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SEASONAL AND SPATIAL VARIATIONS IN THE FISH ASSEMBLAGE OF SHALLOW HABITATS WITHIN THE BIZERTE LAGOON (TUNISIA)

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FISH ASSEMBLAGE
FUNCTIONAL GUILD
ABIOTIC FACTORS
LAGOON
BIZERTE
TUNISIA
MEDITERRANEAN

ABSTRACT. – The diversity and structure of fish populations in southern Mediterranean lagoons are poorly documented. Spatial and temporal variation in uses of shallow habitats for fish fauna in Bizerte Lagoon in Tunisia was investigated in relation to environmental variables. Fish sampling was carried out over four seasons at four stations with a 3 mm mesh beach seine. Multivariate statistical analyses were applied to assess environmental influences (temperature, pH, salinity, dissolved oxygen) on fish spatiotemporal assemblages. A total of 3,612 individuals were collected representing 26 species from 14 families. The fish assemblage was quantitatively dominated by resident species, mainly the big-scale sand smelt *Atherina boyeri* accounting for 69.49 % of the total number of fish captured. The fish assemblage was largely dominated in terms of ecological guild by the marine migrant species and fish feeding groups belonging to microbenthivore and detritivore species. The Bizerte Lagoon functions as a coastal inlet, with euryhaline conditions throughout the year. Hydrological variables measured in the shallow waters were uniform across the whole lagoon and had low influence on the spatiotemporal fish assemblages. The lagoon could be of great importance in providing nursery habitats for juvenile marine migrant fish species.

INTRODUCTION

Coastal lagoons are shallow inland water bodies, separated from the ocean by sandbars and connected to the ocean by one or more restricted inlets which remain open at least intermittently (Barnes 1980, Guélorget & Perthuisot 1992). Coastal lagoons are highly productive ecosystems (Costenza *et al*. 1997). They contribute to the overall productivity of coastal waters by supporting a variety of habitats. They are recognized as important sites for fish species, providing optimal feeding and nursery grounds and hence supporting large numbers of fish (Whitfield 1999). More than 199 fish species are known to be present in coastal lagoons in the Atlantic-Mediterranean region (Basset *et al*. 2006, Pérez-Ruzafa *et al*. 2011a). In addition, several studies have shown that these ecosystems may also be the spot of intense breeding activity for several species (Withfield 1994, Malavasi *et al*. 2004).

Coastal lagoons support a range of natural services that are highly valued by the society (Kennish & Paerl 2010, Pérez-Ruzafa *et al*. 2011a). Their surroundings represent attractive sites for human development and are exploited for different uses including fisheries, aquaculture, recreation and tourism (Barnes 1980). However, water quality and biodiversity in these ecosystems are particularly vulnerable to eutrophication and pollution, and suffer from increasing demographic and economic developments in the coastal zone (De Wit *et al*. 2017). Therefore, managing coastal lagoons in the context of increasing anthropogenic stressors and climate changes (i.e., sea-level rise, seawater intrusion, water warming, change in rainfall and salinity) is critical.

The Mediterranean region hosts around 400 coastal lagoons, covering a surface of over 641,000 ha differing in their typology and use (Cataudella *et al*. 2015). Although several studies have been devoted to the ecology and fish assemblage organization in the north-western Mediterranean (Dumay *et al*. 2004, Malavasi *et al*. 2004, Poizat *et al*. 2004, Mouillot *et al*. 2005, Franco *et al*. 2006a, b, Pérez-Ruzafa *et al*. 2006, Maci & Basset 2009, Franco *et al*. 2012, Verdiell-Cubedo *et al*. 2013), little is known about North African lagoons i.e., Nador (Morocco, Bouchereau *et al*. 2000, Jaafour *et al*. 2015), Ichkeul (Tunisia, Chaouachi & Ben Hassine 1998, Kraiem *et al*. 2003), Mellah (Algeria, Chaoui *et al*. 2006, Embarek *et al*. 2017). However, among biological indicators, fish and their assemblage have been used successfully to detect changes in environmental quality in several aquatic habitats (Whitehead 1986, Soto-Galera *et al*. 1998, Riera *et al*. 2018). They are recommended by the European Commission to assess the ecological status of transitional waters under the European Water Framework Directive (WFD

Directive 2000/60/EC) and are already being considered by many research teams (Pérez-Domínguez *et al.* 2012, Harrison & Kelly 2013, Alvarez *et al.* 2013, Smolinski & Calkiewicz 2015).

Bizerte Lagoon, located on the northwestern Tunisian coast, is an ecologically and economically important water body. It is connected to Ichkeul Lake as well as to wetlands, all classified as a Biosphere Reserve and National Park since 1980, and listed as a World Heritage Site. However, several towns in the surrounding area are undergoing rapid population growth and industrial expansion. The lagoon is thus affected by various anthropogenic activities such as domestic sewage and industrial waste inputs, atmospheric pollution, shellfish farming and eutrophication phenomena during the summer period that may affect the quality of the habitats and the living organisms (Louiz *et al.* 2009, Mahmoud *et al.* 2010, Barhoumi *et al.* 2014, Ben Ameur *et al.* 2015, Zaaboub *et al.* 2015). Although Bizerte Lagoon supports important fisheries (Béji 2000), its ecological functioning (i.e., nursery, functional ecological groups) and importance for fish has never been examined.

The main objective of this year-long study was to describe the fish assemblages of the shallow habitats of Bizerte Lagoon, regarding their taxonomic and functional compositions, and to assess their spatial and seasonal changes in relation to environmental factors.

MATERIAL AND METHODS

Study area: Located in the northwest of Tunisia (37°08'-37°17'N / 9°46'-9°55'E), Bizerte Lagoon is a semi-enclosed ecosystem that is linked to the central Mediterranean Sea (Fig. 1). It has an average depth of 8 m and a surface area of 121.6 km^2 (Quignard & Zaouali 1980), making it the third largest lagoon in Tunisia. It is connected to the Mediterranean Sea through a 7 km-long channel, which is on average 300 m wide and 13 m deep, and to the Ichkeul Lake (110 km^2) through the Tinja Channel (about 5 km long and a few meters deep), which brings fresh water. Since the early 1990s, the channel is equipped with locks to manage trade between the Ichkeul Lake and Bizerte Lagoon. This has resulted in a sharp decrease in freshwater supply to the lagoon (Béjaoui *et al.* 2008). The lagoon also receives fresh water inputs from non-permanent watercourses such as Rharek, Ben Hassine, and Guenich Streams (Fig. 1). Bizerte Lagoon is located in the vicinity of several cities, agglomerations and industrial units (Fig. 1). It is affected by various anthropogenic activities, such as domestic sewage inputs, atmospheric pollution, industrial waste and aquaculture. The surface sediments of the northern and eastern sectors of the lagoon correspond to silty-sandy-muddy or sandy-silty-muddy bottoms. The western and central areas of the lagoon exhibit muddy-silty to muddy sediments (Ben Garali *et al.* 2008, Brahim *et al.* 2013). The macrophytes recorded in the lagoon are most frequently represented by seagrass: *Cymodocea nodosa*, *Zostera noltii, Z. marina,* and *Caulerpa prolifera* (Zaouli 1979, Guélorget & Penhuisot 1983). The shallow waters are characterized by *Cymodocea nodosa* and *Zostera noltii* in the northeast of the lagoon, *Caulerpa prolifera*

