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Research Article
Taxonomic Composition and Seasonal Changes of Fish Larvae Assemblages in Coastal Waters of Muscat, Sea of Oman (2013-2015)

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Abstract

Background: The fish larval abundance and their species composition both could serve as sensible indicators for predicting catches of mature specimens. In the Sea of Oman, seasonal changes of physical, chemical and biological characteristics of the upper mixed layer are mediated by monsoonal winds. However, available data do not allow one to elucidate statistically reliable seasonal changes of fish larvae communities. **Materials and Methods:** A plankton net (60 cm in diameter, equipped with mesh size 400 µm) was used to collect samples. A binocular microscope (model SZ-X7) was used to identify, enumerate and measure fish larvae. **Results:** A total of 1049 fish larvae specimens were collected and their morphometric characteristics identified for the monthly sampling carried out in 2013-2015. Fish larvae were represented by 39 families, 50 genera and 55 species. The top ten most abundant families were Clupeidae, Pomacentridae, Sparidae, Carangidae, Blenniidae, Scombridae, Mullidae, Gerreidae, Chanidae and Sphyraenidae. **Conclusion:** Seasonal changes of the total fish larvae abundance revealed two peaks corresponding to the time of North-East monsoon and spring inter-monsoon (SIM). The Shannon diversity index was highest during SIM (1.62±0.3). For this season, the total abundance of development stages was 59 ind/100 m^3 for the yolk-sac stage, 556 ind/100 m^3 for pre-flexion, 175 ind/100 m^3 for flexion and 117 ind/100 m^3 for the post-flexion stage. The *Sardinella* spp., fish larvae were the most abundant throughout the year. Seasonal changes of these larvae were consistent with artisanal sardine landings in the region. Consequently, data on fish larvae abundance could be treated as a sensible indicator for predicting seasonal catches of sardines in the region.

Key words: *Sardinella* spp., Arabian sea, fish larvae, fish landings, Gulf of Oman

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The fish larval abundance and their species composition are important characteristics of ichthyoplankton surveys. Both could serve as sensible indicators for predicting catches of mature specimens[1]. On the other hand, fish larvae abundance and diversity exhibit thigh spatial-temporal variations in tropical and temperate waters[2,3]. One of the reasons is that pelagic fish communities populate highly dynamic habitats. These refer to reef associated, inshore, neritic, oceanic and shallow water types of communities[4]. An attractive theoretical point in studies of fish larvae is the role they play in connecting distant populations through the process of larval drift, with currents. This enables the population to be receded in a distant location, sometimes a hundred miles away[5].

In Omani coastal waters, initial studies on fish larvae abundance and taxonomy were conductedin the 1980s. Those were available mainly in the form of internal reports of the Ministry of Fisheries (Oman). Later on, the analysis of diversity and abundance of fish larvae was carried out for the South-Western part of the Sea of Oman[6]. Also, some data on the same characteristics were collected in the neighboring waters of the Arabian Gulf and the Western Arabian sea[7,8]. However, these sampling campaigns were short-term, so they didn't elucidate statistically reliable seasonal changes of fish larvae communities.

In the Sea of Oman, seasonal changes of physical, chemical and biological characteristics of the upper mixed layer (in which our sampling was carried out) are mediated by monsoonal winds[9-11]. The North-East monsoon is felt particularly in the Northern part of the Arabian sea where large heat losses from the ocean cause convective overturn and result in the formation of a deep mixed layer.

The spring inter-monsoon period (from April through June) takes place when the northeasterly winds have weakened after the winter monsoon, leading to low wind velocities (~0.25 m sec^{-1}) and calm waters. During the South-West monsoon (from June or July, through September), warm, moist air prevails over the region, which results in the development of a strong South-Western wind across the Arabian sea, with persistently high speeds[12] of ~10 m sec^{-1}. This strong forcing accelerates the surface currents. The South-West monsoon is followed by the fall inter-monsoon period (from October through December) in which the wind speed decreases significantly. Solar heating and weak winds result in a shallow mixed layer and nutrient depletion, hence relatively low primary productivity.

This study provides insights into the seasonal change of the abundance and taxonomic composition of fish larvae assemblages, in particular their development stages, averaged over a 3 years period (2013-2015).

MATERIALS AND METHODS

Field surveys were carried out in the coastal waters of Muscat, at 23°35' 04.6"N, 58°36' 29.8"E (Fig. 1). The sampling site was located in a region with 30 m depth, populated by different types of corals at the bottom. Monthly hydrographic measurements and net sampling were carried out from January, 2013 to December, 2015. Temperature and chlorophyll-a, were measured with an Idronaut-Ocean Seven 316 CTD probe fitted with an additional sensor for chlorophyll-a fluorescence.

