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EDITED BY
Carlo Pipitone,
CNR - IAS Institute of Anthropic Impacts and Sustainability in Marine Environment, Italy

REVIEWED BY
Arturo Zenone,
University of Kiel, Germany
William D. Heyman,
LGL, United States

*CORRESPONDENCE
Hadayet Ullah
M.H.Ullah@cgiar.org

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Local ecological knowledge can support improved management of small-scale fisheries in the Bay of Bengal

Hadayet Ullah*, Md Abdul Wahab, Md Jalilur Rahman, Shaheed Nasrullah Al Mamun, Uttam Kumar, Muhammad Arifur Rahman, Sazeed Mehrab Souhardya, Ilias Ebne Kabir, Monayem Hussain, Md. Bokthier Rahman and Sk Md Saeef Ul Hoque Chishty

WorldFish, Bangladesh Office, Dhaka, Bangladesh

Fishers' local ecological knowledge (LEK) can be used to reconstruct or supplement long-term trends in heavily exploited population or poorly assessed species with low biomass. We used historical memories of small-scale fishers to understand their perceptions of changes in catch trends in marine fisheries over the last 20 years. The study aimed at evaluating how fishers could provide consistent and reliable data on major fish species/groups comparable with official catch data and to explore the potential of increasing their participation in fishery management. We conducted focus group discussions (FGDs) and key informant interviews with experienced fishers and stakeholders, using a structured template related to the catch and effort data. Using FGD data, we systematically compared changes in fish catch rates and effort over time and space. Data were collected on major groups of species that had reasonable landing over time. Overall, the analysis revealed changes in catch rate, monthly landings per landing center, factors that likely influence the catch trends, and the spatial expansion of fisheries. Our study provides insight into species' abundance over time. Fishers' LEK shows declining catch rates for major species and groups, but monthly harvests at landing centers have increased over two decades because of increased fishing efforts. Small-scale fishers are catching more fish from deeper waters over time, indicating a geographical expansion and/or development of fisheries beyond traditionally exploited areas. Such expansions of nearshore fisheries may result from the overfishing of nearby areas. On the contrary, this could be viewed as a positive indication of the potential for growth and development of small-scale fisheries in the region, especially in the context of the blue economy. The agreement between official statistics and fishers' data on species catch trends over time suggests that fishers have a good understanding of their fishing system. This indicates that fishers' knowledge could be invaluable, especially in data-poor areas. LEK integration into policy and management is thus expected to facilitate the efficient management of small-scale fisheries.

KEYWORDS

Fisher's local ecological knowledge, artisanal, small-scale fishery, fishing capacity, conservation, Bay of Bengal, Bangladesh, CPUE (catch per unit effort)

1 Introduction

The exact number of small-scale fishers in the world is unknown. Globally, there are about 51 million small-scale fishers, most of whom are in developing countries, according to estimates by the Food and Agriculture Organization (FAO, 2018). In addition, hundreds of millions of people throughout the value chain depend on the fishing industry for their livelihoods. New fishers enter the system every day, so it is expected that this number will continue to increase. Consequently, it is difficult to determine how many fish are caught by small-scale fisheries every year. The Sea Around Us project estimates that about one-quarter of the world's catches come from small-scale fisheries (Zeller et al., 2016). Although the actual numbers may be uncertain given the lack of statistics, these approximations indicate that the small-scale fishery sector is too large to ignore. Because of the importance of this sector and its dynamic nature, the Committee of Fisheries of FAO endorsed the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries on 9 June 2014.

The small-scale fishery is, by far, the most important sub-sector of the national fisheries regime because it contributes significantly to the national economy and promotes poor coastal fishing communities. Most small-scale fishers catch fish using conventional techniques and equipment that have been passed down through generations. The fishery sector employs more than 17 million people, which make up about 11% of the population of Bangladesh. It contributes 3.5% to the national economy and 25.72% to the agricultural sector (DOF, 2020). Marine fisheries account for 20%–24% of the country's total fish production of which small-scale fisheries contribute greater than 80% (range between 80% and 95%) to the total marine catch (DOF, 2020; Alam et al., 2021). Consequently, marine fisheries contribute directly to food security, poverty reduction, employment, and improving the socio-economic conditions of the majority of the population.

From a management perspective, however, it is the sector with the most challenges, because fishers are spread out along the shore, access to the fishery is free, and fishing provides most of the livelihood for coastal fishing communities. The rapid expansion of the fisher community led to an uncontrolled expansion of the fishing effort, which resulted in low catches and conflicts over fishing rights in coastal areas. These new entrants have likely adopt innovative fishing methods that imply a potential risk of overfishing and depletion of fish stocks (Islam, 2021). In addition, domestic industrial fishing fleets have been accused of violating national fisheries laws, such as fishing below 40-m depths.

Despite the importance of small-scale fisheries, coastal fishery management in Bangladesh has been dominated by industrial trawlers, with little attention paid to others. It would be impossible to manage such vast resources without a holistic management plan. Such a plan will require both historical and current statistics. Data on small-scale marine fisheries in Bangladesh, particularly species-specific harvest and effort data, are not comprehensively updated because of the lack of manpower and logistic support. The absence of reliable species-specific baseline information makes it difficult to form robust management guidelines for inshore open-water fisheries. Using local ecological knowledge (LEK) to comprehend past patterns of catch and effort trends could be a potential solution to fill up the data gap where there is no other alternative way.

LEK refers to the knowledge gained by local resource users through interactions with the ecosystem (Beaudreau and Levin, 2014; Braga et al., 2018). Fishers possess a profound understanding of the ecosystems in which they operate. Unfortunately, decision-makers rarely use this information when deciding about exploited populations, particularly in areas lacking scientific data (Hind, 2015). Fishers' LEK is used to reconstruct previous ecological states (McQuatters-Gollop et al., 2019), conservation of cartilaginous fish (Colloca et al., 2020), fisheries catch or catch rate (Martins et al., 2018; Veneroni and Fernandes, 2021), and biodiversity (Bastari et al., 2017; Veneroni and Fernandes, 2021). Together with quantitative information, LEK has contributed to better fishery management (Novacek and Cleland, 2001; Barclay et al., 2017; McQuatters-Gollop et al., 2019). Fishers' political and social role has been enhanced through the use of LEK, with involvement in decision-making and participation in discussions with local stakeholders (Turner et al., 2000).

LEK is widely viewed as an effective tool for engaging communities at the scale of natural resource management (Shephard et al., 2007; Fischer et al., 2015). In particular, this approach is helpful when limited data make it difficult to assess the stock abundance, and historical time series of marine population abundance becomes crucial (Beaudreau and Levin, 2014). Local knowledge, however, is not always reliable, and validating it before experimentation or observation can be performed is needed. For validation, most researchers apply a cross-checking and consensus approach, reasoning that beliefs held by a majority have greater merit (Neis et al., 1999; Wilson et al., 2006). International bodies have encouraged the involvement of fishing communities in decision-making processes for marine resource management and to have positive impacts on science and policy (Veneroni and Fernandes, 2021).

