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What role do environmental and anthropogenic factors play in the variability of benthic macrofauna in the northern lagoon of Tunis?

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Abstract: The northern lagoon of Tunis is closed, except for a limited communication with the sea via a very narrow channel. It is subjected, as the majority of Mediterranean lagoons, to environmental/anthropogenic constraints related mainly to the slowness of circulation and renewal of its waters, and also to surrounding human activities. Fifteen stations distributed in the northern lagoon of Tunis were sampled seasonally. The main physicochemical parameters of the water and the sediment were measured and the macro-invertebrates were sampled and identified. Results show that the nitrogen and phosphorus nutrients are relatively low in the study site compared with other Tunisian and Mediterranean lagoons, and the dissolved oxygen content and the pH are relatively satisfactory. However, the temperature and salinity which are higher compared with other Tunisian lagoons show remarkable seasonal variations, and seem to play interesting role in shaping community structure. Thus, the macrofauna community is poorly diversified and impoverished during warm/dry seasons, but slightly improved with precipitation and flow of freshwater during cool/rainy seasons. According to our own results and those of the literature, it seems that the northern lagoon of Tunis has for several years been affected by some major factors, mainly high temperature and salinity, sediment silting and perhaps an excess of organic matter. This has led to deep changes in the macrofauna community before being in its current status.

Introduction

Since the beginning of the 20th century, the need to satisfy a growing world population has led to a strong industrialization which has affected almost all economic sectors. This has clearly impacted the ecological quality of the environment and the equilibrium between species within communities, already affected by climate change. The economic interest and ecological importance of the coastal marine areas, which are a nursery for most organisms and where main primary production take place, have prompted the international scientific community to invest in the field of marine ecology (Van Hoey et al. 2010, Rice et al. 2012). Thus, since the pioneering work of Petersen (1918), the ecological studies of benthic communities have multiplied and the methods and models using assemblages to detect the ecological status of marine coastal areas have proved to be promising (Afli et al. 2008b).

Transitional waters, particularly estuaries and lagoons, represent important and fragile ecosystems in the coastal landscape, providing key ecosystems services such as fisheries resources, habitat and food for migratory and resident animals, and recreational areas for human populations (Islam and Tanaka 2004). These areas are continuously subjected increasingly to harmful human activities.

In general, the Mediterranean region is of sub-wet shade climate type, the summer is hot and dry and the winter is cool and rainy. These general particularities and also some other regional characteristics, such as the fluctuations of floods, temperature and salinity give some specificities to the Mediterranean biocoenoses (Pérès 1972, Bellan-Santini et al. 1994, Lardicci et al. 1997, Albertelli et al. 1999, Salen-Picard and Arlhac 2002). These special characteristics seem to be the most important factors in affecting the macroinvertebrate fauna in the northern lagoon of Tunis with the decrease of human impacts over time (Diawara et al. 2008, Tlig-Zouari and Maamouri-Mokhtar 2008).

In Tunisian lagoons, studies carried out on benthic macro-invertebrates are generally few; among them Ben Souissi (2002) had studied the southern lagoon of Tunis, Chakroun (2004) and Afli et al. (2009b, 2009c) both the southern lagoon of Tunis and the lagoon of Ghar El-Melh, Khedhri et al. (2016a, 2016b, 2016c) the lagoon of Boughrara, Afli et al. (2009a) and Zaabar et al. (2014) the lagoon of Bizerte, etc.

