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Population Status of *Sardinella longiceps* of the Sultanate of Oman: Perspectives of Length-based Approach

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Abstract

Indian Oil Sardine (*Sardinella longiceps*) is a commercially exploited small pelagic resource in the Indo-Pacific region and it contributes majorly to the total fish catch of the Sultanate of Oman (SO). Stock status of the *S. longiceps* from the SO was studied between 1997 and 2009 following a length based approach. The stock status of the *S. longiceps* was evaluated for its sustainable management in the SO. The length (mm) data have been collected in 1997, 2004, 2007 and 2009 for the specimens collected from the Seeb fish market of the SO. Asymptotic lengths ($L\infty$) was 227.95 mm in 1997 and 236.25 mm in 2004; however, in 2007 and 2009 the $L\infty$ (234.15 mm) were similar. The mean growth coefficient ($K = 1.06 \pm 0.11$/year) ranged from 0.94/year to 1.2/year. During the study period (1997–2009), the fishing effort steadily increased ($R^2 = 0.81$, $p < 0.01$). The catch ($R^2 = 0.11$, $p > 0.05$) and catch per unit effort (CPUE) ($R^2 = 0.04$, $p > 0.05$) of the S. longiceps; however, did not varied significantly. The exploitation rates (E) of the *S. longiceps* in 1997, 2004 and 2009 were > 0.5 and the annual catch of those years were higher than the calculated maximum sustainable yield (MSY). The *S. longiceps* stock were mostly overexploitaed except in 2007 (E = 0.46/year, catch = 34,280.50 tonnes, MSY = 36,812.58 tonnes). Results are useful for the stock assessment and management of the *S. longiceps* in the SO and the neighboring countries, which may interest fishery biologists, managers and conservationists.

Keywords Length frequency · Exploitation rate · Maximum sustainable yield · Sustainable management · Mortality

Introduction

Many fisheries across the world lack quality and quantity of the data required for a comprehensive stock assessment of a fish species. That compels the fishery managers to make decisions of stock management in data limited situation (Quinn et al. 2016). Under such circumstances, data-limited stock assessment methodologies are deployed which are in high demand specially in open access fisheries (Wetzel and Punt 2011; Chrysafi and Kuparinen 2016). For many small-scale or nontarget species, it is relatively easier to get valid length measurements of a subset of the fishery catch by using the length-based evaluation methods than to measure the entire catch or to obtain effort data (Harley et al. 2001; Kokkalis et al. 2015; Nadon et al. 2015; Prince et al. 2015). In order to estimate stock status of a fish species, a length-based assessment presumes that recruitment and fishing mortality are predictable or have not changed throughout a time relevant to fishery management and the species' life history (Rudd and Thorson 2018). Obtaining a length-frequency data of a given fish species from the commercial captures is relatively less complicated and often not that expensive; for such reasons length data are frequently used as the principal data type in data-limited fisheries (Hordyk et al. 2015; Mildenberger et al. 2017).

Small pelagic fish are an important part of any pelagic ecosystems and support global fisheries (Cury et al. 2000). Sardines, Anchovies and Herrings are small pelagic fish that are globally important for biomass and commercial interests (Izquierdo-Peña et al. 2020). Sardines bridge the trophic link between plankton and Salmon, Tuna, Sharks and many other large marine species including seabirds

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and mammals (Cury et al. 2011). Sardines account for a significant portion of the global fish catch because their populations are widely distributed in the global oceans (Fréon et al. 2005; Bimbo 2013; Takasuka 2018). In addition to regional diversity, sardine fisheries demonstrated wide changes over the last century with relatively high abundance in some years and scarcity in other years (Ma et al. 2019). According to a 2019 stock assessment study on the Pacific Sardine, the (*Sardinops sagax*) stock is overfished; however, 2020 capture data suggests that the species is not overfished (NOAA Fisheries 2022). For those uncertainties of a stock, a preventive mesure has been put in place in the management of the Pacific Sardine stock which sets 150,000 metric tonnes as a threshold stock level, if the stock level falls below that then the stock would be assumed to be overfished (NOAA Fisheries 2022). The European Pilchard (*Sardina pilchardus*) landings from the Northern stock (Europian Union Atlantic waters) have increased over time reaching 45000 tonnes in 2014 (Silva et al. 2015). Spawning stock biomass of Japanese Sardine population (excluding Russian catches) in Pacific Ocean exceeded the $\text{Biomass}_{\text{limit}}$ (B_{limit}) in 2018, which suggests that the stock biomass would increase unless recruitments are overfished (Furuichi et al. 2018).

The Indian Oil Sardine (*Sardinella longiceps*) is a small pelagic, migatory, plantivorous, clupeid school fish that lives in Indian Ocean (Kripa et al. 2018; Froese and Pauly 2021). It is a cheap source of protein for millions of people and forms a staple, sustenance, and nutritious food for many in the Indian Ocean region (Vivekanandan et al. 2009). *Sardinella longiceps* is a species found only in the tropical waters of the northern and western Indian Ocean, including the Gulf of Aden, Gulf of Oman and eastward to India, including the Andaman Islands (Froese and Pauly 2021; Hamza et al. 2021). In addition to direct human consumption, *S. longiceps* population is widely utilized as aquaculture feed, fish meal, industrial oil and health supplements (Alder et al. 2008). India led in the catch of *S. longiceps* from 1950 to 2014, accounting 66% to 96% (on average 80%) of *S. longiceps* catch (Kripa et al. 2018). In the recent decades due to the variability of the sea surface temperature the abundance of *S. longiceps* has increased in the Bay of Bengal and in the Arabian Sea (Burrows et al. 2014; Vivekanandan et al. 2016).