A plankton net (60 cm in diameter, equipped with mesh size 400 µm) was used to collect fish larvae. Ten minutes hauls were conducted at the surface, at a speed of about 2 knots. The volume of sea water filtered during each tow was estimated by the "Hydrobios" flowmeter attached to the mouth of the net[13]. Collected samples were preserved with 10% buffered formaldehyde. In the laboratory, fish larvae was sorted out from other zooplankton and stored in small vials in 4% buffered formaldehyde. The catch of fish larvae were standardized to number per 100 m^3 of sea water volume filtered.

A binocular microscope (model SZ-X7) was used to identify, enumerate and measure fish larvae. Ichthyoplankton guides were used to identify fish larvae to the lowest taxonomic level and development stages[14-23]. Damaged and unknown fish larvae were included in the analysis as well. The larvae abundance was standardized to the number of fish[13] larvae per 100 m^3. Diversity was assessed by the Shannon biodiversity index[24], calculated to compare this results with that of previous studies.

In analyzing seasonal changes, we grouped all monthly data into four categories (seasons). This approach was based on previous (historical) data on winds and temperature measurements: North-East monsoon (NEM), lasting from January through March, spring inter-monsoon (SIM) from April to June, South-West monsoon (SWM), from July through September and fall inter-monsoon (FIM), from October to December.

The NCEP-NCAR reanalysis database which is a joint product from the National Center for Environmental Prediction (NCEP, USA) and the National Center for Atmospheric Research (NCAR, USA) was used to retrieve data on seasonal changes of wind speed and atmospheric pressure at sea surface. The product represents gridded data on atmospheric and physical parameters worldwide from 1948 to the present time[25]. The

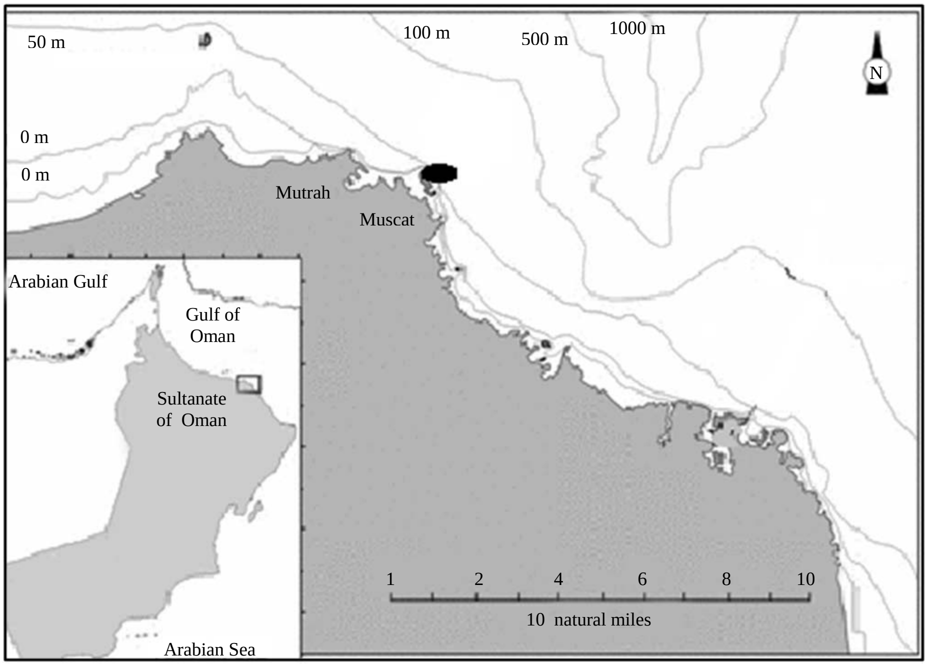

Fig. 1: Map of the Sultanate of Oman and the location of the sampling station

temporal resolution depends upon the parameter. Time series at a temporal resolution of 1 month and grouped them over 4 seasons was used.

Monthly landings data for sardines in the Sea of Oman (Muscat region) were retrieved from the annual reports of the Ministry of Agriculture and Fisheries.

The Principle Component Analysis (PCA) in "Statistica v.9" was employed to elucidate statistical links between 13 physical, chemical and biological parameters. Data were log x+1 transformed. The PCA is the data compression procedure which enables the reduction of variables (used to describe the variability of data) to a few principal components (Factors) reflecting the compression result. A statistical technique of PCA is based on a rotation of the coordinate system of the variables involved in the analysis, in a way where the new coordinate system of these variables is maximally uncorrelated.