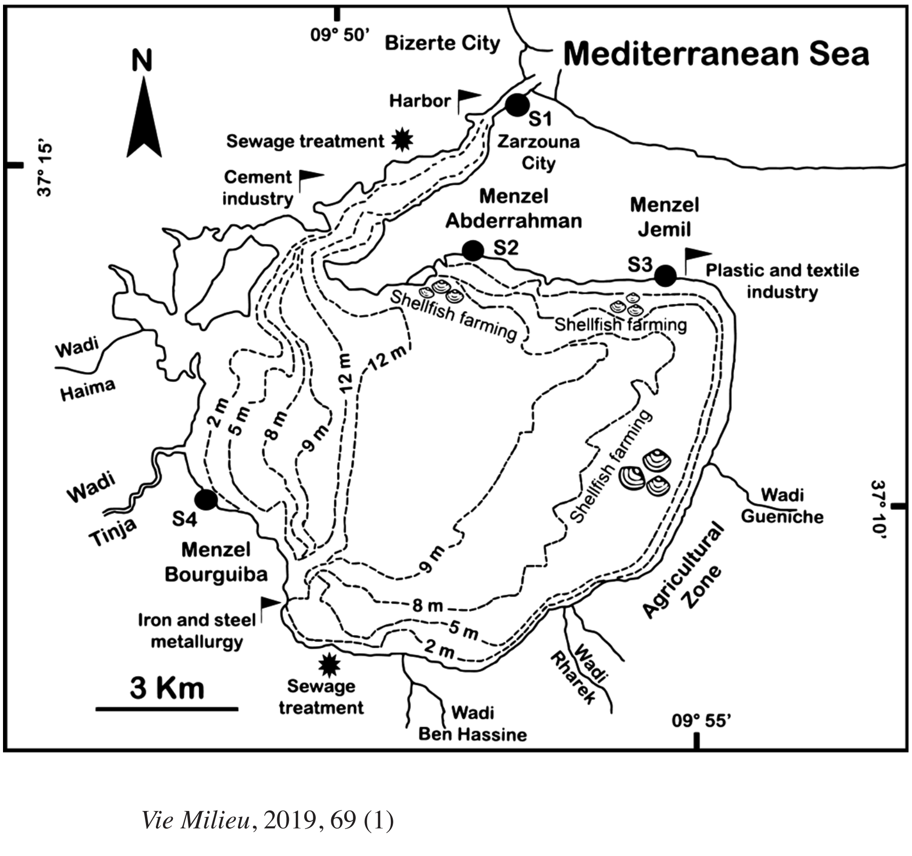

Fig. 1. – Bizerte Lagoon and location of the four sampling stations. Fresh water input (wadis), urban zones, industrial zones, agricultural zones and shellfish farming zones are indicated.

in the southwest part and at the outlet of Wadi Tindja with some *Ruppia spiralis*. *Zostera marina* is encountered mainly in the northwest of the lagoon and in the channel connected to the sea (Zaouli 1979). Given the many changes that have occurred in the lagoon since the 1990s (Aleya *et al.* 2019), monitoring of the macrophytes' spatial distribution would have certainly exhibited some sharp changes during the last decades, but no data exist.

Sampling protocol: Sampling was performed at depths less than 1.5 m at four stations (Fig. 1) in contrasting habitats in terms of distance from the sea, substrates, vegetation and anthropogenic pressures. Station 1 (S1), located in the channel, is influenced by the seawater input and affected by intense fishing, passage of ships, and urban effluents from the city of Bizerte as well as a cement factory; station 2 (S2), located at Menzel Abderrahmen, between the port and the outfall of the National Sanitation Utility (ONAS), is characterized by urban effluent (Mahmoud *et al.* 2010); station 3 (S3), near Menzel Jemil, is located in the main aquaculture part of the lagoon. This station is exposed during summer to the eutrophication process and is characterized by shellfish releases and industrial contamination (Louiz *et al.* 2008); station 4 (S4), located at Menzel Bourguiba, is a heavily industrialized area (e.g., metallurgical industry, boatyard, tyre production factories, etc.).

Fish sampling was carried out during daylight hours using a beach seine net (L = 14 m, H = 2 m, mesh size = 3 mm). This gear is appropriate for catching small (< 100 mm TL) fish, which abound in shallow waters (Pierce *et al.* 1990, Franco *et al.* 2012). Hauls were taken parallel to the shoreline at a distance of about 15-20 m. Each seine haul covered an area of about 240 m^2. At each station, two replicates were collected. Samples were collected once per season during autumn (2012) and winter, spring and summer (2013). After each sampling, fish were preserved in plastic bags and transported to the laboratory in a cooler with ice. Each individual caught was identified to species level, measured (total length, TL) and weighed (total weight Wt). For each species, catches were standardised to densities (number of individuals per 100 m^2). Environmental variables (temperature, salinity, dissolved oxygen and pH) were measured on each sampling occasion immediately before the fishing procedure.

Data analysis: Species richness (the total number of species caught per season or at each station) and the Shannon-Wiener (H') index were used to quantify species diversity. Following the classification of Franco *et al.* (2008), fish species were allocated to functional groups according to their habitat use and feeding modes. Total length (TL) data for the most abundant species were analyzed with the nonparametric Kruskal-Wallis test in order to investigate possible seasonal and spatial variations in individual size. Whenever differences were detected, the Mann-Whitney test was applied to quantify and establish those differences by pairs.

Cluster Analysis and nonmetric multidimensional scaling (nMDS) were carried out, with the Bray-Curtis similarity index, to investigate spatial and seasonal differences in fish assemblage (PRIMER software package, Version 6.1.9**,** Clarke & Warwick 2001). Canonical correspondence analysis (CCA), performed with R software (R Development CoreTeam, 2005), was used to explore the relationships between species distribution and environmental variables (Ter Braak, 1986). Logarithmic transformations (log10(x+1)) of the abundance of species were applied and only the most abundant species (> 0.1% abundance) were included in the analysis to reduce the effects of rare species.