Benthic invertebrates have been largely used as bio-indicators for aquatic monitoring because they respond rapidly to anthropogenic and natural stressors (Pearson and Rosenberg 1978, Munari and Mistri 2012). Furthermore, they have relatively long life spans, meaning they are unable to escape disadvantageous conditions and allowing their use in evaluation of accidental and chronic variations (Dauvin1993, Reiss and Kroncke 2005, Khedhri et al. 2015, 2016c). Studies carried out on benthic macrofauna in the study site are generally very few (Afli et al. 2008a), and after the restoration measures (Chouari 2015), the benthic community was not yet studied except for the works undertaken by Diawara et al. (2008) and Tlig-Zouari and Maamouri-Mokhtar (2008). These researches focused on the recovery of the macroinvertebrates community in response to sanitation period. According to these studies, the managements of 1984-1988 have led to major positive changes in the physicochemical characteristics of the sediment and the water (Chouari 2015), which led, in turn, to remarkable changes in the benthic community. In fact, a total of 226 macrobenthic species have been collected from the northern lagoon of Tunis since the work of Wesenberg-Lund (1939) until last studies conducted in 2003-2004 by Diwara et al. (2008). But certain species disappeared (37 species), others appeared (139 species), and only 87 species were present before and after managements (Diwara et al. 2008).

Facing this lack of information, this study proposes to assess the ecological status of the benthic organisms in the northern lagoon relying on their trophic organization and ecological features and to analyze the main physicochemical parameters governing the functioning of this transformed lagoon ecosystem. The temporal variation of the ecological quality of the lagoon, which could provide some answers to the current status, will be also studied. Marine surveys will be conducted seasonally, while the historical data available in the literature would also allow understanding the long-term changes in the community composition and structuring related to main human and natural constraints.

Materials and methods

Study site

The northern lagoon of Tunis is a shallow seawater body (depth < 4 m) covering 2600 ha area and located close to the city of Tunis (Fig. 1). It was formerly part, with the southern lagoon, of a unique lagoon that was divided in 1885 by a railway and a road made following the digging of the navigation canal (12 km) (Ben Charrada 1992, Chouari 2015). It is connected to the open sea (gulf of Tunis) by only a narrow channel at Kheireddine town and to the southern lagoon by few channels (Trabesli et al. 2013). A sea wall (pathway), 5-8 m large and 8.2 km long, has been created in 1988 following the implementation of the new water circulation system subdividing the northern lagoon and favoring the circulation of marine waters (Tlig-Zouari and Maamouri-Mokhtar 2008, Chouari 2015). The weather reports of the National Institute of Meteorology of Tunisia show that in the study area the main air temperature ranges between 11.5°C in winter and 29.1°C in summer, evaporation varies between 10.7 and 144 mm in September and August respectively and the mean annual rainfall is about 457 mm. Maximum water temperatures reach 30°C in summer (Armi et al. 2012). The salinity is slightly higher than that of the Gulf of Tunis, mostly in summer in the southern shallow part when it can reach 42 due to high evaporation and low rainfall. This site has long been the major receptacle of urban/industrial discharges from the Tunis City and its suburbs with a settlement estimated in 2014 to approximately 2,643,695 inhabitants, and also from other diverse pollution sources as ports and power stations (Armi et al. 2008, 2010, 2011). The persistence of these factors led to a progressive establishment of eutrophic conditions (Chouari 2015). Accordingly, periodic anoxia, fish kill and mortality and extinction of benthic fauna, especially in the west part of the lagoon, have occurred (Molinier and Picard 1954, Harbridge et al. 1976, Zaouali and Beaten 1983, 1984, Belkhir 1984, Bahri Trabesli et al. 2013). To resolve this pollution problem, a sanitation project was applied. It consisted firstly of the establishment of a fitted circulation water system and the reduction of its residence time in the lagoon, then of dredging the sediment, regulating the macroalgal biomass and stopping the entry of waste water (Chouari 2015). Only urban storm water runoff was permitted to prevent flood (Bahri Trabelsi et al. 2013). Consequently, the nutrient concentrations decreased and large changes of the plant communities have been reported (Ben Charrada 1992, 1995, Ben Maiz 1993, Bahri Trabelsi et al. 2013). Ben Charrada (1992) noticed the first proofs of northern Tunisian lagoon sanitation that appeared just after the decrease of very eutrophic areas showed by the vanishing of *Ulva rigida* and *Enteromorpha*'s biomasses and the reduction of *Ficopomatus enigmaticus* and the disappearance of red water phenomenon's. Diwara et al. (2008) have conducted in 2003-2004, fifteen years after managements, an interesting study of this site. They showed a global amelioration of ecological parameters compared to extreme values recorded before managements (Ben Charrada