Data for the PCA were arranged in the form of averaged seasonal cycles for each variable. The obtained correlation matrix of 13 parameters was Varimax-transformed. Varimax procedure amounts to a variance maximizing rotation of the original variable space. The transformed products were further treated as the measures of similarity between variables implying a similar distribution pattern over seasons. The extraction of eigenvectors of the matrix enables one to reduce the diversity in the system of numerous variables to a few principal components (Factors) in which the component scores are standardized units based on a correlation matrix. In other words, the eigenvectors are the results of the projection of the original variable axes into the space of new principal components. Eigenvectors forming the principal components are based on the similarity coefficients in linear combinations of variables. Once the internal structure of principal components is elucidated and these components are interpreted (labeled) in some way, the relationship between the first two components (most signification terms of load) might be analyzed in the form of a scatter plot. In the space of two components, distances between sites approximate the Euclidean distance of the transformed data.

RESULTS

The seasonality of wind speed implied a strong pattern in its zonal and meridional constituents. Zonal and meridional components of wind speed point out directions on the globe. Zonal means the West-to-East direction, while meridional points to the North-to-South direction.

In the NCEP/NCAR database, data are given in the form of deviations from the mean. Values are positive when the wind blows from West-to-East: West wind has a positive zonal component and the East wind is featured by a negative zonal component. The meridional wind is positive if it comes from the South and negative if it comes from the North. Zonal and meridional wind speed anomalies–both were positive during NEM only (Fig. 2).

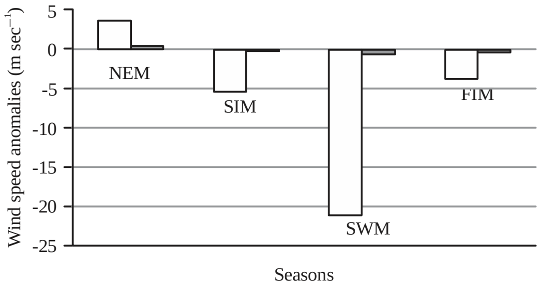

Fig. 2: Seasonal changes of the zonal and meridional components of the wind speed anomalies (m sec^{-1} at 10 m). NEM: North-East Monsoon, SIM: Spring inter-monsoon, SWM: South-West monsoon, FIM: Fall inter-monsoon season

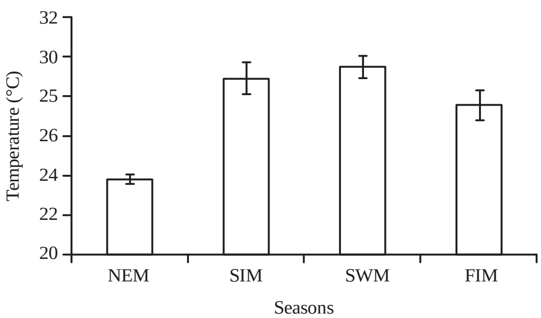

Fig. 3: Averaged seasonal sea surface temperature (2013-2015)

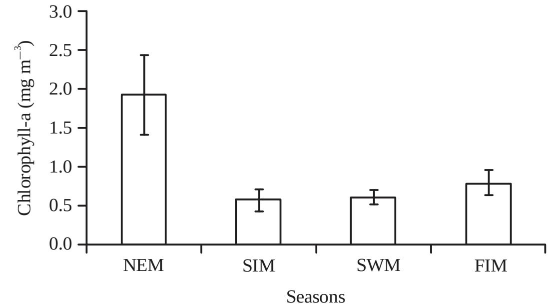

Fig. 4: Averaged seasonal concentration of the chlorophyll-a (2013-2015)

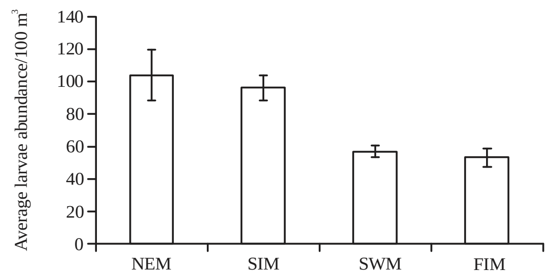

Fig. 5: Averaged seasonal concentration of the fish larvae abundance (2013-2015)

Changes in sea surface temperature showed a typical regional trend reflecting the seasonal cooling, followed by a subsequent warming of the upper mixed layer. The lowest temperature was recorded during NEM where it ranged between 20 and 23.8°C, whereas the maximum value of 29.4°C was observed during SWM (Fig. 3). A non-parametric (Spearman rank order) correlation analysis implied a statistical concordance in seasonal changes of the sea surface temperature and the total fish larvae abundance (r = -0.4, at $p<0.05$).