Our current understanding of the overexploitation of Bay of Bengal (BOB) fisheries is based on fairly recent data, although most of it relates to industrial fishing (Fanning et al., 2019). There is a dearth of information on the long-term trends of species abundance and diversity in the shallow water bodies (<40 m depth) where small-scale fishers operate. The information available currently on the status of populations in shallow water is ambiguous with varying spatial scales during a time of high fishing pressure when populations are probably at their lowest historical biomass. Furthermore, the possibility of illegal fishing in these fisheries makes any estimation uncertain. Conservation is also a high priority in this area because it includes highly productive areas that provide nursery grounds and shelter for many young species.

The study aimed at determining how fishers could provide consistent and reliable data on major fish species/groups comparable to official catch data, with the intention of exploring the potential of increasing their participation in fishery management. To accomplish this, we first (a) made an attempt to construct historical catch and effort trends for small-scale marine fisheries in the BOB using small-scale fishers' memories and (b) subsequently compared the trends in catch and effort between the data provided by fishers and the official statistics obtained from the Fishery Resource Survey System (FRSS) of the Department of Fisheries (DoF), Bangladesh.

2 Materials and methods

2.1 Study area

Landing centers of seven study sites in four coastal districts—the Patharghata and Taltali area of Barguna district; Alipur area of Patuakhali district; Shamraj area of Bhola district, Teknaf, Ukhiya, and Maheshkhali; and Nazirartek/BFDC areas of Cox's Bazar district—were selected for this study owing to their significant contribution to marine fisheries production in Bangladesh (Figure 1). Most coastal

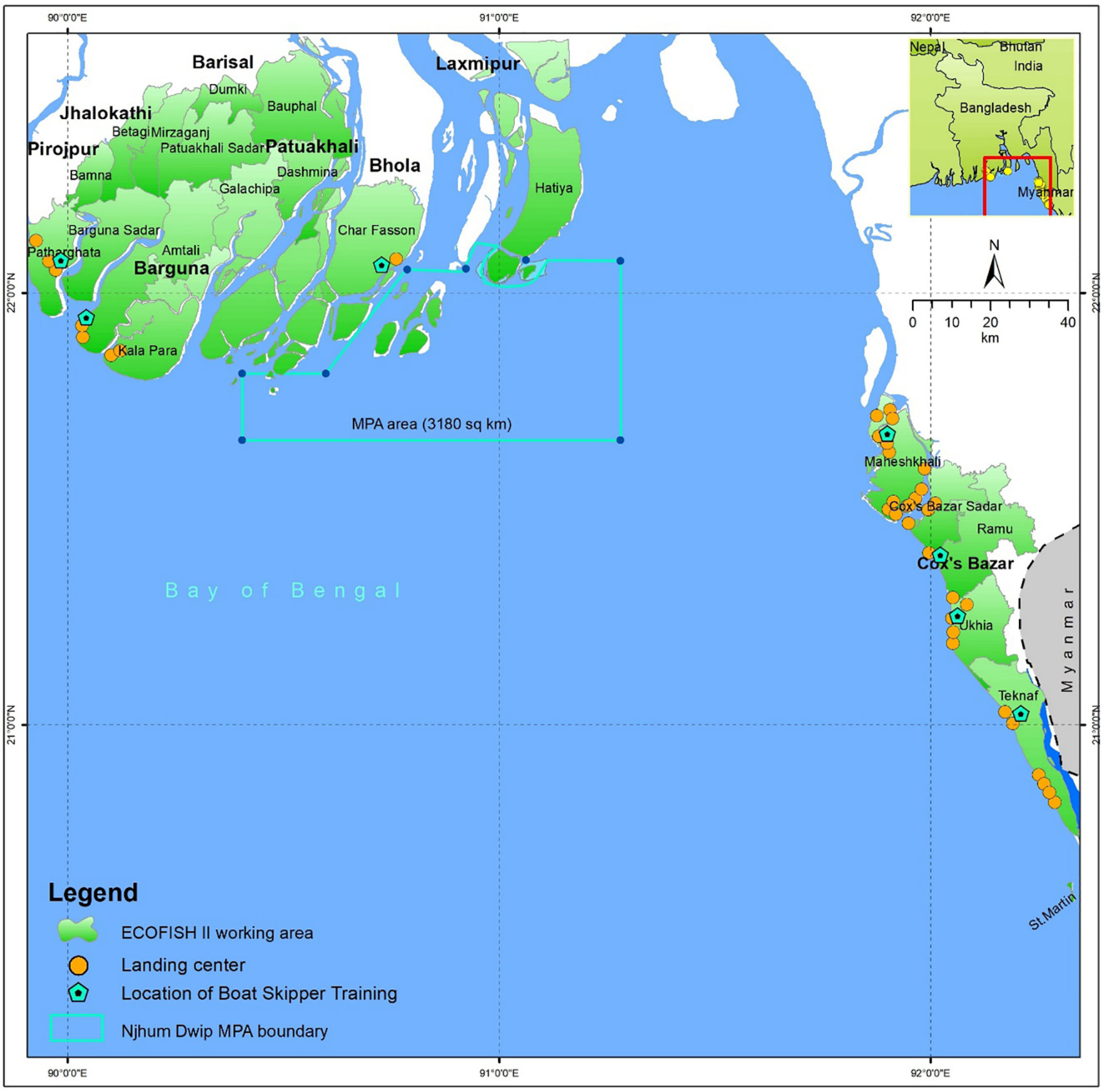

FIGURE 1
Map of the study area showing the locations of the landing stations from where artisanal fisheries operate.

inhabitants in the study sites are entirely dependent on fishery resources for their livelihoods, either directly or indirectly.

2.2 Study overview

This study was carried out as a part of a series of training programs designed to train boat skippers about biodiversity conservation and safety at sea. Each training lasts 3 days with 30 fishers whose experience as boat skippers ranges from 5 to 30 years. We have engaged old fishers alongside younger fishers in the training program. This is because despite being in constant contact with the marine ecosystem, fishers can also be prone to shifting baseline syndrome (Turvey et al., 2010). This training is the first of its kind organized for these very important actors of small-scale fishing, who are responsible for leading a team of up to 25 fishermen on trips. This study demonstrates how boat skippers understanding and willingness can help better manage artisanal fisheries that are poorly monitored. Artisanal fishers consider themselves as safeguards of the sea and fight against any irregularities that might jeopardize their wellbeing. Once the fishers had engaged in lively discussion and understood the importance of good data in managing small-scale fisheries, two groups were formed to conduct the focus group discussion (FGD). In each group, there were both experienced (more than 20 years of experience) and younger boat skippers.

