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RESEARCH PAPER

Does Minimizing Seabed Contact Alleviate the Impacts of Bottom Trawling? An Experimental Study on Bycatch from North-western Bay of Bengal

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Abstract

In light of the ecological concerns associated with bottom trawling in tropical multispecies fisheries, an attempt was undertaken to implement operational modifications in experimental trawling practices aimed at reducing bottom contact. This endeavour was pursued to investigate the resulting effects on bycatch biomass and diversity along the north-western Bay of Bengal. The average total catch rate and bycatch rate in 66 hauls from January 2017 to December 2019 were 35.46 kg/h and 9.70 kg/h respectively. Bycatch biomass was mainly contributed by Teleostei (77.90%), of which the dominant species was *Equuilites lineolatus*. Temporal variations in bycatch composition were recorded, and average seasonal dissimilarity ranged between 35.03% and 59.61%. Juvenile percentages varied among six commercial species from 1.42 to 28.0, and their occurrences were related to their peak spawning seasons. The trophic index of bycatch calculated was 3.65. Species diversity and richness in bycatch were higher during post-monsoon and summer seasons. Biomass and abundance plots indicated the bycatch fauna to be relatively unstressed during most seasons. Trawling marginally above the bottom had improved ecological outcomes; as evident from the decreased proportion of bycatch to total trawl catch, reduced growth overfishing from lower juvenile proportions and within optima for various diversity indicators.

Introduction

Trawling is one of the most efficient methods of catching fish. Globally, one-quarter of marine landings, around 19 million tonnes of fish and invertebrates are contributed annually by bottom trawlers (Amoroso *et al*., 2018). Being a non-selective fishing method, trawling is highly controversial as it captures a large quantity and diversity of non-target species, including endangered ones. Trawling has a profound effect on the marine ecosystem. It kills a substantial number of juveniles of commercially valuable species, mechanically disturbs the sea bottom and injures a wide variety of marine benthic life (Bijukumar & Deepthi, 2008). The use of square mesh cod end in recent years, however, has been shown to increase size selectivity in the catches, thereby reducing juveniles (Madhu *et al*., 2023). As benthic habitats provide shelter and food for a variety of important demersal fish species, frequent alterations in the habitat result in declining marine fish landings (Bhagirathan *et al*., 2014). The situation is particularly complex and grave in tropical multispecies

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fisheries affecting both the ecosystem function and biodiversity. Along with the targeted species, there is considerable capture of incidental species for which there is no directed effort, termed as 'bycatch' (Borges *et al*., 2001). Bycatch includes not only juveniles of targeted fish and other resources but also juveniles and spawners of non-targeted organisms (Ranjith *et al*., 2018). Bycatch of juveniles for target and non-target species does not have much financial value but has a high ecological importance. Bycatch of juveniles contributes to reduced recruitment and future financial loss through growth overfishing (Najmudeen & Sathiadhas, 2008).

Bottom trawling uses heavy otter boards or shoes to maintain contact with the seabed and ground ropes and chains to force fish into the net causing irreversible, extensive, and long-lasting biological damage to the coastal and marine habitats (Eigaard *et al*., 2017). Physical disturbances from such devices causes significant changes to the seabed, causes mortality among the animals encountered, and affects the biogeochemical processes of the sediment-water interface impacting community production, trophic structure and function (Hiddink *et al*., 2006).

The Bay of Bengal, an embayment of the north-eastern Indian Ocean is the largest bay in the world and is one of the most productive ecosystems (>300 g C cm^{-2} y^{-1}) characterized by marked seasonal fluctuations of water-quality parameters caused by monsoons (Heileman *et al*., 2009). Though a plethora of crafts and gears exploit the multispecies fishery in this region, trawlers (overall length of 12-20 m and engine horsepower of 90-250 HP) are the most important fishing fleet and are extensively operated in the coastal waters at depths from 10 m to 150 m (Vivekanandan, 2013a). Incessant trawling in this climatically sensitive marine habitat has slowly resulted in disproportionate destruction of non-target groups including a vast array of benthic organisms and juveniles and sub-adults of commercially important shellfishes and finfishes. All these species are vital in the food web of exploitable resources (Menon & Pillai, 1996). With intense trawling pressure (Vivekanandan, 2013b), overfishing (Ghosh *et al*., 2015) and high bycatch levels (Heileman *et al*., 2009) have become a matter of great apprehension. Due to the increasing demand for low-cost fish protein from the aquaculture industry for fish meal manufacture, bycatch from trawling has increased substantially over the years and constitutes 17-21% of the trawl landings in the north-west Bay (Dineshbabu *et al*., 2014).

There have been several recent studies on trawl bycatch and its impact on marine fisheries resources along the Indian coast (Bijukumar & Deepthi, 2009; Rajeswari *et al*., 2010; Dineshbabu *et al*., 2012; Murugesan *et al*., 2012; Murugesan & Purusothaman, 2011; Madhu *et al*., 2015; Sambandamoorthy *et al*., 2015; Dinesh & Chandrasekhar, 2015; Mahesh *et al*., 2017; Samantha *et al*., 2018; Mahesh *et al*., 2019; Ramkumar *et al*., 2019). Though the Central Institute of Fisheries Technology has developed a bycatch reduction device for use in bottom trawl nets, policy-makers in the country have failed to implement it, primarily due to resistance from mechanized fishing sectors (Bijukumar & Deepthi, 2008). Despite being mandatory in most maritime states, fishers are extremely reluctant to use bycatch reduction devices due to the perceived negative impact on catch and operational costs, potentially reducing their income (Gupta *et al*., 2020). For wider adoption among the fisherfolk, in tune with the ecosystem approach, modifications in gear operation are perceived to be ideal for integrating these social and economic issues into the biological and environmental concerns of bycatch.

Operational modifications resulting in reduced bottom contact of the gear will lessen the impacts on benthic species and habitats per unit of effort (McConnaughey *et al*., 2019). Trawls operating off the bottom, making occasional contact with the seafloor, are widely regarded as an innovation to reduce bycatch (Menon *et al*., 2006). The present study provides novel information on the bycatch landed in the bottom trawl operated marginally above the seabed, thereby minimizing contact and physical and biological damage to the seafloor. The ichthyofaunal diversity, quantity caught and composition of the bycatch, including temporal variations, along with the bycatch trophic level, have been extensively studied. The results, coupled with a comparison with earlier reports on bottom trawling, would assist fisheries managers to devise suitable management plans aimed at decreasing the impacts of trawling at the bottom. This would ensure the sustainability of fishery resources in the region. The perspective on bycatch is also ever-changing with yesterday's bycatch becoming today's target catch (Boyce, 1996). Previous studies from the same region are not comprehensive and are a decade old; therefore, the present study assumes significant importance.

Materials and Methods

Study Area and Sampling

Bycatch and discards, combined, formed 43% (38900 t) of the annual trawl landings at Visakhapatnam in Andhra Pradesh during 2011 (Dineshbabu *et al*., 2013), and this decreased to 30% (9500 t) during 2017-2019 (Dineshbabu *et al*., 2022). A similar contribution (41.1%) of bycatch to total trawl catch was also reported in another study from the same location during 2010-2014 (Muktha *et al*., 2018). Single-day trawlers operating off Visakhapatnam perform an average of 2 hauls during the day hours. Their fishing locations were obtained on inquiry from the skipper, either directly from the geocordinates (active georeferencing) or indirectly computed from the information on distance and direction (passive georeferencing).

Experimental trawling was carried out twice a month from January, 2017 to December, 2019 off

Visakhapatnam using the research vessel, R V Cadalmin-1 (13.5 m OAL; 248 hp stern trawler). A single haul of 60 min duration was performed during each trawling. The trawling locations, which are commercial fishing grounds for mechanized single-day fishing vessels, are represented in Figure 1. The length of the four-seam bottom trawl net was 40 m; with mesh sizes of 400 mm in the wing sections, 300 mm to 90 mm in the belly sections, and 30 mm in the cod end. Diamond-shaped meshes were used in the cod end. The head rope and foot rope lengths were 31 m and 30 m respectively. The head rope was attached to nine 150 mm Ø plastic floats, and the foot rope was rigged with 25 kg lead sinkers. A pair of V-form steel otter boards were used, each weighing 90 kg. The vessel was towed at a speed marginally higher than 3 knots, and the ratio of released wire rope length to water depth was maintained at 2:1. This enabled minimal contact with the seabed ensuring trawling slightly above the bottom. For commercial trawlers performing bottom trawling, the speed is around 2 knots and the ratio is generally 3:1 or higher. The geographical position and bottom depth for each location were measured using the Geographical Positioning System (FURUNO GP 150) and echo sounder (FURUNO FCV 627). Operational information including real-time net depth, and continuous monitoring of bottom contact was performed using net sonde (SIMRAD FS 70), the transducer of which was attached to the head rope of the trawl net. All trawling operations were executed during day time and identical net setting and hauling procedures were adopted during the entire fishing operations. The bottom trawl net used presently, including the diamond-shaped mesh in the codend, is identical to that operated by commercial trawlers.