Chlorophyll-a concentrations showed seasonal changes with the maximal value (1.9 mg m^{-3}) observed in NEM, whereas the lowest (0.3 mg m^{-3}) was associated with the time of SIM. Overall, throughout the 3 years sampling period, seasonal variations remained in the 0.5-2.5 mg m^{-3} interval (Fig. 4). Moreover, chlorophyll-a concentrations were seasonally correlated with sea surface temperature changes (Spearman rank correlation r = -0.8, at $p<0.05$).

Zooplankton organisms (in particular copepod development stages) are believed to be a food source for many fish larvae. In this regard, we compared seasonal dynamics of zooplankton biomass (which was the only parameter available) with seasonal changes of the total fish larvae abundance, which showed no consistency. However, statistically significant correlation was found between zooplankton biomass and the abundance of *Sardinella* spp., larvae (r = 0.8, at $p<0.05$).

A total of 1049 fish larvae specimens were identified based on their morphology and morphometric characteristics during the study. The taxonomic composition was represented by 39 families, 50 genera and 55 species (Table 1). Five families (Clupeidae, Pomacentridae, Mullidae, Scombridae and Sparidae) had concentrations exceeding 50 ind/100 m^3 and accounting for 57% of the total abundance. Five other families occurred in low abundances (less than 1% of the total abundance). The highest abundance of fish larvae was observed during NEM (104 ind/100 m^3) and SIM (96 ind/100 m^3), whereas the abundance was twice as much less during SWM and FIM (Fig. 5).

The Shannon diversity index (H') had an annual mean of 1.3±0.53 and showed changes over seasons. The highest value was observed during SIM (1.62±0.30) followed by NEM (1.38±0.47), SWM (1.14±0.65) and FIM (1.06±0.7).

Clupeidae (represented by *Sardinella* spp., *Herklotsichthys* spp., *Hilsakelee* and *Etrumeus* spp.) was the dominant larvae, contributing 22% to the total

Table 1: Taxonomic composition and fish larvae abundance of (2013-2015)

Family	Genus or species	Fish larvae abundance/100 m^3	Total catch (%)
Ambassidae	*Amdassis gymnocephalus*	6.4	0.71
Apogonidae	*Apogon* spp.	18.9	2.08
Blenniidae	*Omobranchus* spp.	20.2	2.23
	*Parablennius*s pp.	21.0	2.31
Bothidae	*Psettina* spp.	2.7	0.30
	Arnoglossus spp.	0.6	0.07
Bregmacerotidae	*Bregmaceros nectabanus*	4.3	0.47
Bythitidae	*Dinematichthys* ssp.	2.2	0.24
Callionymidae	*Callionymus* spp	0.9	0.10
Carangidae	*Carangoides* spp.	30.0	3.31
	Scomberoides lysan	12.8	1.41
	Selar crumenophthalmus	10.4	1.15
	Selaroides leptolepis	2.3	0.25
	Seriola dumerili	0.7	0.08
	Trachurus indicus	3.4	0.37
Chanidae	*Chanos chanos*	23.5	2.59
Clupeidae	*Etrumeus* spp.	20.2	2.23
	Herklotsichthys spp.	5.1	0.56
	Hilsa kelee	1.1	0.12
	Sardinella spp.	168.7	18.59
Damaged		2.6	0.29
Eleotrididae		0.9	0.10
Engraulidae	*Encrasicholina punctifer*	7.3	0.80
Exocoetidae	*Cheilopogon* spp.	1.2	0.13
Gerreidae	*Gerres* spp.	42.7	4.70
Gobiidae		7.9	0.87
Gonorynchidae	*Gonorynchus greyi*	6.8	0.74
Hemiramphidae	*Oxyporhamphus micropterus*	7.3	0.80
Isonidae	*Iso* sp.	5.1	0.56
Leoignathidae		0.7	0.08
Lutjanidae	*Lutjanus* spp.	6.2	0.68
Mugilidae	*Mugil cephalus*	1.6	0.18
	Mugil spp.	10.7	1.18
Mullidae	*Upeneus* spp.	52.0	5.73
Myctophidae	*Benthosema fibulatum*	2.0	0.22
	Benthosema pterotum	4.8	0.53
Nemipteridae	*Pentapodus* spp.	5.6	0.62
Nomeidae	*Cubiceps whiteleggii*	8.8	0.97
Paralepididae	*Lestrolepis intermedia*	4.6	0.51
Pempherididae	*Pempheris* spp.	4.3	0.47
Pomacanthidae	*Pomacanthus* spp.	5.8	0.64
Pomacentridae	*Abudefduf vaigiensis*	77.3	8.52
	Amphiprion spp.	4.6	0.51
	Chromis spp.	4.9	0.54
	Pomacentrus spp.	21.2	2.34
Rachycentridae	*Rachycentron canadum*	0.9	0.10
Scaridae		3.0	0.33
Scombridae	*Auxis rochei*	10.0	1.11
	Euthynnus affinis	2.1	0.23
	Rastrelliger kanagurta	53.1	5.85
	Thunnus albacares	1.0	0.11
	Thunnus obesus	4.3	0.47
Scorpaenidae	Damaged	0.4	0.04
Sillaginidae	*Sillago sihama*	3.0	0.33
Sparidae	*Acanthopagrus latus*	94.2	10.38
Sphyraenidae	*Sphyraena* spp.	29.1	3.21
Synodontidae	*Saurida undosquamis*	10.9	1.20
Terapontidae	*Terapon jarbua*	6.1	0.67
	Terapon theraps	5.8	0.64
Tripterygiidae	*Tripterygiid* spp.	12.2	1.34
Unknown		19.3	2.13

