2012 period in India and found that the discards contained juveniles of as many as 237 species, indicating increased stress on fish stocks due to industrial fishing, with poorly understood disruptive consequences on the aquatic food chain. Even species important for human consumption such as sardines were landed as bycatch and ultimately went for FMFO production. In some seasons, the price of sardines landed as part of trash was higher than even fresh sardines. As shown in Panel C of Fig. 3, fishmeal prices have increased continuously in the export markets, which induces greater demand in the supplies of raw material. Accordingly, data show that the share of exported FMFO out of total FMFO produced in India jumped from an average of about 4% before 1996, to about 23% after 1996[15].

There are other changes in the seafood value chain of India pushed by dominance of industrial fishing.

[14] Fish brought to the landing center even in a deteriorated state are bought by fishmeal companies (Dineshbabu et al. 2013; Scholtens et al. 2020) note that Karnataka's fishmeal companies are large enough to indulge in multiple arrangements to ensure consistent supply of raw material for their operations, including mechanisms such as forward contracts, trade credits etc.

[15] In fact, the average share of exported FMFO in total FMFO production of India from 2014 onwards is 47.5%.

Larger vessels bring their catch to larger fishing harbors since they have better docking facilities, better provision of services such as ice plants, and presence of larger buyers who cater to export markets and distant inland markets (DFID 2003). Thus, rural fish landing centers- often called *beach landing centers*- do not receive sufficient fish for supplying to local markets, and there is increased uncertainty about the timing of arrival of landings. This has resulted in competition for scarce landings among buyers, inducing changes in fish utilization patterns. Fishers at large landing centers prefer to sell to larger buyers (DFID 2003), who are mostly involved in marketing of fish in fresh, iced, chilled, and frozen forms for export markets or distant urban markets. Even in rural fish landing centers, factors such as better road connectivity, electrification, and improved adoption of insulated trucks have favored a shift in fish utilization towards fresh and frozen forms. This implies less fish for small-scale processors involved in traditionally important processing activities such as fish curing and drying.

Growth of aquaculture in India

Another major change in India's fisheries sector is the emergence of aquaculture as the dominant source of fish production. A descriptive analysis of the *FAO Global Fishery and Aquaculture Production Statistics* database reveals that from a mere 0.018 MMT farmed fish production in 1950, India's aquaculture production in 2019 had risen to 7.8 MMT. Thus, the share of aquaculture in India's total fish production quantity increased from about 2.4% in 1950 to about 59.7% in 2019. In terms of monetary value of aquaculture production of India, farmed freshwater finfishes, mostly carps, form the largest category, with a share of about 71% in the 2015–2019 period. Much of the rest of the share is that of farmed crustaceans, mostly prawns and shrimp farmed in brackishwater[16]. Indian Major Carps (Catla- *Catla catla*; Rohu *Labeo rohita*; and Mrigal- *Cirrhinus mrigala*), Chinese carps (Silver carp- *Hypophthalmichthys molitrix*; and Grass carp *Ctenopharyngodon idella*), Common carp (*Cyprinus carpio*), and Orangefin labeo (*Labeo calbasu*) together formed about 66% of the total aquaculture production quantities of India during 2015–2019, while their average share for the 2005–2014 period was about 77%. Farmed (freshwater) prawns, and (brackishwater/marine) shrimp constituted on average about 10% of total aquaculture production quantities of India during 2015–2019, while for the 2005–2014 period average share was 5%. Thus, the share of prawns and shrimp has increased in recent years even as the share of carps has declined. Much of the farmed shrimp produced is destined for export markets, whereas farmed freshwater finfishes are mostly for the domestic market. Thus, shrimp farming earns valuable foreign exchange for India, whereas farmed freshwater finfish contribute more directly to the food and nutritional security in the country.