Species Abundance and Biomass

Trawl catches from each haul were iced on board, and brought to the laboratory of Central Marine Fisheries Research Institute, Visakhapatnam, and were analysed on the same day. Every finfish or shellfish species in the catch was identified up to the species level, following Fischer and Whitehead (1974), Fischer and Bianchi (1984), Smith and Heemstra (1986), Carpenter and Niem (1998), Sathianandan *et al*. (2017) and Jarms and Morandini (2019). Specimens of each finfish species were counted, individually measured for standard length or total length (depending upon the species) to 1.0 mm, and weighed to 0.01g. Carapace length or width was measured in shellfish, depending on the species, and mantle length was measured in cephalopods. The targeted catch and the bycatch were segregated following Alverson *et al*. (1994). Bycatch included non-commercial (nonedible) species and juveniles of commercial species. Minimum size at maturity (MSM) was considered for segregation of

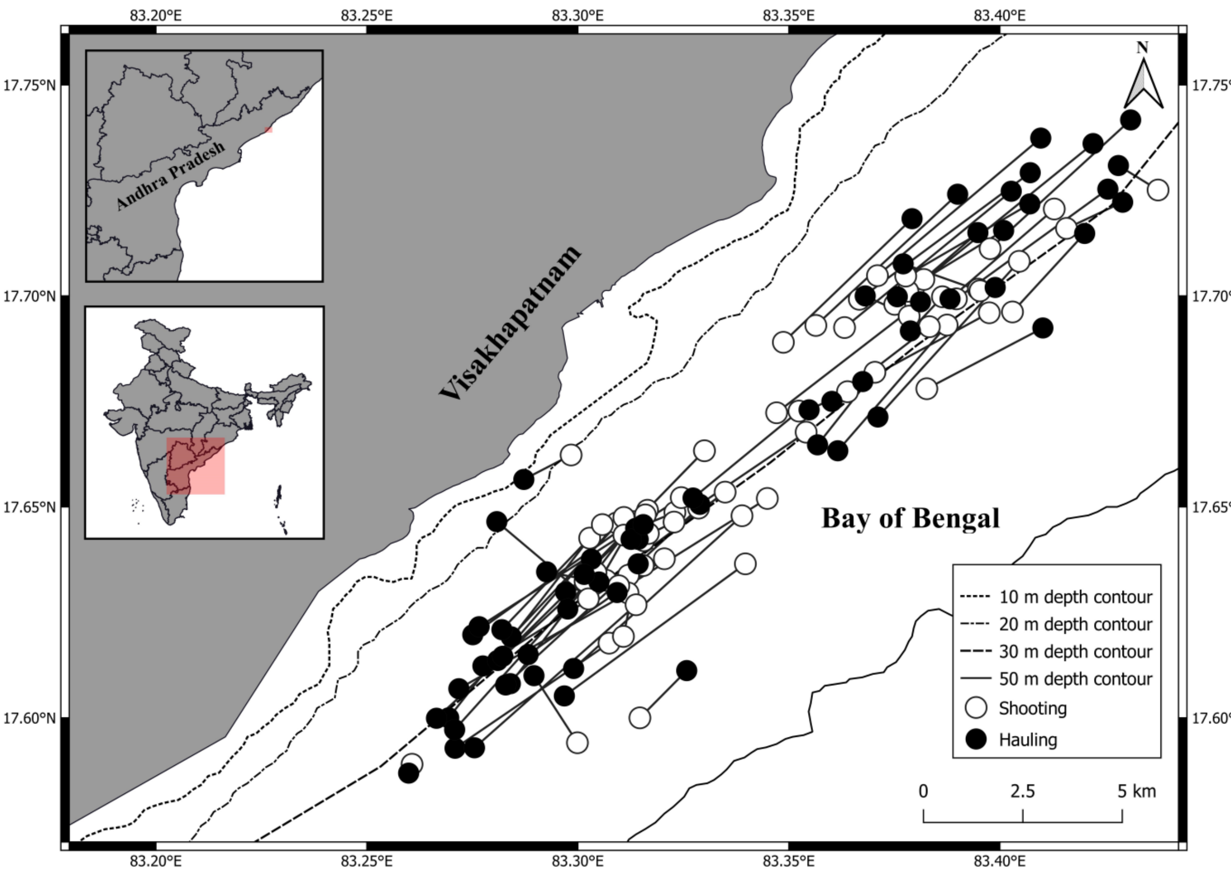

Figure 1. Map showing the trawling locations including the shooting and hauling points in the study area along the north-western Bay of Bengal.

juveniles from adults (Hubbs, 1943). Data on maturity sizes for finfishes and shellfishes were obtained from published literature (Froese & Pauly, 2023; Muktha *et al*., 2018). Total biomass and bycatch biomass per haul, expressed in kilogram per hour (kg/h), was calculated by summing the weight of individual species caught in that haul. Biomass obtained from two fortnightly surveys was averaged to obtain monthly biomass. Based on the cyclic phenomena of meteorological events, particularly sea surface temperature, months in individual years were pooled and results were expressed as seasons; summer (March-May), pre-monsoon (June-August), monsoon (September-November) and post-monsoon (December- February).

Trophic Level

The trophic level of individual species in the bycatch was adopted from Vivekanandan (2009), Froese and Pauly (2023), and Das *et al*. (2018). Ontogenetic variations in feeding were not considered and only adults were accounted for in determining the trophic level. For some invertebrate species, there was no information on the trophic level, and hence, they were excluded from the trophic level estimation. The Marine Trophic Index (MTI) of bycatch was calculated by multiplying the biomass of each species with their corresponding trophic level and then by taking the weighted means (Pauly *et al*., 1998).

Diversity Indices

Seasonwise abundance data of bycatch were subjected to univariate analyses for estimation of various biodiversity indices (Margalef species richness - d, Pielou's evenness - J', Shannon–Weiner's diversity index - H', Simpson's index – γ, Brillouin index, Fisher's Alpha index – α, taxonomic diversity index - Δ, taxonomic distinctness index - Δ*, average phylogenetic diversity – ϕ+ and total phylogenetic diversity –sϕ+) using PRIMER-6 software (Plymouth marine laboratory, Plymouth, UK). The k-dominance curve was plotted to measure the temporal variations in bycatch.

Abundance-Biomass Comparison (ABC) plots were built for each season to depict the impact of trawling on bycatch species. The differences between biomass and abundance curves were quantified by the measure of the w-statistic. Fauna was unstressed when the abundance curve lay below the biomass curve (w>0), moderately stressed when the two curves were close together (w=0), and grossly stressed when the biomass curve was below the abundance curve (w<0).

Statistical Analysis

Bycatch biomass was square-root transformed, then converted into a triangular matrix using the Bray–Curtis similarity coefficient for multivariate analyses, and hierarchical dendrogram plots were constructed using the group average function. Significant differences between clusters were examined using similarity profile (SIMPROF) analysis. Similarities percentage (SIMPER) analysis was carried out to identify the species that contributed to the similarities or dissimilarities. For SIMPER analysis, a cut-off for low contributions was set at 90.0%, beyond which rarer species were ignored.

Principal Component Analysis (PCA) was performed to elucidate the predominant species in different seasons and to correlate the most common species with the respective season. Components were selected based on the eigenvalue.

Results

Species Abundance and Biomass

The average total catch rate and bycatch rate for the whole study period were 35.46 kg/h and 9.70 kg/h, and bycatch formed 27.35% of the total catch. Total trawl catch observed in the 24 hauls performed, each during 2017 and 2018 was 1290.07 kg and 522.08 kg, at catch rates of 53.75 kg/h and 21.75 kg/h. In 2019, 18 hauls were performed and the total trawl catch was 528.42 kg with a catch rate of 29.36 kg/h. Bycatch and bycatch rates were 299.79 kg and 12.49 kg/h in 2017, 158.66 kg and 6.61 kg/h in 2018 and 181.59 kg and 10.09 kg/h in 2019. The proportion of bycatch in total catch was 23.24%, 30.39% and 27.70% in 2017, 2018 and 2019. Seasonal catch rate, bycatch rate and percentage contribution of bycatch to total catch are depicted in Table 1.

