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Population dynamics of the geographically defined metapopulations of brown shrimp *Metapenaeus monoceros* (Fabricius, 1798) from Indian waters

A. P. DINESHBABU, P. T. SARADA, G. MAHESWARUDU, S. LAKSHMI PILLAI, GYANRANJAN DASH, INDIRA DIVIPALA, RAJAN KUMAR, REKHA DEVI CHAKRABORTY, M. RAJKUMAR, J. JAYASANKAR, R. RATHEESHKUMAR, K. N. SALEELA AND JOSILEEN JOSE
ICAR-Central Marine Fisheries Research Institute, Ernakulam North P. O., Kochi - 682 018, Kerala, India
e-mail: dineshbabuap@yahoo.co.in

ABSTRACT

Population dynamics of the brown shrimp *Metapenaeus monoceros* (Fabricius, 1798) was studied along the Indian coast using catch and effort data of trawlers from 8 States and 2 Union Territories for the period 2007-2015. Classical length-based stock assessment methods and spatial database of the shrimp catch were used to derive fishing ground related conclusions. Inclusion of spatial data revealed the possibility of existence of metapopulations of *M. monoceros* in the region. Maximum sustainable yield (MSY) cannot be a reasonable reference point for deciding the fishing pressure in *M. monoceros*. By analysing stock fluctuations noticed during the study period with varying spawning stock biomass combinations, retention of 40% spawning biomass seems to be a safe option for sustaining *M. monoceros* production from Indian waters. Based on this, the study recommends reduction of fishing pressure along north-west, south-west and northeast coast by 70, 60 and 70% respectively from the base level of effort in 2017. The study illustrates that the spatial data from fishing ground, can serve as an additional tool to derive management options. The study also emphasises the need for further investigations on the possibilities of metapopulations of *M. monoceros* which is widely distributed in all agro-climatic zones along the Indian coast.

Keywords: Indian coast, Metapopulation, *M. monoceros*, Spatial study, Stock assessment

Introduction

The brown shrimp *Metapenaeus monoceros* (Fabricius, 1798) is distributed across the world from the eastern Mediterranean, the east coast of Africa, Madagascar, Tanzania, Red Sea, all along the coasts of India, Sri Lanka, Pakistan, Malaysia, Straits of Malacca, Indonesia to Australia and Japan (Crosnier, 1965; Racek and Dall, 1965). It is a commercially important high-value species in India, fetching up to ₹400 per kg. It is exploited by trawlers all along the Indian coast from both Arabian Sea and Bay of Bengal. Reproductive biology, population characteristics, life history and morphological traits of this species have been described (Crosnier, 1965; Racek and Dall, 1965). In India, fishery, biology, and stock characteristics of *M. monoceros* have been well studied (Rao and Krishnamoorthi, 1990; Rao, 1993; Sukumaran, *et al.*, 1993; Nandakumar and Srinath, 1999)

The success of marine fisheries management depends on infallible stock assessment of the resources. Extension of fishing grounds and adoption of innovative fishing technologies have resulted in unprecedented challenges in stock assessment of resources in modern times. To overcome these challenges, incorporation of geo-spatial data and adoption of information technologies in fishery management are projected as efficient supporting tools (Wilson *et al.*, 1999; Martien *et al.*, 2013: Cadrin, 2020). Lack of incorporation of spatial data in stock assessment leads to severe stock collapses (Berkeley *et al.*, 2004; Ciannelli *et al.*, 2013), since the assumptions thus derived do not reflect the extension of fishing grounds and thus may unintentionally support overfishing. Such calamities are more profound in less mobile groups like crustaceans (Rothschild *et al.*, 1970; Koeneman, 1985; Orensanz *et al.,* 1998). Conventionally the stock assessment of a species with continuous distribution along the coast were carried out by considering the group as one population, and a general fishery management measure was applied for the entire stock (Gulland, 1969). Apart from attempts on *Solenocera choprai* (Dineshbabu and Manissery, 2009) from Mangalore coast, spatial dimension using GPS data has not been incorporated in stock assessment of shrimps from Indian waters. The present investigation incorporated the spatial distribution of *M. monoceros* as a supporting database and tool to the conventional methods of stock assessment. This attempt will be an encouragement for planning future studies utilising spatial data to formulate marine fishery management plans in India.

Biological characteristics of a species inhabiting different zones have been reported to be influenced by climatic and geographical variabilities which are considered to be the reason for the likelihood of metapopulations (Hanski, 1999) These environmental considerations are important for management of marine resources (Earn *et al.*, 2000). Based on the geographical characteristics and climatic variability, the coastline of India is divided into four zones *viz.,* north-west (NW), south-west (SW), north-east (NE) and south-east (SE) regions (Vivekanandan, 2011). *M. monoceros* is distributed in all the four climatic zones and studies on climate change related species vulnerability have proved that the species is highly vulnerable in SW, SE, NE zones due to its life history traits and its response to trawling pressure (Dineshbabu *et al*., 2020). The present study was carried out to understand fishing ground-based stock status of the species, so that region-specific management plans can be derived to sustain this economically important fishery resource.

The concept of metapopulations has been disregarded in most of the earlier studies, as there was no supporting information on the geographical distribution of the species. As GIS technological support was recognised as a reliable tool in fisheries management, more and more metapopulation-oriented studies were reported worldwide (Smedbol *et al*., 2002; Grimm *et al.*, 2003a; Fogarty and Botsford, 2006). Advantage of metapopulation analysis over single population concept in stock assessment was illustrated by Botsford *et al.* (1998) and they found that unless the metapopulation is considered in the analysis, stock assessment results can be an over-estimation or under-estimation of the stock, which eventually leads to over-exploitation of resources or wastage of input resources. Smedbol *et al.* (2002) and Grimm *et al.* (2003b) suggested that spatial separation across environmentally separated ecosystems can be a criterion for metapopulations of well distributed species in marine zone. Categorisation for the ecologically defined population into separate metapopulations was argued to be extremely necessary for benthic species with low capability for seasonal migrations (Fogarty and Botsford, 2006). In recent years, stock assessment of metapopulations within the stock and separate management plans for the well defined metapopulations were reported to be highly useful in deriving very effective management tools in shrimps, crabs and lobsters (Hanski, 1999; Begg, 2005; Cadrin, 2010; Brophy, 2014). In the present study, geographical separation and uniqueness in biological and population characteristics of the species were used as a baseline for metapopulation identification of *M. monoceros*.