As a prelude to the formal FGD aimed at collecting data, we conducted a pre-workshop in which experienced small-scale fishers responded to a questionnaire individually and later collaborated on developing a template to collect historical data on fish harvest trends and the associated effort dynamics. To clarify, by defining a template, we mean that several sections were developed with specific questions (see data collection) to which fishers were asked to respond. We found that asking questions individually to fishers produces sporadic and, in some cases, erroneous data points, whereas asking a group of fishers results in more reliable data. Most of these fishers fish together in similar habitats and fisheries over time. Hence, the collective answer generated through the FGD appears to have helped avoid ambiguity and bias and increased the reliability of the information over the individual data points in a historical context. In this way, the data template facilitates a structured and focused discussion. Fishers were, however, allowed to discuss freely specific topics of discussion according to the order in which data were requested. The use of a group approach to collect and validate data seems particularly useful when working with historical data. For example, through participatory workshops, researchers showed how LEK could be incorporated into model outputs and improve our understanding of historical trends (Sánchez-Jiménez et al., 2019). During the data collection using FGDs, we interviewed fishers to identify the species that they have harvested in the past 20 years, using their catch data as a reference. We listed the names of the species in chronological order, with the most frequently caught species at the top of the list. We only included species that had at least 5 kg of landings per trip in a given year for further analysis. To facilitate our analysis, we grouped the identified species into major groups (categories) following the same groups reported in the annual report of the FRSS of the DoF, Bangladesh (DOF, 2020). This allowed us to identify the most significant changes in the abundance of each group over time and compare them with the DoF reports.

The catch data for the major fisheries groups were evaluated, along with the effort data for the gears that accounted for the bulk of the landings for a specific fisheries type. We then looked at whether fishers' data were consistent with official statistics to determine whether fishers' LEK integration into the management system is feasible.

2.3 Data collection and analysis

Our study utilized the historical memories of Bangladeshi fishers (boat skippers) to gain insight into the status of the small-scale marine fishery in the BOB. In total, 21 FGD groups comprising 630 fishermen were consulted across seven sites (Barguna = 4, Bhola = 1, Cox's Bazar = 2, Maheshkhali = 1, Patuakhali = 1, Teknaf = 8, Ukhiya = 4) during 2020 and 2021. The participants were given an overview of the exercise and potential applications of their input, as well as an explanation of the objectives of the data collection. Our study focused on the period between the 2000s and the present. We divided these 20-year period into three segments: 2000 (reflect fisheries status between 1995 and 2000), 2010 (reflect fisheries status between 2005 and 2010), and 2020 (reflect fisheries status between 2015 and 2020), which are roughly thought to be representative of the various phases of the recent development of BOB fisheries from moderate exploitation to overexploitation of many commercial fish stocks (Table S1).

To gather data on the abundance of a particular species or group, fishers were asked to provide their perceived average harvest per trip in the given year (time segment) compared with that in the present day. Fishers were given the flexibility to express their views on their harvests as an average over 5 years (Table S1). This was done to mitigate the impact of years with significantly low or high catch, as these fishers primarily target clupeid species. Linear interpolation was used to generate annual time series between years where data were not asked from fishers, using the collected (fishers) data as anchor points (Pauly and Zeller, 2015). Interpolating temporally between time snapshots (e.g., 2000, 2010, and 2020) is a common practice in ecology (Fordham et al., 2012), although this approach can potentially mask important decadal variations (Fordham et al., 2018). Nonetheless, we pointed out that it is more appropriate to ask fishers to provide data of a particular time frame, rather than requesting data for individual years. Fishers were additionally asked to provide information about the name of the landing center, the distance of the fishing ground from the landing center, the number of boats at the landing center that they belong to, the length of the boat, the engine power, the number of fishers per boat, the number of fishing days per trip, the number of fishing days per month, the number of active fishing hours per day, the type of nets they use, the length of the net, the number of nets, and the depth of the fishing. Each of the data points that were recorded from the FGD was the result of a comprehensive discussion involving all fishers. A total of three key informant interviews were conducted, primarily, to validate the findings from FGD data.

We calculated catch per unit effort (CPUE) as the average catch (in metric tons) as a function of fishing effort (number of boats). This was calculated by dividing the total annual catch by the number of fishing boats operating over all landing centers studied. The total annual catch was estimated by multiplying the monthly catch data by the number of fishing months during which each fisher operates. Monthly harvests were calculated by multiplying the catch rate per day per boat by the number of fishing days in a month and the number of boats at each landing center.

We used FRSS data of the DoF to calculate the CPUE (in metric tons) per craft per year for the artisanal fishery in the BOB. This was estimated by dividing the total annual catch by the number of crafts (boats) accounted for each year. These data enable us to determine whether the catch data reported by the fishers align with the official data provided by the DoF. DoF carries out catch assessment survey of marine artisanal fisheries to sample catch and corresponding fishing effort data (DOF, 2020). A frame survey is conducted yearly, and sample landing centers are selected for each type of gear. Sample days are selected on the basis of gear type and landing center, and up to five sample landings are observed per day. Data are recorded on Form-MA-1 and used to estimate monthly total catches by the district. The average catch per fishing unit per month is calculated using the average catch per trip and the average number of trips per fishing unit per month. Thus, the data collection method of DoF, which involves different fisheries administrative units, covers significantly larger areas and samples.

We further calculated several variables that could potentially affect fishing efforts, such as active fishing hours, engine power, and the length of fishing gear used during fishing activities. These data were collected using a similar approach that was used for catch and effort data and estimated as an annual mean over a five-year period. The term “active fishing hour” refers to the period during which a fishing net is deployed in the water. Engine power is calculated by multiplying the power of each engine, measured in horsepower, by the number of engines on the vessel. Net length is determined by measuring the combined length of several pieces of nets that are either set on the surface of the water or submerged below it.

To determine the spatial distribution of fisher catch, we allocated the catch to the areas where fishers primarily reported fishing (based on the depth). To maintain the accuracy and consistency of our spatial catch data, we cross-checked the reported distances traveled by the fishermen with the corresponding depth data. Fishing effort variables were compared using non-parametric Kruskal–Wallis test. If significant differences were found, then Wilcoxon rank sum tests were used to compare variables between two time segments. Normality (Shapiro–Wilk’s test) and homogeneity of variance (levene test) were performed prior to non-parametric tests, and outliers were removed using boxplots where necessary. We used R statistical package for data exploration, visualization, and descriptive statistics (version 4.1.1).

3 Results

3.1 Temporal dynamics of marine small-scale fisheries

3.1.1 Catch trends

Fishers’ ecological knowledge suggested that long-term trends of catch rate exhibited almost similar patterns across major species/groups. All the major species/groups show a decline in catch rates except surgeonfishes. Catch rates for all species declined from 13 metric ton boat^{-1} year^{-1} in 2000 to 4 metric ton boat^{-1} year^{-1} in 2020. According to fishers’ LEK, hilsa catch rates decreased almost linearly over the last 20 years (Figure 2), from an average rate of 34 metric ton boat^{-1} year^{-1} in 2000 to about 8 metric ton boat^{-1} year^{-1} in 2020. This equals a decrease of about 77% between 2000 and 2020. Among other groups, sardine, bombay duck, anchovy, herrings, and pomfret all were reduced (between 52% and 84%) in their catch rate in the 20-year period. Surgeonfishes and ribbon fish on the other hand showed an increase (61% and 36%, respectively) between the two time periods.