A total of 105 finfish species and 35 shellfish species, apart from one species of jellyfish were encountered. Finfishes were classified into Teleostei (102 species) and Elasmobranchii (3 species). Teleostei consisted of 21 orders and 49 families and formed

Table 1. Catch rate, bycatch rate, and percentage contribution of bycatch to total catch in different seasons along north-western Bay of Bengal

Season	2017			2018			2019		
	Catch rate (kg/h)	Bycatch rate (kg/h)	% Bycatch	Catch rate (kg/h)	Bycatch rate (kg/h)	% Bycatch	Catch rate (kg/h)	Bycatch rate (kg/h)	% Bycatch
Post-monsoon	20.82	7.98	38.31	23.30	8.97	38.51	25.50	9.49	37.22
Summer	105.33	21.49	20.40	12.47	2.51	20.09	15.08	9.80	64.99
Pre-monsoon	29.37	10.06	34.26	39.55	10.29	26.02	-	-	-
Monsoon	59.49	10.44	17.55	11.69	4.67	39.97	47.49	10.97	23.10

70.71% of the total biomass. Elasmobranchii, with three orders and three families, contributed a meagre 0.11%. Shellfishes were classified into Cephalopoda (7 species), Gastropoda (5 species), and Malacostraca (23 species). Cephalopoda was represented by 3 orders and 3 families, and Gastropoda by 2 orders and 5 families. Malacostraca included 2 orders and 7 families. The share by biomass of Cephalopoda, Gastropoda and Malacostraca to the catch was 9.01%, 5.12% and 11.03%, respectively. Schyzophoan jellyfish, *Rhopilema hispidium* accounted for 4.04%. The major catch by biomass, with elaborations for individual seasons, is presented in Table 2.

Totally in bycatch, 47 species of finfishes (class Teleostei) belonging to 16 orders and 28 families, and 13 species of shellfishes from three classes (Cephalopoda, Gastropoda and Malacostraca) comprising 5 orders and 9 families were encountered. Cephalopoda included 3 species from 2 orders and 2 families, Gastropoda 2 species from 1 order and 2 families, and Malacostraca 7 species from 2 orders and 5 families. Bycatch, by biomass, was dominated by Teleostei with a contribution of 77.90%, followed by Malacostraca and Gastropoda with shares of 12.79% and 8.04%. Bycatch composition percentage by biomass, seasonally and for the study period is shown in Table 3.

For six commercial species viz., *Trichiurus lepturus*, *Nibea maculata*, *Nemipterus japonicus*, *Saurida tumbil*, *Pampus chinensis*, and *Uroteuthis duvaucelii*; the proportion of juveniles in the catch of the operated trawlnet were 10.19%, 13.42%, 4.82%, 28.0%, 1.42%, and 7.48%, respectively. For *T. lepturus*, juveniles were more abundant (38.0% of the catch) in the pre-monsoon months; whereas for *N. maculata*, juvenile abundance was more (38.40%) in the monsoon months. Juveniles of *N. japonicus* and *S. tumbil* were encountered more frequently in the summer months (11.25% and 46.87%), followed by the post-monsoon months (7.25% and 33.39%). In *P. chinensis*, juveniles were observed only in the summer months (6.56%). The juvenile contribution was high in the post-monsoon (11.47%) and summer (8.83%) months for the cephalopod species, *U. duvaucelii*.

The similarity in species composition of bycatch was analysed using the Bray-Curtis similarity coefficient and the dendrogram plot for seasons is shown in Figure 2. The average similarity within seasons was 54.18%. Individual species contributing majorly to the similarities in bycatch for seasons are shown in Table 4. The average dissimilarity between seasons ranged from 35.03% to 59.61%. Dissimilarities in the bycatch between various seasons, with the major species contributing to the dissimilarity, are presented in Table 5. Over the years, the average similarity was 63.29%. The major species contributing to the annual similarities were *Gazza minuta*; followed by *Equuilites lineolatus*, *Charybdis feriata*, *Secutor insidiator*, and *Lepidamia multitaeniata*.

Trophic Level

The MTI of fauna in trawl bycatch was 3.65. Omnivores (trophic level < 3.0) (13 species) constituted the majority of the bycatch biomass, 45.39%; followed by top-carnivores (trophic level > 4.0) (13 species), which formed 32.29% (Figure 3). The mid-carnivores (trophic level 3.1-4.0) (31 species) contributed 22.32% to the bycatch biomass (Figure 3). Among mid-carnivores, 12 species belonged to trophic levels 3.1-3.5, and 19 species were at trophic levels 3.6-4.0.

Diversity Indices

The various diversity indices during seasons are presented in Table 6. Species diversity (Shannon-Wiener diversity H', Brillouin index, and Fisher Alpha index) and richness (Margalef Species Richness) were higher in the post-monsoon and summer. Taxonomic diversity and distinctness, and phylogenetic diversity were also maximum in post-monsoon. The Evenness index (Pielou's evenness), a measure of equitable species distribution, was highest in pre-monsoon and lowest in monsoon. Conversely, the dominance index (Simpson's index) was highest in monsoon indicating the contribution of fewer species to bycatch in this season. Results of the K-dominance plot during different seasons (Figure 4) also indicated that, unlike other seasons wherein several species contributed substantially to the bycatch, during summer domination was by only a few species.

Seasonal ABC plots are depicted in Figures 5a (post-monsoon), 5b (summer), 5c (pre-monsoon) and 5d (monsoon). The biomass curve was marginally above the abundance curve with a positive w-statistic during post-monsoon, summer, and pre-monsoon; whereas, during monsoon, it was the opposite with a negative w-statistic.

PCA evaluation demonstrated three principal components (PCs) based on eigenvalues. The three components: PC1, PC2, and PC3; with eigenvalues of 20.10, 11.50, and 7.42 explained 51.6%, 29.4%, and 19.0% of the seasonal variation in faunal abundance. The correlation matrix loading of the significant principal components for the four seasons is shown in Table 7 and the respective PCA plot for various families is shown in Figure 6.

Discussion

Bottom trawling, designed for efficient catch, involves gear that makes contact with the sea bottom, leading to a reduction in habitat structural heterogeneity and consequent biodiversity loss (Pilskaln et al., 1998; Van Merlen, 2000). Modifications in trawl design and operation, aimed at reducing bottom contact, play a crucial role in minimizing trawling impacts. The mortality of benthic species and damage to benthic habitats are correlated with the gear's

Table 2. Percentage composition by biomass (98% cut-off in total for low contribution) of different marine fauna encountered in trawl catch during different seasons