Contribution of the freshwater aquaculture segment to food security in India is evident from Fig. 4 which plots the per capita fish supplied (i.e., *apparent consumption*) to the domestic market in India, by segment, for the years 1961–2017. Apparent fish consumption was about 1.852 kg/capita in 1961, which increased to about 6.902 kg/capita in 2017 (but is still considerably low compared to neighboring Bangladesh and Sri Lanka). Contribution of the "Freshwater and diadromous fish" segment has increased over the years, and has remained the largest contributor to apparent fish consumption since 1990. Though the FAO fish balance sheets do not differentiate between capture fisheries sources and aquaculture, it can be argued based on the *FAO Fishery and Aquaculture Production Statistics* that freshwater aquaculture is the primary source of this increase- since the share of inland capture fisheries in India's total fish production has remained stagnant at about 10–13% since around 1990 even as the share of inland aquaculture increased. From around 2008, inland aquaculture has overtaken marine capture fisheries to be the biggest contributor to total fish production. The other two segments shown in Fig. 4, i.e., "Marine finfish" and "Shellfish" can be assumed to mostly come from marine or brackishwater sources with major production from capture fisheries[17]. Per capita apparent

[16] In terms of quantity of aquaculture production, freshwater finfishes constituted about 88% of total aquaculture production and farmed crustaceans had a share of about 10% during the 2015–2019 period.

[17] The variable "Marine finfish" is constructed by aggregating the variables "Aquatic animals NEI", "Demersal fish", "Marine fish NEI", and "Pelagic fish" available in the raw data. Similarly, the variable "Shellfish" is constructed by aggregating the