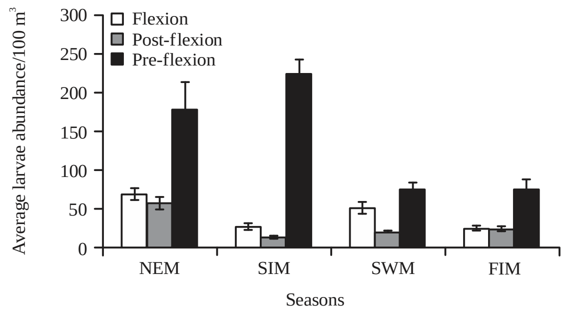

Fig. 6: Averaged seasonal changes of fish larvae abundance based on their development stages (2013-2015)

fish larvae abundance. The maximum density (92 ind/100 m^3) was observed in NEM.

Pomacentridae (represented by *Abudefduf vaigiensis*, *Amphiprion* spp., *Chromis* ssp. and *Pomacentrus* spp.) was the second highest contributing family (with12%). The larval abundance varied between 1 and 20 ind/100 m^3.

Sparidae (represented by one species; *Acanthopagrus latus*) was pertient in terms of its contribution (with 11%) to the total fish larvae abundance. Larvae of this family have been observed throughout the year, with the maximal abundance associated with NEM.

Scombridae family (with five species, namely *Auxis rochei*, *Euthynnus affinis*, *Rastrelliger kanagurta*, *Thunnus albacares* and *Thunnus obesus*) has accounted for 8% of the total fish larvae abundance. The larval abundance varied between 1 and 27 ind/100 m^3. The highest abundance of larvae was observed during SIM.

Mullidae (represented by one species; *Upeneus* spp.), with the abundance of 52 ind/100 m^3 has contributed 6% to the total larvae abundance. The peak was observed during SIM.

In providing more insights into seasonal changes, we also distributed fish larvae abundance accordingly to their life stages (Pre-flexion, flexion and post-flexion). These changes were quite different by their seasonal dynamic. For example, the pre-flexion stage showed the highest abundance during SIM (226 ind/100 m^3), whereas flexion and post-flexion stages showed the highest larval abundance during NEM (with 69 and 58 ind/100 m^3 respectively, Fig. 6).

The analysis of seasonal changes for all groups implied two major patterns pronounced: The fish species spawning over the entire year and those that have a fragmental spawning period (for instance, the Sphyraenidae larvae observed during NEM period only or the Chanidae larvae family observed during SWM only).

We compared our data on seasonal changes of the *Sardinella* spp., larvae abundance (which was the dominant group in Table 1) with data on artisanal landings of sardines (in 2013-2015) available from archives of the Ministry of Agriculture and Fisheries (Oman) for the Muscat region. The correlation between seasonal changes of the *Sardinella* spp., larvae abundance and sardine landings was statistically significant ($r = 0.8$, at $p<0.05$).

Principal component analysis was used to elucidate a statistical association of sardine larvae abundance with the environmental parameters we thought to be ecologically important in mediating the seasonal change of this abundance. Some of the parameters (i.e., chlorophyll-a, zooplankton biomass and sea surface temperature) came up from direct measurements complementing fish larvae sampling. Data on seasonal changes of nitrates, phosphates, silicates ammonia and dissolved oxygen concentration in the upper mixed layer were taken from a neighboring coastal station[9]. Also, we used seasonal data on sardine catches as the factor potentially affecting the fish larvae abundance through the eliminated part of the sardine population producing fish larvae. Characteristics of wind speed for the region were retrieved from the NCEP-NCAR reanalysis database for 2013-2015.

