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Spatial structure and distribution of ribbonfish *Trichiurus lepturus* Linnaeus, 1758 along the eastern Arabian Sea

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Abstract

Ribbonfish *Trichiurus lepturus* is one of the most important pelagic fish resources in India. The west coast of India (WCI) is considered to be the major region where the species is abundant and forms a sizeable fishery. Determining the spatio-temporal abundance of fish is a key requirement for sustainable resource harvest. This paper illustrates the spatial structure and distribution of ribbonfish along the WCI using the geostatistical technique, semi-variogram modelling. The spatio-temporal distribution map was generated by kriging interpolation using the global neighbourhood in the study area. The results show that the areas of higher abundance of ribbonfish shifted between seasons, abundance along the northern region was high during the post-monsoon, while later shifting southward up to 17°N, peaking between 18°N and 19°N. Furthermore, summertime peak abundance tended to be more coastal in the Mumbai region. Ribbonfish abundance was relatively lower along the southern region *i.e.,* below 15°N year-round. This finding provides additional information to fishery managers and policymakers which will help improve the sustainability of fisheries coupled with traditional fisheries management measures.

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Introduction

Ribbonfish *Trichiurus lepturus* is one of the most important pelagic fish resources of the Indian Exclusive Economic Zone (EEZ), particularly off the west coast of India (WCI). A reconnaissance fishery conducted by *M. T. Murena* revealed a significant presence of ribbonfish in the region between 15°N and 23°N (Bapat *et al.*, 1982). Ribbonfish accounted for 5.6% (0.19 million t) of the total Indian marine fish production and WCI alone contributed 72.26% (0.14 million t) of ribbonfish production in 2018. Gujarat has been recorded as the top ribbonfish landing state *i.e.*, 0.09 million t (CMFRI, 2019). Ribbonfish is the top predator and feeds on a wide variety of prey (Rohit *et al.*, 2015; Koya *et al.*, 2018b) and therefore plays an important role in controlling the populations of lower trophic level species, including fish, crustaceans and cephalopods. The species plays a significant role in marine ecology, justifying the need for prudence in its exploitation. The trawl net is the major fishing gear for ribbonfish resources in the region (Azeez *et al.*, 2021b).

Due to international export demand, ribbonfish fishing constituted an important source of income in the region. The profitability of fishing depends on several factors, including the efficiency of the fishing operations. Of the various recurring expenses in fisheries, fuel costs are the main factor contributing to the high expenses (Radhakrishnan *et al.*, 2018). To reduce the expenditure on fishing activity, it would be wiser to reduce spending on fuel. This can be achieved by reducing the time taken to find fishing grounds and minimising scouting and travel time to fishing grounds. Prior knowledge of the potential locations of fish shoal aggregations would significantly reduce the time spent for searching. Moreover, information on the spatio-temporal abundance of fishery resources is crucial for spatial management measures, particularly for tropical trawl fisheries such as India, where many species occur in the fishery (Bijukumar and Deepthi, 2009; Dineshbabu *et al.,* 2015; Mahesh *et al.,* 2019). Furthermore, mapping of fishery resources will help policymakers decide where more attention is needed and help improve fisheries sustainability alongside traditional fisheries management measures (Morfin *et al.,* 2012; Azeez *et al.,* 2016; 2023; Koya *et al.*, 2018a).

Ribbonfish is known for its unique spatio-temporal movement along the Indian coast. The juveniles and sub-adults aggregate in coastal waters for feeding and the adults migrate offshore to spawn (Prabhu, 1950; Narasimham, 1972; James *et al.*, 1986; Ghosh *et al.*, 2009; Avinash *et al.*, 2014). Azeez *et al.* (2021a) observed the influence of environmental factors on the abundance of the species on the north-west coast of India. However, there is limited information on the spatial structure and distribution of ribbonfish in the WCI, other than the study conducted by Azeez *et al.* (2016; 2023) along the north-west coast. Therefore, the present study attempts to analyse the structure and distribution of ribbonfish in the WCI.