The coastline of the Sultanate of Oman (SO) is 3165 km long and it spreads over the Arabian Sea, the Sea of Oman and Arabian Gulf of the Indian Ocean (Al-Jufaili et al. 2006; Al-Azri et al. 2012). On the peninsula, fishing is one of the oldest industries and marine fisheries are one of the most important sector of the SO's economy after the crude oil (NCSI 2013; Al-Marshudi and Kotagama 2006; Al-Shehhi et al. 2021). Fish also supply the nutritional need to the people of the SO (Al-Busaidi et al. 2016). Due to overfishing most of the economically important marine fishes are facing the overexploitation effects (Sumaila et al. 2016). Over half (56%) of the SO's large pelagic fish and 68% of its important demersal species are fully to over exploited (World Bank 2015). Small pelagic fish accounted for approximately 34% of artisanal production of the SO, while demersal fish accounted for 32% and the large pelagic fish accounted for approximately 23% and the crustaceans and molluscs for 5%, sharks for 3% and rest for others (Al-Anbouri et al. 2011). The clupeids are the leading group in landings among the small pelagic fishing resources of the SO (Al-Anbouri et al. 2013). Among the clupeids, *S. longiceps* is one of most important fisheries of the SO and the *S. longiceps* fishery is distributed throughout the SO coast (Al-Anbouri et al. 2011; Zaki et al. 2021). *Sardinella longiceps* makes a major contribution to the SO's marine fish landings (Piontkovski et al. 2014). The traditional fishermen of the SO use beach seines, gillnet, and purse seines to catch Sardine (Zaki et al. 2012; Piontkovski et al. 2014) and those gears are generally deployed in shallow waters (depths up to 5 m). In the SO, *S. longiceps* is used as food for locals, in fertilizer industry, food for cattle and a large portion of the catch is exported (Al-Jufaili and Al-Jahwari 2011). The SO has the second highest average production of *S. longiceps* (63,439 tonnes) after India (376,189 tonnes) which occupies the first position (FAO 2016). For the last three decades landing of the Sardines contributed 28% to the total fish landings of the SO (MAFWR 2019).

For such reasons a few work have previously been done on the *S. longiceps* caught from the coast of Oman (Al-Anbouri et al. 2011; Zaki et al. 2013; Jayabalan et al. 2014). Zaki et al. (2013) conducted a study on the age, growth and stock status of the *S. longiceps* off Salalah coast of the SO from October 2007 to September 2009 and the authors concluded that the stock was not overexploited. Al-Anbouri et al. (2011) estimated the exploitation of the *S. longiceps* in the Muscat coast and suggested that the species is not that exploited (E = 0.46); therefore, there is a need to increase the fishing effort to obtain appropriate level of exploitation. Jayabalan et al. (2014) suggested the scope for additional catches of the *S. longiceps* from the Mahout coast of the SO. The most recent data on several aspects of the Sardine fishery are required due to the extensive exploitation of this resource and its significance in terms of total landings. Spatio-temporal variability of the growth parameters is an important factor for the stock assessment of any fish species. A multi year (1997–2009) time-series assessment of the population (parameters including: length frequency distribution, allometry coefficient, recruitment pattern, mortality rate, exploitation rate, and stock assessment (catch per unit effort (CPUE), maximum sustainable yield (MSY), total annual stock, standing stock) of the *S. longiceps* of the SO was conducted using length based model with the aims to understand their population structure and stock status for sustainable management.

Materials and Methods

Length and weight data of the *S. longiceps* were collected in 1997, 2004, 2007 and 2009 from Seeb Fish Market (23°41′17.92"N, 58°10′36.04"E; see Fig. 1) of the Muscat Governorate of the SO. The length and weight of the 1476, 369, 393, and 1399 *S. longiceps* individuals were measured in 1997, 2004, 2007 and 2009, respectively. the length was measured using metric scale in millimeter (mm) and the weight (gms) was measured using a digital weighing machine (providing a maximum measuring capacity of 5 kg and an accuracy of 0.5 g). The total length of individual fish (i.e., from the lower jaw to the tip of the tail (without any stretching)) was considered. Yearly catch-effort data of 1997 to 2009 were