Materials and methods

Spatial analysis

Spatial data for trawl operations and the distribution of *M. monoceros* in the trawling grounds were identified using customised log sheets provided to selected commercial trawlers (Dineshbabu *et al.*, 2006). Onboard information from trawlers that operated from Veraval, Mumbai, Mangalore, Calicut, Kochi and Visakhapatnam fisheries harbours during 2012-2015 were used for mapping the fishing ground using ArcGIS software. Geo-referenced coordinates marking the vertices were used for the area calculation of the fishing ground (Wood and Baird, 2010). Based on information thus obtained on the spatial distribution and fishery of the species, it was evident that the fishing ground for *M. monoceros* landed at Visakhapatnam was along the north-east coast of India, suggesting that the stock landed at Visakhapatnam represented *M. monoceros* distributed off north-east coast of India. Thus, for region-based analysis, pooling of data from states was done as follows: north-west (NW; Gujarat - Veraval and Maharashtra - Mumbai), south-west (SW; Karnataka - Mangalore and Kerala - Calicut and Cochin) and north-east (NE; Andhra Pradesh - Visakhapatnam).

Fishery and biology

Trawl landing and effort data for the period between 2007 and 2015 from eight states and two Union Territories (UTs) along the Indian coast, obtained from National Marine Living Resource Data Centre (NMLRDC) of ICAR-Central Marine Fisheries Research Institute (ICAR-CMFRI), Kochi, India, were used for the study. Data for biological and stock studies were collected during 2012-2015 from Veraval, Mumbai, Mangalore, Calicut, Kochi and Visakhapatnam fisheries harbours, representing three geographic zones - NW (Gujarat and Maharashtra), SW (Karnataka and Kerala) and NE (Andhra Pradesh). The total number of samples analysed for the study was 47,700, comprising 21,528 males and 26,172 females. Sex-wise pooled data were raised to landing centre catch and further, the landing centre data were raised to state-wise landings collected from NMLRDC of ICAR-CMFRI (Srinath, 1991). Total length of *M. monoceros* (measured at 1.0 mm scale) was used as basic data for morphometric and biological studies. For length-weight relationship (LWR), shrimps were weighed up to 1.0 g accuracy and LWR were derived individually for the representative samples collected from NW, SW and NE zones using standard techniques (Ivanov and Krylov, 1980). Size at first maturity (Lm_{50}) for males and females from individual samples representing the geographic zones were estimated by fitting a logistic curve (King, 1995).

Stock assessment

Sex-wise length frequency data generated from samples collected from trawl landings in Gujarat, Maharashtra, Karnataka, Kerala and Andhra Pradesh during the period 2012-2015 were used for stock assessment. Lengths were classified into 5 mm class intervals and the length frequency data were raised to the catch in weight on the corresponding days of observation and later to the month (Srinath, 1991).

L_{max} of male and female *M. monoceros* was estimated from the largest size in the samples collected from Gujarat, Maharashtra, Karnataka, Kerala and Andhra Pradesh. Estimates of von Bertalanffy growth parameters (L_∞ and K) were derived by applying ELEFAN I program from FiSAT II (Gayanilo and Pauly, 1997). Total mortality, exploitation rate and probabilities of capture were derived following Pauly's model (Pauly, 1983) from FiSAT software, with the input of natural mortality value derived from Srinath's formula (Srinath, 1991). Thompson and Bell model was used for estimating maximum sustainable yield (MSY), maximum economic yield (MEY) and for biomass estimation (Gulland, 1969). Growth, mortality and exploitation parameters of male and female *M. monoceros* were estimated independently from each zone and for stock estimation studies, sexes pooled data of different states and zones were used. Yield per recruit analysis (Beverton and Holt, 1964) was carried out to understand the relative yield per recruit based on presentage of capture (T_C) and to understand the safety of stock at the present exploitation pattern.

Matapopulation identification

Distribution of *M. monoceros* in the different zones with independent environmental variability (Hanski, 1999) was considered as the basic criterion for metapopulation identification. Estimation of biological and population characteristics was done separately for each zone to confirm the possibility of existence of metapopulations of *M. monoceros* in the region.

Results

Spatial studies

The area of distribution of *M. monoceos* and the area of abundance of the species is given in Table 1. *M. monoceros* was found to be distributed up to 100 m depth from the coast, but spatial studies indicated that bulk of the fishery of the species took place between 30 and 80 m depth zones. These fishing grounds are usually beyond the territorial waters (TW) of the maritime states along the west coast of India (TW falls within 30 to 40 m depth). Beyond TW, the resources are shared by the neighbouring states. This reality brings in new challenges and necessitates fishing ground-based stock analysis.

Catch landed in the states of Maharashtra and Gujarat and UT of Daman and Diu, together can be treated as the catch from NW zone since the trawlers from these states and UT share common trawl fishing ground (Fig. 1a). The continental shelf is broadest along this coast and the trawlers from these states and UT cover about 1,85,453 km^2 in trawling.

Along the SW coast, trawl fishing grounds are largely shared by Kerala and Karnataka (Fig. 1b). Trawlers from these states cover approximately 96,442 km^2 in which *M. monoceros* were caught from 74,140 km^2 within the 100 m depth zone (Table 1). Even though overlapping was observed in fishing grounds of SW and NW states along Goa and south Maharashtra coasts, this accounted for only ~8% of the total trawled area along the west coast (22,140 km^2). Moreover, the overlapping was found to be highly seasonal (September-November) in most of the years.