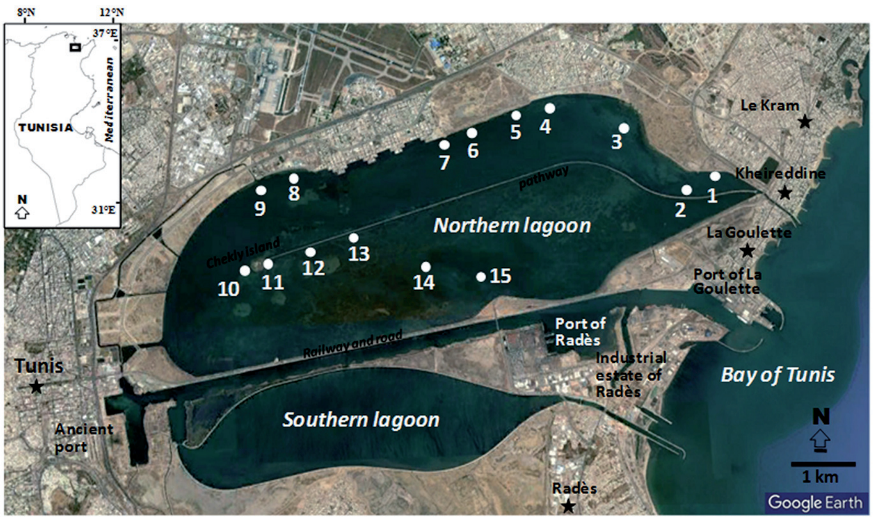


Figure 1. Study area with location of sampling stations (1 to 15) (Google Earth, 2016).

1995). The sediment was sandy (fine sand, medium sand and coarse sand) in all the lagoon and the macrobenthic community was diversified with 189 species whose 64 polychaetes, 51 molluscs, 48 arthropods and 26 species belonging to 8 other phyla (Diwara et al. 2008).

Sampling and laboratory procedures

In total, 15 stations that covered almost all the northern lagoon of Tunis were sampled (Table 1). Marine surveys were carried out seasonally aboard a research vessel during 2015-2016, October 21-22 (autumn), January 26-27 (winter), April 26-27 (spring) and August 4 (summer). Sampling stations were located using a Magellan Explorist 210 GPS. Field measurements of physicochemical parameters as water temperature, dissolved oxygen were measured by a WTW multi 3410. Salinity was measured by a WTW cond3310 conductivity meter and pH by a 330i pHmeter. Water destined to nutrients and chlorophyll *a* determinations was taken in 1000 ml polypropylene containers, and then filtered in the laboratory using Whatman GF/C glass fiber filter. The chlorophyll *a* concentrations were assessed according to spectrophotometric methods (Lorenzen and Jeffrey 1980). Unfiltered water fractions were used to determine total phosphorus (TP) and total nitrogen (TN), while filtered ones to assess nitrites (NO_2^-), nitrates (NO_3^-) according to colometric Griess reaction (Aminot and Kérouel2004). Phosphates (PO_4^{3-}) were analyzed according to Murphy and Riley (1962).

A scuba diver collected samples intended for macrofaunal studies at seasonal intervals with a 0.09 m^2 quadrat (10 cm depth). Thus, 3 replicates were taken at each station/survey for biological analysis and another for sediment grain size. Biological samples were gently sorted out through a 1 mm mesh sieve and preserved in a 7% formaldehyde/seawater solution to sort out the macrobenthic organisms (Anonymous 2003, Sokołowskiet al. 2015). The collected animals were conserved with diluted alcohol (50%) before identification, for most of them, up to species level. The sediment grain size was determined by drying for 48 hours at 60°C, then washed through a 63 mm sieve in order to eliminate the thin fraction (silt and clay) (Afli and Chenier 2002). The refuse was dried again at 60°C, after that all samples were filtered on AFNOR succession meshes (Holme and McIntyre 1984). Consequently, the quantity of sediment recovered in each sieve represents the sedimentary fraction of size ranging between its meshes and those of the top sieve.