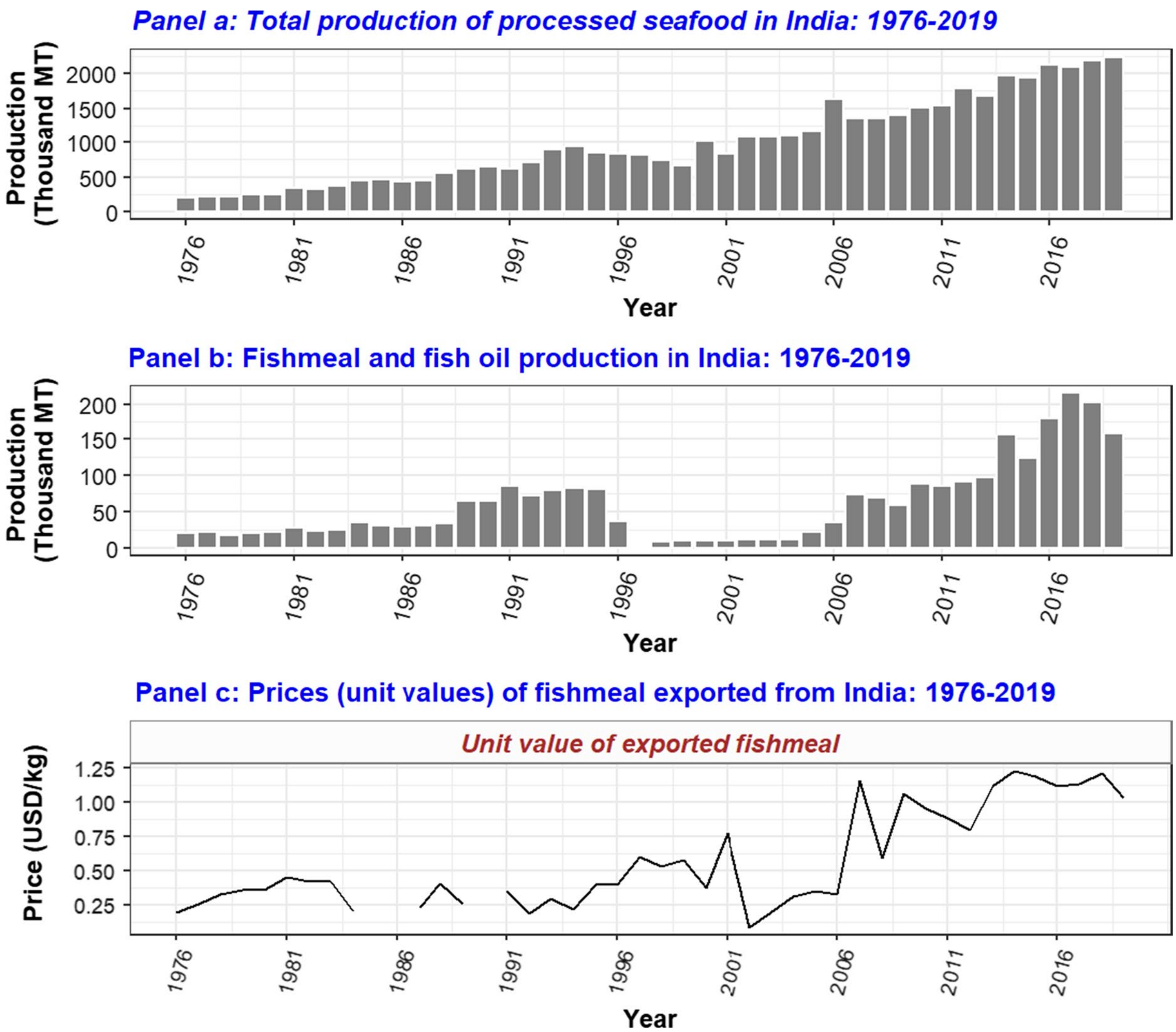


Fig. 3 Production of processed seafood and FMFO, and the prices of FMFO in India: 1976–2019. Data source: For Panel A, the FAO Global Fish Processed Products Production Statistics; For Panel B and Panel C, the FAO Global Fish Trade Statistics

consumption of "Freshwater and diadromous fish" and "Marine finfish" were almost identical until about 1990. Per capita supply of "Marine finfish" has been declining from around 2010. Per capita supply of "Shellfish" is the smallest among the three segments, and has marginally increased from around 2010.

One important implication of these developments is that though mechanized fishing has resulted in a tremendous increase in marine fish production in India, much of the increased production is destined either for the export market or for non-food uses. This has placed limitations on the potential of the marine fisheries sector in contributing to the food and nutritional security of the country, especially with respect to micronutrients and animal-sourced protein in the diet.

Footnote 17 (continued)

variables "Cephalopods", "Crustaceans", and "Molluscs excl. cephalopods" available in the raw data. The "Freshwater and diadromous fish" variable is presented as available in the raw data without any aggregations. The abbreviation NEI stands for Not Elsewhere Included. All the variables are measured as total supply to the domestic market in tons of live weight, transformed into per capita values.

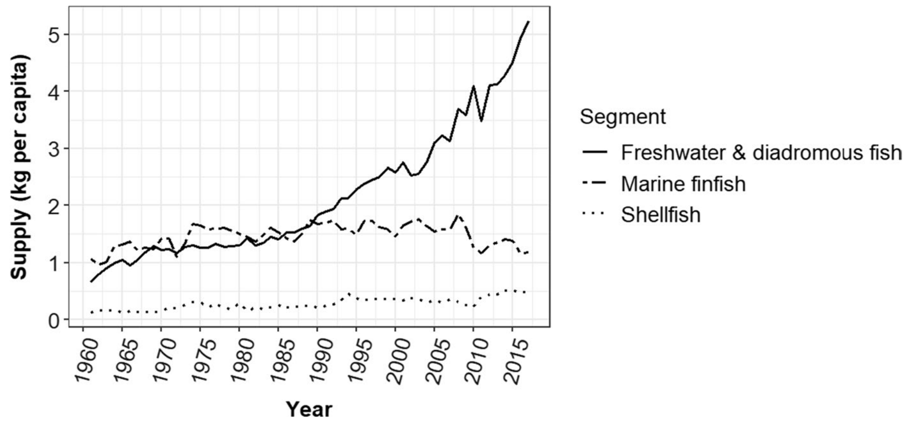


Fig. 4 Per capita fish supply in India, by fish production segment: 1961–2017. Data source: The *FAO Food Balance Sheets of Fish and Fishery products* database

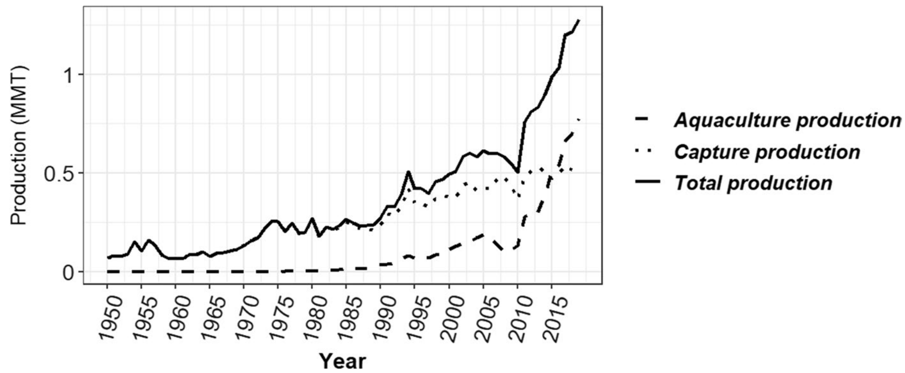
Kobayashi et al. (2015) predict that aquaculture production in India would grow by 100% over the 2010–2030 period. Recent initiatives of the Government of India such as the PMMSY and the Blue Economy initiative are expected to further facilitate growth of aquaculture in coastal and marine waters. As seafood export promotion is a major goal of the Government of India, shrimp farming in the country is likely to expand considerably in the coming decades. Figure 5 shows evidence to the rapid surge in aquaculture production of prawn and shrimp in India. The figure shows that aquaculture production of shrimp has not only overtaken that from capture fisheries production since 2011, but that the gap in production between the two sources has continued to increase.