Analysis of spatial data collected on the species from trawlers operating from Visakhapatnam Fishing Harbour (Andhra Pradesh) showed that the vessels exploit fishing grounds to the south and north of Andhra Pradesh coast and in the northern part, fishing operations extend till West Bengal coast (Fig. 1c). Fishery from the grounds to the south contributed only ~5% of the average annual trawl landings of *M. monoceros* in India, of which trawlers from Tamil Nadu too had a share. However, trawlers from Visakhapatnam that fished in the NE zone contributed to ~47% of the average annual landings of the species. Based on this, the stock represented by the landings at Visakhapatnam was considered to be from the NE zone. Details of the area covered and abundance of the species are presented in Table 1.

Fishery

During the period 2007-2015, Andhra Pradesh was the major contributor to the *M. monoceros* landings in India with 32% of the landing, followed by Maharashtra (18%) and Kerala (13%) (Fig. 2). Trawl net was the exclusive contributor of the species all along the Indian coast with an exception in Gujarat and Diu, where a modest part of the catch was contributed by dol net also. There was an increasing trend in overall landings of *M. monoceros* till 2012; thereafter the fishery was subjected to wide fluctuations, with a declining trend. The reduction was more profound in the NE coast of India (Fig. 3) where 55% decline (13,321 to 6,009 t) was observed from 2012 to 2015. Analysis of catch rates (catch per hour) also showed similar trend as the catch (Fig. 4).

The annual average landing of *M. monoceros* in India during 2012-2015 was to the tune of 18,988 t. The contribution of NW, SW, SE and NE zones was 27, 21, 5 and 47% respectively. Zone-wise annual average catch of *M. monoceros* and percentage of *M. monoceros* in trawl landings is given in Table 2. The SE coast showed seasonality in the fishery, with trawlers from Tamil Nadu

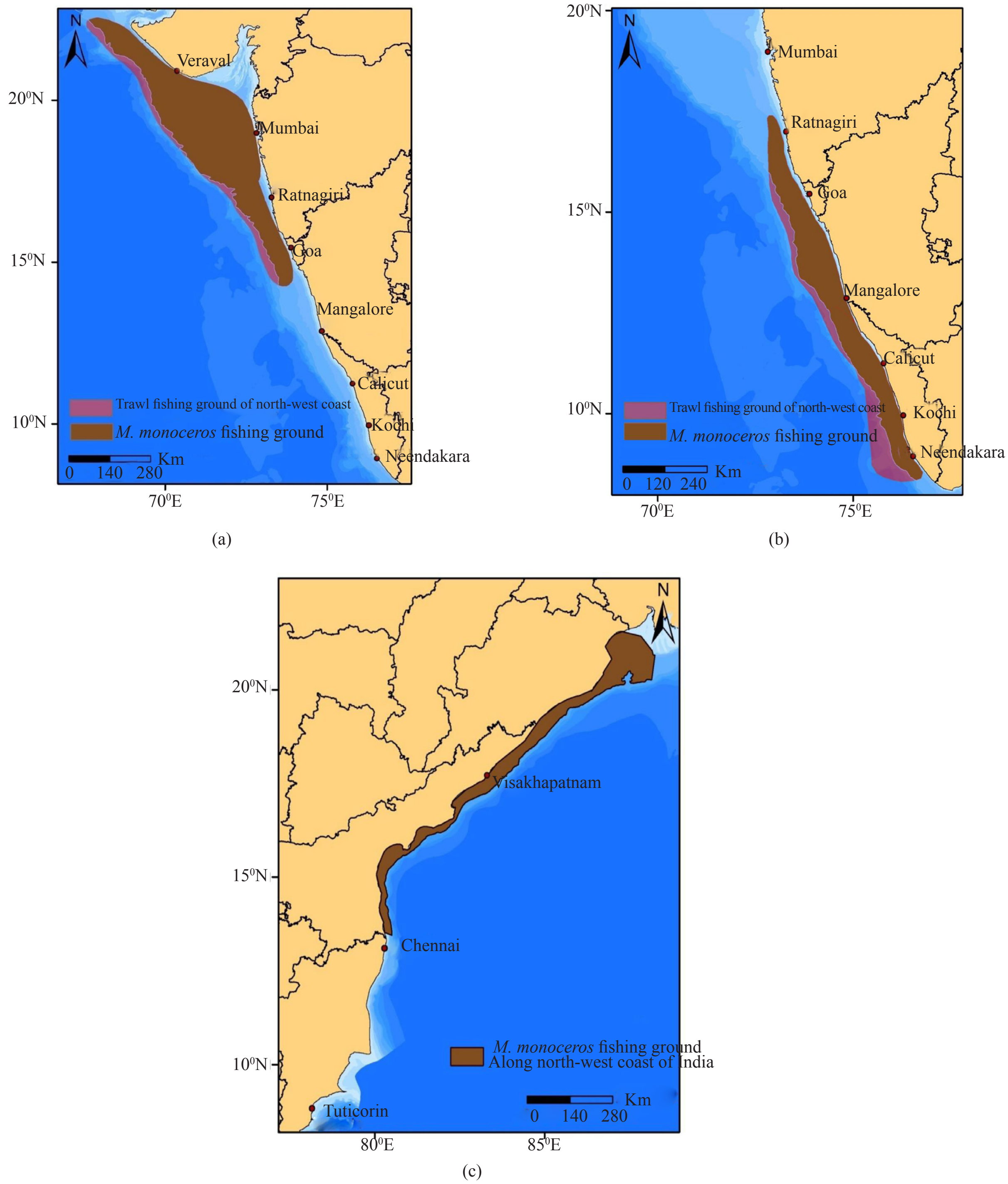

Fig. 1. Spatial extension of trawlers along (a) NW, (b) SW and (c) NE coasts of India for *M. monoceros* fishery

Table 1. Spatial analysis of trawling and *M. monoceros* fishing grounds

Region	Total trawling ground area (km^2)	Trawling area under 100 m depth (km^2)	Average fishing hours (2012-2015)	Average catch of *M. monoceros* (t)	Weight of *M. monoceros* caught (kg km^{-2})	CPH (kg)	Percentage of fishing hours within 100 m
NW	185453	167466	16284424	5120	30.5726	0.31	90.30
SW	96442	74140	9186946	3979	53.6632	0.43	76.88
NE*	53445	53445	8104570	8861	165.8044	1.09	100