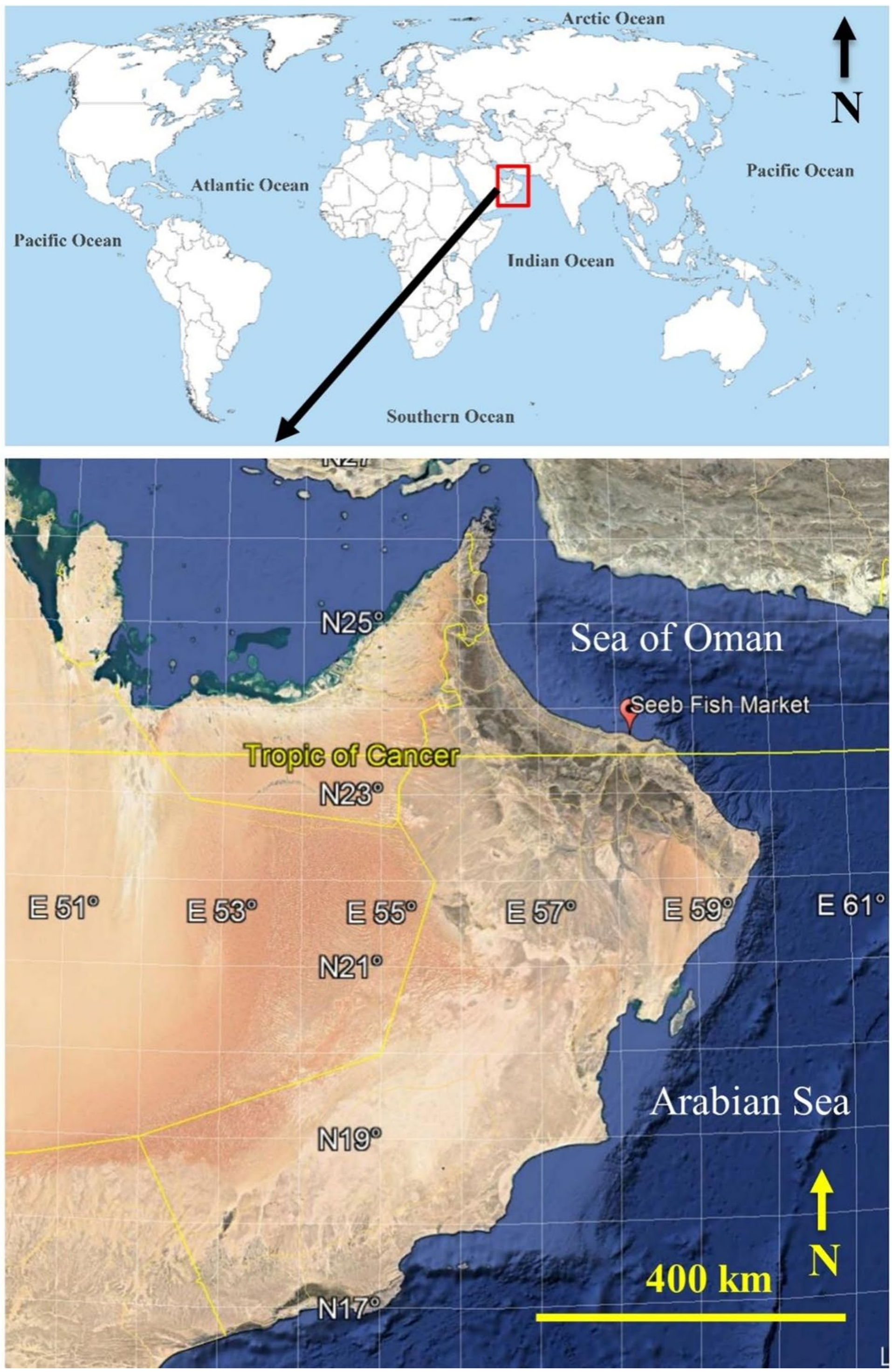

Fig. 1 Study area map and location of Seeb fish market of the Sultanate of Oman

obtained from the Ministry of Agriculture, Fisheries and Water Resources of the SO. Those data were used to calculate CPUE (tonnes/boat) of the *S. longiceps* stock of the SO.

Population parameters (asymptotic length (L∞) and growth coefficient (K)) were estimated using the ELEFAN I (electronic length-frequency analysis) routine of FiSAT (FAO-ICLARM Stock Assessment Tools) II version 1.2.2. For estimating L∞ and K, monthly data of length measurements of 1997, 2004, 2007 and 2009 were grouped into different classes of 10 mm intervals. The length frequency data was fit with the von Beralanffy growth function (VBGF) for estimate the growth parameters (Gayanilo et al. 2005). The equation is:

$$L_t = L_\infty (1 - e^{[-K(t-t_0)]}) \tag{1}$$

where, L∞ is the asymptotic length (mm) (Froese and Binohlan 2000), K (year − 1) is a growth coefficient, that determines the rate at which the asymptotic length (or weight) is approached and t_0 is the theoretical age at which fish would have had zero length if they had always grown according to the above equation (Pauly 1987).

The growth performance index (φ′) (Pauly and Munro 1984) was estimated using Eq. 2:

$$\varphi' = \log K + 2 \log L\infty \tag{2}$$

where, K and L∞ were the same as in Eq. 1.

Lifespan or longevity (tmax) was obtained from the following equation (Pauly 1983):

$$t_{max} = t_0 + 3/K \tag{3}$$

where, t_{max} is the approximate maximum age the fish of a given population would reach.

Total mortality (*Z*) could be estimated using parameters of the VBGF as follows (Pauly 1983):

$$Z = K * \frac{L\infty - \overline{\overline{L}}}{\overline{L} - L'} \tag{4}$$

where, K and L∞ were the same as in Eq. 1, $\overline{L}$ is the mean length of the fish population and L′ represents the mean length at entry into the fishery.

The natural mortality (*M*) of the *S. longiceps* was calculated using the Pauly's *M*-empirical equation (Pauly 1980) as follows:

$$Log_{10}M = .0066 - 0.279Log_{10}L\infty + 0.6543Log_{10}K + 0.4634Log_{10}T \tag{5}$$

where, K and L∞ were the same as in Eq. 1 and the mean habitat temperature (*T*) is considered as 28.1 °C.

The fishing mortality rate *(F)* was calculated as

$$F = Z - M \tag{6}$$

where, Z is the total mortality and the M is the natural mortality.

The rate of exploitation *(E)* was calculated using the the formula given by the Beverton and Holt (1957); Ricker (1975), the quotient between fishing mortality (F) and total mortality (Z):

$$E = F/Z \tag{7}$$

Optimum length (L_{opt}), the length at 50% maturity or the length at which the total biomass of a year-class reaches a maximum value in an unfished population can be calculated using Beverton (1992).

$$L_{opt} = L\infty(3/3 + M/K) \tag{8}$$

where, K and L∞ were the same as in Eq. 1 and M is same as Eq. 6.

The length of the *S. longiceps* depending on age was estimated from the von Bertalanffy growth equation:

$$L_t = L_\infty (1 - e^{-K(t-t_0)}) \tag{9}$$

where, L_t = Length at age *t*, K and L_∞ were the same as in Eq. 1, t_0 = Age at length zero and t_0 was calculated from the following expression:

$$Log(-t_0) = 0.392 - 0.275Log(L_\infty) - 1.038K \tag{10}$$

Again, the weight of Indian Oil Sardine depending on age was estimated from the von Bertalanffy growth equation:

$$W_t = W_\infty (1 - e^{(-K(t-t_0)})^3 \tag{11}$$

where, W_t = Weight at age *t*, K and L∞ were the same as in Eq. 1, and t_0 = Age at weight zero.

The recruitment pattern was calculated by the backward projection of the length-frequency data, using the von Bertalanffy growth equation and the estimated growth parameters (L_∞ and K) (Pauly 1982).

Probability of survival (*P*) in different mortality condition (fishing mortality and natural mortality) at different age was calculated from

$$P(survive\ to\ age\ t) = exp\ (-Mt) \tag{12}$$

for without fishing i.e. natural mortality and

$$P(survive\ to\ age\ t) = exp\ (-Ft) \tag{13}$$

for with fishing i.e. fishing mortality, where, *M* = natural mortality rate, and *F* = fishing mortality rate.

The relative yield-per-recruit and biomass-per-recruit were estimated based on the Beverton and Holt model. Relative yield-per-recruit (*Y'/R*) was computed from:

$$Y'/R = EU^{M/K}\left\{1 - 3U/(1+m) + 3U^2/(1+2m) - U^3/(1+3m)\right\}, \tag{14}$$

where, $U = 1 - (L_c/L_\infty)$ and L_c is the mean length of fish at first capture. In standard case L_c is taken as L_{50},

$$m = (1 - E)/(M/K) = (K/Z) \quad (15)$$

Relative biomass-per-recruit (B'/R) was estimated from the following equation:

$$B'/R = (Y'/R)/F \quad (16)$$

where, (Y'/R) is the relative yield-per-recruit and F is the fishing mortality.

The total annual stock size, average standing stock size and MSY of the *S. longiceps* were estimated. In that regard, the initial exploitation rate (U) was estimated using the following equation (Beverton and Holt 1957; Ricker 1975):

$$U = F/Z(1 - e^2) \quad (17)$$

The total annual stock is calculated as.

$$\text{Total anuual stock} = \text{Y/U} \quad (18)$$

where, Y is the annual yield and U is same as Eq. 14.

and standing stock was calculated as.

$$\text{standing stock} = \text{Y/F} \quad (19)$$

where, Y is same as Eq. 18 and F is the fishing mortality.