Class	Order	Family	Genus	Species	Postmonsoon	Summer	Premonsoon	Monsoon	Total
Teleostei	Acanthuriformes	Leiognathidae	*Secutor*	*insidiator*	1.194	1.220	0.000	0.926	0.890
Teleostei	Acanthuriformes	Leiognathidae	*Secutor*	*ruconius*	0.297	0.000	0.000	0.616	0.274
Teleostei	Acanthuriformes	Siganidae	*Siganus*	*canaliculatus*	0.303	0.094	0.131	0.105	0.157
Teleostei	Anguilliformes	Muraenesocidae	*Congresox*	*talabonoides*	0.147	0.000	0.692	0.227	0.239
Teleostei	Aulopiformes	Synodontidae	*Saurida*	*tumbil*	0.780	0.203	0.300	0.096	0.330
Teleostei	Aulopiformes	Synodontidae	*Saurida*	*undosquamis*	0.263	0.375	0.129	0.194	0.242
Teleostei	Aulopiformes	Synodontidae	*Trachinocephalus*	*myops*	0.283	0.128	0.000	0.000	0.101
Teleostei	Carangiformes	Carangidae	*Alectis*	*indica*	0.203	0.002	0.000	0.231	0.126
Teleostei	Carangiformes	Carangidae	*Megalaspis*	*cordyla*	0.129	0.048	0.729	1.225	0.578
Teleostei	Centrarchiformes	Terapontidae	*Terapon*	*jarbua*	9.812	0.122	0.080	0.260	2.574
Teleostei	Clupeiformes	Dussumieriidae	*Dussumeiria*	*acuta*	0.987	0.371	1.550	0.410	0.757
Teleostei	Clupeiformes	Pristigasteridae	*Opisthopterus*	*tardoore*	0.113	0.080	1.555	0.111	0.374
Teleostei	Clupeiformes	Engraulidae	*Thryssa*	*mystax*	0.382	1.785	0.721	0.532	0.830
Teleostei	Clupeiformes	Engraulidae	*Thryssa*	*setirostris*	3.664	1.297	0.582	0.096	1.363
Teleostei	Clupeiformes	Engraulidae	*Stolephorus*	*indicus*	7.713	0.258	0.032	3.991	3.287
Teleostei	Eupercaria incertae sedis	Haemulidae	*Pomadasys*	*maculatus*	0.394	0.010	0.048	0.242	0.188
Teleostei	Kurtiformes	Apogonidae	*Lepidamia*	*multitaeniata*	1.505	0.492	2.282	1.043	1.258
Teleostei	Kurtiformes	Apogonidae	*Ostorhinchus*	*fasciatus*	0.145	0.000	0.788	0.000	0.183
Teleostei	Mulliformes	Mullidae	*Upeneus*	*indicus*	1.962	0.000	0.697	0.116	0.656
Teleostei	Mulliformes	Mullidae	*Upeneus*	*sulphureus*	0.828	0.136	0.000	0.983	0.558
Teleostei	Mulliformes	Mullidae	*Upeneus*	*vittatus*	0.175	1.532	0.241	0.676	0.675
Teleostei	Perciformes	Drepaneidae	*Drepane*	*punctata*	0.263	0.000	2.035	0.273	0.534
Teleostei	Perciformes	Serranidae	*Epinephelus*	*coioides*	0.000	0.000	0.539	0.000	0.101
Teleostei	Perciformes	Leiognathidae	*Gazza*	*minuta*	7.884	0.272	1.464	0.586	2.494
Teleostei	Perciformes	Leiognathidae	*Photopectoralis*	*bindus*	1.274	2.129	0.000	0.895	1.117
Teleostei	Perciformes	Leiognathidae	*Equuilites*	*lineolatus*	15.917	4.084	8.177	7.135	8.790
Teleostei	Perciformes	Leiognathidae	*Leiognathus*	*equulus*	0.060	1.021	0.000	0.009	0.262
Teleostei	Perciformes	Trichiuridae	*Lepturacanthus*	*savala*	0.474	0.539	0.000	17.279	5.863
Teleostei	Perciformes	Lutjanidae	*Lutjanus*	*indicus*	0.000	0.000	0.000	0.518	0.168
Teleostei	Perciformes	Nemipteridae	*Nemipterus*	*japonicus*	1.521	0.486	1.193	0.379	0.841
Teleostei	Perciformes	Sciaenidae	*Nibea*	*maculata*	0.695	2.856	3.532	2.504	2.330
Teleostei	Perciformes	Stromateidae	*Pampus*	*chinensis*	0.303	0.421	0.421	0.641	0.463
Teleostei	Perciformes	Uranoscopidae	*Uranoscopus*	*archionema*	0.458	0.010	0.000	0.020	0.124
Teleostei	Pleuronectiformes	Cynoglossidae	*Cynoglossus*	*macrostomus*	0.790	0.010	0.190	0.160	0.287
Teleostei	Pleuronectiformes	Psettodidae	*Psettodes*	*erumei*	0.233	0.050	0.000	0.339	0.180
Teleostei	Pleuronectiformes	Paralichthyidae	*Pseudorhombus*	*arsius*	0.251	0.092	0.067	0.260	0.182
Teleostei	Scombriformes	Trichiuridae	*Trichiurus*	*lepturus*	8.523	52.504	13.967	29.734	26.947
Teleostei	Siluriformes	Plotosidae	*Plotosus*	*lineatus*	0.000	0.000	1.258	0.091	0.264
Teleostei	Syngnathiformes	Fistulariidae	*Fistularia*	*petimba*	0.707	0.103	0.051	0.122	0.250
Teleostei	Tetraodontiformes	Tetraodontidae	*Arothron*	*stellatus*	0.657	0.828	0.204	0.932	0.703
Teleostei	Tetraodontiformes	Tetraodontidae	*Chelonodon*	*patoca*	0.199	0.042	1.848	0.407	0.537

Table 2. *Continued*

Class	Order	Family	Genus	Species	Postmonsoon	Summer	Premonsoon	Monsoon	Total
Teleostei	Tetraodontiformes	Diodontidae	*Cyclichthys*	*spilostylus*	0.042	0.000	0.558	0.025	0.123
Teleostei	Tetraodontiformes	Tetraodontidae	*Lagocephalus*	*inermis*	1.324	0.314	1.459	0.119	0.716
Elasmobranchii	Myliobatiformes	Dasyatidae	*Himantura*	*gerrardi*	0.171	0.063	0.064	0.120	0.108
Cephalopoda	Myopsida	Loliginidae	*Uroteuthis*	*duvaucelii*	3.358	1.274	1.282	1.572	1.891
Cephalopoda	Octopoda	Octopodidae	*Amphioctopus*	*membranaceus*	9.663	2.838	10.912	2.879	6.060
Cephalopoda	Sepiida	Sepiidae	*Sepia*	*aculeata*	0.450	0.086	0.000	0.017	0.138
Cephalopoda	Sepiida	Sepiidae	*Sepiella*	*inermis*	0.382	0.262	1.861	0.866	0.787
Gastropoda	Littorinimorpha	Tonnidae	*Dolium*	*unidentified*	0.299	0.075	1.580	1.442	0.857
Gastropoda	Littorinimorpha	Ficidae	*Ficus*	*gracilis*	4.419	1.901	8.464	2.803	4.047
Gastropoda	Neogastropoda	Conidae	*Conus*	*inscriptus*	0.000	0.000	0.201	0.539	0.213
Malacostraca	Decapoda	Sergestidae	*Acetes*	*indicus*	0.348	0.004	0.000	0.518	0.256
Malacostraca	Decapoda	Calappidae	*Calappa*	*lophos*	0.107	0.098	0.493	0.669	0.360
Malacostraca	Decapoda	Portunidae	*Charybdis*	*feriata*	0.973	5.970	1.655	1.589	2.495
Malacostraca	Decapoda	Portunidae	*Charybdis*	*natator*	0.291	0.084	0.000	6.780	2.296
Malacostraca	Decapoda	Solenoceridae	*Solenocera*	*crassicornis*	0.036	0.000	0.652	0.060	0.150
Malacostraca	Decapoda	Penaeidae	*Metapenaeopsis*	*barbata*	0.185	0.088	0.000	0.179	0.125
Malacostraca	Decapoda	Penaeidae	*Metapenaeus*	*affinis*	0.113	0.151	2.550	0.088	0.569
Malacostraca	Decapoda	Penaeidae	*Metapenaeus*	*monoceros*	0.082	3.315	0.303	0.034	0.881
Malacostraca	Decapoda	Palaemonidae	*Nematopalaemon*	*tenuipes*	0.092	0.000	0.909	0.185	0.252
Malacostraca	Decapoda	Penaeidae	*Parapaeneopsis*	*longipes*	0.018	0.000	0.657	0.012	0.131
Malacostraca	Decapoda	Penaeidae	*Penaeus*	*indicus*	0.267	0.075	1.869	0.452	0.580
Malacostraca	Decapoda	Penaeidae	*Penaeus*	*monodon*	0.042	0.145	1.647	0.092	0.383
Malacostraca	Decapoda	Portunidae	*Portunus*	*pelagicus*	0.000	0.057	0.118	0.342	0.147
Malacostraca	Decapoda	Portunidae	*Portunus*	*sanguinolentus*	0.127	0.096	2.572	1.113	0.897
Malacostraca	Stomatopoda	Squillidae	*Oratosquilla*	*nepa*	0.105	0.046	0.000	0.957	0.348
Malacostraca	Stomatopoda	Squillidae	*Harpiosquilla*	*harpax*	0.113	1.595	2.650	0.522	1.074
Scyphozoa	Rhizostomeae	Rhizostomatidae	*Rhopilema*	*hispidium*	1.992	5.991	10.821	0.270	4.037

penetration into the seabed (Hiddink et al., 2017). Also, higher levels of bottom contact increase net abrasion and fuel use. Widely recognized changes to reduce the gear's contact with the seabed include shortening the warp-length-to-depth ratio and altering the towing speed (Ramm et al., 1993; Brewer et al., 1996; Valdemarsen et al., 2007; He & Winger, 2010). Similar attempts were made in the present study, wherein the ratio of released wire rope length to water depth was reduced and the towing speed was increased to minimize bottom contact of the gear during operation.

The average catch rate (35.46 kg/h) from experimental trawling was higher than that recorded from commercial bottom trawlers (22.06 – 33.0 kg/h) operating in the same fishing grounds during the same period (Central Marine Fisheries Research Institute, Annual Report 2017-2018, 2018-2019, 2019-2020). From Visakhapatnam, Andhra Pradesh, during 2008-2011, the average discarded bycatch and landed bycatch from trawl fishery were 22% and 21%, respectively (Dineshbabu *et al*., 2013). Recently, Dineshbabu *et al*. (2022), for the same period (2017-2019), had reported discards to constitute an average of 30% to the commercial trawl landings from the same fishing location. Currently, with no discard, the bycatch contribution of 27.35% to the trawl landings represents a substantial decrease. In tropical waters of the Indian exclusive economic zone, bycatch has generally been reported to form 21% to 88.5% of the trawl landings (Dineshbabu *et al*., 2012; Gibinkumar *et al*., 2012; Dineshbabu *et al*., 2013; Velip & Rivonker, 2015; Samanta *et al*., 2018; Mahesh *et al*., 2017; Mahesh *et al*., 2019; Ramkumar *et al*., 2019), and barring one study (Mahesh *et al*., 2019), others have observed higher

Table 3. Seasonal trawl bycatch composition (%) by biomass (99.5% cut-off in total for low contribution)