The declining CPUE trends were observed for the most of the species. Likewise, hilsa (*Tenualosa ilisha*), many of the important commercial species including the Indian threadfin (*Leptomelanosoma indicum*), blood snapper (*Lutjanus malabaricus*), silver pomfret (*Pampus argenteus*), chinese silver pomfret (*Pampus chinensis*), panna croaker (*Otolithoides pama*), black pomfret (*Parastromateus niger*), silver croaker (*Pennahia argentata*), and indo-pacific king mackerel (*Scomberomorus guttatus*), caught under small-scale fisheries showed somewhat negative or linearly declining trend excepts a few (Figures S1, S2). The CPUE of sea catfish (*Arius arius*), mackerel tuna (*Euthynnus affinis*), and smallhead hairtail (*Eupleurogrammus muticus*) was found to be increased, whereas concertina fish (*Drepane longimana*) remained stable over the past two decades. Regardless of whether these trends are at the group or species level, there is considerable variability (as indicated by 95% confidence intervals) around the mean values reported by the fishers harvested across fisher types, areas, and years.

This decrease in catch rates does not, however, translate into an overall lower harvest at various landing centers. Fishers’ data suggest that all major groups have experienced an increase in their harvest (small to large) over the past 20 years (Figure 3).

Between 2000 and 2010, the amount of hilsa landings across all the landing centers studied was found increased by 41%, which then reached 67% by 2020. Hilsa has consistently maintained a high ranking in total monthly landings, with a range of 779 to 814 metric ton per month per landing center between 2010 and 2020 (Figure 3). Among the seven sites studied, fishers from Barguna, Patuakhali, Bhola, and Cox’s Bazar contributed the most to hilsa production over the years. There was no hilsa fishery reported for Ukhiya during 2000. Patuakhali, in contrast, has experienced a remarkable increase (10 folds) in its monthly historical landings between 2000 and 2020.

Among the other groups, bombay duck (13%), sardines (31%), herrings (120%), and anchovies (179%) all showed positive trends in monthly historical landings between 2000 and 2020. The largest

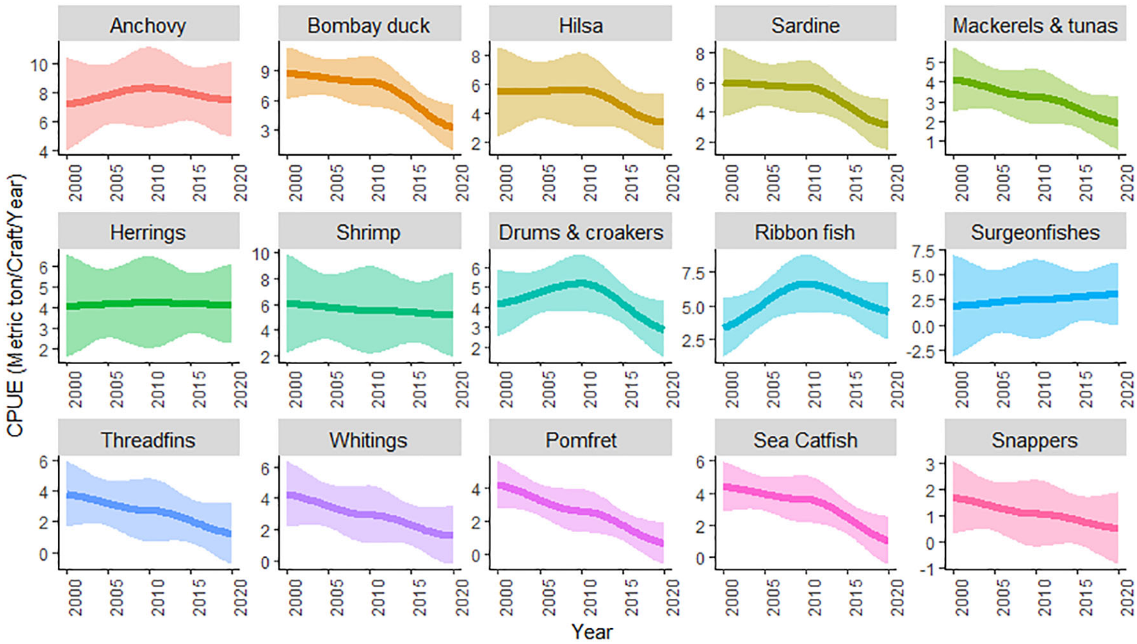

FIGURE 2
Trends of catch per unit effort (CPUE) of the major marine fish groups in the Bay of Bengal small-scale marine fishery from 2000 to 2020. The solid line is the smooth function estimate and shaded regions represent 95% confidence interval (CI). Source: Fishers' FGD data.

increases were observed, however, in shrimp (1368%), surgeonfishes (955%), sea catfish (629%), and ribbonfish (623%).

The official catch and effort statistics for Bangladesh (FRSS, DoF) showed both consistency and disagreement with those obtained from fishers' LEK. In agreement with fishers' LEK data, five of the seven fish groups showed a decrease in CPUE (metric ton/craft/year) between 2002 and 2020 (20%–73%), except for hilsa and bombay duck that showed an increase of >20% (Figure 4A). Similarly, the positive trends for the total annual harvest nationwide (20%–84% increase across groups) closely resemble those reported for the majority of the fish groups by fishers (Figure 4B). Contrary to fishers' opinions, the total catch of catfish and indian salmon,