Finally, the approximate MSY was calculated using the following relationship, proposed by Gulland (1979),

$$MSY = Z_t * 0.5 * B_t \quad (20)$$

where, Z_t is the instantaneous total mortality in the year t and B_t is the standing stock size in the year t.

Statistical Analysis

Central tendencies and variance of the length and the population parameters (e.g., growth coefficient, mortalities) were calculated. Regression analysis of year wise (from 1997 to 2009) catch-effort and the CPUE data were conducted. T-test was conducted for assessing inter-annual differences of mortality. All the analysis were conducted using CRAN R (version 4.2.1) (R Core Team 2022). Alpha (α) was set at 95% significance level.

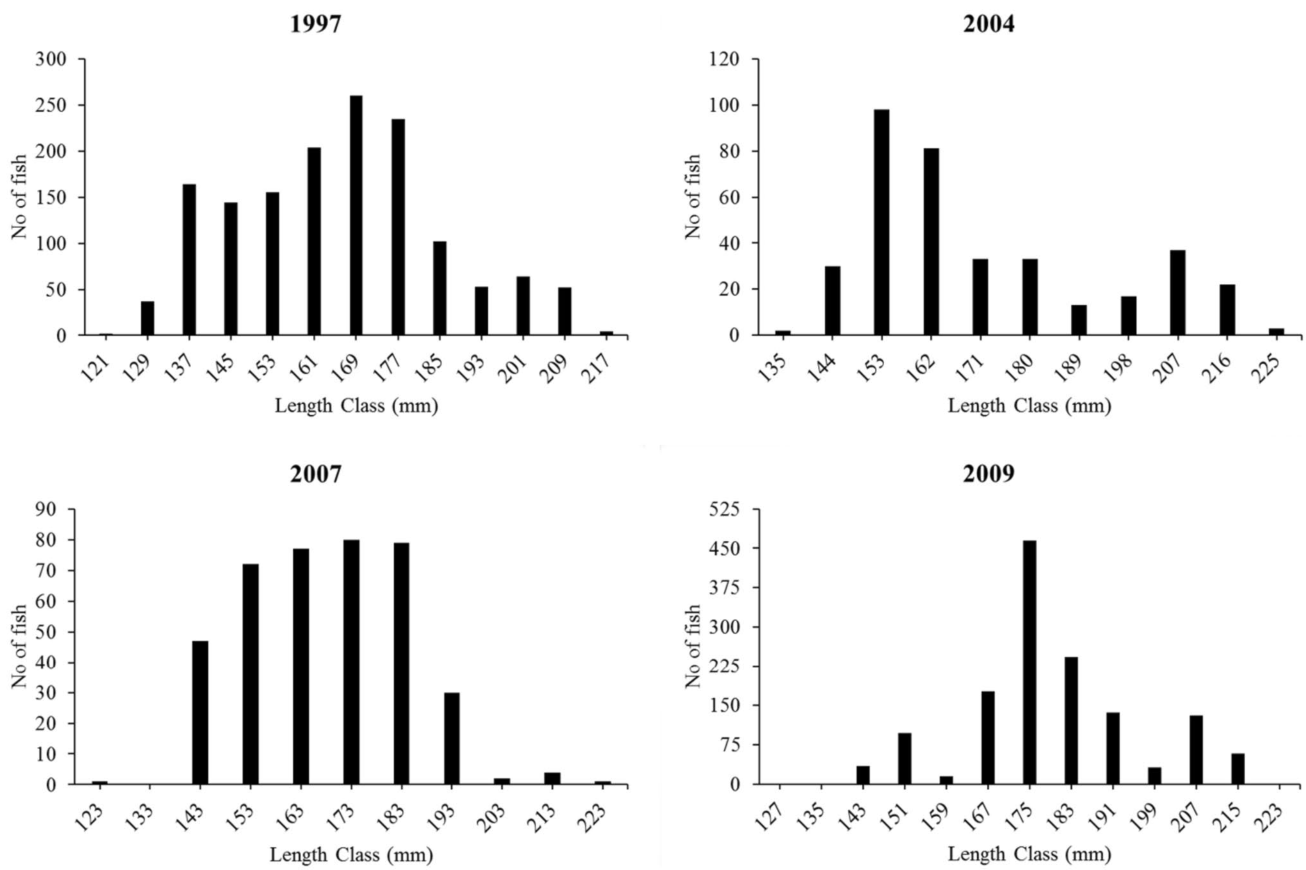

Fig. 2 Length frequency of the Indian Oil Sardine (*Sardinella longiceps*) in 1997, 2004, 2007 and 2009 sampled from the Seeb fish market of the Sultanate of Oman

Table 1 Population growth parameters of the Indian Oil Sardine (*Sardinella longiceps*) caught from the coast of the Sultanate of Oman between 1997 and 2009

Year	L_∞ (mm)	K (/year)	Z (/year)	M (/year)	F (/year)	E (/year)	t_0	t_{max} (year)	Age at Maturity (year)	φ′	L_{opt} (mm)
1997	227.95	1.10	4.69	1.08	3.61	0.77	-0.08	2.64	0.88	2.757	171.74
2004	236.25	1.20	4.50	1.13	3.37	0.75	-0.07	2.43	0.85	2.826	179.81
2007	234.15	1.00	1.89	1.01	0.88	0.47	-0.09	2.91	0.94	2.739	175.17
2009	234.15	0.94	6.30	0.97	5.33	0.85	-0.10	3.10	0.97	2.712	174.22

L∞ assymptotic length, *K* growth coefficient, *Z* total mortality, *M* natural mortality, *F* fishing Mortality, *E* exploitation rate, *tmax* life span, *φ′* growth performance index, *Lopt* optimum length

Results

Length Frequency Distribution

Sardinella longiceps length ranged from 121 to 220 mm (Fig. 2). The mean length was 161.99 ± 19.66 mm, 167.07 ± 21.91 mm, 163.42 ± 15.72 mm and 175.61 ± 16.34 mm in 1997, 2004, 2007 and 2009, respectively. In 1997, 2004 and 2009, the dominant length classes were 169 mm, 153 mm and 175 mm, respectively (Fig. 2). In 2007, from 153 to 183 mm length classes were abundant (Fig. 2).