Data analysis

The most common and appropriate macrofauna biodiversity indices that describe the ecological status were determined at each station/season. Thus, the abundance (A, number of individuals/m^2), the species richness (S, number of species), the Shannon index (H') (Shannon and Weaver 1963) and the evenness (J') (Pielou 1966) were calculated. Two biotic indices, AMBI (Borja et al. 2000) and BENTIX (Simboura and Zenetos 2002) based on the sensitivity of benthic macrofauna species to organic pollution (Glémarec and Hily 1981), were calculated for the assessment of environmental quality. The assignment of species into their respective ecological groups (I: sensitive species, II: indifferent species, III: tolerant species, IV: second-order opportunistic species and V: first-order opportunistic species) was relied on AMBI taxa list and expert opinion (as suggested by Borja and Muxika 2005). Identified species were also assigned into trophic groups according to Fauchald and Jumars (1979), modified notably by Grall and Glémarec (1997), Hily and Bouteille (1999), Afli and Glémarec (2000), Pranovi et al. (2000) and Afli et al. (2008a) (Table 2) :

Table 1. Characteristics of sampling stations.

Station	Latitude °N	Longitude °E	Depth (m)	% mud (< 63 µm)
1	36.82947	10.29980	0.5	0.17
2	36.82663	10.29468	0.6	87.67
3	36.83612	10.28393	1.3	10.10
4	36.83918	10.27032	1.3	15.28
5	36.83883	10.26410	0.8	86.90
6	36.83627	10.25601	0.9	68.30
7	36.83452	10.25083	0.9	3.20
8	36.82918	10.22365	1.0	72.14
9	36.82677	10.21865	1.2	0.51
10	36.81517	10.21603	1.0	1.55
11	36.81727	10.21980	0.5	1.65
12	36.81863	10.22720	0.5	3.60
13	36.82073	10.23475	0.5	14.45
14	36.81665	10.24780	1.4	67.07
15	36.81438	10.25863	1.5	2.80

Table 2. Principal trophic groups identified in this study in 2015-2016.

Trophic group	Code	Definition	Examples
Micrograzers	µG	Feeding on benthic microalgae, bacteria and microbial detritus.	Essentially polyplacophores and gastropods
Suspension feeders	SF	Feeding on suspensed food in the water column.	Most bivalves
Non-selective deposit feeders	NSDF	Burrowers which ingest the sediment from which they take their food.	Mainly sedentary polychaetes as *Notomastus latericeus*
Selective deposit feeders	SDF	Feeding on organic particles settled on the sediment	Most sedentary polychaetes and some bivalves and crustaceans
Detritus feeders	DF	Feeding on particular organic matter, essentially vegetable detritus	Mainly amphipods and tanaids
Carnivores	C	Predatory animals	Mobile polychaetes, sea anemones

Table 3. Seasonal values measured in 2015-2016 for main physicochemical factors (T: temperature; S: salinity; O_2: dissolved oxygen; pH; NO_2^- : nitrite; NO_3^- : nitrate; N-total : total nitrogen, PO_4^{3-} : phosphate, P-total : total phosphorus) and chlorophyll *a* (Chl *a*) over seasons (Sp : spring; S : summer; A : autumn and W : winter). %Mud: sediment fraction whose grain size < 63 µm.