*Classification was done based on the spatial study of fishing ground which is illustrated in Fig. 1

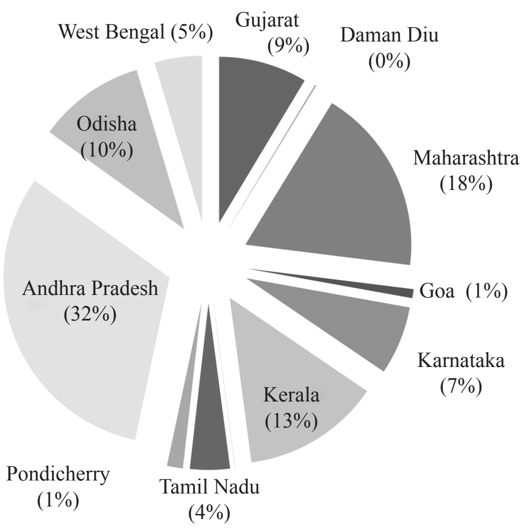

Fig. 2. Percentage composition of *M. monoceros* landings by different states and UTs along the Indian coast during 2007-2015

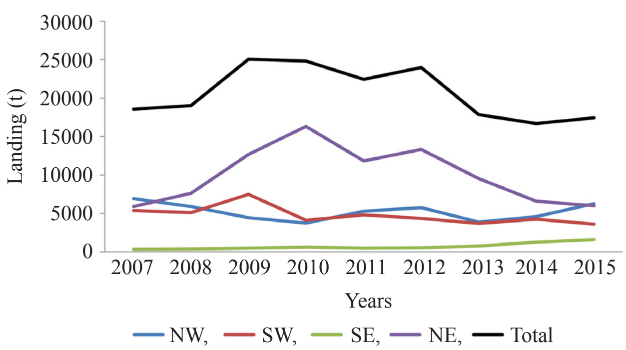

Fig. 3. Regional and national trends of *M. monoceros* landings during 2007-2015

and some trawlers from Andhra Pradesh sharing the same fishing ground along the Coromandel coast. Since this zone contributed only ~5% of the average annual landing of *M. monoceros* in the country, regional analysis was done for the three dominant zones *i.e.,* NW, SW and the NE coasts.

The annual catch rate (catch per hour, CPH) of the species in the NW, SW and NE zones during the period

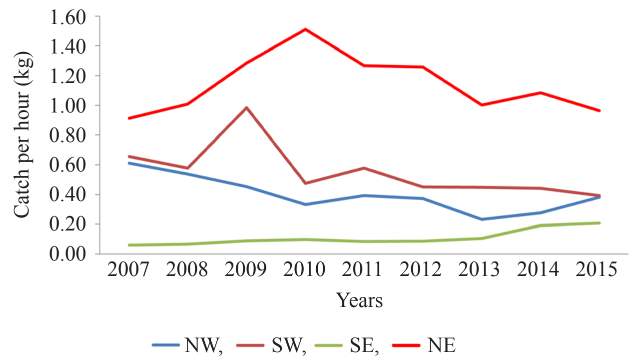

Fig. 4. Regional trends in catch rate of *M. monoceros* during 2007-2015

2012-2015 is given in Table 3. In the NW zone, the overall CPH did not show much reduction. However annual analysis showed reduction of up to 30% in CPH across a year, indicating the vulnerability of the stock to additional fishing pressure. In SW zone, there was an overall reduction of 13% in the catch rate; however, the CPH fluctuation was low compared to the NE zone, indicating better revival capabilities. In the NE zone, the reduction in catch rate was 24%.

Length-weight relationship

Length-weight relationship of sexes pooled data for each region was derived for NW, SW and the NE coast for stock assessment studies. The relationship derived for these zones were:

NW zone : $W = 0.004713*L^{3.1365}$

SW zone : $W = 0.003998*L^{3.2510}$

NE zone : $W = 0.006432*L^{3.1489}$

Table 3. Catch rate (CPH) of *M. monoceros* (kg h^{-1}) during 2012-2015 from three geographical zones studied

Year	NW	SW	NE
2012	0.37	0.45	1.26
2013	0.23	0.45	1.00
2014	0.28	0.44	1.08
2015	0.38	0.39	0.96

Table 2. Zone-wise annual average catch and percentage of *M. monoceros*

2012-2015	*M. monoceros* catch (Average)	% Crustaceans in trawl	% of Penaeid shrimps in trawl	% of *M. monceros* in trawl	Zone-wise percentage of *M. monoceros*
NW	5120	17.09	11.96	0.87	26.96
SW	3979	14.78	10.01	0.74	20.95
SE	1028	10.02	6.04	0.21	5.42
NE	8861	30.02	20.54	3.04	46.67
All India	18988	16.6	11.2	1.00	

Growth and population studies

State-wise analysis

The L_{max}, L_∞ and Lm_{50} were estimated for samples from each state and compared (Fig. 5). On the west coast, Kerala and Karnataka showed similarity in values of L_{max}, L_∞ and L_m, whereas the estimates from Gujarat and Maharashtra showed considerable difference from these values. Analysis of length distribution, L_{max}, L_∞ and L_m showed distinct zonal difference in SW and NW states, which were found to have different fishing grounds as seen in the spatial studies. This distinct independence necessitated independent stock assessment of the species considering SW and NW stocks as metapopulations of *M. monoceros* along the west coast. Length distribution, L_{max}, L_∞ and L_m of the NE coast showed similarity with those of NW coast of India, but physical separation of the two stocks necessitated independent analysis of data for stock assessment from both these zones.

Zone-wise analysis for growth and stock assessment

Growth

The von Bertalanffy growth parameters, L_∞ (asymptotic length) and K (annual growth coefficient) were estimated sex-wise for the NW, SW and NE zones. The growth curves generated for male and female *M. monoceros* are shown in Fig. 6a and b, respectively. The growth parameters derived from sexes pooled data for the three zones were: NW - L_∞ = 240.8 mm TL and K = 1.62 y^{-1}; SW - L_∞ = 200.6 mm TL and K = 1.6 y^{-1}; NE - L_∞ = 231.0 mm TL and K = 1.43 y^{-1}. These growth parameters were used as input values for stock assessment.