Growth Parameters, Mortalities and Exploitation

The growth parameters of the *S. longiceps* are summerised in Table 1. In 2007 and 2009 the asymptotic lengths (L_∞ = 234.15 mm) were similar. L∞ was 227.95 mm in 1997 and 236.25 mm in 2004. The highest growth coefficient (K = 1.10/year) was reported in 1997 and 2007. The lowest growth coefficient (K = 0.64/year) was recorded in 2004. The growth coefficient (K = 1.06 ± 0.11/year) ranged from 0.94/year to 1.2/year. The mean lifespan of the *S. longiceps* was 2.77 ± 0.29 years and the mean maturity age was 0.91 ± 0.05 years. The total mortality (Z) of the *S. longiceps* varied significantly ($t = 4.762$, $df = 3$, $p < 0.05$) on yearly basis (Table 1). The maximum value of total mortality (Z) was 6.3 $year^{-1}$ recorded in 2009 whereas the minimum value of total mortality (Z = 1.89/year) was recoded in 2007 (Table 1). The natural mortality (M) (1.05 ± 0.07/year) did vary significantly ($t = 29.36$, $df = 3$, $p < 0.001$) during the study period. Fishing mortality was 3.61/year, 3.37/year, 0.88/year and 5.33/year in 1997, 2004, 2007 and 2009, respectively (Table 1). During the study period, the mean exploitation rate (E) was 0.71 ± 0.17/year. The exploitation rates were 0.77, 0.75, 0.47 and 0.85/year in 1997, 2004, 2007 and 2009, respectively. The mean growth performance index (φ′) was 2.76 ± 0.05 and the mean optimum length was 175.2 ± 3.37 mm.

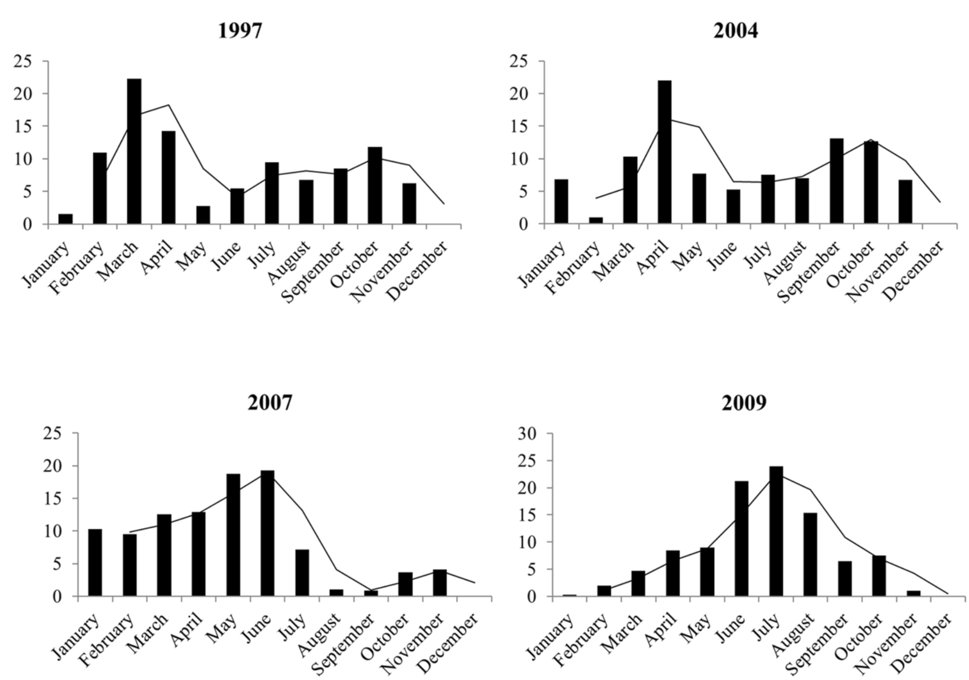

Fig. 3 Recruitment patterns of the Indian Oil Sardine (*Sardinella longiceps*) in 1997, 2004, 2007 and 2009 in the coast of the Sultanate of Oman

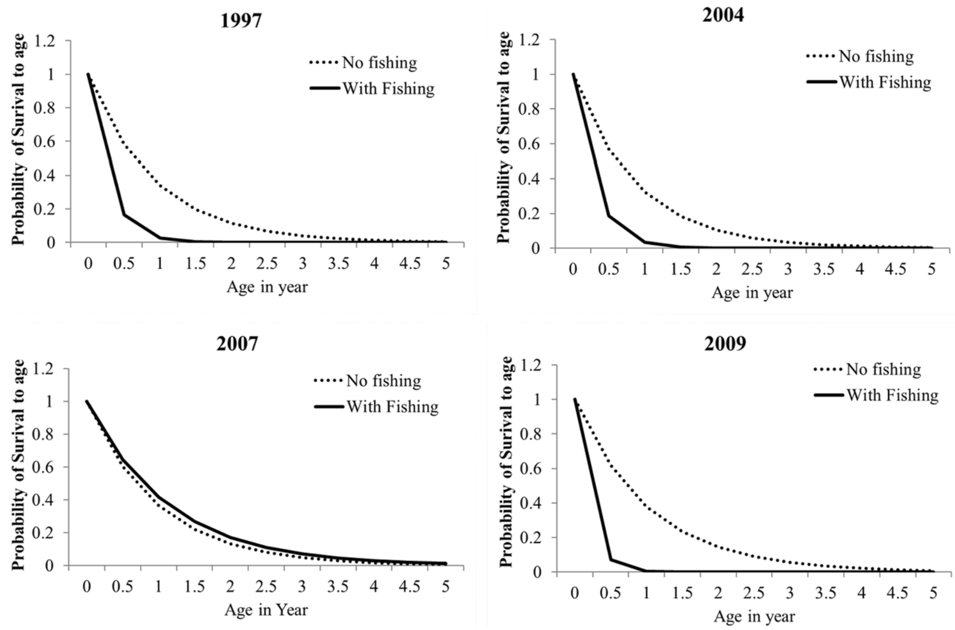

Fig. 4 Probability of survival to age with fishing and without fishing condition of the Indian Oil Sardine (*Sardinella longiceps*) in 1997, 2004, 2007 and 2009 in the coast of the Sultanate of Oman

Recruitment Patterns and Survival Probability

Recruitment of the *S. longiceps* peaked (Fig. 3) between May and July in both 2007 and 2009. In 1997 and 2004, recruitment peaked between March and April (Fig. 3). In 1997 and 2004, two distinct recruitment peaks were observed a major peak between March and April followed by a minor peak which was seen between September and October (Fig. 3). Age dependent natural and fishing mortalities of the *S. longiceps* are described in Fig. 4. In 1997, 2004 and 2009 the *S. longiceps* population died (at the age of 1 to 2 years) earlier than their natural life span (2.77 ± 0.29) due to fising; however, in 2007 the *S. longiceps* lived through its natural life span (Fig. 4).