		Stations														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
% Mud (< 63 µm)	A	0.17	87.67	10.10	15.28	86.90	68.30	3.20	72.24	0.51	1.55	1.65	3.60	14.45	67.07	2.80
T (°C)	A	18.80	18.80	18.80	18.90	19.20	18.90	18.00	18.00	18.60	18.80	18.90	18.80	18.80	18.30	18.20
	W	12.80	10.80	11.40	11.40	11.70	11.30	10.80	10.80	10.80	10.80	10.60	10.90	10.80	11.10	11.30
	Sp	19.30	19.40	19.30	19.20	19.70	19.00	19.50	19.40	19.50	19.30	19.40	19.30	19.40	19.80	19.60
	S	25.00	25.50	25.20	26.20	26.10	26.30	26.50	25.60	26.20	26.20	26.70	25.80	26.20	25.90	25.80
S	A	37.10	37.30	36.90	36.80	36.70	36.60	36.60	36.60	36.60	37.00	37.00	37.30	37.60	38.50	38.20
	W	36.60	35.80	36.50	36.50	36.50	36.00	36.40	36.40	36.40	36.90	36.90	36.40	36.80	36.60	36.60
	Sp	35.40	35.80	34.60	35.50	35.90	35.80	35.50	35.90	35.50	35.70	35.80	35.90	35.70	35.90	35.70
	S	38.10	38.30	38.80	38.60	38.60	38.50	38.70	39.40	39.20	40.00	40.40	41.30	42.60	40.00	39.50
O_2 (mg l^{-1})	A	8.35	8.52	8.50	8.52	8.52	8.50	8.52	8.51	8.51	8.52	8.56	8.50	8.52	8.52	8.50
	W	8.31	8.26	8.28	8.29	8.31	8.28	8.30	8.29	8.32	8.32	8.30	8.30	8.29	8.22	8.21
	Sp	8.25	8.32	8.12	8.28	8.31	8.24	8.26	8.35	8.41	8.30	8.41	8.45	8.20	8.00	8.20
	S	6.30	6.50	5.00	5.00	5.40	5.40	5.20	4.80	5.20	7.50	7.97	6.70	4.65	6.41	6.45
pH	A	8.32	8.37	8.42	8.45	8.44	8.41	8.44	8.44	8.47	8.48	8.47	8.42	8.41	8.52	8.55
	W	8.31	8.26	8.28	8.29	8.31	8.28	8.30	8.29	8.32	8.32	8.30	8.30	8.29	8.22	8.21
	Sp	8.26	8.30	8.28	8.28	8.34	8.26	8.31	8.35	8.38	8.44	8.39	8.40	8.28	8.37	8.40
	S	8.25	8.27	8.22	8.28	8.34	8.38	8.40	8.43	8.40	8.50	8.51	8.47	8.40	8.42	8.59
NO_2^- (µg l^{-1})	A	8.83	9.34	2.66	21.56	2.01	3.15	2.01	8.83	6.47	2.99	6.64	22.48	7.65	3.32	2.01
	W	13.84	9.17	6.64	10.88	15.78	7.31	13.31	14.72	8.66	7.48	11.57	12.44	11.75	14.19	7.31
	Sp	19.00	2.83	2.67	2.50	4.81	3.15	2.50	2.17	1.68	20.82	1.03	3.48	3.32	5.30	5.47
	S	6.64	4.47	1.85	1.03	3.81	3.48	1.52	8.15	2.99	5.80	0.39	3.32	9.00	4.31	1.36