RESULTS

Environmental variables

There was clear and significant ($p < 0.001$) seasonal variation in hydrological conditions with lower tempera-

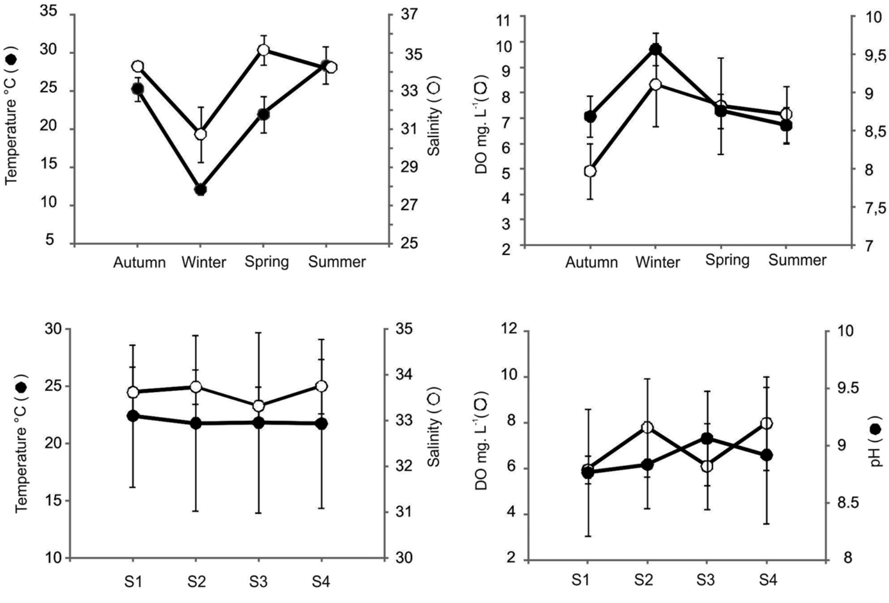

Fig. 2. – Seasonal and spatial fluctuations in environmental variables (mean ± SD) in Bizerte Lagoon shallow waters.

Table I. – Species composition, mean density (D. ind.100 m^{-2}) and occurrence (% Occ) of fish in the Bizerte Lagoon. The ecological groups (EG) and feeding groups (FG) are indicated for each species. Residents (R), marine migrants (MM), omnivores (OV), hyperbenthivores/zooplanktivores (HZ), detritivores, (DV), microbenthivores (Bmi), macrobenthivores (BMa), hyperbenthivores/piscivores (HP), planktivores (PL), herbivores (HV).

					Autumn		**Winter**		**Spring**		**Summer**	
Family	Species	Code	EG	FG	D.	Occ.	D.	Occ.	D.	Occ.	D.	Occ.
Cyprinodontidae	*Aphanius fasciatus* (Valenciennes, 1821)	*Afas*	R	OV	4.45	50	0	0	1.2	75	2.72	50
Atherinidae	*Atherina boyeri* Risso, 1810	*Aboy*	R	HZ	70.95	100	73.83	100	7.17	50	39	100
Mugilidae	*Liza saliens* (Risso, 1810)	*Lsal*	MM	DV	0.93	25	0.42	50	0.89	50	0.1	25
	Liza aurata (Risso, 1810)	*Laur*	MM	DV	0	0	0.1	25	6.04	75	0	0
	Mugilidae n.i.	*Mug n.i.*	MM	DV	2.4	25	0.36	25	6.93	25	1.61	25
Gobiidae	*Pomatoschistus marmoratus* (Risso, 1810)	*Pmar*	R	BMi	4.06	50	0.31	50	0.78	50	0	0
	Pomatoschistus tortonesei Miller, 1969	*Ptor*	R	BMi	5.91	25	0.89	100	5.38	50	2.48	50
	Gobius paganellus Linnaeus, 1758	*Gpag*	R	BMi	0	0	0	0	0.05	25	0	0
Sparidae	*Diplodus sargus sargus* (Linnaeus, 1758)	*Dsar*	MM	OV	0	0	0	0	2.21	50	0	0
	Diplodus puntazzo (Walbaum, 1792)	*Dpun*	MM	OV	0	0	0.1	25	0.52	75	0	0
	Lithognathus mormyrus (Linnaeus, 1758)	*Lmor*	MM	BMi	0	0	0	0	0	0	0.05	25
	Sarpa salpa (Linnaeus, 1758)	*Ssal*	MM	HV	0	0	0	0	0.52	50	0	0
	Sparus aurata Linnaeus, 1758	*Saur*	MM	BMi	0	0	0	0	0.63	75	0	0
Syngnathidae	*Syngnathus abaster* Risso, 1827	*Saba*	R	BMi	6.99	100	0	0	3.05	75	0.33	25
	Syngnathus typhle rondeleti Delaroche, 1809	*Styp*	R	HZ	2	100	0	0	0.54	75	0	0
	Nerophis ophidion (Linnaeus, 1758)	*Noph*	R	Bmi/HZ	0.11	25	0	0	0.16	50	0	0
Soleidae	*Solea senegalensis* Kaup, 1858	*Ssen*	MM	Bmi/BMa	0.05	25	0	0	0.16	25	0	0
	Dagetichthys lusitanicus (de Brito Capello, 1868)	*Dlus*	MM	Bmi/BMa	0.11	25	0.11	25	0.05	25	0	0
	Pegusa impar (Bennett, 1831)	*Pimp*	R	Bmi/BMa	0.05	25	0	0	0	0	0	0
Labridae	*Symphodus tinca* (Linnaeus, 1758)	*Stin*	MM	BMa	0.21	50	0	0	0	0	0.05	25
	Symphodus cinereus (Bonnaterre, 178)	*Soce*	MM	BMa	0	0	0	0	0	0	0.1	25
Mullidae	*Mullus surmuletus Linnaeus*, 1758	*Msur*	MM	Bmi/BMa	0	0	0	0	0	0	0.05	25
Engraulidae	*Engraulis encrasicolus* (Linnaeus, 1758)	*Eenc*	MM	PL	1.5	25	0	0	0	0	0	0
Moronidae	*Dicentrarchus labrax* (Linnaeus, 1758)	*Dlab*	MM	HZ	0.05	25	0	0	0.21	50	0	0
Belonidae	*Belone belone* (Linnaeus, 1761)	*Bbel*	MM	HP	0.31	50	0	0	0	0	0.38	50
Hemiramphidae	*Hemiramphus picarti* (Valenciennes, 1847)	*Hpic*	MM	HV	0.31	50	0	0	0.21	50	0.05	25
Blenniidae	*Salaria pavo* (Risso, 1810)	*Spav*	R	OV	0.36	50	0	0	0.05	25	0	0

ture and salinity and higher dissolved oxygen and pH during winter (Fig. 2). Temperature ranged from 12.1 °C in winter to 28.4 °C in summer and salinity from 30.8 in winter to 35.2 in spring. Dissolved oxygen ranged from 4.91 mg.L^{-1} in autumn to 8.32 mg.L^{-1} in winter and pH ranged from 8.6 in summer to 9.5 in winter. The environmental variables measured in the shallow waters were uniform across the whole lagoon. There were no significant spatial differences (between stations) ($P > 0.001$) (Fig. 2).