Rapid growth in farmed shrimp production after 2011 was enabled by the introduction of *Litopenaeus vannamei* (Pacific Whiteleg Shrimp) and its increasing adoption. As shown in Fig. 6, production of Pacific Whiteleg Shrimp has skyrocketed since 2011 from zero production, surpassing production of Giant Tiger Prawn (*Penaeus monodon*) which was the main shrimp species farmed in India since the 1990s. Farming of *P. monodon* was hit by outbreaks of the White Spot Syndrome Virus (WSSV) in the mid-2000s. *L. vannamei* was introduced into India as a Specific Pathogen Free species. Average net returns for *P. monodon* in Navsari district of Gujarat was USD 16313.13/ha/year, whereas for *L. vannamei* it was USD 41640.99/ha/year (Nisar et al. 2021). Comparison of farming of the two species across different intensities of farming showed that *L. vannamei* farmed at very high densities gave the highest yield, highest net returns, and the best benefit-cost ratio. Suitability for very high-density farming, excellent yields, and high returns probably explain the jump in production of *L. vannamei* since 2011.

This surge in farmed shrimp production raises the question of ecological impacts of shrimp farming. While there are many environmental flashpoints such as eutrophication, destruction of mangroves, and pesticides that are associated with Asian aquaculture, a major challenge acutely facing shrimp farming is the negative environmental impact from the use of fishmeal in the feed (Pahlow et al. 2015). Feeds used in shrimp farming typically contain 20 to 25% fishmeal, whereas feeds of carps farmed in India typically contain less than 5% fishmeal (Pahlow et al. 2015). Global farmed shrimp production in 2012 was 4.33 MMT, consuming 6.18 MMT feed with a feed conversion ratio (FCR) of 1.70 (Tacon and Metian 2015). Scholtens et al. (2020) estimate that 220,000 tons of fishmeal is required to grow 680,000 tons of shrimp (approximately the production quantity of farmed *L. vannamei* in India). Given that the FCR in shrimp farming has not substantially changed over the years, further growth in coastal aquaculture in India implies greater demand for fishmeal from the aquafeed industry.

The growth of FMFO and production of farmed shrimp are intertwined (Scholtens et al. 2020). Thus, with growing demand and higher price for FMFO especially from the aquaculture industry (Chen et al. 2020), there is even more incentives for carrying out unsustainable fishing practices in India's marine fisheries. This, in turn, would make the dried fish segment of India's seafood industry even more susceptible to uncertainties in raw material procurement.

Fig. 5 Production of penaeid shrimps in India, total and by source: 1970–2019. Data source: the FAO Global Fishery and Aquaculture Production Statistics database



Regression analysis

Log-ratios of the shares were calculated with the FMFO as the base/reference category. Explanatory variables in the regression model include the following: the logarithm of India's per capita gross national income (GNI) measured in 2015 US dollars, to control for factors affecting demand[18]; the share of the industrial fishing segment in India's total marine capture fisheries production, to control for technological changes that may impact fish catch; the logarithm of farmed shrimp production; and, a dummy variable that takes on a value of 1 for the years 1995 and later, and a value of zero otherwise, to capture the impact of change in marine fish capture technology. Farmed shrimp production is assumed to impact the demand for FMFO, as well as the supply of fresh/frozen (shrimp) products in the country. The dummy variable is included to control for any other changes in India's seafood value chain brought about by factors such as advances in technology that may influence the production of processed seafood products.