NO_3^- (µg l^{-1})	A	14.92	4.16	2.86	0.30	13.59	4.67	2.30	4.83	15.46	7.33	0.19	8.03	7.89	4.04	3.18
	W	20.16	17.44	11.93	9.87	4.46	14.79	8.45	6.04	16.37	14.80	4.19	2.19	6.98	9.80	12.09
	Sp	22.78	21.35	31.34	15.57	13.09	88.55	9.40	104.53	51.03	21.74	29.50	32.19	19.47	34.93	146.83
	S	19.61	10.48	3.98	5.86	5.72	4.65	10.70	0.02	2.99	4.83	8.99	7.88	13.62	7.91	6.31
N-total (µg l^{-1})	A	170.60	503.33	595.33	103.33	210.90	720.67	216.47	370.67	560.33	963.33	984.33	756.67	1030.33	1113.33	1016.67
	W	695.33	749.00	544.00	868.00	868.00	1043.00	963.33	1046.00	1232.33	925.00	1330.67	1518.00	1390.67	1258.00	1068.00
	Sp	607.00	477.00	528.00	288.83	446.33	470.33	318.33	804.67	340.33	450.67	567.00	922.33	1283.33	1271.67	1903.33
	S	143.70	170.98	366.67	626.33	127.97	616.67	963.33	865.00	772.67	854.00	887.67	876.00	1308.33	1574.00	972.33
PO_4^{-3} (µg l^{-1})	A	14.69	0.49	27.41	11.25	1.84	16.34	22.93	20.64	1.50	8.23	13.23	16.89	1.33	1.16	17.64
	W	7.61	4.23	4.23	3.54	8.76	2.01	4.96	4.06	6.65	2.18	1.85	21.21	5.96	1.84	3.03
	Sp	4.06	3.38	2.18	2.35	1.84	4.74	3.37	5.78	0.66	0.83	13.21	7.17	4.48	7.03	1.16
	S	4.06	1.70	5.96	2.69	2.51	2.01	6.30	1.50	4.57	4.92	0.66	9.10	5.96	1.00	4.74
P-total (µg l^{-1})	A	31.88	4.82	4.96	20.21	13.83	15.98	6.40	10.06	20.86	16.44	8.59	13.21	19.58	10.81	23.29
	W	10.51	16.90	10.51	7.85	18.79	9.32	31.35	45.19	22.48	36.48	9.77	22.48	38.10	5.11	21.66
	Sp	15.35	14.59	13.06	15.35	13.36	33.98	12.46	19.43	9.77	8.59	91.90	31.53	16.13	23.78	14.74
	S	23.51	23.78	4.92	10.71	16.34	19.14	11.25	11.07	16.53	16.14	7.35	14.86	23.51	23.90	13.95
Chl a (µg l^{-1})	A	2.44	4.27	8.53	3.05	4.88	9.14	3.05	1.83	3.05	2.44	2.44	0.61	6.09	3.66	2.44
	W	0.60	0.61	1.22	0.61	7.31	2.44	0.61	0.61	1.83	<0.01	4.27	3.05	2.44	2.44	2.44
	Sp	<0.01	1.22	<0.01	3.05	2.44	1.83	3.05	0.61	0.61	<0.01	0.61	0.61	1.83	1.83	<0.01
	S	1.22	2.44	1.22	1.22	3.66	9.14	3.05	1.83	1.22	0.61	2.44	1.83	<0.01	<0.01	1.83