We constrained the PCA analysis by the extraction of two factors (components), which explained 86% of the total variance in the system of 13 selected variables. Apparently, factors were different according to variables driving the factor load. For instance, factor 1 labeled as "the trophic factor", in which the major load was contributed by sardine larvae statistically associated with zooplankton, chlorophyll-a, nitrates, phosphates, silicates (positively) and sea surface temperature (negatively). In factor 2 (labeled as "the physical-chemical factor"), the major load was contributed by zonal wind, salinity and dissolved oxygen concentration.

A group of variables contributing to factor 1 has explained 45% of the total variance, while factor 2 has contributed 41%, which came to 86% of the total variance explained. Overall, the two principal components (two factors)

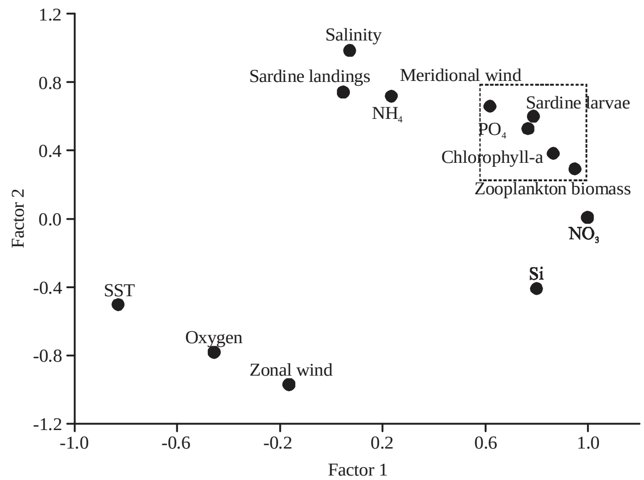

Fig. 7: Factor loading: The eigenvalue extraction by the principal component analysis

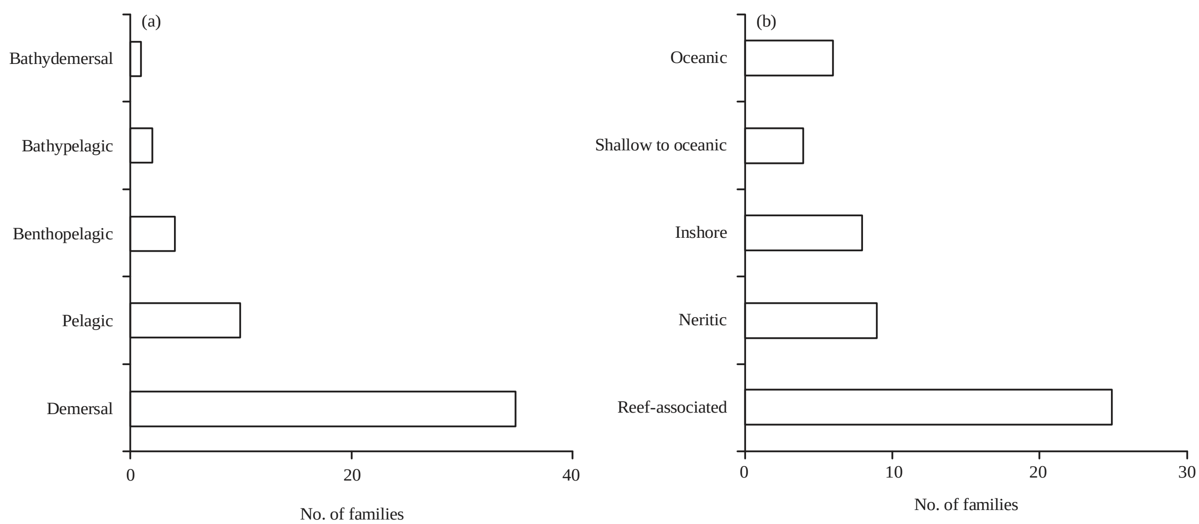

Fig. 8(a-b): Fish larvae groups based on adult habitats (2013-2015)

employed have explained the major part of seasonal variation within the system of 13 selected variables. Clusterization of variables in the field of two factors implied a tight association of sardine fish larvae with zooplankton biomass, chlorophyll-a, concentration of dissolved phosphates and meridional wind speed- all contoured by a dashed line in Fig. 7.

Smith and Heemstra[4] proposed the ecological classification of fish species based on their habitats. In terms of this approach, the most common in our samples were demersal reef-associated larvae which contributed 41%, followed by neritic and inshore-associated larvae with 21 and 18%, respectively (Fig. 8).