Species	Postmonsoon	Summer	Premonsoon	Monsoon	Total
Alectis indica	0.000	0.000	0.000	0.695	0.188
Arothron stellatus	0.296	2.522	0.603	3.651	1.773
Callionymus gardineri	0.117	0.465	0.000	0.000	0.142
Cyclichthys spilostylus	0.000	0.000	0.779	0.116	0.184
Cynoglossus macrostomus	0.219	0.000	0.000	0.124	0.100
Dussumeiria acuta	3.114	1.194	0.000	1.342	1.587
Fistularia petimba	1.215	0.376	0.000	0.569	0.611
Gazza minuta	24.906	0.852	5.174	1.642	9.256
Grammoplites scaber	0.131	0.000	0.398	0.232	0.181
Lagocephalus inermis	4.184	1.268	5.398	0.554	2.772
Photopectoralis bindus	1.469	8.615	0.000	2.677	3.143
Leiognathus elongatus	0.368	0.000	0.000	0.000	0.112
Leiognathus equulus	0.087	4.129	0.000	0.045	0.983
Equuilites lineolatus	29.825	13.718	22.522	20.154	22.099
Leiognathus splendens	0.000	0.627	0.000	0.000	0.143
Lepidamia multitaeniata	2.418	1.828	2.120	3.919	2.631
Lepturacanthus savala	0.085	0.016	0.000	26.699	7.256
Megalaspis cordyla	0.072	0.000	0.000	0.350	0.117
Nemipterus japonicus	0.348	0.221	0.000	0.000	0.157
Nibea maculata	0.000	0.000	0.000	4.471	1.210
Opisthopterus tardoore	0.000	0.114	1.095	0.000	0.240
Ostorhinchus fasciatus	0.375	0.000	0.000	2.106	0.685
Pseudorhombus arsius	0.402	0.321	0.000	0.767	0.404
Saurida tumbil	0.822	0.386	0.000	0.066	0.357
Saurida undosquamis	0.067	0.189	0.000	0.304	0.146
Secutor insidiator	2.089	4.017	0.000	2.266	2.170
Secutor ruconius	0.093	0.000	0.000	2.126	0.604
Siganus canaliculatus	0.961	0.383	0.490	0.000	0.477
Stolephorus indicus	18.251	0.666	0.000	3.303	6.620
Terapon jarbua	0.000	0.253	0.209	1.519	0.510
Trichiurus lepturus	0.605	24.258	19.667	3.912	10.631
Amphioctopus membranaceus	0.820	0.000	0.000	0.082	0.273
Loligo uyii	0.055	0.000	0.000	0.404	0.126
Uroteuthis duvaucelii	1.217	0.455	0.000	0.267	0.548
Ficus gracilis	0.209	4.279	17.852	0.713	4.721
Dolium unidentified	0.946	0.303	5.847	6.704	3.315
Acetes indicus	0.000	0.000	0.000	2.404	0.651
Calappa lophos	0.000	0.238	1.467	1.834	0.837
Charybdis feriata	1.737	21.244	4.826	1.448	6.722
Harpiosquilla harpax	0.358	6.456	9.807	2.427	4.157
Nematopalaemon tenuipes	0.000	0.000	1.748	0.000	0.341
Rhopilema hispidium	1.100	0.000	0.000	0.000	0.336

bycatch percentages. The current average bycatch catch rate (9.70 kg/h) was also lower than 16.82 kg/h reported by Samanta *et al*. (2018) from an experimental shrimp bottom trawl operated off Mumbai, Maharashtra. A temporal perusal of the bycatch contribution to total catch revealed it to be consistently higher during the post-monsoon months for all the years, and in the monsoon months of 2018 and the summer months of 2019. The reduced trawl catches during the above seasons resulted in bycatch forming a significant percentage. For other periods, trawl catch and bycatch quantities were in close conformity with each other. Similar patterns in temporal variations of trawl catch rate and bycatch rate were reported for 2013-2015 from the same fishing grounds (Behera *et al*., 2017).

Commercial trawlers operating off Visakhapatnam during 2000-2014 contributed substantially to the catch of ribbonfishes, croakers, threadfin breams, Indian mackerel, carangids, penaeid shrimps and cephalopods (Muktha *et al*., 2018). No major shift in catch composition was observed presently from experimental trawling, with the dominant species being ribbonfishes, silverbellies, croakers, anchovies and cephalopods. Of the 105 species of finfish and 35 species of shellfish caught in trawls, 47 and 13 constituted the bycatch. Teleostei dominated, both trawl catch and bycatch. An

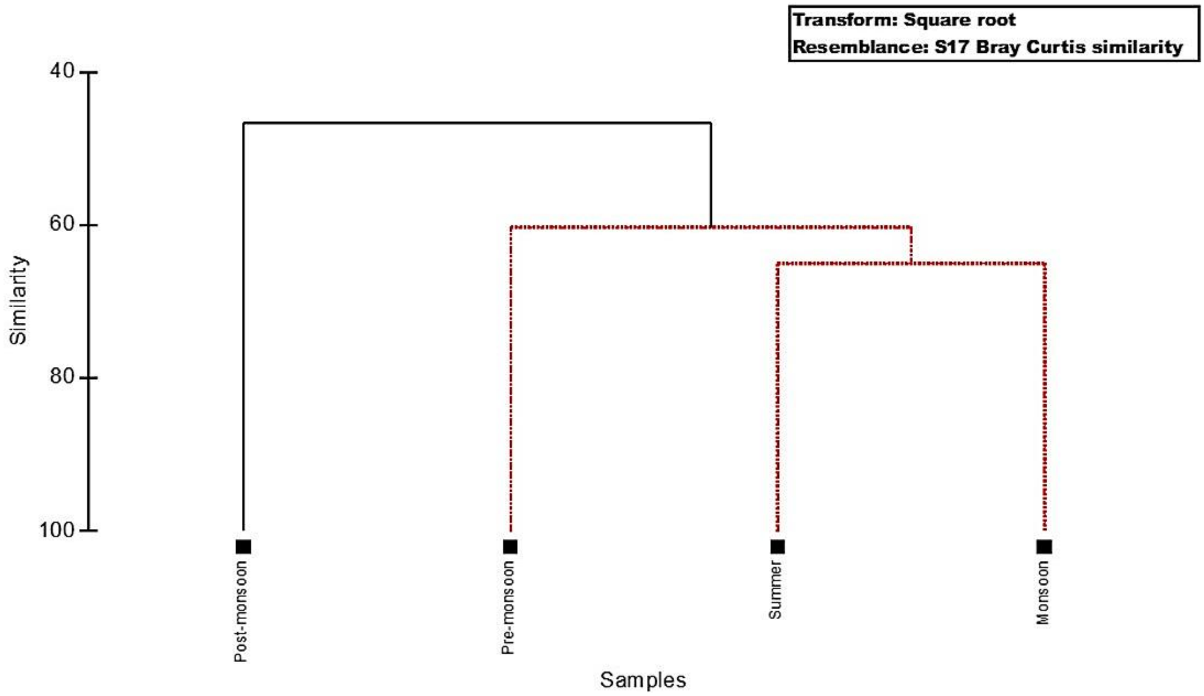

Figure 2. Dendrogram plot for bycatch faunal biomass during different seasons; dotted lines imply significant similarities.

Table 4. Seasonal similarity percentages (SIMPER) in the biomass contributions of trawl bycatch using Bray Curtis similarity with cut-off for low contributions being 90.0%

Species	Average Abundance (%)	Average Similarity (%)	Similarity/SD	Average contribution (%)
Equuilites lineolatus	3.09	9.08	6.68	16.76
Trichiurus lepturus	2.59	5.81	1.33	10.72
Charybdis feriata	2.03	4.71	2.15	8.70
Harpiosquilla harpax	1.47	3.70	1.46	6.84
Ficus gracilis	1.61	3.48	1.21	6.42
Lagocephalus inermis	1.20	3.45	2.97	6.36
Gazza minuta	1.66	3.08	2.42	5.69
Lepidamia multitaeniata	1.00	3.08	7.82	5.68
Arothron stellatus	0.73	1.75	2.59	3.23
Secutor insidiator	0.83	1.61	0.90	2.96
Siganus canaliculatus	0.52	1.45	7.48	2.68
Stolephorus indicus	1.21	1.13	0.81	2.09
Dussumeiria acuta	0.69	1.11	0.91	2.05
Photopectoralis bindus	0.85	1.01	0.76	1.87
Calappa lophos	0.46	0.77	0.80	1.41
Fistularia petimba	0.45	0.70	0.89	1.29
Pseudorhombus arsius	0.32	0.60	0.91	1.10
Uroteuthis duvauceli	0.39	0.59	0.88	1.09

earlier study conducted off Visakhapatnam during 1986-1989 from the catch of multiday bottom trawlers revealed 85 species in the bycatch, of which more than half was constituted of immature specimens (Sivasubramanyam, 1990). During 2008-2011 from the same locality, Dineshbabu *et al*. (2013) recorded 65 species of finfish and 26 species of shellfishes in commercial trawl bycatch. The preponderance of teleosts in trawl bycatch biomass, as observed, supports the findings of Dineshbabu *et al*. (2013) and Behera *et al*. (2017). Though, the same authors had similarly observed individuals of the Leiognathidae family to be the most abundant species in the bycatch; however, unlike their reports on the dominance of *Photopectoralis bindus*, the present study recorded *E. lineolatus* to contribute the most. Other major bycatch contributing finfish species; *T. lepturus*, *G. minuta*, *Lepturacanthus savala*, and *Stolephorus indicus* did not form notable proportions in the earlier studies. Among shellfishes, *C. feriata* and *Harpiosquilla harpax* dominated the bycatch, contrary to Dineshbabu *et al*. (2013) and Behera *et al*. (2017), who observed *C. hoplites* and *Oratosquilla* spp, and *Portunus sanguinolentus* to contribute the most. These subtle differences in species contribution and dominance could be attributed to the spatial changes in the gear operations over time. Previous reports were from the operation of commercial bottom trawlers, but currently, experimental trawling was performed marginally above the bottom and benthopelagic fauna were captured in