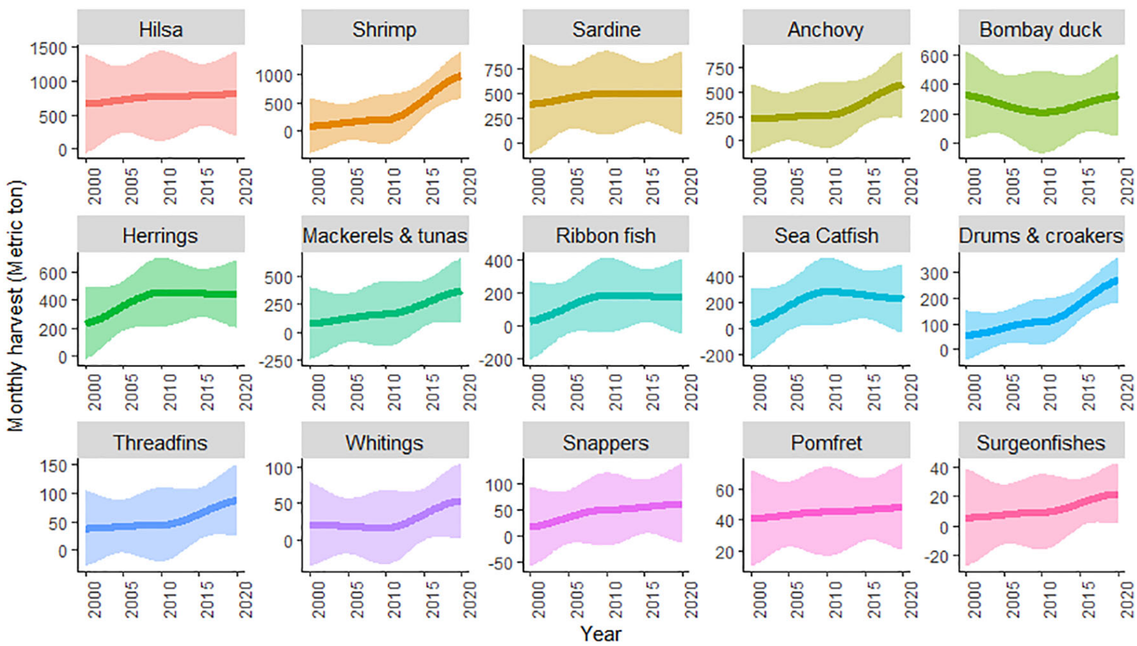

FIGURE 3
Total relative landed catches per month per landing center in the Bay of Bengal small-scale marine fishery from 2000 to 2020. The solid line is the smooth function estimate and shaded regions represent 95% confidence interval (CI). Source: Fishers' FGD data.

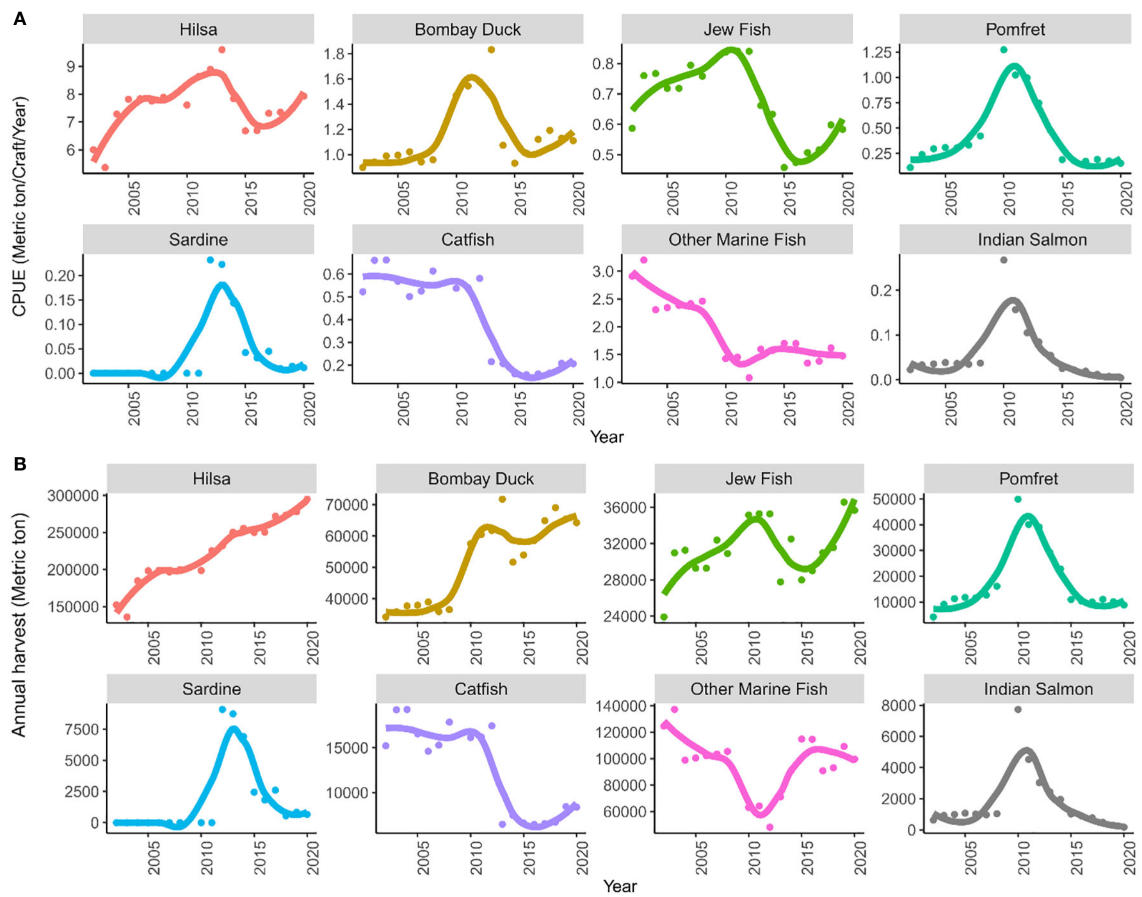

FIGURE 4
Trends in landed catches by small-scale fishers in the Bay of Bengal from 2002 to 2020 (FRSS data). **(A)** CPUE (metric ton/craft/year). **(B)** Total annual harvest by major groups (metric ton).

however, decreased by more than 50% between the two time periods. Other marine fish groups (miscellaneous fish) were also reported to be declined (16%). Inter-annual oscillations are evident in the FRSS time series data that were difficult to detect in the data provided by the fishers. Such disparities in historical time series data dominated by pelagic species are not unexpected. However, the trends showed by major targeted (and landed) species such as the hilsa, bombay duck, and jewfish need further attention.

3.1.2 Fishing effort

The increase in landings reported between 2000 and 2020 has been attributed to an increase in fishing efforts. We evaluated nine different types of factors associated with fish catch rates (see Figure 5).

All the nine different effort variables varied significantly ($P < 0.001$) between over the 20 years period (Table S2). The largest and most rapid growth was reported for engine power ($\chi^2 = 324.19$, df = 2, $p < 0.001$), fishing months in a year ($\chi^2 = 164.40$, df = 2, $p < 0.001$), and the number of fishing boats ($\chi^2 = 102.76$, df = 2, $p < 0.001$), all of which changed significantly during the last 20 years. Among other factors, fishing days per trip, the number of fishers per boat, net lengths, active fishing hours per day, and the length of the boat all increased by 20% to 77%, whereas the number of fishing months experienced a decline (34%) because the government imposed several seasonal closures and bans.

3.2 Spatial dynamics of marine small-scale fisheries

3.2.1 Catch trends

This study analyzed the changes in the catch of the small-scale marine fishery in the BOB over time and space. Our results showed that small-scale fishers now primarily target deeper waters (slightly beyond the 40-m-depth line) for harvesting, with catches taken beyond the 40-m zone increasing from 4% in 2000 to 53% in 2020, whereas catches below the 10-m depth zone reduced from 64% to 8% during the same period (Figure 6). The volume of harvest for depths between 11 and 20 m and 21 and 40 m remained relatively stable between 2000 and 2020. These findings highlight a marked shift in the spatial distribution of fish harvest over time, with small-scale fishers adapting to changes in fish stocks.