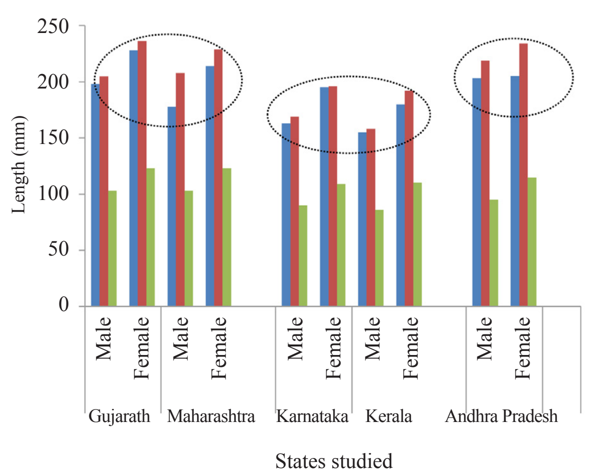

Fig. 5. Comparison of maximum length (L_{max}), asymptotic length (L_∞) and length at first maturity (Lm_{50}) of male and female *M. monoceros* estimated from different states

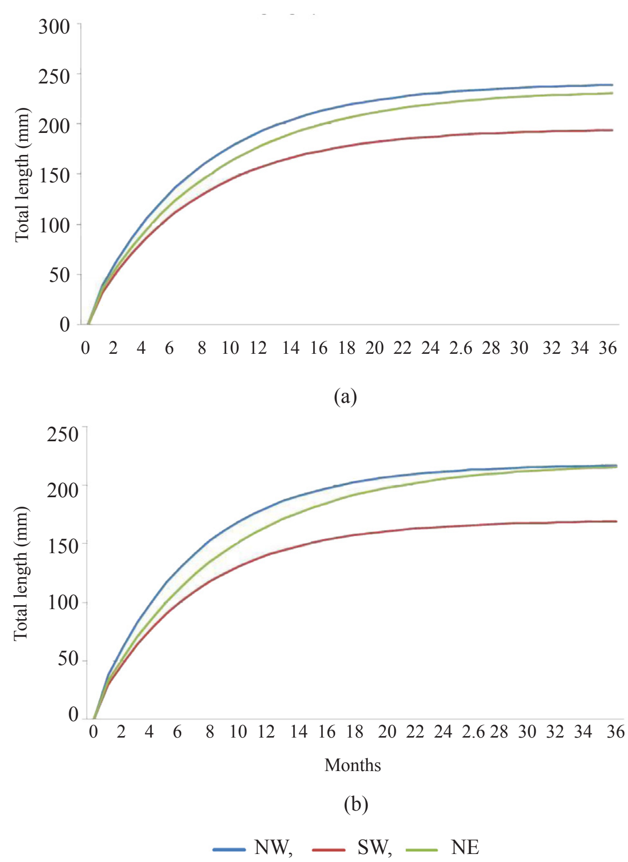

Fig. 6. Comparison of growth curve of *M. monoceros*. (a) Females and (b) Males from different zones

Metapopulation identification

Fogarty and Botsford (2006) reviewed methodologies for identifying metapopulation in crustaceans and suggested that variation in the spatial distribution showing variation in life history traits of the same species needs to be considered separately for their population dynamics. When a species has wide spatial distribution and shows distinct population characteristic parameters like growth, life span and size at maturity, pooling them together leads to erroneous assumptions, leading to over-exploitation or under-estimation of the species from different geographical zones. The present study evaluated the population characteristics of *M. monoceros* from different regions along the Indian coast, analysing their similarities and dissimilarities based on information on their spatial distribution. To come out with the most realistic exploitation policy for the species in each region, from the practical point of view, deriving individual stock assessment criteria and treating them as metapopulations of the species is the most useful applicable criteria (Post and Forchhammer, 2002). Following Fogarty and Botsford (2006), in the present study the populations of the widely distributed *M. monoceros* in different regions along the Indian coast were considered metapopulations to get the best stock estimate of the species from a regional perspective. The spatial data of *M. monoceros* catch from NW, SW and NE zones were analysed independently for understanding geographic distinction of *M. monoceros*. Morphometric, growth and reproductive characteristics of the major maritime states in these three zones were compared to understand the similarity and the differences if any among and between the states and also to justify the geographic classification with biological evidences. The results presented in the growth and stock parameters sections and results on the spatial distribution of *M. monoceros* from different regions formed the basis for the present metapopulation classification.

Stock assessment

Mortality, exploitation and probability of capture

The estimates of natural mortality (M), fishing mortality (F), total mortality (Z), exploitation rate (E) and probability of capture (L_{25}, L_{50} and L_{75}) are presented in Table 4. While natural mortality estimates were similar in the NW and SW zones and slightly lower in the NE zone, fishing mortality showed considerable difference between the three zones, with the highest 'F' being in the NE zone. The exploitation rate was 0.65, 0.7 and 0.76 for the three zones, respectively, indicating that the fishing levels were beyond optimum.

Virtual population analysis (VPA)

Results of the VPA using the pooled length-frequency data for each zone for the period 2012-2015 showed that in the NW zone, maximum fishing mortality was in the size classes between 150 to 165 mm TL whereas in the SW and NE zones, maximum fishing mortality was observed on the higher size classes between 175 to 195 mm and 170 to 185 mm TL, respectively. Maximum yield was from the 185-190 mm size class in NW and NE zones, whereas in the SW zone, the maximum yield was observed from the 160-165 mm size class. Spawning stock biomass was above 50% of total standing stock biomass in all the three zones studied.