Materials and methods

Data collection and analysis

The WCI included five coastal states of India namely Gujarat, Maharashtra, Goa, Karnataka and Kerala (Fig. 1). The fishery data for the study was collected for the period 2012-2019 from a logbook sheet of selected multiday trawlers operating at three major fisheries harbours *viz.,* Veraval (Gujarat), Mumbai (Maharashtra) and Mangaluru (Karnataka) along the WCI. Logbook sheets were provided to the three multiday trawlers targeting ribbonfish at each harbour, and spatial data consisted of 2521 observations. The catch at each station is recorded from 2-3 hauls in a week by each of the three trawlers with details of the latitude and longitude of net casting, date and time of fishing, depth of the fishing area and trawl speed. The total weight of fish in a haul was standardised using catch per unit effort (CPUE) in kilogram per hour (kg h^{-1}) of fish. Data were grouped based on fishing seasons such as post-monsoon (August-November), winter (December-February) and summer (March-May) (Azeez *et al.*, 2016; Solanki *et al.*, 2016; Koya *et al.*, 2018a) to analyse ribbonfish structure and distribution. Non-parametric analysis of the Kruskal-Wallis test was performed to test the significant variation in CPUE in different seasons, latitudes and bathymetries. For the semi-variogram modelling, the frequency distribution of the CPUE data was highly skewed with a large proportion of low values and fewer high values. Therefore, Box-Cox transformation to CPUE was carried out to correct such patterns. The optimal transformation was the square root as the lambda value was close to 0.5 in the Box-Cox transformation. Furthermore, CPUE was averaged at 50 km × 50 km grid blocks for different seasons to reduce the influence of excess fishing effort in the study area (Azeez *et al.,* 2023).

Spatial structure and abundance pattern

The spatial structure of fish abundance is defined as the spatial autocorrelation between fish abundance at two locations (Saraux *et al.*, 2014; Azeez *et al.*, 2023). Such spatial structure depends on the biotic and abiotic factors in the region such as spawning, marine

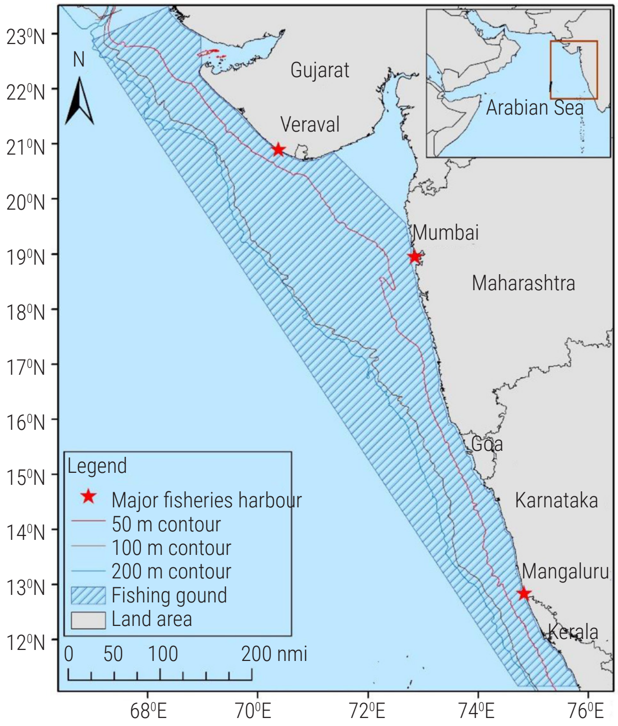

Fig. 1. Map of the study area

environmental factors and prey. The spatial structure and abundance pattern of the fish were analysed with a semi-variogram (spherical model), which is defined as the mean squared difference (*h*) between points. The semi-variance function was calculated for all directions (isotropic semi-variogram) to assess the spatial dependence of the data. Equation 1 describes the empirical semi-variogram fit for a geospatial data set.

$$\gamma (h) = \frac{1}{2|N(h)|} \sum_{N(h)} (Z_x - Z_y)^2 \quad \text{..} (1)$$

where γ *(h)* is the semi-variance function, *N(h)* is the set of all pair-wise Euclidian distances, $h = x - y$, |*N(h)*|, is the number of discrete pairs in *N(h)* and Z_x and Z_y are data values at location *x* and *y*, respectively (Goovaerts, 1997).