Fish species composition

We sampled a total of 3,612 fish specimens comprising 26 species and 14 families (Table I). Two ecological groups were sampled: residents (R) and marine migrants (MM). In terms of diversity, the fish assemblage was dominated by marine migrants (16 species compared to 10 resident species) but in terms of abundance, the resident species dominate largely (85.94 % and 14.06 % of the total catches respectively for the resident and marine migrant species). Eight feeding groups were identified: omnivores (OV), hyperbenthivores/zooplanktivores (HZ), detritivores (DV), microbenthivores (Bmi), macrobenthivores (BMa), hyperbenthivores/piscivores (HP), planktivores (PL), herbivores (HV). The microbenthivores (Bmi) were dominant in the fish assemblage in terms of species number (10 species), but the hyperbenthivores/zooplanktivores (HZ) were dominant in terms of abundance, representing 71 % of total catches.

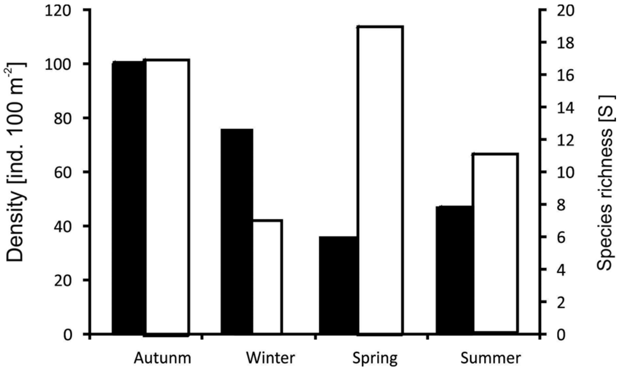

Fig. 3. – Seasonal variation in fish species richness and densities in the Bizerte lagoon. Black bar: fish abundance and white bar: species richness.

Spatial and seasonal fish assemblage differed both in terms of fish abundance and diversity and also in terms of functional group composition. Fish abundance ranged from 37 ind.100 m^{-2} to 101 ind.100 m^{-2} and was highest in autumn and lowest in spring (Fig. 3). Fish diversity was highest in spring and autumn (19 and 18 species, respectively) and lowest in winter (7 species). The Shannon-Wiener diversity index varied from 0.28 in winter to 3.22 in spring. The most abundant fish species in the catches was the sand smelt *Atherina boyeri* Risso, 1810 (2,510 individuals, 69.49 % of total catches), followed by the Tortonese's goby, *Pomatoschistus tortonesei* Miller, 1969 (197 individuals, 5.45 % of total catches), the Mediterranean killifish, *Aphanius fasciatus* (Valenciennes, 1821) (136 individuals, 3.77 % of total catches) and the Black-striped pipefish, *Syngnathus abaster* Risso, 1827 (134 individuals, 3.71 % of total catches). Together with *Pomatoschistus marmoratus* (Risso, 1810) and *Liza aurata* (Risso, 1810), these 4 species represented more than 85.88 % of the total catch. These species showed seasonal variation in density (Table I). *A. fasciatus*, *S. abaster* and *P. marmoratus* were abundant during autumn, whereas *P. tortonesei* (Miller, 1969) was abundant during spring and autumn. *A. boyeri* was mainly abundant in autumn and winter and *L. aurata* was abundant in spring. In autumn, winter and summer, resident species dominated the fish assemblage accounting for 88.15 %, 98.05 % and 94.57 % of the total catches, respectively, whereas in spring fish assemblage was distributed equally between the residents and the marine migrants accounting for 42.97 % and 57.03 % of total catches (Fig. 4). In terms of fish density, the feeding groups were similar in autumn,

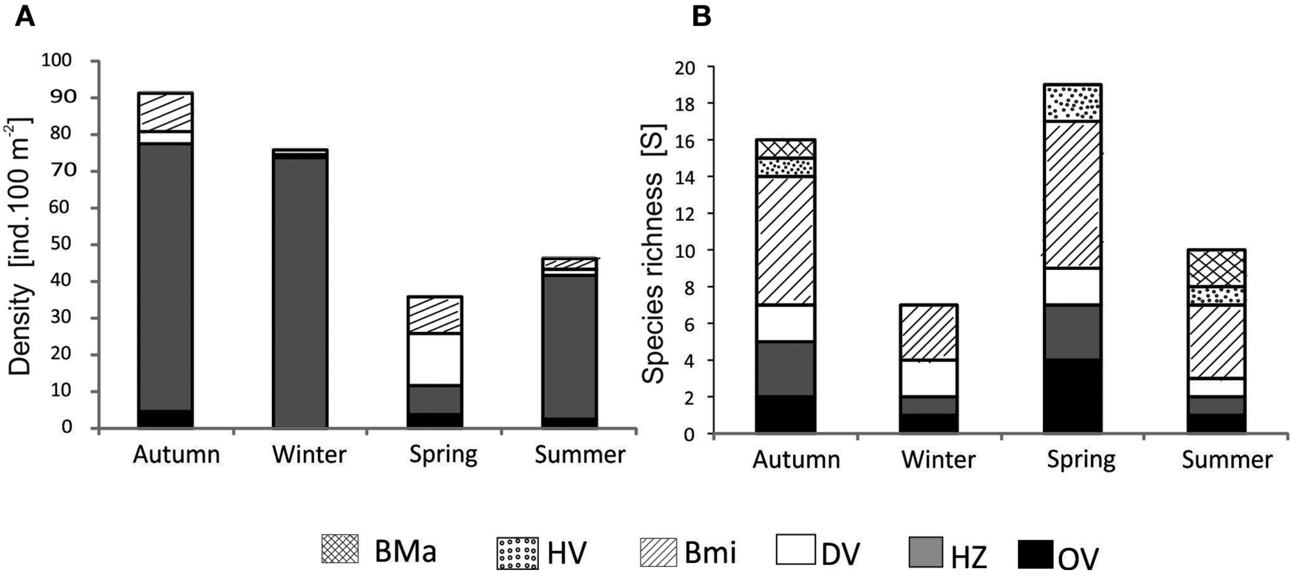

Fig. 4. – Seasonal variation of fish feeding groups. **A**: In terms of fish density; and **B**: In terms of fish species number. Omnivores (OV), hyperbenthivores/zooplanktivores (HZ), detritivores, (DV), microbenthivores (Bmi), macrobenthivores (BMa), hyperbenthivores/piscivores (HP), planktivores (PL), herbivores (HV).

winter and summer and were largely dominated by hyperbenthivore/zooplanktivore (HZ) species accounting for 77.80 %, 96.93 % and 83.29 % of total catches respectively during autumn, winter and summer (Fig. 4A). However, in terms of number of fish species, microbenthivores (Bmi) were dominant (Fig. 4B).