Relative Yield and Relative Biomass per Recruit

The relative yield per recruit (*Y/R*) and the relative biomass per recruit (*B/R*) of the *S. longiceps* with respect to exploitation rate (*E*) are summerised in Fig. 5. In 1997 and 2004, the exploitation rates were 0.77 and 0.75, respectively and the corresponding *Y/R* values were 0.092 and 0.095, respectively whereas the corresponding *B/R* values were 0.025 and 0.028, respectively (Fig. 5). In 2007 and 2009, the exploitation rates were 0.47 and 0.85, respectively and the corresponding *Y/R* values were similar (i.e., 0.081) and the corresponding *B/R* values were 0.092 and 0.015, respectively (Fig. 5).

Catch Structure and Stock Status

During the study period (1997–2009), the fishing effort steadily increased ($R^2 = 0.81$, $p < 0.01$) but neither the catch of the *S. longiceps* ($R^2 = 0.11$, $p > 0.05$) nor the CPUE ($R^2 = 0.04$, $p > 0.05$) varied significantly (Figs. 6, 7). *Sardinella longiceps* catch peaked in 2001 (Fig. 6). The annual catch of the *S. longiceps* ranged from 16765.2 tonnes to 58959 tonnes (Fig. 6). Annual catch (tonnes), total annual stock (tonnes), standing stock (tonnes) and the maximum sustainable yeild (tonnes) are summerised in Table 2. The anuual catch of 1997, 2004 and 2009 were higher than the MSY of those years (Table 2) but the annual catch of 2007 was lower than the MSY of 2007.

Discussion

In the present study the average length class of the *S. longiceps* was 160–170 mm. Jayabalan et al. (2014) while working on the *S. longiceps* of the SO found 191–200 mm length class had the highest frequency among all other length classes. Zaki et al. (2013) showed that the smaller individuals (111-150 mm) of the *S. longiceps* contributed 5.3% of the total catch and individuals that ranged 171–210 mm contributed 72.1% of the landings of the *S. longiceps* in the SO. The mean length class of the *S. longiceps*; therefore, was 160–200 mm in the SO (Zaki et al. 2013). Results showed that the $L\infty$ was 233.125 ± 3.59 mm. Studies of Zaki et al. (2013) and Jayabalan et al. (2014) suggested $L\infty$ to be 230.2 mm and 230 mm, respectively. Zaki et al. (2013) and Jayabalan et al. (2014), however, found higher K values (i.e., 1.57/year and 1.33/year, respectively) than the present study (K = 1.06 ± 0.11/year). A Low K value possibly indicate that the fish has a lengthy life span whereas a high K value indicate that the species has a shorter life span (Pauly 1980). According to Al-Anbouri et al. (2011) the *S.*

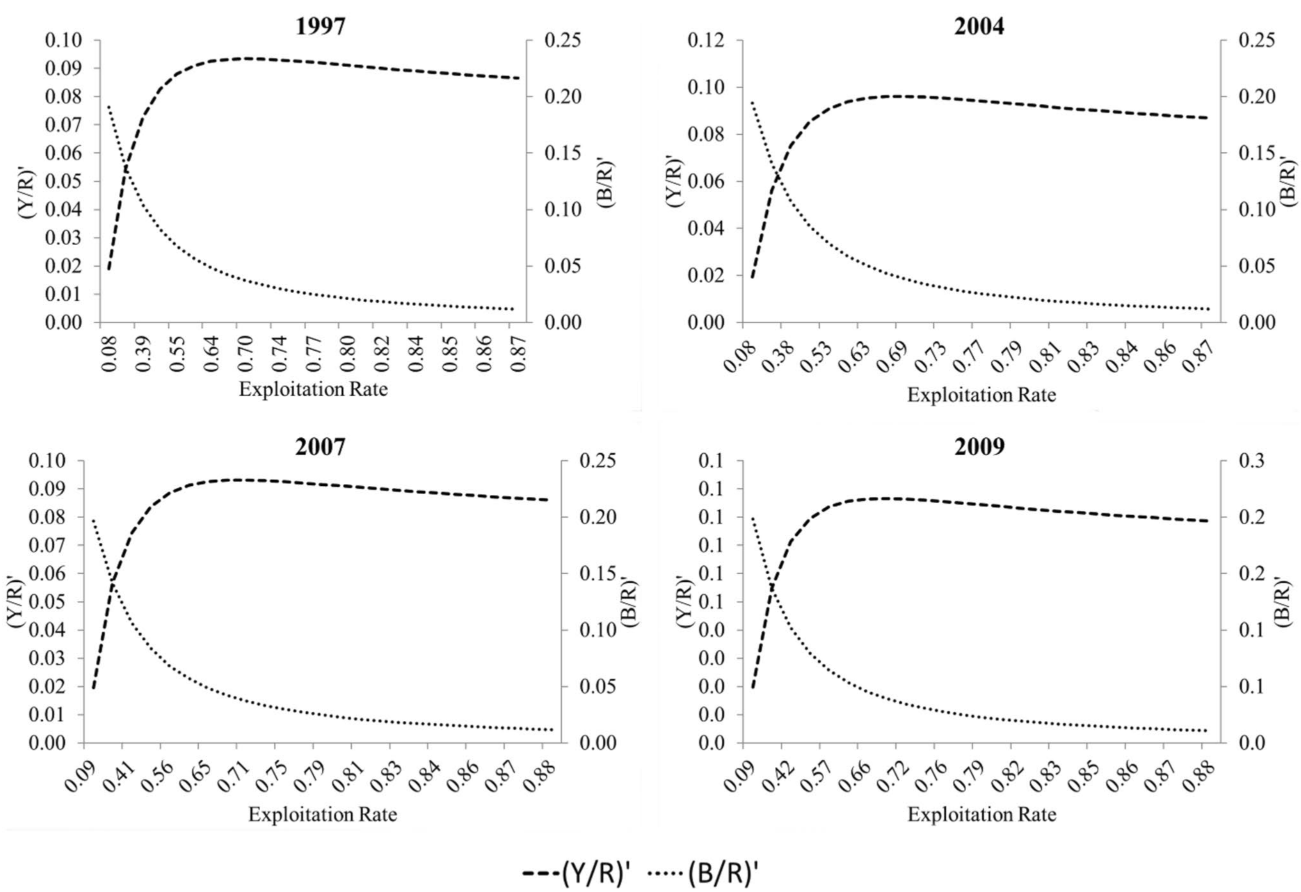

Fig. 5 Biomass/Recruitment (B/R) and Yield/Recruitment (Y/R) in different exploitation rates of the Indian Oil Sardine (*Sardinella longiceps*) in 1997, 2004, 2007 and 2009 in the coast of the Sultanate of Oman