Semi-variograms have a sill (an asymptote) that indicates reaching a distance (often called the range of autocorrelation) where autocorrelation does not exist and a nugget (point of intersection on the *y*-axis) indicates the variability scale. Semi-variograms were estimated using the ‘geoR’ package (Ribeiro Jr *et al.*, 2020), a robust semi-variogram estimator in R version 3.6.1 (R Core Team, 2019). The consistency of semi-variograms (spherical model) was evaluated using the jack-knifing test. The estimate is considered adequate when the mean (μ_{jk}) and variance (σ_{jk}) of the reduced error are close to zero and one, respectively (Vieira *et al.*, 2010). The spatial dependence index (ISD) serves as a tool for examining spatial structure and variability. It is derived by computing the percentage ratio between the nugget effect (C_0) and the combined level represented by the sum of the nugget effect and structured variation (C) using Equation (2).

$$\text{ISD} = \frac{C_0}{C_0 + C} \times 100 \quad \text{...} (2)$$

The ISD was categorised as: strong (ISD < 25%), moderate (25% ≥ ISD ≤75%) and weak (ISD >75%) based on degree of spatial dependence (Cambardella *et al.*,1994).

Spatial distribution mapping

The spatiotemporal mapping of ribbonfish was performed by kriging interpolation using the global neighbourhood within the study area. The parameters are estimated from the theoretical spherical semi-variogram model used in kriging interpolation. The kriging interpolation for sqrt (CPUE) was performed using geoR package (Ribeiro Jr *et al.*, 2020). Centre of gravity and inertia indices were used for detecting the spatial shift in fish distribution (Woillez *et al.*, 2007) indices are designed not to depend on arbitrary delineation of the domain. They characterise the location (centre of gravity and spatial patches). The centre of gravity is the mean location of the fish population and also the mean location of an individual fish taken randomly in the field. Inertia describes the dispersion of the population around its centre of gravity.

Results and discussion

Ribbonfish, like several other coastal fish, is known for continuously moving from one place to another for food and reproductive biological needs (Prabhu, 1955; James *et al.*, 1986; Martins and Haimovici, 1997; Azeez *et al.*, 2016). The fluctuations in fish abundance affect the quantity of fish that is landed. Seasonal average CPUE of ribbonfish (Fig. 2) were significantly different (χ^2 = 115.67, p = <0.001, df = 2), the lowest average CPUE (30.35±16.78 kg h^{-1}) was during summer and the highest average CPUE (51.26±19.20 kg h^{-1}) was during the post-monsoon. CPUE variations with latitude (Fig. 3) were also significantly different (χ^2 = 22.54, p = <0.01, df = 5), with a lower catch rate (23.85±15.22 kg h^{-1}) between 11°N and 13°N, while higher catch rate (43.33±14.65 kg h^{-1}) was observed between 17°N and 19°N. Ribbonfish catch was significantly different (χ^2 = 31.98, p = <0.01, df = 3) at different depths in WCI (Fig. 4). The lowest CPUE (25.98±11.13 kg h^{-1}) was observed in deeper (offshore) waters *i.e.,* beyond 200 m depth, while the highest average CPUE (52.11±15.68 kg h^{-1}) was observed between 50 and 100 m depth.