Table 4. List of principal species collected in the northern lagoon of Tunis during the 4 seasons of 2015–2016. P: occurrence (percentage of stations where the species was collected), HA: high abundance (ind.m^{-2}). TG: trophic groups, EG: ecological groups.

Species	TG	EG	Autumn		Winter		Spring		Summer	
			P	HA	P	HA	P	HA	P	HA
Capitella capitata (Fabricius, 1780)	NSDF	5			6.7	4	6.7	3		
Cerastoderma glaucum (Bruguière, 1789)	SF	3	60.0	30	60.0	59	26.7	78	6.7	81
Cerithium vulgatum (Bruguière, 1792)	SDF	1	13.3	48						
Dosinia exoleta (Linnaeus, 1758)	SF	1					6.7	3	13.3	7
Dysidea sp. (Johnston, 1842)	SF	1					6.7	3		
Gammarus sp.	DF	1			6.7	7				
Gibbula varia (Linnaeus, 1758)	µG	1	26.7	15	6.7	15				
Glycera tridactyla (Schmarda, 1861)	C	2	6.7	11	33.3	7	6.7	1		
Hexaplex trunculus (Linnaeus, 1758)	DF	1	26.7	7	33.3	7			6.7	7
Hydrobia sp.	µG	3	6.7	18						
Lagis koreni (Malmgren, 1866)	NSDF	1			6.7	4				
Loripes orbiculatus (Poli, 1791)	SF	1	26.7	85	46.7	66	6.7	8		
Lumbrineris latreilli Audouin and Milne Edwards, 18340	C	2	20.0	4						
Nephtys hombergii Savigny in Lamarck, 1818	C	2	6.7	4	6.7	4				
Notomastus latericeus (Sars, 1851)	NSDF	3			13.3	4				
Orbinia bioreti (Fauvel,1919)	NSDF	1	20.0	7						
Paractinia (Andres, 1883)	C	1	13.3	7	6.7	4				
Paranemonia cinerea (Contarini, 1844)	C	1	13.3	7	33.3	26				
Perinereis cultrifera (Grube, 1840)	DF	3	20.0	4	13.3	7				11
Phylo norvegicus (M. Sars in G.O. Sars, 1872)	NSDF	1	40.0	7	26.7	7				
Polititapes aureus (Gmelin, 1791)	SF	1	6.7	4	33.3	22	6.7	11		
Processa canaliculata Leach, 1815 [in Leach, 1815-1875]	DF	1	6.7	7						
Ruditapes decussatus (Linnaeus, 1758)	SF	1	66.7	26	80.0	114	46.7	42		63
Sabella pavonina (Savigny, 1822)	SF	1	6.7	4						
Tricolia sp.	µG	1	13.3	4						

Most statistical analyses were carried out using STATISTICA 8 software (StatSoft, Inc. 2012). Statistically significant differences in the numerical values of abiotic variables and biotic indices were tested through analyses of variance (ANOVA). The normality of data was assumed; the ANOVA test was used when homogeneity of variance (Bartlett's test) was achieved. If significant heterogeneity was identified, data were $\log_{10}(x+1)$ transformed. To assemble the similar variables, correspondence factor analyses (CFA) were carried out using the software XLSTAT 2015 and CHI-2 as distance criteria on data organized in rectangular matrices where stations or seasonal surveys occupy the columns and parameters occupy the lines (Hill 1974, Lebart et al. 1982).

Results

The sediment in the northern lagoon of Tunis is heterogeneous, the fine fraction (< 63 µm) constitutes 67-88% at stations 2, 5, 6, 8 and 14, 10-16% at stations 3, 4 and 13, and less than 2% at the other stations (Table 3). The water temperature varies from 10.6°C in winter (station 11) to 26.7°C in summer at the same station, and the salinity from 34.6 (station 3 in spring) to 42.6 (station 13 in summer). It should be noted that stations inside the lagoon (stations 10-15) present the highest salinity values during summer (> 40). The dissolved oxygen ranges from 4.65 mg l^{-1} (station 13 in summer) to 8.50-8.56 mg l^{-1} in autumn at all stations, except at station 1 where the registered value is slightly lower (8.35 mg l^{-1}), and the pH from 8.21 (station 15 in winter) to 8.32-8.52 at stations 1-9, 13 and 14 in autumn, and to 8.47-8.59 at stations 10-12 and 15 in summer.

Nitrites vary from 0.39 µg l^{-1} (station 11 in summer) to 22.48 µg l^{-1} (station 12 in autumn). High values were recorded in winter (on average 11.00 µg l^{-1}), and low values in summer (on average 3.87 µg l^{-1}). Nitrates exceed 20 µg l^{-1} only in spring (stations 6 (88.55 µg l^{-1}), 8 (104.5 µg l^{-1}), 9 (51.03 µg l^{-1}) and 15 (146.8 µg l^{-1})). N-total varies from 103.30 µg l^{-1} (station 4 in autumn) to 1903 µg l^{-1} (station 15 in spring), and stations 10-15 show the highest values all year.