The least common group were bathypelagic fish larvae of Myctophidae and Paralepididae, which are normarly supposed to be observed at depths below 200 m in the Sea of Oman during daytime[26] and benthopelagic larvae of Mugilidae and Nomeidae which usually inhabit the water just above the bottom.

DISCUSSION

Thangaraja and Al-Aisry[27] reported 34 genera and 16 species found in the samples collected in 1989-1990 between Muscat and Shinas. In this study, a total of 1049 fish larvae (which included 39 families 50 genera and 55 species) were identified in the samples collected in 2013-2015. Carangidae was the most diverse family (with 6 genera), followed by Scombridae (with 5 genera), Clupeidae and Pomacentridae (with 4 genera each). Blenniidae, Bothidae, Mugilidae, Myctophidae and Terapontidae were contributed by 2 genera each. The rest was represented by 1 genera or species. Our assessment of the most diverse family (Carangidae) is consistent with earlier findings of Chesalina *et al*.[6] who sampled the South-Western part of the Sea of Oman in 2011-2012.

A notorious difference in taxonomic findings based on the past and present collections has affected values of the species diversity index. Thangaraja and Al-Aisry[27] reported the Shannon index value of 0.76. This was followed by Chesalina *et al*.[6] who reported the value of 0.89. Both values seemed to be low in comparison to our averaged estimate corresponding to 1.31.

Seasonal changes of larvae abundance revealed its highest association with NEM and SIM. For instance, the peak of the total fish larvae abundance during NEM was in the region of 104/100 m^3 and was contributed by 14 families whereas the second highest abundance (in SIM) was equal to 69/100 m^3 and was associated with 10 families (Fig. 5).

In terms of ecological footprints, NEM is the most important season for the whole pelagic ecosystem of the Sea of Oman, because this is the time of high primary productivity driven by winter convective mixing and the upwelling developing along the coast of Iran. These processes (complemented by mesoscale eddies and filaments of currents across the sea), spread out a high concentration of phytoplankton all over the basin. No wonder that in this study maximal chlorophyll-a concentration was observed during NEM (Fig. 4).

Chesalina *et al*.[6] elucidated two peaks of fish larvae abundance in the South-Western part of the Sea of Oman, in 2011-2012. The highest abundance (with 1534 larvae/100 m^3 from 17 families) was observed in February (which is the time of NEM), whereas the second peak (with 385 larvae/100 m^3 from 13 families) was associated with the month of July (SWM). However, the reported peaks were not accompanied by statistical validations.

Across the Sea of Oman, in the Iranian waters, the season dynamic was different. The highest fish larvae abundance and diversity was observed in FIM, in comparison to the SIM period[28]. However, the researchers used nets with the 300 µm mesh size, which makes the comparison of our data with theirs, a difficult task. The same refers to the sampling of coralline fish larvae in the Arabian (Persian) Gulf, which gave a quite different seasonal cycle. The researchers used the 500 µm mesh size. The peak of abundance comprised by 22 fish larvae families was observed in spring[29].

Factor Analysis (FA) enabled us to simplify in some way, the complexity of a coastal pelagic ecosystem through the reduction of independent and dependent variables. This reduction was based on a procedure of statistical rotation ensuring the orthogonal pattern of extracted variables grouped into two uncorrelated (Varimax-rotated) factors. The rotated factors allow one to delineate certain clusters of statistical relationships between variables comprising these factors. Various rotation methods have been proposed of which the Varimax method is broadly used and can be found as a standard option in many statistical software packages. In FA, selection of principal components is the extractive method enabling uncorrelated liner combination of variables to be achieved. In the space of two factors, numeric values are interpreted as "factor loadings" rather than correlation values. In our case, two principal components pointed to the statistically significant link between sardine fish larvae, sea surface temperature, meridional wind speed and salinity as well as links with biological variables represented by zooplankton biomass and chlorophyll-a. Unfortunately, the zooplankton samples we collected have not been processed to the species level. Nonetheless, the studies carried out in a neighboring region had implied copepods to be main contributors to the total zooplankton abundance throughout the seasonal cycle. The dominance of small-sized copepods of genus *Oithona*, *Temora*, *Oncaea*, *Parvocalanus*, *Paracalanus*, *Microsetella*, *Acartia* and some others was a typical feature of the plankton community. Presumably, the nauplii stages of these (abundant) copepod species constitute the main food source for fish larvae, which used to feed on copepod nauplii stages[30]. In 2010-2011, monthly microzooplankton samples were collected in coastal waters of Muscat by Niskin bottles and filtered further through a 20 µm mesh net (Piontkovski). Samples were processed to the genera level. Data analysis showed the presence of copepod nauplii at the surface (1 m) in huge quantities, with maximal concentrations observed during NEM and SIM seasons (7461 and 9404 ind m^{-3} correspondently).