Table 4. Estimates of mortality, exploitation and probabilities of capture of *M. monoceros* from different zones

	M	Z	F	E	L_{25}	L_{50}	L_{75}
NW							
Female	2.80	5.80	3.00	0.52	139	204	211
Male	3.02	9.45	6.43	0.68	123	131	141
Sexes pooled	2.85	8.08	5.23	0.65	126	136	143
SW							
Female	2.82	7.90	5.08	0.64	154	166	171
Male	2.97	7.29	4.32	0.59	116	124	130
Sexes pooled	2.82	9.52	6.70	0.7	136	159	165
NE							
Female	2.52	12.57	10.05	0.8	165	171	176
Male	2.45	10.84	8.39	0.77	110	117	122
Sexes pooled	2.60	10.90	8.29	0.76	126	136	143

Length-based Thompson and Bell analysis

For the NW zone, the maximum sustainable yield (MSY) and maximum economic yield (MEY) were obtained at effort levels of 1.8 and 1.2 respectively, using the current fishing effort level as the base level. However, the biomass and spawning stock biomass reduced by ~40% from their initial estimates at effort level of 0.8 (Fig. 7 and 8). Hence, a reduction of effort to 80% of the current effort level is recommended for the NW zone.

For the SW zone, the MSY and MEY were obtained at effort levels of 1.8 and 1.0 respectively, while the biomass and spawning stock biomass reduced by ~40% from their

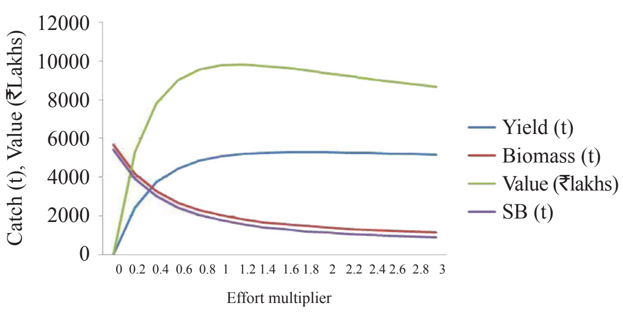

Fig. 7. Results of Thompson and Bell analysis for *M. monoceros* with length-frequency data pooled from NW coast of India for 2012-2015

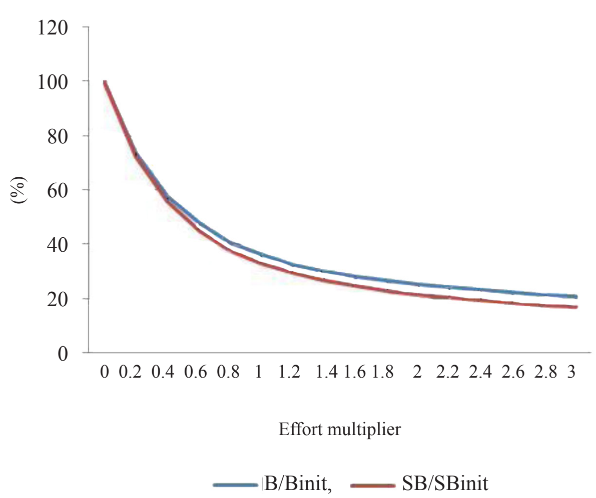

Fig. 8. Progressive reduction of total biomass and spawning biomass and spawning stock biomass with increasing effort levels, derived from Thompson and Bell analysis for *M. monoceros* from NW coast of India for 2012-2015

initial estimates at effort level of 0.8 (Fig. 9 and 10). Hence, as in the case of the NW zone, a reduction of effort to 80% of the current level is recommended.

For the NE zone, the MSY and MEY were obtained at effort levels of 2.4 and 1.0 respectively, while the biomass and spawning stock biomass reduced by ~40% from their initial estimates at effort levels of 1.2 and 0.8 respectively (Fig. 11 and 12). Hence, as in the case of the NW and SW zone, a reduction of effort to 80% of the current level is recommended.

Target reference points for management of M. monoceros

Since *M. monoceros* fishery of all three zones was found to show a declining trend, appropriate target reference points (TRP) were determined to ensure sustainable fishery of the species in all the three zones. The results of the Thompson and Bell analysis indicate that MSY is an impractical option as a TRP to manage *M. monoceros* fishery in the three zones as the species is only a minor contributor in the trawl fishery (Table 1) and limiting/raising the trawl fishing effort to a level of MSY

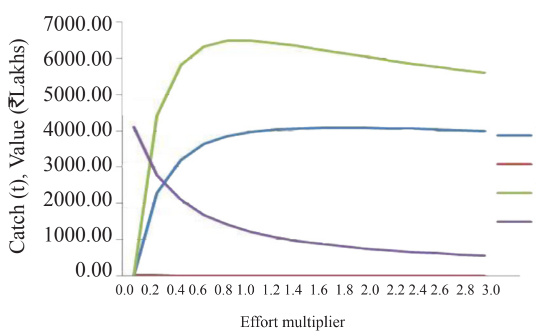

Fig. 9. Results of Thompson and Bell analysis for *M. monoceros* with length-frequency data pooled from SW coast of India for 2012-2015

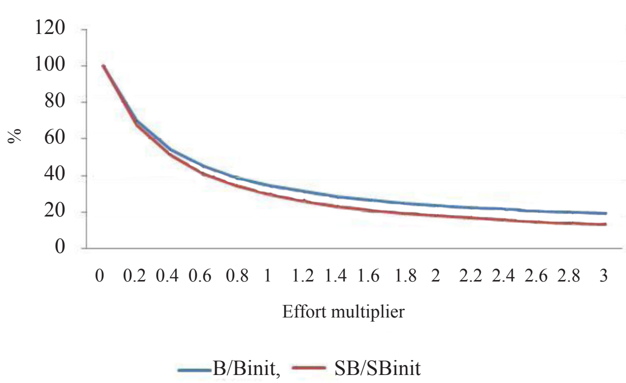

Fig. 10. Progressive reduction of total biomass and spawning biomass and spawning stock biomass with increasing effort levels, derived from Thompson and Bell analysis for *M. monoceros* from SW coast of India for 2012-2015