Most fish species had a mean length under 8 cm. For the four most abundant species (*A. boyeri, P. tortonesei, A. fasciatus* and *S. abaster*), there was a significant difference in fish size between seasons and between the four stations sampled (Kruskal-Wallis, $P < 0.05$) (Table II). The temporal evolution of the length-frequency distribution showed that the mean size of *A. boyeri, P. tortonesei* and *A. fasciatus* was lower during summer (Fig. 5). There was a spatial pattern in fish length with generally bigger fish at station 3 (Table II). The fish lengths of *A. boyeri* at

Table II. – Mean fish length (TL ± SD, cm) for the four most abundant fish species at the four stations prospected.

	S1	**S2**	**S3**	**S4**
A. boyeri	4.18 ± 0.98	4.55 ± 1.22	5.21 ± 1.49	4.02 ± 1.16
P. tortonesei	–	2.91 ± 0.41	2.63 ± 0.09	3.03 ± 0.61
A. fasciatus	–	2.85 ± 0.65	3.37 ± 0.87	1.77 ± 0.21
S. abaster	8.91 ± 1.81	9.28 ± 2.05	–	8.60 ± 1.28

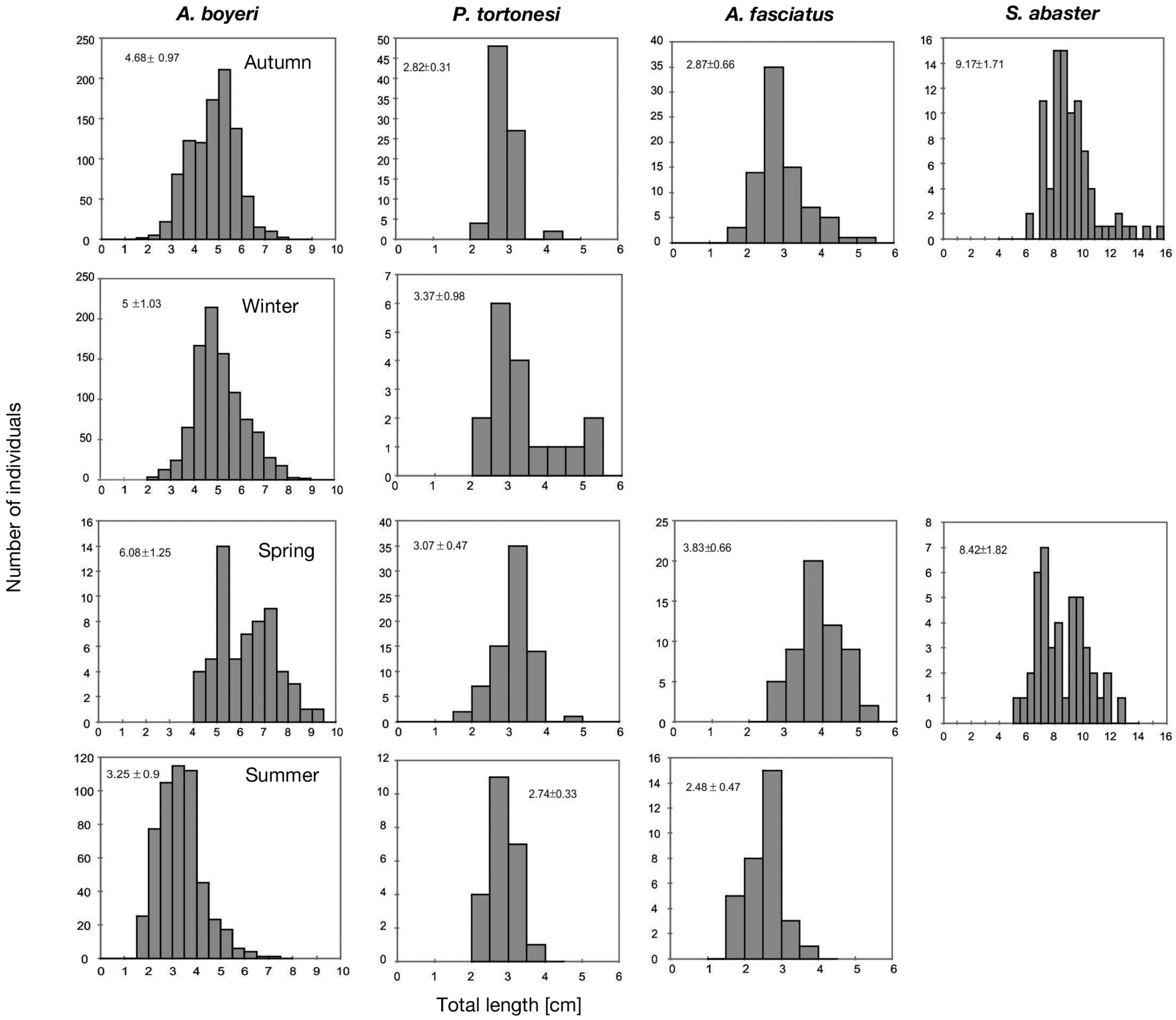

Fig. 5. – Seasonal length-frequency distribution of the four main species caught in the Bizerte Lagoon. Mean fish length ± SD (cm) and number of individuals measured are indicated.

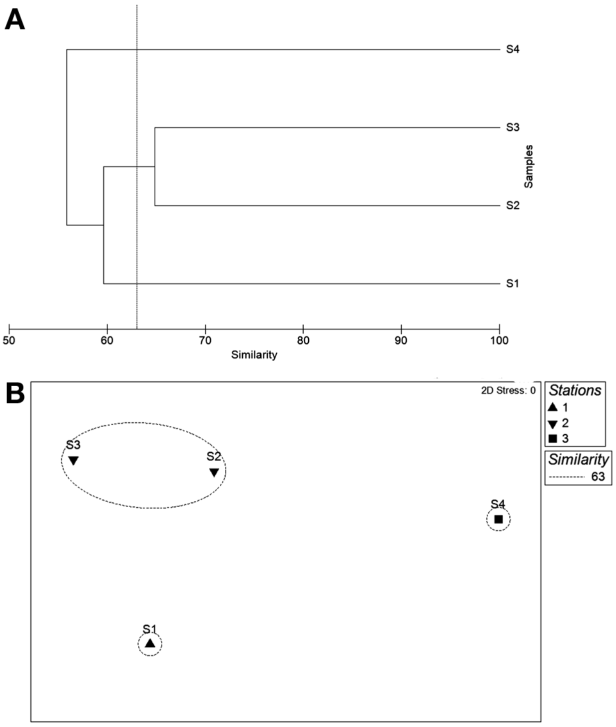

Fig 6. – Cluster analysis (**A**) and Non-metric Multi-Dimensional Scaling ordination plot (**B**) based on fish species densities showing interrelationships between the four sampled stations in the Bizerte lagoon according to Bray-Curtis similarity.