In terms of a classical concept, the survival rate of fish larvae is a result of the match-mismatch interplay between the timing of egg hatching and seasonal phytoplankton blooms[31]. Interestingly, statistical analysis of seasonal dynamics of sardine catches in the Muscat region for the range of 2000-2011 had demonstrated that 51% of the seasonal variability in catches might be approximated by the seasonal variations of the zonal component of wind speed and chlorophyll-a concentration[32]. In the Sea of Oman, phytoplankton comprise about 62-68% of the adult sardine diet[33].

The fish larvae abundance exhibits marked changes of seasonal cycles over development stages (Fig. 6). The pre-flexion stage was most sensible to monsoonal changes.

The abundance of this stage was highest during NEM and SIM and gradually declined during SWM and FIM seasons. Perhaps, this phenomenon was associated with the availability of phytoplankton which had maximal concentrations during NEM. The next two development stages showed much less pronounced magnitudes of seasonal changes, although their maxima were associated with NEM as well.

Seasonal patterns of fish larvae abundance revealed a different breadth of spawning periods. For instance, two most abundant fish larvae species in our samples (*Sardinella* spp. and *Acanthopagrus latus*) have been observed throughout the year, whereas the less abundant Sphyraenidae larvae were found during the NEM period only or the Chanidae larvae observed during SWM only. Overall, it is believed that the duration of the pelagic larval stages is highly variable, ranging from days to months[34-36].

The other form of adaptation is the shift of spawning periods over the seasonal cycle. For instance, the Clupeidae family exhibited the peak corresponding to the time of NEM, while larvae of Blennidae family were most abundant during the SWM. Both phenomena might be interpreted as mechanisms reducing inter- and intra-specific competition for food resources in pelagic habitats, because the survival of larval fish depends on the timing as well as matching or mismatching of seasonal phytoplankton blooms[31,37].

Seasonal patterns of temperature are important as well. An optimal temperature is essential for fish spawning because low temperature is impeding the larval growth and swimming ability of individuals[38]. In this study, the highest total larvae abundance during NEM was associated with a seasonal cooling usually observed in the Sea of Oman in the upper mixed layer[9].

In the Muscat region, the seasonality of sardine landings with dominant NEM maximum was the pattern pronounced through out 11 years of historical records[32], from 2000-2011. In particular, annual reports of the Ministry of Agriculture and Fisheries enabled us to analyze the pattern retrieved from monthly data specifically for the time range of our sampling (2013-2015). Seasonal changes of sardine larvae (*Sardinella* spp.) were consistent with artisanal sardine landings in the region, which is important because regionally, sardines contribute over 50% to total landings over the Western and Eastern sides of the Arabian sea[39-41]. Along the coast of Oman, approximately 80% of sardine landings from traditional fishery are contributed by the Indian oil-sardine *Sardinella longiceps*[42].

In analyzing data, we averaged them over years. All 4 plots featuring seasonal changes (Fig. 3-6) implied a certain inter-annual variation reflected by standard deviation bars. For instance, the year of 2015 was quite different based on the number of fish larvae families. This could have affected averaged values of fish larvae abundance and the diversity index. In general, all major characteristics we exposed in the above 4 plots exhibited maximal values of standard deviations associated with the NEM.

CONCLUSION

Three years sampling program has enabled us a statistically validated seasonality of fish larvae abundance and species diversity to be elucidated, for the coastal waters of the Muscat region. Seasonal changes in the total fish larvae abundance revealed two peaks corresponded to the time of the North-East Monsoon and the spring inter-monsoon period. The Shannon diversity index was highest during the spring inter-monsoon. The *Sardinella* spp., fish larvae were the most abundant throughout the year. Seasonal changes of these larvae were consistent with artisanal sardine landings in the region. Consequently, data on fish larvae abundance could be treated as a sensible indicator for predicting seasonal catches of sardines in the region.

SIGNIFICANCE STATEMENT

The fish larval abundance and their species composition both could serve as sensible indicators for predicting catches of mature specimens. We showed that the *Sardinella* spp., fish larvae were the most abundant throughout the year. Seasonal changes of these larvae were consistent with artisanal sardine landings in the region. Consequently, data on fish larvae abundance could be treated as a sensible indicator for predicting seasonal catches of sardines in the region.

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