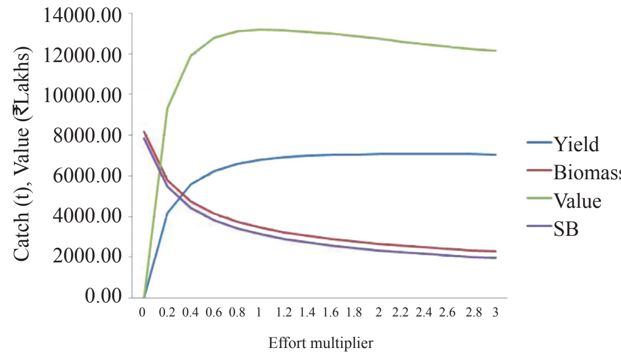

Fig. 11. Results of Thompson and Bell analysis for *M. monoceros* with length-frequency data pooled from NE coast of India for 2012-2015

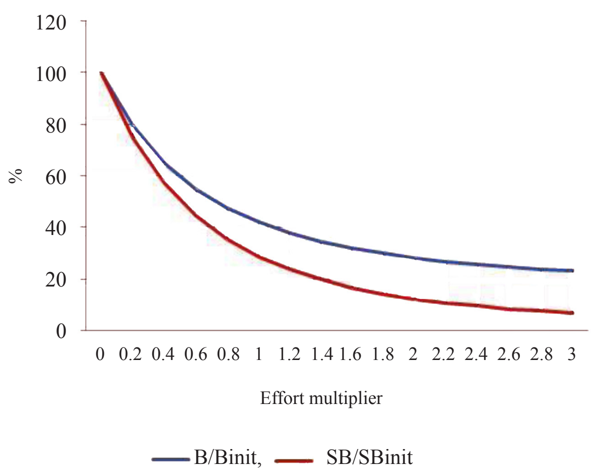

Fig. 12. Progressive reduction of total biomass and spawning biomass and spawning stock biomass with increasing effort levels, derived from Thompson and Bell analysis for *M. monoceros* from NE coast of India for 2012-2015

of a single resource in a multispecies fishery may impact other resources exploited by the same gear.

In this scenario, TRP based on stock parameters like total biomass and spawning stock biomass need to be attempted so that the species can be managed without stock depletion. It is imperative to look at spawning stock biomass in these three zones and appropriate measures taken to retain a healthy spawning stock biomass annually can be a better option to reduce the fluctuation and also to arrest the decline of the fishery. Spawning stock biomass of 32.9% (Table 5) retained at the present effort level along NW coast, which was the highest noticed in Thompson and Bell analysis, was also not found to be enough to ensure sustainability of the catch of the species. Instead, baseline fishing efforts enabling retention of 40% of the spawning biomass can be a practical TRP for managing *M. monoceros* from all the three coasts under study.

Target reference point based on spawning stock biomass

The results of the impact of MSY as TRP on total biomass and spawning stock biomass are given in Table 5. The spawning stock biomass is found to deplete drastically with MSY as the TRP. Since the concept of TRP is to permit long-term sustainable exploitation of the stocks with the best possible catch, analytical procedures should focus on retaining healthy spawning stock biomass in each of these zones, which can thus be a measure for species oriented fishery management options. Table 6 provides the results of options for TRPs for the management of *M. monoceros* based on spawner stock percentage and biomass percentage as TRP for fishing effort. The effort levels of 70% in NW and NE coasts and 60% in the SW coast can be suggested TRPs to retain healthy spawner percentage (~40%) in total biomass and to ensure sustainable production of *M. monoceros* in Indian waters.

Analysis of growth overfishing - Relative Y/R analysis

Results of the study indicated that *M. monoceros* had different L_C for the three zones. The estimated L_C for NW, NE and SW zones were 136 mm, 159 mm and 158 mm respectively and the corresponding T_C estimates were 0.6, 0.8 and 0.8 years respectively. Yield per recruit for present fishing effort in the NW, SW and NE zones were 3.239, 1.444 and 4.745 g year^{-1} respectively.

Discussion

In India, *M. monoceros* is caught exclusively by trawlers, and the fishing and fishery management plans for the species need to be designed by considering the enormity of growth and development in trawl fishery. Earlier, since the coastal states and UTs were responsible for the management of coastal fisheries, resource-wise management plans were advocated. Ever since trawl fishing in India extended beyond the limits of territorial waters, landing-based information in each state ceased to reflect the resource composition in the coastal fishing grounds of the states. Regional management plans were advocated to overcome these practical difficulties (Dineshbabu *et al.*, 2017; Mohamed *et al.*, 2018). *M. monoceros* is a commercially important and well-targeted species. The fishing grounds of the species are being shared by trawlers of different states, resulting in catches from the same grounds being landed in landing centers in two or more states. Lack of information of the fishing ground often leads to over-estimation or under-estimation of biomass, making management plans for the species practically ineffective. To bring clarity on the species distribution, spatial study of the species distribution was incorporated in the present study and this is the first attempt of its kind in India. Incorporating available spatial information in stock assessment models for achieving efficient fishery management in space and time was endorsed by Cadrin (2020), by reviewing different stock assessment models and outputs. He stated that lack of spatial dimension of the catch data may lead to erroneous decisions for stock assessment leading to instances of severe stock collapse, or failures in rebuilding the stocks. Such stock collapse was reported by Berkeley *et al.* (2004) and Ciannelli *et al.* (2013) in the Pacific ground fishes.

Table 6. TRPs of fishing efforts calculated for NW, SW and NE coast based on spawning stock % and biomass %

Zones	Effort level for retaining 40% spawning biomass	Effort level for retaining 40% of total biomass
NW	0.7	0.8
SW	0.6	0.8
NE	0.7	1.0

Spatial study incorporated in the present investigation illustrated the distinct sharing of common fishing ground by NW coastal states and UTs (Gujarat, Maharashtra, Daman and Diu). Similarly, Kerala, Karnataka and Goa were found to share a common fishing ground for *M. monoceros*. Fishing grounds off the NE coast were shared by Andhra Pradesh, Tamil Nadu, Odisha and West Bengal for the exploitation of *M. monoceros*. A species distributed along extensive area belonging to different climatic zones may have different biological characteristics which need to be analysed with different stock models (Fogarty and Botsford, 2006). *M. monoceros* in Indian waters was found to be distributed in four eco-climatic zones and its vulnerability to fishing pressure and climatic variation vary considerably in all these four eco-climatic zones. The species was found to be highly vulnerable (Dineshbabu *et al.*, 2020) to the synergic impact of climate change and fishing pressure from SW, SE and NE eco-climatic zones, due to its life history characteristics and market demand driven high fishing pressure. These findings necessitate area-based stock assessment for the species to derive fishery management options.