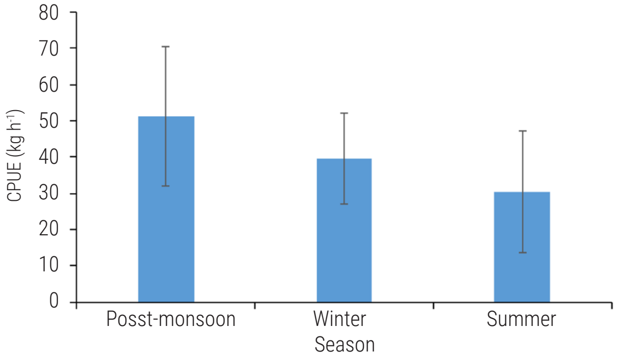

Fig. 2. Seasonal variation of ribbonfish CPUE in the study area

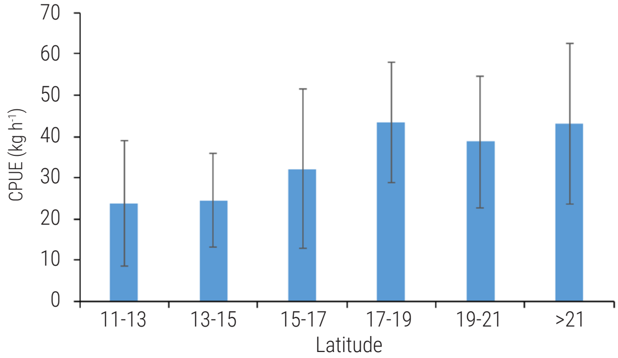

Fig. 3. Latitudinal variation of ribbonfish CPUE in the study area

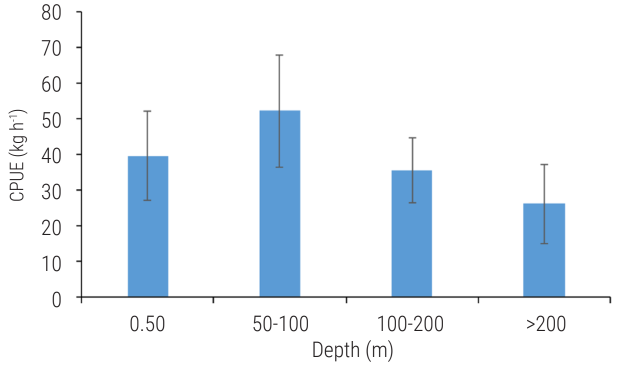

Fig. 4. Depth-wise variation of ribbonfish CPUE

Semi-variograms were computed for each season (Fig. 5) and all showed distinct spatial structures characterised by increasing variance with distances between samples. These semi-variograms revealed different patterns of fish abundance across seasons, such as variance stabilised rapidly during the post-monsoon period, with values of 5.46, whereas it reached 6.50 and 8.32 during summer and winter, respectively. The shape of the semi-variogram structure is influenced by factors such as bathymetry, prey availability and oceanic environmental conditions, as these biotic and abiotic factors directly impact fish abundance (Badenhorst and Smale, 1991; Morfin *et al.,* 2012; Alabia *et al.*, 2016). The abundance of ribbonfish is intricately linked to the oceanic environment and prey availability (Martins and Haimovici, 1997; Azeez *et al.*, 2021a, b). Consequently, the spatial autocorrelation of ribbonfish distribution exhibited a moderate ISD scale during the post-monsoon and summer seasons, while it demonstrated a strong ISD scale in winter (Table 1).