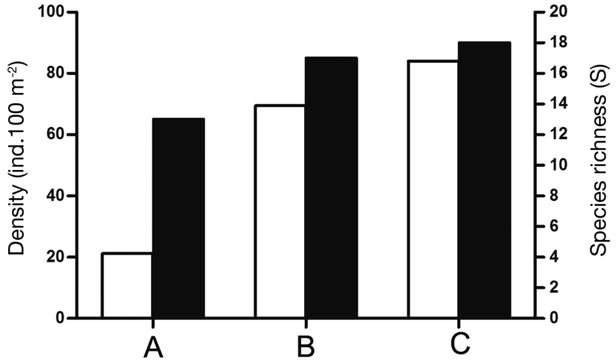

Fig. 7. – Spatial variation in fish species richness and densities according to the three groups of stations identified: group A: station 4, group B: station 1 and group C: stations 2 and 3. White bar: fish abundance and black bar: species richness.

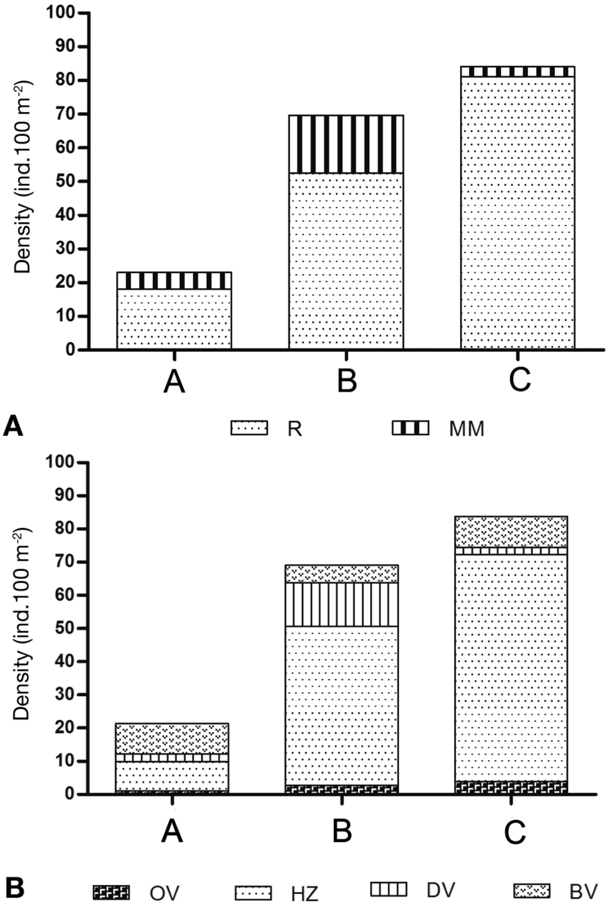

Fig 8. – Spatial variation of fish functional groups according to their habitat use and feeding modes in the three groups of stations identified. **A**: Fish ecological groups: residents (R) and marine migrants (MM). **B**: Fish feeding groups: omnivore (OV), hyperbenthivores/zooplanktivores (HZ), detritivores, (DV), microbenthivores (Bmi), macrobenthivores (BMa), herbivores (HV).

stations 1 and 4 were significantly lower than at station 2 and 3 and the lengths of *A. fasciatus* were significantly higher at station 3 compared to station 2. *S. abaster* were bigger at station 3 compared to the other stations.

Spatial analysis (cluster analysis) revealed three groups of stations (Fig. 6): group A (station 4 located in a heavily industrialized area characterized by muddy sediments and the presence of macroalgae *Caulerpa prolifera*), group B (station 1 influenced by the marine waters) and group C (stations 2 and 3 located on the northeast part of the lagoon characterized by a sandy bottom, the presence of *Cymodocea nodosa* and *Zostera noltii* and shellfish farming). Fish diversity and abundance were highest in group C and lower at station 4 (group A) (Fig. 7). At all stations, resident species (R) and hyperbenthos-zooplanktivore (HZ) species were dominant in the fish assemblage in terms of abundance (Fig. 8). However, marine migrant and detritivore (DV) species were also abundant at station 1 (group B) whereas microbenthivore (Bmi) species were relatively abundant at station 4 (group A).

CCAn analysis of species abundance indicated the absence of spatial and temporal patterns in the assemblage (Fig. 9). Four axes were determined, but only the first and second ones were plotted as they accounted for 65 % of variance of species-environment relationships (36 % and 29 % for axis 1 and 2, respectively) (Table III). Station samples from the same season were mostly grouped in the same region of the CCA plot indicating a weak spatial separation. Associations between environmental variables and species indicated that species located near the origin either do not show a strong relationship to any of the variables or are found at average values of environmental var-