The log-ratios plotted over time in Fig. 7 show a similar pattern for the share of Dried/Salted/Smoked/Preserved products, as well as in the share of Live/Fresh/Chilled/Frozen products, with respect to the share of FMFO. There was some increase in the two log-ratios until the mid-1990s, but from then on, both log-ratios have been on a declining trend.

Parameter estimates from the regression model (1) are provided in Appendix 1. For the reasons stated previously, we do not discuss model coefficients in detail. Instead, in Fig. 8 we present the dynamic simulations of the impacts on shares of the three seafood categories of a one-standard deviation increase each in the share of industrial fishing in India's total marine catches, in farmed shrimp production, and in the GNI. Such simulations can be made for any time period in the dataset (i.e., at any time point in the available range). We chose to create simulations for the year 2005 when industrial fishing and shrimp farming in India were already established, and the country's economy was relatively stable and growing. This corresponds to time period 30 in Fig. 8.

The x-axis of Fig. 8 shows the time horizon up to which simulations are carried out, and the y-axis shows the predicted shares of each processed seafood category, and the black vertical lines along the predicted shares are the 95% confidence intervals. Longer lines indicate greater uncertainty associated with the predicted shares. Figure 8 shows that there is a decrease in the share of dried fish immediately after the shock, even as the shares of fresh/frozen products and FMFO increased. The share of fresh/frozen products increases slightly and for 2 time periods, and then adjusts to a new equilibrium level of market share that is slightly higher than the previous level. Meanwhile, the share of FMFO increases more steeply and keeps increasing for 4 time periods before adjusting to a new equilibrium market share level that is much higher than the previous level. The only category to lose market share is that of dried products. Thus, the regression model predicts that, under the hypothesized demand shocks and supply shocks, market share of only dried fish products would decrease, while the residual market share is absorbed mostly by FMFO and to a lesser extent by the fresh/frozen products.

[18] Data for India's GNI were obtained from the World Bank (https://databank.worldbank.org/reports.aspx?source=2&series=NY.GNP.PCAP.KD&country=IND#).

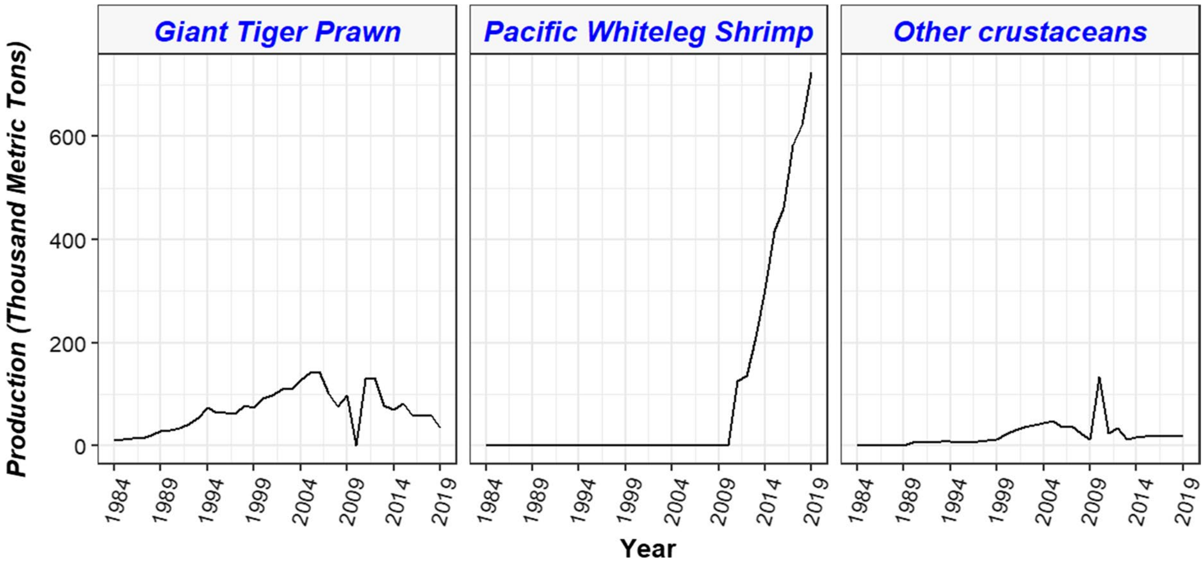


Fig. 6 Aquaculture production quantities of crustaceans in India, by species groupings: 1984–2019. Data source: the FAO Global Fishery and Aquaculture Production Statistics database