The seasonally calculated centre of gravity and inertia were more stable and no directional trend was observed between seasons (Fig. 6). However, the spatiotemporal distribution of ribbonfish revealed dynamic shifts in areas of higher abundance across seasons (Fig. 7). For instance, high abundance was observed along the northern region during the post-monsoon period. In contrast, the abundance area was shifted southward, reaching up to 17°N latitude and peaking between 18°N and 19°N during winter. Furthermore, peak abundance during summer tended to be more coastal, particularly in the Mumbai region. Ribbonfish abundance, on the other hand, remained relatively low throughout the year in the southern region, particularly below 15°N latitude. The peak predicted abundance *i.e.*, sqrt (CPUE) during the post-monsoon was 5.72 sqrt (kg) h^{-1} and later reduced to 4.95 sqrt (kg) h^{-1} and 4.80 sqrt (kg) h^{-1} in winter and summer, respectively. The spatial abundance of ribbonfish was high during the post-monsoon period as it is considered to be the most productive in terms of catch and catch rate, coinciding with increased fishing activity (Ghosh *et al.,* 2009; Avinash *et al.*, 2014). Ghosh *et al.* (2009) reported high catch rates for ribbonfish during post-monsoon, probably due to high fishing effort just after the monsoon fishing ban from June to August in the region. In addition, the northern Arabian Sea experiences both south-west and north-east monsoon. Cyclonic currents from Somalia and coastal upwelling during the south-west monsoon induce primary productivity in the WCI (Solanki *et al.,* 2016) and provide a favourable environment for the wide abundance of ribbonfish during the post-monsoon. The spatio-temporal abundance of ribbonfish is known to be strongly linked to the feeding environment and suitable physiological conditions (Martins and Haimovici, 1997; Azeez *et al.*, 2021a). The cool dry winds of the north-east monsoon lower the sea surface temperature (SST) in the northern Arabian Sea leading to winter convection in the region, resulting in winter blooms (Banse *et al.,* 1986; Madhupratap *et al.,* 1996). High phytoplankton concentration and lower water temperature are beyond the favourable range of ribbonfish abundance (Azeez *et al.*, 2021a); Therefore, fish migrate towards the south in winter. Furthermore, adult ribbonfish move offshore during winter, the peak spawning season, and juveniles move inshore for feeding and are recruited to the fishery in summer (Prabhu, 1950; Narasimham, 1972; James *et al.*, 1986; Avinash *et al.*, 2014; Azeez *et al.,* 2016). This unique spatiotemporal migration of ribbonfish linked to their feeding and reproductive biology is visible on the seasonal maps (Fig. 7). Such information on the spatiotemporal aggregation of fish is crucial for the spatial management of fisheries in coastal waters (Koya *et al.*, 2018a; Dineshbabu *et al.*, 2019). Therefore, the present study supports fisheries managers and policymakers in development of marine spatial planning (MSP) as a management

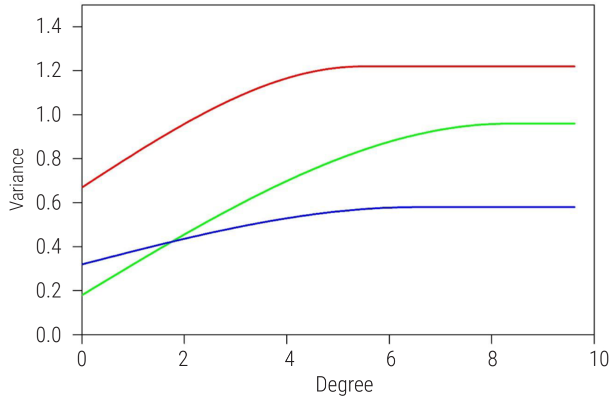

Fig. 5. Seasonal mean semi-variogram modelled for ribbonfish in the study area (Red line: Post-monsoon; Green line: Winter; Blue line: Summer)

Table 1. Geo-statistical parameters from the semi-variogram model. μ_{jk} = Average reduced error and σ_{jk} = Reduced error variance

Season	Nugget	Sill	Distance	ISD	μ_{jk}	σ_{jk}
Post-monsoon	0.67	0.55	5.46	54.91	0.0027	1.06
Winter	0.18	0.78	8.32	18.75	0.0074	1.01
Summer	0.32	0.26	6.50	55.17	0.0014	1.04