Table 5. Average seasonal and annual dissimilarities of the major contributing species in trawl bycatch using Bray Curtis similarity with cut-off for low contributions being 90.0%; 1, 2, 3 and 4 represent summer, pre-monsoon, monsoon and post-monsoon seasons; a, b and c depict the years of 2017, 2018 and 2019

	Seasons						Years		
	1 vs 2 (42.65%)	1 vs 3 (35.03%)	2 vs 3 (36.87%)	1 vs 4 (51.80%)	2 vs 4 (59.61%)	3 vs 4 (48.96%)	a vs b (37.73%)	a vs c (77.25%)	b vs c (74.90%)
Alectis indica		0.89	0.97			0.84	1		1.1
Arothron stellatus	1.27		1.09	1.13		1.02	2.69	2.84	
Callionymus gardineri	0.99	0.67			0.52			0.81	0.96
Chelonodon patoca				0.46	0.50				
Congresox talabonoides				0.43					
Cyclichthys spilostylus	1.19	0.79			1.07	0.75	0.99	0.92	
Cynoglossus macrostomus				0.64	0.71	0.42			
Dussumeiria acuta	1.58		1.35	1.12	2.68	0.71	2.03	1.93	
Fistularia petimba	0.89	0.33	1.02	0.78	1.67				0.9
Gazza minuta	1.71	0.89		5.73	4.81	3.62	1.68	1.56	
Grammoplites scaber	0.85	0.66		0.50				0.72	
Histrio histrio			0.45	0.50		0.39			
Lagocephalus inermis	1.49	0.87		1.47			0.79	2.13	3.39
Photopectoralis bindus	4.26	1.12	1.9	4.10	2.50	2.12		4.84	5.73
Leiognathus elongatus				0.83	0.92	0.65		0.71	0.85
Equuilites lineolatus	3.94	3.31	0.97	5.08	2.53	0.93		9.30	10.88
Leiognathus splendens	1.15	0.77		0.94				0.81	0.96
Lepidamia multitaeniata		0.55	0.6	0.53	0.58			1.69	1.54
Lepturacanthus savala		5.36	5.99			4.85		5.77	6.84
Megalaspis cordyla		0.63	0.68					0.73	0.87
Nemipterus japonicus	0.68	0.46			0.90	0.63		0.85	1.01
Nibea maculata							2.54	2.36	
Opisthopterus tardoore	0.91	0.41			1.27	0.69		0.78	0.84
Ostorhinchus fasciatus		1.54	1.68	0.84	0.93	0.79	0.96	0.72	1.91
Pampus argenteus					0.55	0.39			
Pomadasys maculatus					0.51				
Pseudorhombus arsius	0.82		0.78		0.96				
Pterois mombasae				0.45					
Saurida tumbil	0.90			0.51	1.38	0.70		1.28	1.52
Saurida undosquamis	0.63		0.64					0.82	0.97
Secutor insidiator	2.91	0.36	1.75		2.19			1.22	1.19
Secutor ruconius		1.55	1.69	0.43		1.13		1.67	1.97
Siganus canaliculatus				0.61	0.65		1.6	1.48	
Stolephorus indicus	1.19	1.13	2.1	4.88	6.48	2.72		5.51	6.53
Terapon jarbua		0.94	1.11	0.60	0.55	1.34	0.87		1.67
Trichiurus lepturus	1.20	1.63	2.66	4.76	4.20	5.22	6.91	3.64	3.28
Amphioctopus membranaceus				1.25	1.38	0.67	1.21		1.32
Loligo uyii		0.67	0.74			0.39		0.77	0.9
Uroteuthis duvauceli	0.98		0.6	0.71	1.68	0.66	0.86		0.80
Ficus gracilis	2.67	1.68		1.82	4.44	2.99	1.54	3.93	2.96
Acetes indicus		1.65	1.8			1.55	1.86		2.04
Calappa lophos	0.91	0.84		0.58	1.47	1.23	0.60	1.63	1.28
Charybdis feriata	3.75		2.97	3.65	0.67	3.02	3.54	3.51	
Harpiosquilla harpax		0.72		2.19	2.90	2.37	1.25	3.61	2.91
Nematopalaemon tenuipes	1.78	1.20			1.60	1.12	1.35	1.25	
Portunus gladiator				0.50	0.71	0.49			0.67

greater amounts. *E. lineolatus* contributed majorly across all seasons, whereas the dominance of other prominent bycatch species varied between seasons. Temporal variations in bycatch assemblages are common (Stobutzki *et al*., 2001; Tonks *et al*., 2008; Behera *et al*., 2017). Regeneration of nutrients due to upwelling in monsoon results in the subsequent proliferation of favoured planktonic prey items leading to enhanced abundance of *S. indicus* and *G. minuta* in the post-monsoon season. Greater contributions by *T. lepturus* during summer and pre-monsoon are probably related to their peak spawning during post-monsoon (Ghosh *et al*., 2014), and the consequent recruitment of large numbers into the fishery during summer and pre-monsoon. A similar scenario of strong recruitment exists for *L. savala* during monsoon, leading to them being profusely caught.

Unlike commercial bottom trawling, where more than half of the bycatch was reported to comprise of immature fishes (Sivasubramanyam, 1990; Luther & Sastry, 1993); the proportion of juveniles in trawl catch for commercial species in the present study ranged between 1.42% and 28.0%. For the same location during the same period (2017-2019), Dineshbabu *et al*. (2022) reported that the juveniles of different species caught in commercial bottom trawlnets contributed 63.6% to the total trawl catch. Currently, apart from *S. tumbil*, juvenile catch for the other five commercial species was far lower. From locations along the Indian coastline, various studies (Pillai, 1998; Dineshbabu *et al*., 2012; Kizhakudan *et al*., 2013; Dinesh & Chandrasekhar, 2015; Madhu *et al*., 2017; Mahesh *et al*., 2019) have reported juveniles to contribute abundantly (40% to 89%) in bycatch. Removal of juveniles for commercially important and target species by bottom trawls results in growth overfishing; impacting severely the species lifecycle, including their stock renewal and recruitment (Bhathal & Pauly, 2008). The economic loss associated with juvenile fishing is more significant in tropical waters because the most diversified and productive fishing grounds which are within the 50 m depth are also the nursery grounds for many finfishes and shellfishes

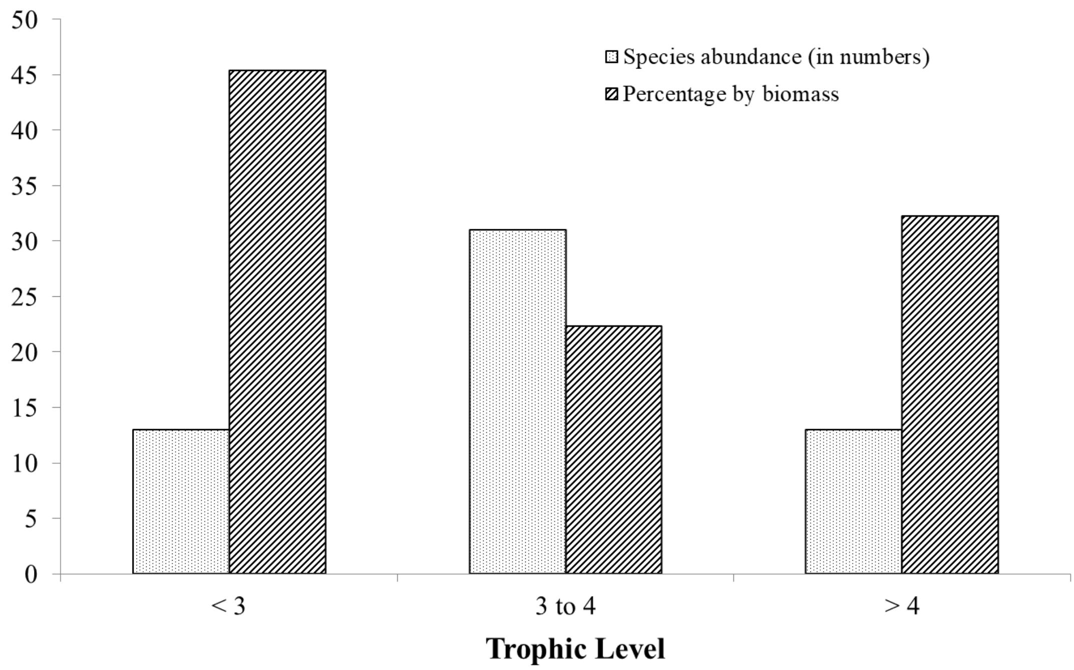

Figure 3. Species abundance and biomass percentage in different trophic levels of bycatch.