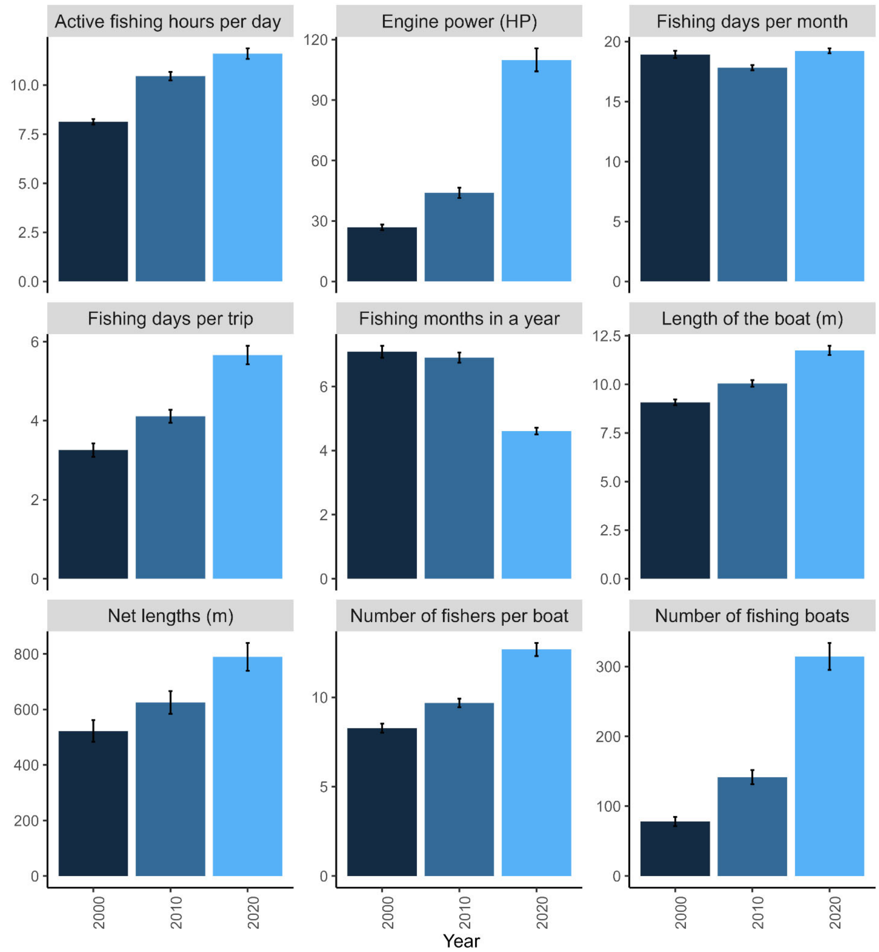

FIGURE 5
Temporal evolution of fishing effort between 2000 and 2020 in the small-scale marine fisheries of the Bay of Bengal. Source: Fishers' FGD data.

3.2.2 Fishing effort distribution

The increasingly higher catch from deeper water suggests that fishers have frequently traveled longer distances to fish, which is also evident from the data they provided on the average distance traveled per trip over the last 20 years (Figure 7A). While fishers can also travel a longer distance around a circle or through a defined area close to nearshore and harvest fish, we examined the historical change in the depth of their harvest area. Over time, fishers tend to reach deeper waters to catch their fish, as evidenced by the distribution of depths of their harvesting areas (average depth increased by about two and a half folds in 20 years). There have been occasions when fishers have reported catching fish at far distances and depths around the 2000s, but this becomes common around 2020 (Figure 7B), confirming that small-scale fishers are now fishing deeper water frequently.

4 Discussion

The long-term patterns inferred by this study for small-scale fisheries provide insights into species' abundance over time. According to the fishers' LEK, fish catch in terms CPUE declined for all major species and groups. Although CPUEs have decreased overall, the monthly harvest landed at various landing centers has shown a positive trend over the past two decades. Increasing landings between 2000 and 2020 have been primarily the result of increased fishing effort, as the fishing fleet capacity has reached its historical maximum. Small-scale fishers frequently traveled longer distances and are increasingly targeting deeper waters as their primary harvesting area to fish. Temporal dynamics of catch and fishing effort

4.1 Temporal dynamics of catch and fishing effort

In this study, we have shown that the decline of species catch (CPUE) in the coastal ecosystem of BOB has perceived for the most of the species caught by small-scale fishers. The situation in small-scale fisheries is extremely concerning for managers as they need to pay special attention to this sector. In general, a reduction in the catch rate of two or three times since 2000 indicates a stressed ecosystem, which is at risk of overexploitation (Rashed-Un-Nabi and Ullah, 2012). A previous study showed that the CPUE