Discussion and conclusions

As pointed out by Cashion et al. (2017), there is a dearth of research on fish utilization, i.e., on the conflicting uses of fish directly as a food item and as a non-food item. There are ecological, livelihood, food and nutritional security dimensions associated with fish utilization and in its change. Our analysis extends the work along this line by first presenting a descriptive and graphical analysis of the marine fisheries sector of India, the fish processing sector, the role of exports, and the growth in aquaculture production. The purpose of the descriptive analysis was to illustrate the implications of historical developments, particularly the production and technological changes, that have occurred in these segments of India's seafood value chain. We discuss the implications of these developments in terms of fish utilization patterns, focusing on the dried fish segment.

Our results show that the output growth of small-scale fishing segment in India slowed considerably after the 1970s as the industrial fishing segment grew. Spatial expansion into offshore and deep-sea areas by industrial fishing is not sustainable over the longer term since India's deep waters are low in productivity and deficient in dissolved oxygen levels (Hornby et al. 2015). This implies increased competition for small-scale fishing operations in India's coastal/near-shore waters.

Mechanization of marine fishing fleets especially since the late 1990s has had an impact not only on fish landings but also on other nodes further downstream along the seafood value chain in India. Quantity of seafood exported from India, when expressed as a share of total processed seafood produced in the country, shows considerable increase after mechanization. FMFO production has increased with increasing fish landings in the country aided by rising export prices, and hence ever more FMFO is being exported from India. Extrapolating from the findings of Dineshbabu et al. (2013) and Cashion et al. (2017), it is likely that the diversity of fish species being used for FMFO production has increased over the years in India. What was once considered as bycatch became a part of the targeted catch, albeit with increasing indiscrimination. Use of forage fish in FMFO production threatens to impair the sustainability of India's marine ecosystems.

The increasing dominance of the FMFO segment in India has likely affected fish utilization patterns, with substantial food and nutrition security consequences. Achieving food and nutrition security requires satisfying a minimum of four conditions: availability, accessibility, utilization and stability. Since availability is a function of production