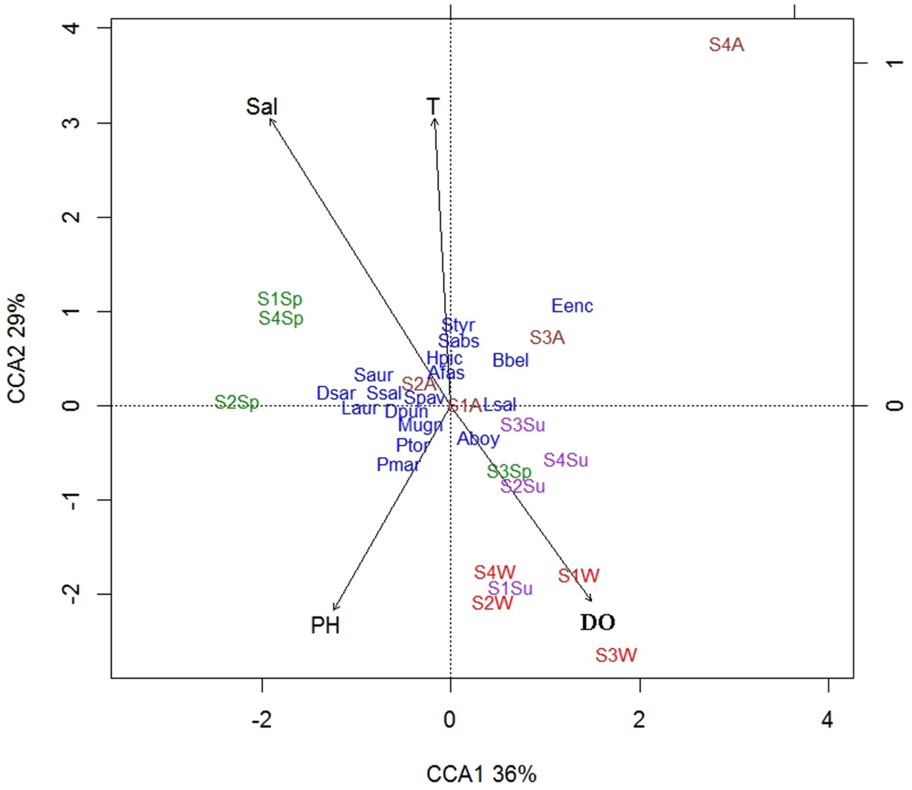

Fig 9. – Triplot of canonical correspondence analysis relating site score, fish taxa densities and environmental variables correlated with axes. Objects (sampling sites) are represented by the name Of the station and the sampling season (i.e. S1Sp: station 1 spring), response variables (species densities) are plotted by species names, arrows represent quantitative explanatory variables (environmental variables: T: temperature, Sal: salinity, DO: dissolved oxygen, pH) with arrowheads indicating their direction of increase. Environmental variables coordinates are placed on the lower X axis and the right Y axis.

Table III. – Statistics associated with the first two canonical axes from canonical correlation analysis.

	CCA1	CCA2
Canonical correlation	0.41	0.27
Percent of variance explained	36%	29%
Standardized correlation with environmental axis		
Temperature	–0.04	0.83
Salinity	–0.52	0.83
Dissolved oxygen	0.4	–0.56
pH	–0.34	–0.59

iables. Most species and particularly the two numerically dominant ones (*A. boyeri* and *P. tortonesei*) had average values in relation to environmental variables. This confirms the low influence of hydrological conditions on the spatiotemporal fish assemblages.

DISCUSSION

Although artisanal fishery is an important activity in the Bizerte Lagoon, the fish fauna is poorly known. Previous studies have addressed the diversity and production of adult commercial catches (Azouz, 1966, Béji 2000). The present study describes the fish diversity and assemblage of Bizerte Lagoon. Twenty-six species were recorded, which is comparable to those found in numerous other Mediterranean lagoons. The number of fish species in the 40 Atlantic-Mediterranean lagoons ranged between 6 and 48, with an average of 23.4 species (Pérez-Ruzafa *et al*. 2007, 2011a). In 19 northern Mediterranean lagoons, 204 fish species were recorded with a mean number per lagoon of 40 (range 14 to 84) (Franco *et al*. 2008). The fish diversity of southern Mediterranean lagoons is less documented and reported that fish species diversity varies between 13 and 26 species: Ghar El Melh in Tunisia (26 species), Lake Manzala in Egypt (17) (Kraïem *et al*. 2009), Ichkeul Lagoon in Tunisia (13) (Sellami *et al*. 2010) and Nador Lagoon in Morocco (18) (Bouchereau *et al*. 2000). With the same sampling gear and protocol, a lower fish species diversity was recorded in Moroccan (Nador, Jaafour *et al*. 2015) and Algerian (Mellah, Embarek *et al*. 2017) lagoons with 15 and 11 species, respectively. The beach seine net used is considered to be a valuable technique for sampling small fish (< 10 cm) in shallow waters, especially in lagoon ecosystems (Franco *et al*. 2012). According to species' habitat use, two ecological groups were sampled in the Bizerte Lagoon: resident species (R), which spend their entire life cycle within the lagoon, and marine migrant species (MM), which spawn at sea and enter lagoons on a regular basis mainly for feeding and shelter (Kara & Quignard 2018). Fish assemblages are quantitatively dominated by the resident species accounting for 86 % of the total fish captured. Nevertheless, marine migrant species that use the lagoon as a nursery ground were the most represented in terms of the number of species, with Sparidae as the dominant family. No freshwater species were caught. Such fish assemblages were comparable to other southern Mediterranean lagoons such as Nador Lagoon in Morocco (Jaafour *et al*. 2015), Mellah Lagoon in Algeria (Embarek *et al*. 2017), Ichkeul Lagoon in Tunisia (Sellami *et al*. 2010) and some northern Mediterranean lagoons (Manzo *et al*. 2016). These data are in accordance with many other studies in European lagoons. Franco *et al*. (2008) found that fish assemblages from 19 northern Mediterranean lagoons were dominated in terms of species number by marine species. The low freshwater input may be responsible for the absence of both freshwater and anadromous species in southern Mediterranean lagoons compared to European lagoons (Franco *et al*. 2008). In the northern Mediterranean lagoons, an increasing number of species was recorded from west to east (Franco *et al*. 2008), probably due to the closer proximity to Gibraltar Strait, a source of colonizing species from the Atlantic Ocean (Bianchi 2007). This is not the case in the North African lagoons where western lagoons (e.g., Nador) have a lower fish diversity (Bouchereau *et al*. 2000, Jaafour *et al*. 2015) than eastern ones (Kraïem *et al*. 2009, present study). Further studies on North African lagoons are needed to verify and interpret this trend. What is the influence of the Suez Canal?

A small number of species dominated the assemblage as in numerous other lagoons (Franco *et al*. 2008, Maci & Basset 2009, Embarek *et al*. 2017). The shallow water fish assemblage in Bizerte Lagoon was dominated, in terms of fish abundance, by the big-scale sand smelt *A. boyeri* (69.49 % of total catches), which is the only commercial euryhaline finfish that reproduces in coastal lagoons. The dominance of this resident species is a common feature of the fish assemblage of different Mediterranean lagoons (Bouchereau *et al*. 2000, Koutrakis *et al*. 2005, Franco *et al*. 2008, Manzo *et al*. 2016, Embarek *et al*. 2017). In terms of feeding groups, the fish assemblage was also largely dominated quantitatively by hyperbenthivore/zooplanktivore fish feeder species (HZ = three species representing 71 % of total catches) as observed in Mellah Lagoon (88.6 % of total catches, Embarek *et al*. 2017). However, microbenthivores (Bmi) were dominant in the fish assemblage in terms of species number suggesting the importance of the benthic compartment in providing food (as detritus). In 19 northern Mediterranean lagoons, microbenthivory was the dominant feeding mode among fish followed by detritivory and omnivory, while the other categories were less represented, particularly herbivores (Franco *et al*. 2008). It has been suggested that lagoons and estuaries, which receive regular inputs of freshwater, as is the case of many European transitional waters, usually have a phytoplankton- and microphytobenthos-dominated trophic structure (Elliott *et al*. 2002, Franco *et al*. 2008). Although, southern Mediterranean coastal lagoons, for climatic reasons, often receive very little freshwater, the feeding functional group categories are similar to those observed in European lagoons. The lowest incidence or absence of herbivores was a common feature of Mediterranean lagoons and more generally for European transitional water fish assemblages (Franco *et al*. 2008, Jaafour *et al*. 2015, Manzo *et al*. 2016).