Table 6. Trawl bycatch diversity indices during different seasons

Season	Post-monsoon	Summer	Pre-monsoon	Monsoon
Margalef Species Richness (d)	4.08	3.59	1.50	3.00
Pielou's evenness (J')	0.60	0.65	0.73	0.59
Shannon-Wiener diversity H' (log2)	2.25	2.30	2.12	2.06
Simpson's index (γ)	0.84	0.85	0.80	0.88
Brillouin index	2.24	2.20	1.94	1.45
Fisher Alpha index (α)	5.00	4.40	1.73	3.52
Taxonomy diversity (Δ)	66.14	55.25	60.70	51.25
Taxonomy distinctness (Δ*)	82.22	76.85	60.25	64.72
Average phylogenetic diversity (ϕ+)	70.00	60.78	58.04	62.42
Total phylogenetic diversity (s ϕ+)	2380	2070	980	2060

(Behera *et al*., 2021). The present study, by trawling above the bottom, could alleviate to some extent the quantities of juvenile capture. If adopted, this practice would ensure stock sustainability.

With peak spawning during post-monsoon (Ghosh *et al*., 2014), *T. lepturus* juveniles were most abundant during pre-monsoon. Similar higher prevalence of *T. lepturus* juveniles in the trawl fishery during March–August was reported by Narasimham (1972). Sciaenids spawn during the summer months of March to May off Visakhapatnam (Rajkumar *et al*., 2004), and the enhanced occurrences of *N. maculata* juveniles during monsoon indicate it to be their peak months of recruitment. From the same fishing ground, both *N. japonicus* and individuals belonging to the genus *Saurida* are known to spawn mostly from September – February (Rajkumar *et al*., 2003a, b; Rao *et al*., 2017). Recruitment followed subsequently, leading to increased juvenile contributions during post-monsoon and summer months. Presently, the proportion of juveniles for *N. japonicus* was only 4.82%. Regarding *P. argenteus* along the northern Arabian Sea, peak recruitment occured

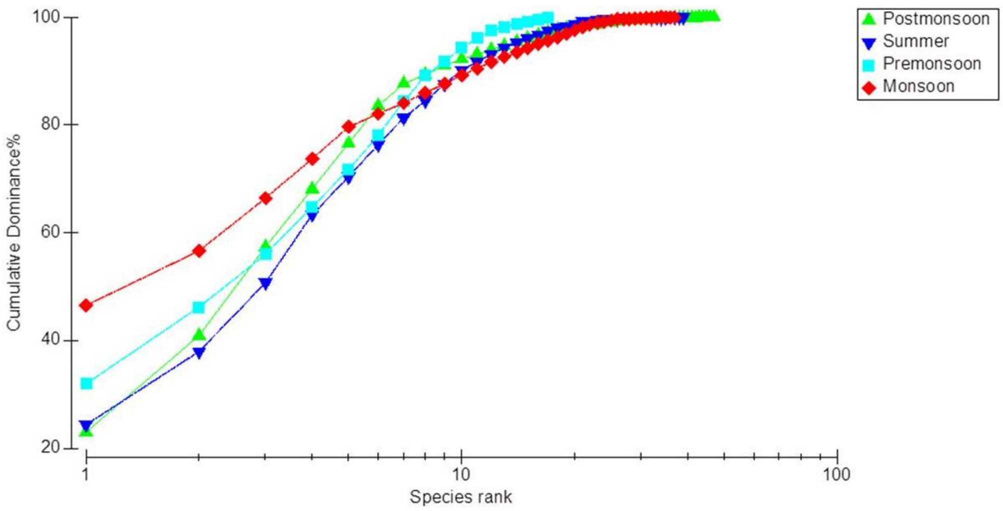

Figure 4. Abundance-based seasonal dominance plot for bycatch faunal biota

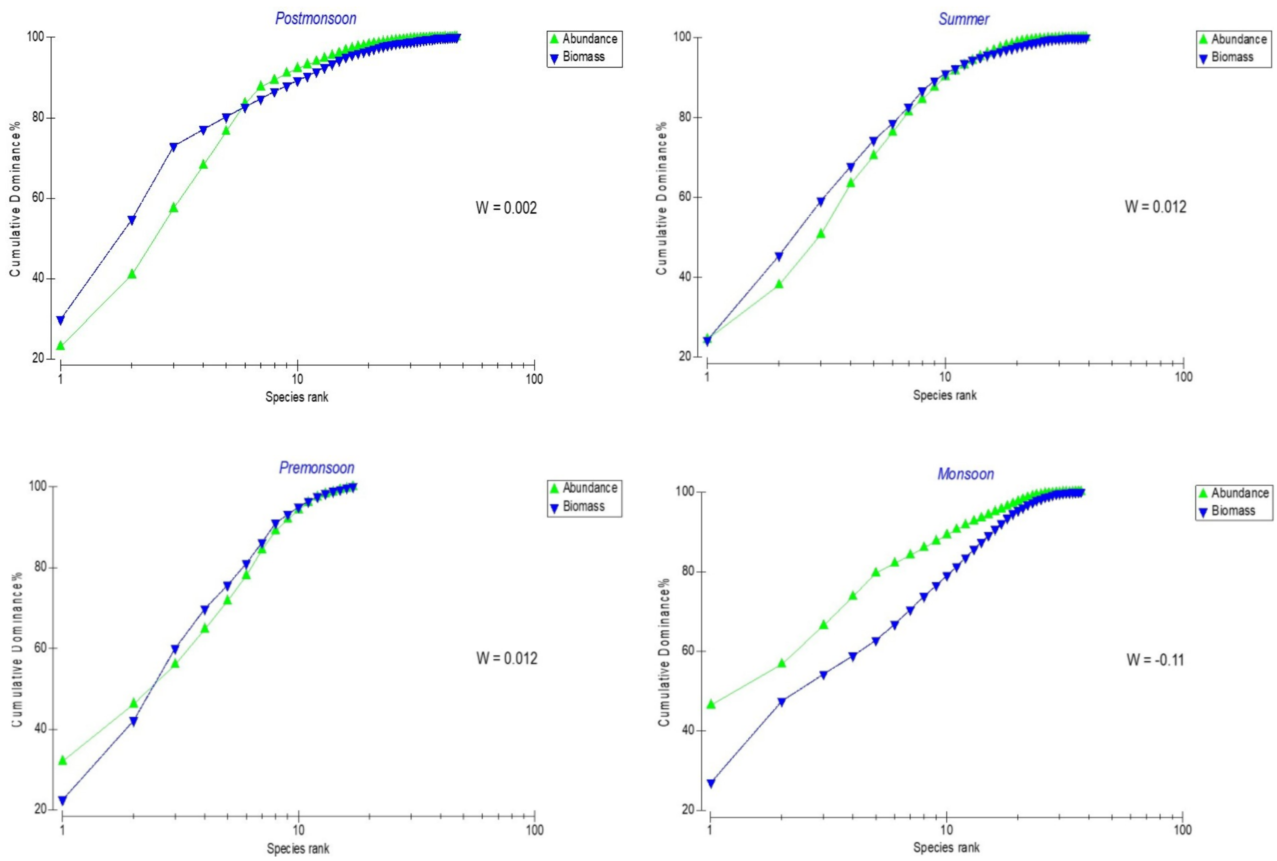

Figure 5. Abundance Biomass comparison plot for bycatch faunal biota in different seasons with w-statistic; a: post-monsoon, b: summer, c: pre-monsoon and d: summer

during February-March corresponding to their maximum spawning period from June to November (Ghosh *et al*., 2009). Probably, along the northern Bay of Bengal peak spawning was delayed by a month or two, resulting in recruitment during March–May with the occurrence of juveniles. Unlike the southern Bay of Bengal, wherein peak recruitment for *U. duvaucelii* was reported during April-May (Chhandaprajnadarsini *et al*., 2020), in the northern region, substantial recruitment was observed in the post-monsoon months in addition to the summer months. Therefore, juveniles were abundant during post-monsoon and summer. A similar observation on maximum juvenile occurrence for *U. duvaucelii* during March has been reported by Behera *et al*. (2021).