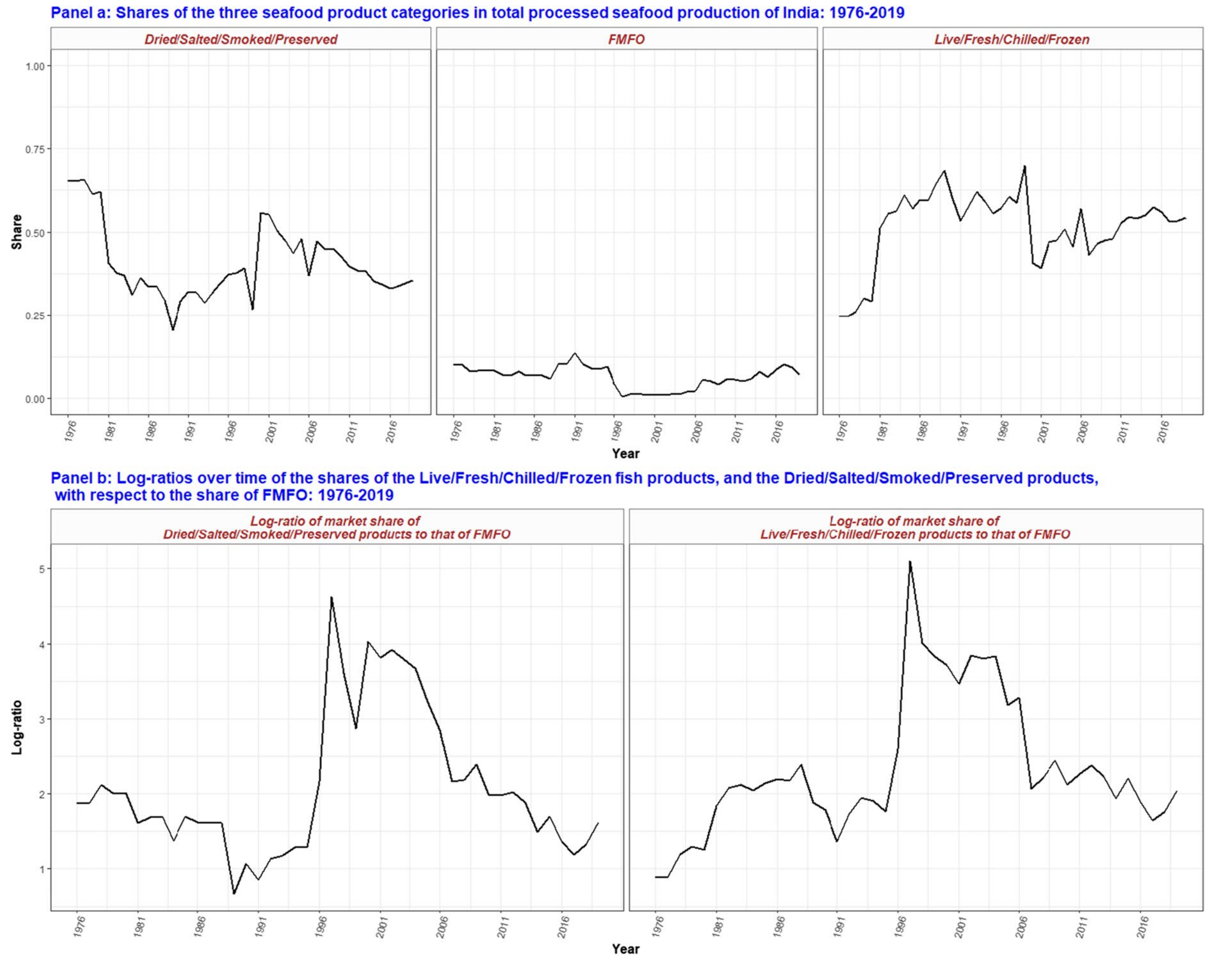


Fig. 7 Market shares of the three processed seafood categories (Panel A), and their log-ratios (Panel B): 1976–2019

and supply, it appears that the actual contribution of the marine fisheries segment to domestic food security in India may be less substantial than the tremendous increase in production of marine fish in India might otherwise suggest. An indirect indication of the disassociation between increased production and national food and nutrition security is that per capita fish consumption in most coastal Indian states decreased between 1983 and 2010 (Ravikanth and Kumar 2015). Increasing production of FMFO and rising share of exports are likely diverting fish from local consumption in India to aquaculture feeds and lucrative export markets. Thus, there is a gap between India's marine fish production and the supply to the domestic market for direct consumption. Indirect fish utilization pathways such as using FMFO for shrimp farming are considerably less efficient compared to direct consumption (Cashion et al. 2017). Meanwhile, India's rapidly growing finfish aquaculture directed at domestic markets uses only limited amounts of FMFO and broadens availability of fish to Indian consumers in those states where there is an appetite for carp species.

A third consequence is associated with livelihood dispossession. As explained previously, a significant number of women are engaged in post-harvest fisheries activities for their livelihood. More than 90% of the individuals involved in post-harvest dried fish operations in India are women, and most of these women are from vulnerable sections of the society. In contrast, industrial fish utilization technologies such as FMFO production rely less on human labor,