The fish assemblage differed between seasons both in terms of fish abundance and diversity and also in terms of functional group composition. Temporal variations in total abundance reflect fluctuations in the most dominant species, which in this case are *A. boyeri* and *P. tortonesei*. Fish abundance in Bizerte Lagoon peaked in autumn and species diversity was higher in spring and autumn. In autumn, winter and summer, resident species constituted the most abundant ecological guild in the lagoon as described in other lagoons (Akin *et al*. 2005, Embarek *et al*. 2017). In autumn and spring, the fish assemblage was characterized by the large share of marine migrant species and various feeding groups. This can be ascribed to the seasonality of the colonization of the lagoon environment by marine migrant species. Seasonal variation in the fish community structure of coastal lagoons is well documented, with the recruitment of many juveniles of marine species during the spring and late summer, resulting in an assemblage dominated by a larger number of species (Pérez-Ruzafa *et al*. 2007, Maci & Basset 2009, Jaafour *et al*. 2015). Fish species richness in coastal lagoons is in great part determined by colonization rates from the neighbouring coastal zone and depends on the rate of water exchange between the sea and the lagoon (Mariani 2001, Perez-Ruzafa *et al*. 2006, Embarek *et al*. 2017).

The temporal evolution of the length-frequency distribution showed that the mean size of the most abundant species (*A. boyeri, P. tortonesei, A. fasciatus*, and *S. abaster*) increased from summer to spring. This pattern in growth was particularly clear for the two resident species *A. boyeri* and *A. fasciatus* with the smallest sizes during summer suggesting that the reproduction of these species occurs mainly during spring/early summer (Boudinar *et al*. 2016). The most abundant species had a mean length under 8 cm and most caught specimens were juveniles, with the exception of *A. boyeri*, *A. fasciatus, P. marmoratus* and *S. abaster* which were mainly adult individuals. This suggests that the Bizerte Lagoon acts as nursery habitats for juvenile fish (Franco *et al*. 2006b, Maci & Basset 2009, Jaafour *et al*. 2015).

The Bizerte Lagoon, like several Mediterranean lagoons, is subject to increasing pressure from anthropogenic activities (urbanization, industry, pollution, aquaculture, tourism, overfishing). The consequences of such anthropogenic pressures have been detected on the general state of ecosystems, mainly in macrofauna, which is more sensitive and more exposed (Afli *et al*. 2008, Ben-Khedher *et al*. 2013). Although the hydrological parameters measured were uniform across the lagoon, the spatial analysis based on fish abundance revealed three groups of stations. Station 4, located on the west part of the lagoon, was characterized by the lowest fish diversity and abundance but also smaller fish size. This may be related to unfavorable environmental conditions since this area of the lagoon is the most heavily industrialized area and characterized with muddy sediments (Brahmi *et al.* 2013). In this area, the levels of metals and hydrocarbons were higher in the seawater and sediments than at the other sampling sites (Ben-Khedher *et al.* 2013, Zaaboub *et al.* 2016), which may represent a threat for aquatic wildlife. The fact that fish are smaller may either reflect the fact that the habitat is a nursery for the smallest individuals or that growth conditions are lower due to the poor quality of the habitat. In contrast, the northeast sector (stations 2 and 3), without an influence of major streams, is largely influenced by the seawater input and is located in the aquaculture part of the lagoon which contributes to the increase in organic matter flux to the bottom promoting the development of the benthic food web (Brahim *et al.* 2013, Martins *et al.* 2016). In addition, rearing structures can provide shelter for juvenile fish. The highest fish diversity and abundance were recorded in this area which is characterized by a sandy bottom and the presence of the seagrasses *Cymodocea nodosa* and *Zostera noltii*. Such environmental conditions may offer favorable shallow habitats for young fish (nursery areas). Fish assemblages are known to be highly sensitive to changes in vegetated and substrate characteristics (Franco *et al.* 2006a, Ribeiro *et al.* 2006, Pérez-Ruzafa *et al.* 2007). Finally, station 1, located in the channel which is largely influenced by the connection with the sea, was characterized by the presence of the highest number of marine migrant and detritivore species. Salinity is usually considered as the major driving factor of spatial patterns of fish fauna diversity and abundance in many lagoon systems (Akin *et al.* 2005, Pérez-Ruzafa *et al.* 2007, Maci & Basset 2009). Pérez-Ruzafa *et al.* (2011b) suggested that the main factor structuring lagoon fish assemblage and which, to a certain extent, integrates all the other factors is related to the degree of isolation from the sea. This salinity effect was not so strong in the Bizerte Lagoon.

In conclusion, the fish assemblage of the shallow waters (< 1.5 m) of the Bizerte Lagoon are quantitatively dominated by a small number of species. The most abundant of these are the resident species *A. boyeri*, *A. fasciatus* and *P. tortonesei*. The latter species is endemic to the south-central Mediterranean Sea and is listed as an endangered species (IUCN Red List). The seasonal and spatial patterns in species richness, abundance and functional group composition seem to be mainly affected by the colonization rates from the adjacent coastal zone. However, the habitat characteristics (presence of macrophytes or shellfish farming, pollution) may also have affected the fish assemblages. The Bizerte Lagoon represents a fragile environment due to its enclosed nature and the growing anthropogenic activities in the surroundings as well as the management of freshwater inputs due to the construction of locks in the Tinja Channel. The lack of historical data on fish fauna prevents us from evaluating the consequences of the evolution of the lagoon such as the increasing anthropogenic pressures or the construction of locks in the Tinja Channel. This study may serve as a reference for future studies to evaluate the consequences of lagoon evolution under the effect of global change. Additional studies of the fish fauna based on monthly and long-term monitoring and taking into account more precisely the characteristics of the habitats (i.e., hydrological conditions, presence of macrophytes and shellfish farming, type of sediments, availability and abundance of prey species, level of pollution) may be useful for detecting human impact on the fish populations of the Bizerte Lagoon and to propose/adopt suitable management strategies.

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