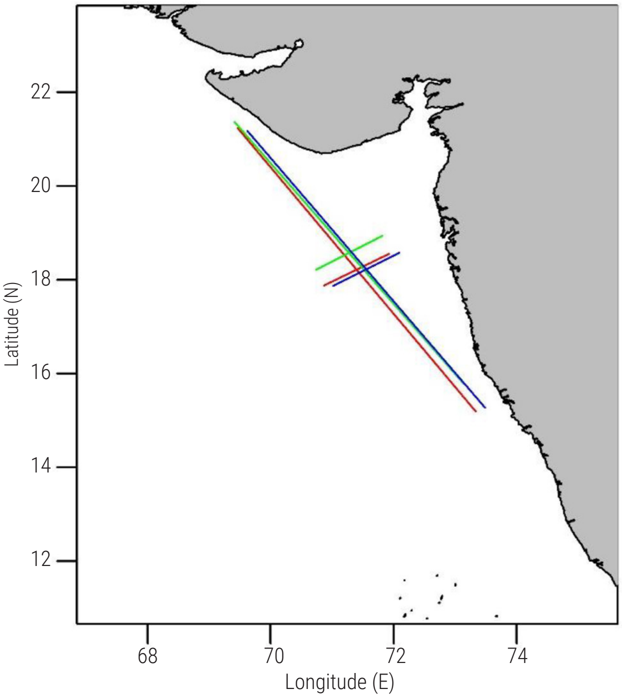

Fig. 6. Map of the centre of gravity and inertia of ribbonfish during post-monsoon (Red), winter (Green) and summer (Blue)

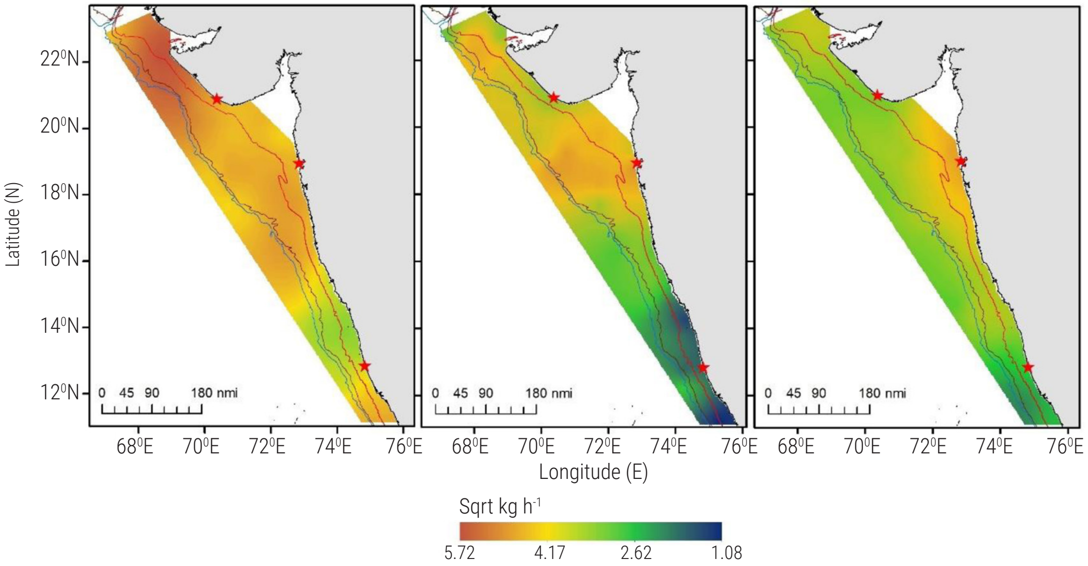

Fig. 7. Kriged map of ribbonfish distribution in the study area during (a) Post-monsoon, (b) Winter and (c) Summer. Red star indicates major fisheries harbours *i.e.*, Mangaluru, Mumbai and Veraval (South to North). Red line represents 50 m depth contour, Brown and blue represent 100 m and 200 m depth contours respectively

tool particularly in multi-gear and multi-species tropical fisheries such as in WCI. Furthermore, this work can be used as a reference for future studies to develop spatiotemporal distribution maps of various marine fishes along the Indian coast more scientifically.

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