Table 5. Depletion of total biomass and spawning stock biomass when MSY is considered as TRP

	Effort levels derived for MSY	Effort levels derived for MEY	% of Spawning biomass at effort level for MSY	% of Total biomass at effort level for MSY
NW	1.8	1.2	22.7	26.1
SW	1.8	1.2	19.5	25.3
NE	2.4	1.2	9.6	25.6

While carrying out stock studies on species having wide geographic distributions, many of the workers noticed wide variations in biological parameters, which necessitated independent stock analysis as metapopulation analysis (Fogarty and Botsford, 2006; Cadrin *et al.*, 2014). Metapopulations are identified by geographic separation (Brophy, 2014), uniqueness in life history and morphology traits like size, maturity characteristics (*e.g.,* Cadrin, 2010) and distinctiveness in population characters like growth and mortality (Begg, 2005). The present study showed distinct differences in biological characteristics in *M. monoceros* caught from NW coast and SW coasts of India, which qualifies these to be considered as separate metapopulations. Even though most of the biological parameters showed similarity between NW and NE coasts, the geographical separation with a metapopulation in between also necessitates its independent analysis to bring out effective fishery management options.

The most important factor deciding the annual yield in these shrimps largely depends on the annual level of recruitment which is widely influenced by environmental conditions (Garcia, 1983). Dependencies on environmental conditions do not allow the adoption of appropriate production models based on fishery alone. Uncertainty in pre-recruit success which is not part of popular production models plays a major role in coastal shrimp fisheries management (Gulland and Rothschild, 1984). So, a major management measure to consider for fishery improvement in coastal shrimps is to monitor recruitment overfishing, larval survival, and estuarine carrying capacity while retaining a healthy spawning stock size (Garcia, 1983). Threats being faced by nursery grounds of *M. monocersos* in terms of anthropological factors have often been highlighted as major concern in Indian waters (Rao, 2013). Recent studies on the vulnerability of Indian fishery resources to climate change also highlighted this threat and the estuarine dependence of *M. monoceros* is also a factor in their classification as "highly vulnerable" in the light of loss of nurseries in estuaries due to climatic and anthropogenic interventions (Dineshbabu *et al.*, 2020). These findings demand a precautionary approach favouring *M. monoceros* sustainability while formulating a fishery management option in multispecies scenario. The TRP suggested to restrict fishing effort to retain 40% spawning stock biomass beyond the existing best (33%) will certainly supplement additional mitigations to tide over the uncertainties in pre-recruitment success.

At present, Indian marine fisheries, especially the trawl fishery is highly selective in targeting fish groups, driven mostly by marketing priorities and it is necessary to bring out the fishing pressure factor on different groups of fishes into reckoning to derive management measures for sustainability of each group. In the four geographic zones of India *viz.,* NW, SW, SE and NE coasts, *M. monoceros* formed only 0.87, 0.74, 0.21 and 3.04% of trawl catch respectively. In this scenario, optimising yield for particular species based on MSY and/or MEY may not be advisable and must be approached with caution since such management options may lead to heavy exploitation of certain other resources (Lhomme and Garcia, 1984); MSY and MEY cannot be taken as target reference points in multi species scenario (Hillborn, 2007). In the present study, MSY estimated for *M. monoceros* for NW, SW and the NE coasts were at 1.8, 1.8 and 2.4 effort levels and for MEY for all the three zones were obtained at 1.2 effort level. Since all the states already have in place management recommendations to reduce fishing pressure to sustain the fisheries, these estimates do not seem practical. Studies on optimum fishing fleet size for west coast (Rohit *et al.*, 2016) and east coast (Muktha *et al.*, 2018) of India suggested that there is more than 50% excess fishing pressure from mechanised fishing vessels and the fishing effort needs to be brought down considerably to ensure sustainability of fish production from these coasts. These recommendations fully endorse the TRP developed in the present study, to retain 40% of spawning stock biomass for *M. monoceros*. Spawning biomass and spawning potential are suggested as fishery management reference points by Garcia (1983) and Gulland and Rothschild (1984). Reproductive criteria were taken as management reference points for eleven Indo-Pacific coral reef fish populations in Palau (Prince *et al*., 2015). In *Penaeus merguiensis* management in Indonesia, spawning potential was used as a fisheries management criterion (Tirtadanu, 2018).

Spawning stock and recruitment relations in penaeid shrimps are much debated topics since the juvenile and larval survival depends on many factors. The studies taken up on the debate "Is recruitment related to spawning stock in penaeid shrimp fisheries?" by Ye (2000) categorically emphasised that sufficient spawning stock abundance is invariably essential for high yield and high recruitment in penaeid shrimps. For fishery managers working with data on post-recruitment phase of shrimps as a basic information for stock assessment and fishery management suggestions, spawning stock biomass is a very handy tool to make policy interventions to arrest any probable collapse in the fishery of penaeid shrimps.

This study showed that, for the stock assessment of species distributed around the coast and being shared by different states, spatial information provides an additional tool in decision making. It is possible to delineate the metapopulation if any, existing within the stock, which are spatially separated. *M. monoceros*, stocks in the similar latitudes showed similar biological characteristics but they were geographically separated without having continuity in distribution. The population in the south and north, especially on the west coast of India showed noticeable variations in their maximum size and size at maturity. The MSY was not found to be a reasonable reference point in deciding the optimum fishing pressure for sustainable fisheries of the species; a retention of 40% spawning biomass seems to be a better option to sustain the fisheries. With this reference point, the reduction of fishing pressure to 70% of the 2017 effort level along NW coast, 60% of the effort level on the SW coast and 70% of the effort level on the NE coast are suggested as scientific recommendations to ensure the sustainability of *M. monoceros* fishery along these coasts.

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