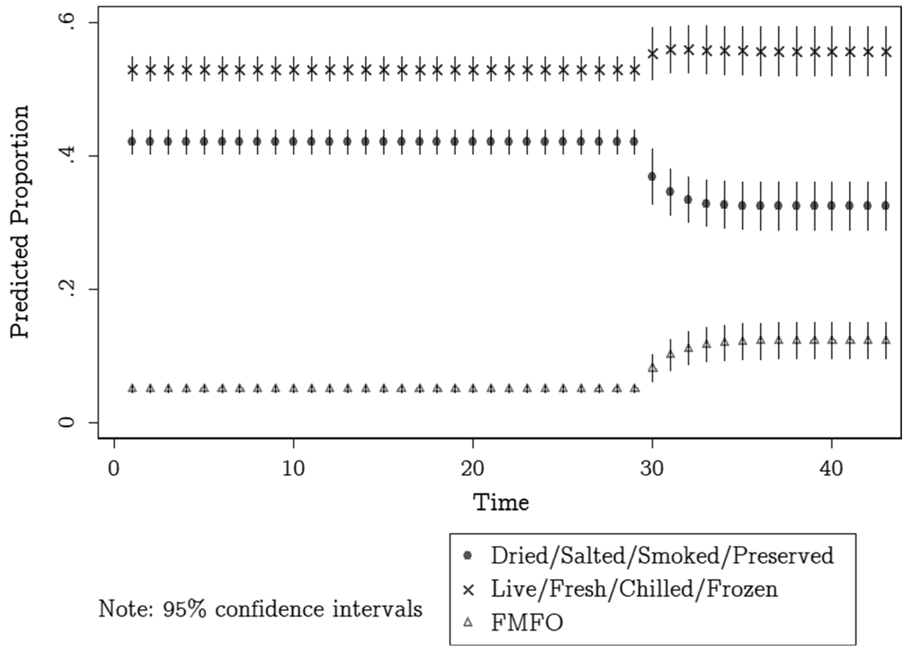


Fig. 8 Dynamic simulation of the impacts of a one-standard deviation increase in farmed shrimp production, total marine fish production, and India's GNI on the proportions of processed seafood categories in India

compared to production of frozen or dried seafood that require pre-processing operations such as cleaning, gutting and scaling often done by manual labor. Industrialized and capital-intensive fish production, processing, and trading thus can displace traditional labor and livelihoods, especially of women.

Outputs from the regression model indicated that increase in market share of FMFO comes at the expense of the market share of the dried fish segment in India. Encouraging industrial use of fish through FMFO essentially implies increased competition for the dried fish segment. Thus, fish processing, including fish curing and drying, are directly being affected by the FMFO segment. Demand shifters–such as demographic changes, per capita income, and increased competition with poultry and fresh fish segments–may also decrease the demand for dried fish. However, competition from FMFO, as pointed out by Fréon et al. (2014), indicates other systemic problems such as inefficient use of fishery resources in relation to human nutritional needs and health, suboptimal rent redistribution, lower performance with respect to employment generation, social costs, and ecological impacts.

Globalization is a latent link connecting the findings of our study. About 67 million tons or 38% of all seafood produced in 2018 was traded internationally, with a total estimated economic value of USD 164 billion (FAO 2020). Globalization has made seafood one of the most globally traded commodities. Technological changes in fish harvesting and the resultant high growth in fish harvests might not have been viable without the opening up of new global markets for seafood. Improved connectedness among local and international markets could be a major driver of overfishing across the globe, including in India. Overfishing leads to problems of decreased fish production, reduction in quality of catches, reduced food and nutritional security in local and regional food systems, and imbalances in employment and livelihood opportunities especially for the small-scale fisheries segment of India that supports some of the most vulnerable sections of the society. Kurien, as early as 1978, warned of the likely impacts of unchecked industrialization in India's marine fisheries. In four decades, Kurien's apprehension appears to have become a reality, as the globalization and industrialization of Indian fisheries now threaten nutritional security, livelihoods, and ecological sustainability in India.

Acknowledgements The authors thank the Dried Fish Matters project, and the Social Sciences and Humanities Research Council (SSHRC) of Canada, for funding support (Grant Number 895-2018-1017).

Data availability The datasets analyzed in the study are available from the corresponding author on request.

Declarations

Conflict of interest The authors do not have any conflicts of interest to declare.

Appendix 1

Outputs from the estimation of regression model (1).

	Equation 1 $\ln\left(\frac{Dried}{FMFO}\right)$		Equation 2 $\ln\left(\frac{Fresh,Frozen}{FMFO}\right)$	
	Coefficient	Standard Error	Coefficient	Standard Error
Lagged log-ratio	0.4825***	0.0855	0.5006***	0.0883
Logarithm of per capita GNI	-1.1034***	0.4349	-1.7080***	0.4683
Logarithm of farmed shrimp production	0.0651	0.0914	0.2340*	0.1270
Share of industrial fishing in India's marine fish catch	-0.0162*	0.0098	0.0285***	0.0173
Dummy variable	1.4610***	0.3353	1.2400***	0.3165
Intercept	7.8472***	1.8845	8.5908***	1.9746
R-squared	0.80		0.77	
Model χ^2test statistic [p-value]	174.5 [<0.01]		154.9 [<0.01]	

The symbols ***, **, and * indicate statistical significance at the 99%, 95%, and 90% confidence levels, respectively.

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