longiceps off Oman Sea had L∞ of 220.3 mm, K of 1.209/year and t_0 of -0.010, respectively. Nadeem et al. (2017) calculated L∞ = 252 mm, K = 1.4/year and t0 = -0.929 for *S. longiceps* from Pakisthani waters. The long-term stability of life history parameters (L∞ and K) as stock structure indicators has been called into question because it has been

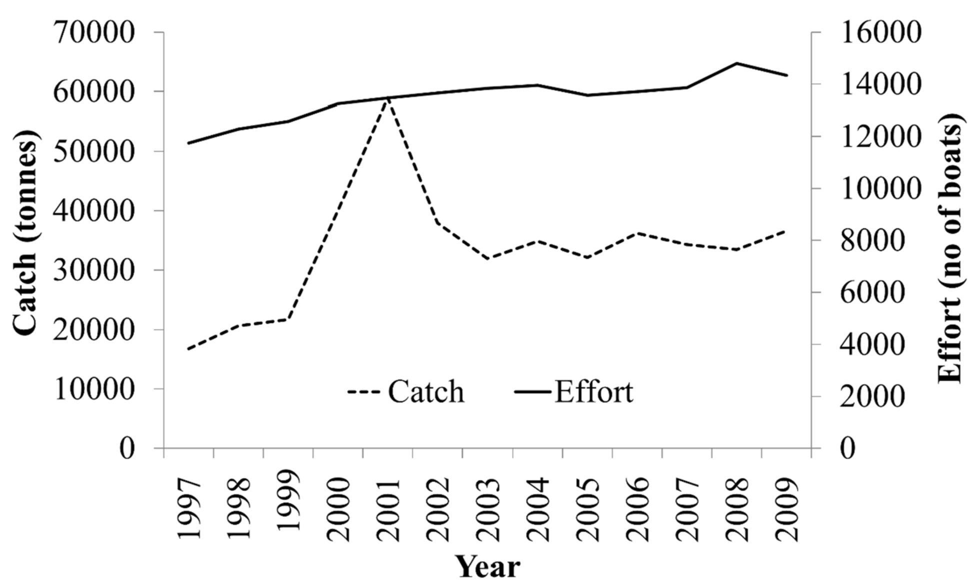

Fig. 6 Catch and effort of the Indian Oil Sardine (*Sardinella longiceps*) between 1997 and 2009 in the coast of the Sultanate of Oman

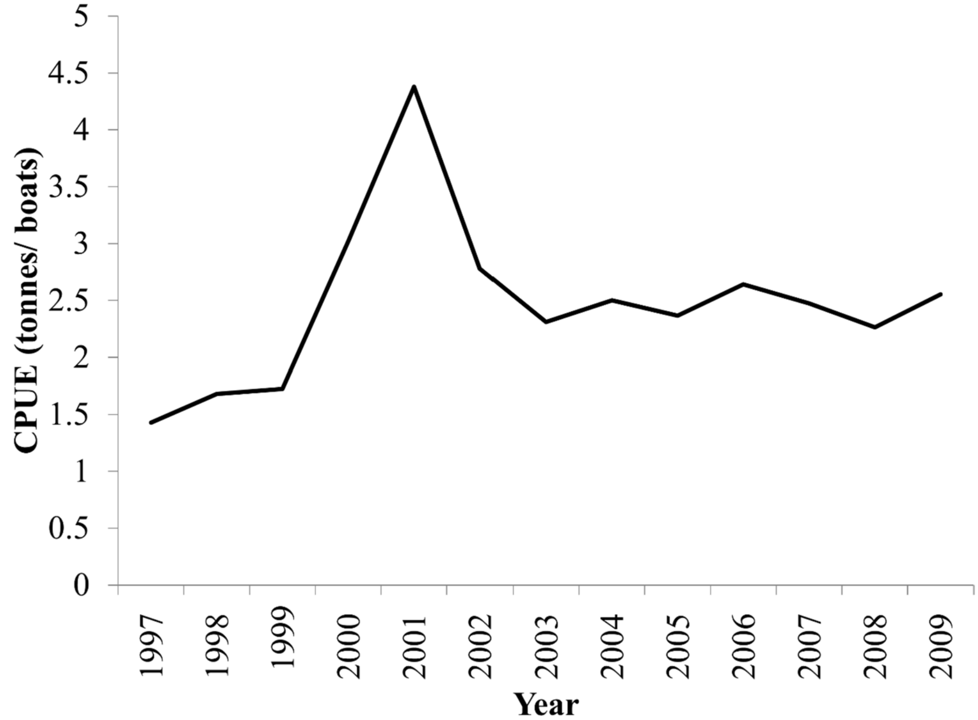

Fig. 7 Catch per unit effort (CPUE) of the Indian Oil Sardine (*Sardinella longiceps*) between 1997 and 2009 from the coast of the Sultanate of Oman

discovered that they fluctuate both temporally and geographically between stocks (Correa et al. 2021).

The growth overfishing was observed in the *S. longiceps* populations in 1997, 2004 and 2009 as the fish died before their life span due to fishing; however, in 1997 the growth overfishing was not observed. Small and pelagic fish such as an Oil Sardine typically die due to fishing or gets predated in old age (Emmett et al. 2005). Fish of 132 mm size class have the highest survival rates due to their small size because they are not caught in the fishing nets; however, they are vulnerable to natural mortality (especially from predators). The 170–180 mm size class, have the highest fishing mortality because of their larger size and commercial value (Shah et al. 2019).