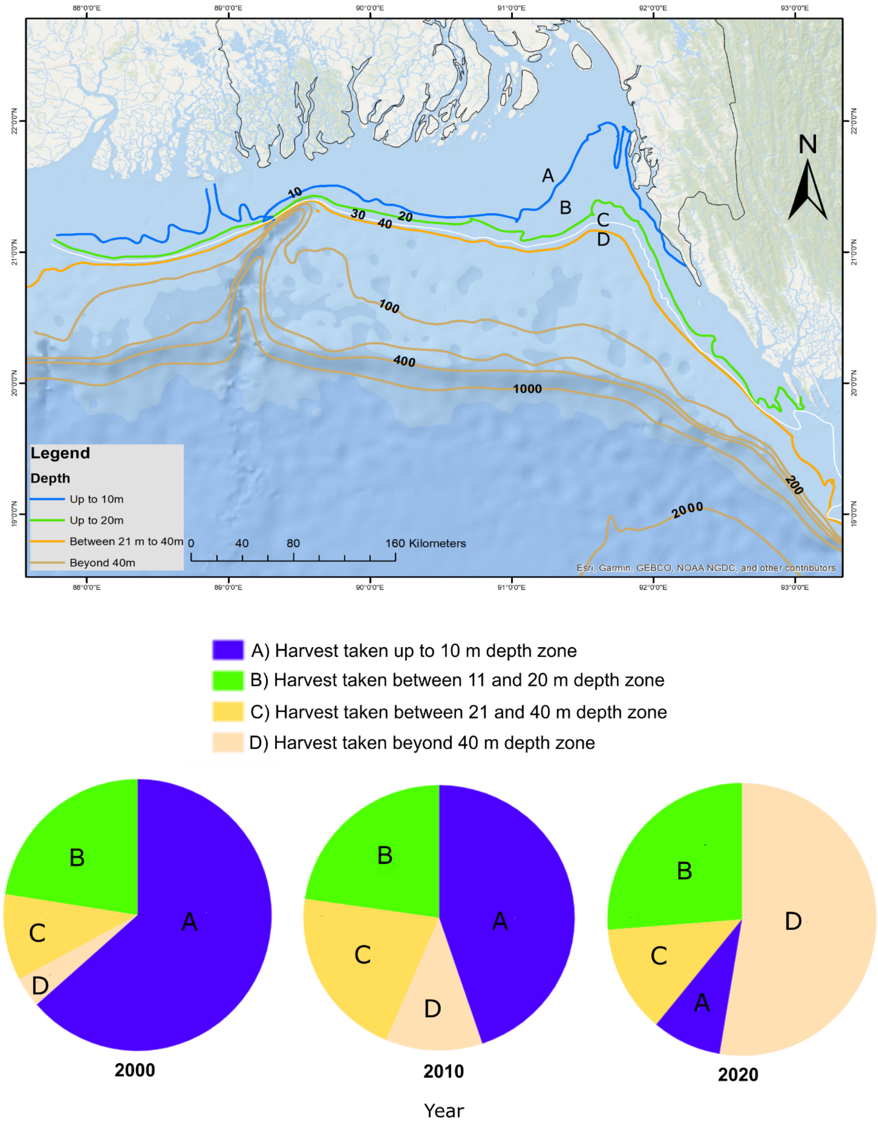

FIGURE 6
Spatial distribution of fish harvested by small-scale marine fishers in four different depth zones of the Bay of Bengal over 20 years. Source: Fishers' FGD data.

estimated from different types of gill nets has declined drastically from 2001–2002 (700 kg) to 2005–2006 (100 kg) at landing sites along the coasts of Chattogram and Cox's Bazar (Hussain and Hoq, 2010). The data used in the study, like the previously mentioned study, also refer to the catch of mechanized small-scale boats that use different fishing gears, targeting species such as grunter, hilsa, bombay duck, jewfish, mullet, shrimp, mackerel, and crabs. This shows that the fishers' observations of perceived temporal changes are supported by the available scientific information, as is the case of similar studies elsewhere (Rochet et al., 2008). To identify baselines against which modern populations can be measured, old fisher's memories are invaluable for assessing long-term changes in exploited populations (McClenachan et al., 2015).

Our study used data from experienced and old fishers that aligned with contemporary information, providing a useful baseline for resource management. Despite the low CPUE, for both species and fish groups, the total monthly landings for each of the landing centers remained high. The overall increase in landings between 2000 and 2020 has been driven primarily by an increase in fishing efforts. A lack of monitoring, control, and surveillance (MCS) in small-scale fisheries resulted in an uncontrolled expansion of the fishing effort (Mome et al., 2007; Hussain and Hoq, 2010; Shamsuzzaman et al., 2017). According to the fishers, all factors (effort type) related to fishing capacity have increased except the number of months in a year. Because of several government bans and seasonal closures, the number of fishing months in a year has been reduced (Islam et al., 2021). The largest and most rapid growth has been in the number of fishing boats and engine power in terms of horsepower (hp). A first attempt at motorizing traditional boats with petrol outboard engines (12 hp) was made in 1966/1967 (BOBP, 1985), where the data from the present study show that most of today's small-scale motorized boats operate with 24 hp and

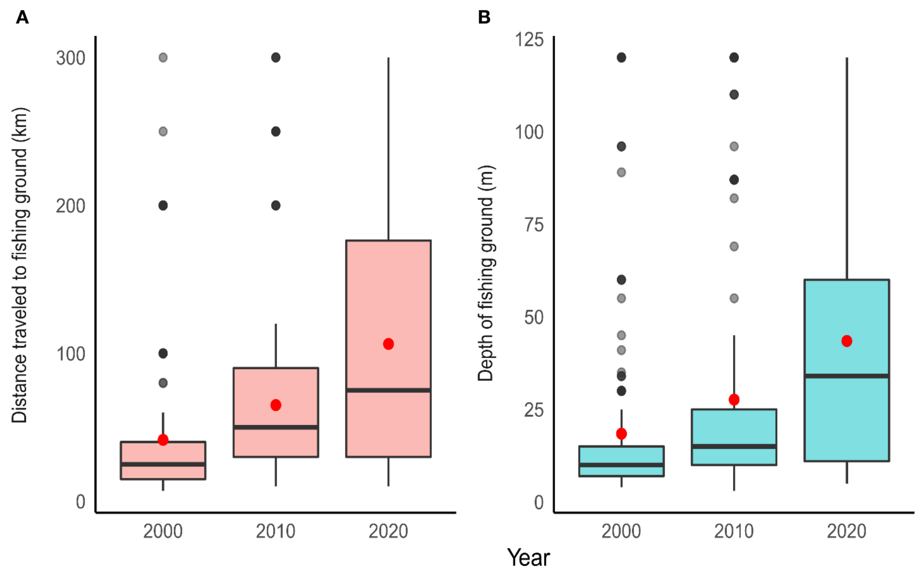

FIGURE 7
(A) Distance traveled by fishers to reach the fishing ground. **(B)** Depth of fishing grounds in the small-scale marine fisheries of the Bay of Bengal where fishers operated for over 20 years. The lower and upper hinges of the boxplots correspond to the first and third quantiles, the middle line corresponds to the mean value, and the whiskers (vertical lines) indicate the highest and smallest values [between 1.5 * the interquartile range (IQR)]. Source: Fishers' FGD data.

a few with approximately 500 hp. The increased engine power provided opportunities for the fishers to harvest fish from deeper and longer distance. Since 1980–1981, the fishing fleet has increased by 25 folds, from 2,700 motorized boats to 67,000 boats now (DoF, 2022). The growing number of fishing boats and engine power indicates an increasing level of direct involvement. Historical baselines can be valuable for improving management practices in the face of an upsurge in fishing efforts, which can put the fishery at risk of collapse, as seen in West Bengal's hilsa fishery without proper monitoring (Dutta et al., 2021).

4.2 Spatial dynamics of catch and fishing effort

Small-scale fishers are now catching more fish in deeper waters. This study reveals a significant change in small-scale fishers' behavior and spatial effort distribution over time, with more than half of the catch now coming from beyond or around the edge of the 40-m depth zone. The heterogeneity and complexity of fisher behavior, often overlooked by data-rich modeling approaches, can be effectively captured using a qualitative approach. This approach may be the only option in a data-poor ecosystem without a management plan. Results suggest that fishing occurs to a greater extent in deeper waters, indicating a geographical expansion and/or development of fisheries beyond the traditionally exploited areas of small-scale fishing. Overfishing of nearshore areas could lead to such expansions because fishers are looking to explore new fishing grounds to maximize profits. When this happens, trophic level declines can be concealed by the geographic expansion of fisheries, in which fishing-down effects closer to shore are offset by higher-trophic-level resources (Kleisner et al., 2014). A failure to detect such shifts in exploitation-driven decline in marine trophic level will hinder taking proper management measures, as could be the case with BOB's small-scale fisheries.