Trophic level and trophic index are considered prime tools in capture fisheries for studying marine ecosystems as they offer information about the complex interactions between fisheries and ecosystems (Pauly & Watson, 2005). The trophic index of trawl bycatch was calculated at 3.65, with 54% of the bycatch species belonging to trophic level 3.1-4.0. The highest species diversity was at trophic level 3.6-4.0. From commercial bottom trawlers operating along the southwest coast of India, Bijukumar and Deepthi (2009) observed almost half of the bycatch species to belong to trophic level 3.50-3.99. Similarly, along the southeast coast, Sambandamoorthy *et al*. (2015) reported species in the trophic level 3.00-3.99 to form three-fourths of the bycatch. The presence of the large number of mid-carnivores in the trawl bycatch indicates considerable removal of top-level predators from the ecosystem (Worm *et al*., 2005). In terms of biomass, however, the major share presently is from omnivores belonging to trophic level < 3.0. Therefore, it is imperative that by trawling marginally above the bottom large-scale

Table 7. Correlation based Principal Component Analysis for different by-catch families

Eigen vectors Coefficients in the linear combinations of variables making up PC's			
Variables	PC1	PC2	PC3
Antennariidae	-0.017	-0.204	0.264
Apogonidae	0.005	0.285	0.097
Ariommatidae	-0.017	-0.204	0.264
Calappidae	-0.158	0.208	-0.010
Callionymidae	0.058	-0.208	0.243
Carangidae	-0.056	0.268	0.123
Clupeidae	0.213	0.024	-0.103
Cynoglossidae	0.185	0.162	-0.041
Diodontidae	-0.146	-0.028	-0.275
Dussumieriidae	0.215	0.077	0.025
Elapidae	0.213	0.024	-0.103
Engraulidae	0.212	0.064	-0.080
Ficidae	-0.142	-0.134	-0.229
Fistulariidae	0.210	0.099	0.013
Gerreidae	0.114	-0.193	0.204
Haemulidae	0.223	0.017	-0.003
Lactariidae	-0.054	0.262	0.146
Leiognathidae	0.218	0.048	-0.043
Loliginidae	0.207	0.108	0.032
Muraenesocidae	0.220	-0.026	0.048
Nemipteridae	0.217	-0.069	0.013
Octopodidae	0.212	0.049	-0.095
Palaemonidae	-0.124	-0.080	-0.288
Paralichthyidae	0.058	0.241	0.190
Platycephalidae	-0.083	0.164	-0.273
Portunidae	-0.024	-0.224	0.235
Pristigasteridae	-0.131	-0.108	-0.265
Psettodidae	0.213	0.024	-0.103
Sciaenidae	-0.072	0.260	0.128
Scorpaenidae	0.213	0.024	-0.103
Sergestidae	-0.072	0.260	0.128
Siganidae	0.198	-0.074	-0.141
Squillidae	-0.177	-0.174	-0.056
Stromateidae	0.196	-0.123	0.088
Synodontidae	0.216	0.026	0.086
Terapontidae	-0.093	0.241	0.147
Tetraodontidae	0.129	0.135	-0.248
Tonnidae	-0.131	0.232	-0.067
Trichiuridae	-0.166	0.106	0.206

removal of predatory fishes residing at a higher trophic level as bycatch is reduced. The presence of species with a higher trophic level in the bycatch is potentially detrimental because large carnivores and top-level predators sustain the fisheries of a region. The long-living large demersal species tend to decline faster due to their lower resilience in life histories than the short-living smaller pelagic species (Pauly *et al*., 2002). Thus, their presence in substantial amounts in the bycatch has far-reaching consequences.

Species composition and richness collectively determine the structure, function, and stability of communities. Therefore, biodiversity loss would transform and destabilise complex food webs, regardless of which species are affected (Worm & Duffy, 2003). Species diversity and richness recorded during different seasons are in line with earlier studies on both commercial (Dinesh & Chandrasekhar, 2015) and experimental (Madhu *et al*., 2015) bottom trawling. Diversity and richness are a consequence of greater numerical abundance in species and are indicative of the stability of a community. Warmer water temperature and availability and stability of preferred prey during post-monsoon and summer months could have resulted in large-scale periodic migration into the area. Diversity and evenness were higher in seasons when all species contributing to bycatch were equally dominant, and vice-versa. The existence of higher diversity indices signifies the lack of influence of trawling depth on species diversity of bycatch. The ABC curve, with a positive w-statistic during three seasons except monsoon, is indicative of the ichthyofauna being relatively unstressed. With higher biomass in species as compared to the corresponding abundance, growth overfishing is restricted to some extent. Ramkumar *et al*. (2019) reported the ABC curve for bottom trawl shrimp fishery with negative w-statistic values during all four seasons, depicting the sea bottom to be heavily stressed with intense fishing pressure.

Conclusion

The present study made an attempt to reduce the impacts of bottom trawling by modifying its operation, ensuring minimal contact of the gear with the seabed. A decrease in the bycatch catch rate and in the proportion of bycatch to total trawl catches represented maximising catches of targeted species while offering a degree of protection to the non-targeted species. Growth overfishing was reduced as evidenced by the lower percentage of juveniles in bycatches. Species diversity and richness were maintained at an acceptable level, and it is apparent from abundance-biomass plots that the fishing zones were under relatively low pressure. From the obtained results, trawling marginally above the bottom ameliorated the ecological consequences without compromising on the capture efficiency. Thus, effort restrictions on the sea bottom by vertical effort relocation seem the most potent and pragmatic solution in reducing the damage to marine ecosystems. Additionally, a temporal closure may be advocated for seasons with higher contributions of bycatch, the post-monsoon months for the present region. Present findings, with the support of further studies across other locations, should form an integral part of management advisories intended for tropical trawl fisheries.

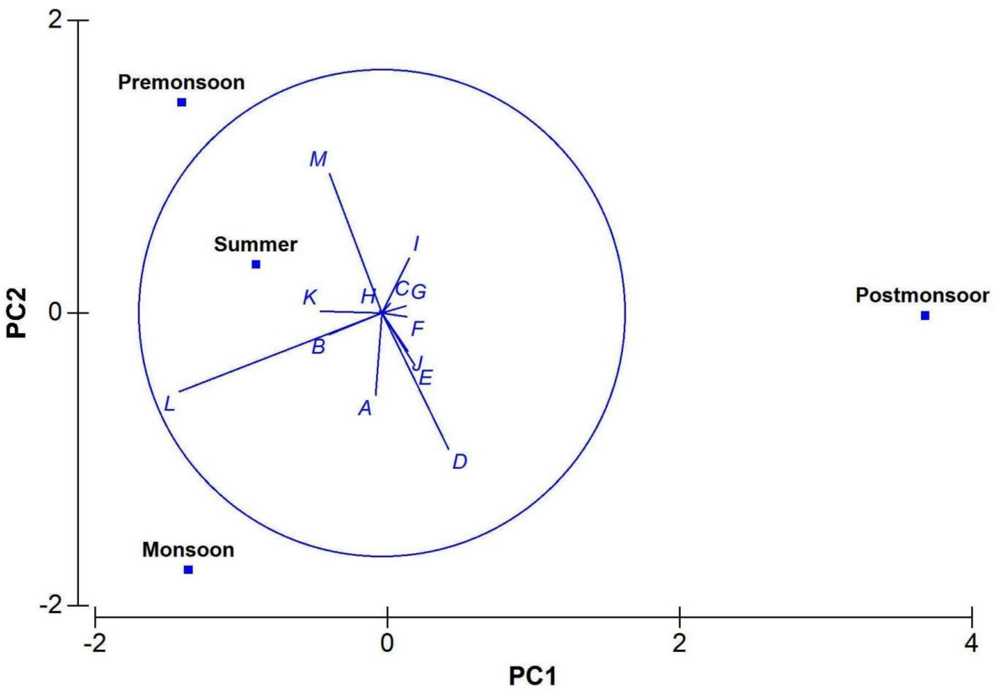

Figure 6. Principal Component Analysis plot showing the seasonal distribution of major bycatch families with respect to the two axes; where A = Apogonidae, B = Calappidae, C = Callionymidae, D = Engraulidae, E = Fistulariidae, F = Leiognathidae, G = Nemipteridae, H = Platycephalidae, I = Siganidae, J = Synodontidae, K = Terapontidae, L = Trichiuridae, and M = Others

Ethical Statement

Not Applicable, as previously captured and killed specimens from commercial fisheries were used as samples in the present study.

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Author Contribution

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D Indira: Data curation, Formal analysis;
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Conflict of Interest

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

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