In fisheries there are two types of mortalities, natural mortalities and fishing related mortalities. Natural mortalities are due to predation, disease, aging and such are

Table 2 Annual catch, Total annual stock, Standing stock and the Maximum Sustainable Yield of the Indian Oil Sardine (*Sardinella longiceps*) fishery of the Sultanate of Oman between 1997 and 2009

Year	Annual catch (tonnes)	Total annual stock (tonnes)	Standing stock (tonnes)	Maximum Sustainable Yeild (tonnes)
1997	16765.20	21982.78	4644.10	10890.41
2004	34864.50	47077.96	10345.55	23277.49
2007	34280.50	86727.20	38955.11	36812.58
2009	36601.76	43342.46	6867.12	21631.43

the primary reasons of mortality for many fish populations (Bax 1998). On the other hand, predation is thought to be far less important than fishing mortality (Sissenwine and Daan 1991). If the relative magnitudes of those two processes are compared then it would be clear which process is more significant for a specific species and how two processes work together to regulate fish populations (Whipple et al. 2000). In the current study, the fishing mortality is higher than the natural mortality of *S. longiceps* in 1997, 2004 and 2009; however, the natural mortality is higher than the fishing mortality in 2007. Jayabalan et al. (2014) found that the natural mortality of the *S. longiceps* of Mahout, the SO to be 2.21/year and the estimated F was 1.451/year. Al-Anbouri et al. (2011) also found natural mortality of the *S. longiceps* was higher than the fishing mortality. Nadeem et al. (2017) while working with the *S. longiceps* population of Pakistani waters considered an average sea surface temperature of 26 °C and found that the natural mortality was 2.255/year while the fishing mortality was 2.560/year and the explotation rate (E) was 0.534/year. If the value of the E was more than 0.50, one may conclude that the fish population is overfished in a particular area over some specific period (Gulland 1971). In the present study, the *S. longiceps* was overexploited in 1997, 2004 and 2009 because the $E > 0.50$ but in 2007 the *S. longiceps* was not overexploited (i.e., $E < 0.50$). *Sardinella longiceps* landings dropped sharply from 58,960 tonnes in 2001 to 32,092 tonnes in 2005 in the SO (Fig. 6). That decline may be a result of the intense fishing pressure at the time (Al-Anbouri et al. 2011).

Pauly (1982) suggested that the recruitment oscillates seasonally even for tropical fish and one or two peaks in each year is common. Two peaks of recruitment of the *S. longiceps* was observed by Nair et al. (2016) in southwest coast of India, a major peak was observed between July and August and a minor peak was seen between February and March. Two peaks of recruitment were also observed in the Ssouthern Indian coast in 2011, firstly in February followed by the other in July (Kripa et al. 2018). Kripa et al. (2018) further suggested that the recruitment might be related to the environmental conditions or fishing but the higher availability of food in those two months and the moderate sea surface temperatures of the Indian Ocean possibly responsible for the observed recruitment peaks.

According to the results, the relative yield of the *S. longiceps* increased with the increasing rate of exploitation up to a certain limit, that possibly suggest MSY of the *S. longiceps*. The anuual catch was higher than the MSY of the *S. longiceps*, which indicates the *S. longiceps* in the SO is overfished. The Indian Oil Sardine landing of the SO fluctuated between 1997 and 2009 with a high peak in 2001 (Fig. 6). After 2001 the total landing drastically dropped due to overfishing. Zaki et al. (2013) reported that the annual catch in the Salalah, the SO varied between 6774 tonnes (in 2000) and 1775 tonnes (in 2002). Using the Catch Effort Data Analysis (CEDA) package, Baset et al. (2017) estimated the MSY of the *S. longiceps* ranged from 26000 to 31000 tonnes and by using A Stock-Production Model Incorporating Covariates (ASPIC) the estimated MSY ranged 29000—31 000 tonnes. Those results suggested that the *S. longiceps* stock is in a safe condition in the Pakistani water.

The study of the Sardines has been characterized by extensive international collaborations due to its widespread range, economic and ecological significance and biological similarities (Peck et al. 2021). Under the Coastal Pelagic Species Fishery Management Plan, the Pacific Fishery Management Council has been in charge of managing the commercial Sardine fishery off the coasts of the United States from the year 2000 (Kripa et al. 2019). Due to the El Nino's catastrophic effects on the Sardine fishery and the extremely low fishing quota for the previous three years the Sardine fishery was shut down in the United States in 2016 (Kripa et al. 2019). There are complementary patterns of global environmental factors that control the decadal variability of sardine populations all over the world for example sardine production is often boosted by La-Nina that comes from the eastern tropical Pacific (Hamza et al. 2022). A single sardine population cannot be classified either as the Mediterranean or the Atlantic because the majority of the available evidences points to a single evolutionary unit for the Sardines (Imsiridou et al. 2021). Thus, a transboundary management of the Sardine stocks is recommended. There are, however, lack of knowledge of the population structure and insufficient catch statistics of the Japanese Sardines in the Japan Sea, East China Sea, and Yellow Sea (Sarr et al. 2021) so is the condition of the Indian Oil Sardines. Along the coasts of the Arabian Sea, the Indian Oil Sardine population experiences significant production fluctuations with distinct periods of high abundances as well as declines (Hamza et al. 2021). Between 2012 and 2020, the SO experienced a sharp increase in the landing of the small pelagic fish species primarily that of Indian Oil Sardines (Al-Jufaili 2021). Recently, seasonal variations in the size class of the Indian Oil Sardines has increased in the SO which may be a result of an increase in the sea surface temperature, a decline in the wind speed, a rise in the frequency of mesoscale eddies and a decrease in the concentration of diatoms which is a dietary component of the Indian Oil Sardines (Al-Jufaili and Piontkovski 2020). Construction of the population dynamics model could be a useful technique to address the effects of climate change on the biological productivity and growth of the Indian Oil Sardines (Hamza et al. 2022). There is currently no such effective management strategy of the *S. longiceps* in the SO because no effective licensing system is in place to restrict the entry of fishery vessels into the coastal fishing zone, owing to diverse cultural, social and political factors. That demands for sustainable fishing in future, which may take place by restricting the number of licenses for the use of equipment, imposing restricted entry or enforcing limits on temporary and spatial fishing in order to preserve this significant commercial fishing industry of the SO. Such responsible/sustainable fishing, however, can not be implemented unilaterally by the SO, therefore, a trans-boundary management of the Sardine fishery among the countries bordering the Sea of Oman, Arabian Sea is recommended.

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Declarations

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