Small-scale fishers are fishing at greater depths and traveling long distances, leading to an increase in the percentage of fish caught in small-scale fisheries from distant sources. Indian shelf fisheries have reported experiencing similar circumstances, where expansion has reached its limit, and catches are likely to stagnate and decline, affecting the sector and consumers (Bhathal and Pauly, 2008). Profit maximization is the main objective of where fishermen go fishing, leading to an effort distribution that maximizes profit per unit effort. Fishers choose fishing locations based on profit maximization, taking into account environmental and weather factors (Daw et al., 2011). Fishers adjust their resource usage according to season and utilize technological resources to mitigate the effects of these factors (Teh et al., 2007; Williams et al., 2008). The small-scale fishing community in Bangladesh relies solely on motor-powered inboard engines to navigate and fish in the deeper water, without any other technological aids for locating fishing spots or forecasting weather. This implies that fishers go to deeper waters because they do not catch enough fish nearshore, despite having insufficient technological or life-saving support.

4.3 Integrating fishers and their knowledge into the science-policy process

Overall, there was good agreement between the general trends of the official statistics and the fishers' data with regard to CPUE and overall harvest. About 10 of the 15 major fish stocks are likely declining, based on LEK data. Recent stock assessment studies in the BOB support these findings. Stock assessments of *Lepturacanthus savala*, *Pampus argenteus*, *Ilisha filigera*, *Saurida tumbil*, and *Upeneus sulphurous* (Al-Mamun et al., 2021); *Parastromateus niger* (Karim et al., 2020), and *Sardinella fimbriata* (Barman et al., 2021); *Bregmaceros mcclellandi*, *Escualosa thoracata*, *Ilisha filigera*, *Johnius belangerii*, and *Coilia dussumieri* (Alam et al., 2022) indicate that all of these species are either over-exploited or grossly over-exploited or likely to be over-exploited. In practice, the traditional way of reporting fishing data, which pools many individual species into one major group, makes it difficult to conduct a preliminary assessment of species using CPUE. In the absence of species-specific comprehensive catch and effort statistics, LEK data could provide a preliminary indication of the status of valuable fisheries and thus contribute to improved official catch statistics and address the data gaps (Damasio et al., 2015).

Successful implementation of traditional knowledge depends, however, on its integration into policy and management. The use and communication of the LEK can be successful in conjunction with datasets and visual product documentation, where research plays an important role. Scientists and policymakers should promote the development of hybrid organizations that combine customary and modern management practices (Cinner and Aswani, 2007). Hybrid management approaches have the potential for effective sustainable resource management as they harness LEK, scientific knowledge, and traditional knowledge. This study shows the promise of integrating LEK data to improve the official catch statistics, which could be particularly valuable in the context of Bangladesh's small-scale marine fisheries, which are difficult to monitor due to their extent, dynamic characteristics, and management practice. Where there is insufficient workforce and logistic support, citizen scientists and boat skippers can provide valuable catch and effort data. Fishers can be recruited voluntarily under a co-management approach requiring them to log their catch either daily or weekly. For example, a Crew-Operated Data Recording System that collects reliable species-wise length-composition data of catches can be introduced (Wibisono et al., 2022). This will facilitate the effective management and harvest strategies through regular updates to stock assessments and developing harvest control rules that would otherwise not be feasible or would lead to a collapse of these important fisheries.

4.4 Limitations

CPUE data are one of the most common indicators used to assess fish stocks. However, catch rate as a proxy of relative abundance indices can be tricky, as inherent catch rate may not always be proportional to abundance over a wide range of exploitation histories (Maunder et al., 2006). Nevertheless, in data-poor systems without any such system in place, these indices are still useful. A more effective approach would be to conduct a scientific stock assessment of these fisheries, at least for the most important commercial species, if not all of them, and then combine those results with the LEKs. To assess historical trends, we limited our analysis to three data periods, each equaling a decade, which may mask some information for species that appear to have increased in recent years. Our data collection method being at a decadal scale may not have truly reflected this increase in hilsa reported by fishers during the FGDs. The aim of this study was, however, to provide a long-term historical baseline that would allow fishers enough flexibility in detecting changes. Because we analyze data collectively (those fishing daily and for multiple days) and across geographic space, we may be unable to uncover some important details about small-scale fisheries. Because the small-scale fishery is so dynamic, it is hard to evaluate it with the same lens. However, we provide the first detailed historical baseline for fishery managers working on small-scale fisheries, to begin with, their preliminary research and develop more robust management decisions.

4.5 Management recommendations

Bangladesh does not currently have a marine small-scale fishery management plan in effect. As a result, fishers' entry or exit to this fishery, as well as their harvests, cannot be assessed properly, particularly at the lowest taxonomic level. If we want to consider the recent increase in engine capacity as we have seen in the small-scale fishing industry, then the decline in catch rate will appear even more pronounced. A small-scale fishery management plan must be immediately in place to prevent further degradation. The DoF should develop and adopt a national plan of action to reduce IUU (illegal, unreported, and unregulated) fishing based on a guidance strategy and a plan to monitor vessel activities and movements. Priority should be given to registering and licensing small-scale commercial fishing vessels. Consequently, an annual assessment of catches and discarded bycatch should be conducted in this sector. Megafauna, including sharks and mammals, require more attention because their removal would disrupt ecosystems functioning through cascade effects. Navigation channels should be kept open year-round on rivers, estuaries, and coastal waters at sea. Instead of banning fishing regardless of the nature of the catch, area- or season-based spatial closures should be introduced wherever required. Most importantly, more funds should be invested to improve fishing communities' socioeconomic conditions. Because fishers' livelihoods could be seriously hampered by any management decision taken, their exclusion from the Fishery Management Plan will not result in success in the long run. Finally, the active involvement of fishers in local fishery management activities and providing them with proper training to use digital catch systems for data collection can be a significant step forward for the sustainable management of these fragile resources

5 Conclusion

This study focused light on the need for urgent action to ensure the sustainability of small-scale fisheries in the coastal ecosystem of BOB. Although it is true that there has been a decrease in the CPUE of the major fish species and groups, the study highlights the resilience and adaptability of small-scale fishers in the face of this challenge. Despite the increase in fishing efforts, the total monthly landings have not declined, indicating that fishers are finding innovative ways to maintain their livelihoods. Moreover, the geographical expansion and/or development of fisheries beyond the traditionally exploited areas is a promising sign of the potential for the growth and development of small-scale fisheries in the region. However, fishery managers also need to keep track of the ecological balance of the ecosystem for the long-term sustainability of the fisheries. This study underscores the importance of implementing effective MCS measures to protect this valuable resource and support the sustainable development of small-scale fisheries. By doing so, we can ensure the long-term viability of this vital sector and safeguard the livelihoods of small-scale fishers in the region.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for this study in accordance with the local legislation and institutional requirements, as no personal data was used. However, all research participants provided oral informed consent, and were informed of the study's purpose and the intended use of collected data prior to consenting. The answers given by participants were anonymized, making it impossible to link any statements back to individual subjects.

Author contributions

HU was responsible for conceptualization, analyzing the data, and writing and editing the entire manuscript. MW and MJR contributed to writing and editing the manuscript. SN, UK, MAR, SM, IK, MH, MBR, and SC collected the data, helped interpret the findings, and contributed to the editing of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.974591/full#supplementary-material

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