Phosphates range from 0.66 (station 9 in spring) to 27.41 µg l^{-1} (station 3 in autumn). The highest values are recorded in autumn (on average 11.70 µg l^{-1}), except at station 12 where the highest value is recorded in winter (21.21 µg l^{-1}). The minimum P-total content registered is 4.82 µg l^{-1} (station 2 in autumn) and the maximum exceeds 45.19 µg l^{-1} (station 8 in winter) only at station 11 in spring (91.90 µg l^{-1}).

Chlorophyll *a* concentrations range from 0 to 9.141 µg l^{-1} (station 6 in summer and autumn). On average, the highest concentrations are recorded in summer (3.86 µg l^{-1}) and the lowest in winter (1.18 µg l^{-1}).

In total, 25 species are identified (Table 4). The species richness varies from 0 (notably at station 8) to 9 (station 2 in autumn) (Fig. 2). The abundance is relatively low, not exceeding 170 ind.m^{-2} (station 14 in winter). It should be noted that in winter species are more present inside the lagoon (stations 9-15), whereas in summer they are confined facing the channel connecting the lagoon to the bay of Tunis (stations

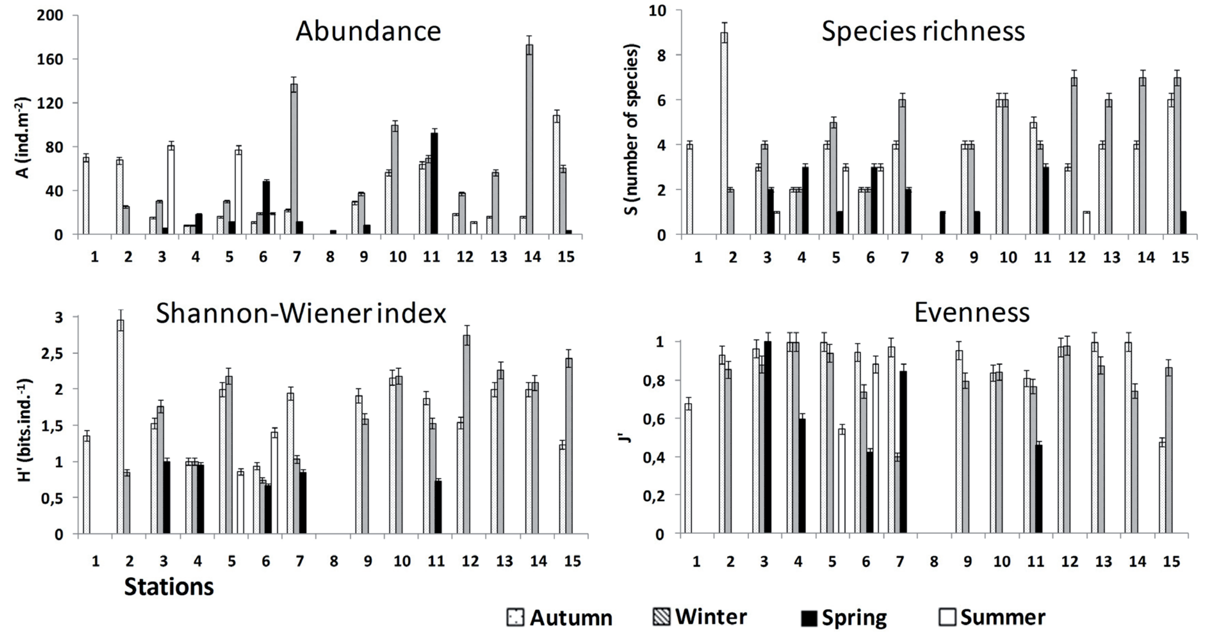


Figure 2. Seasonal variations of main macrofauna biodiversity parameters in the northern lagoon of Tunis in 2015-2016.

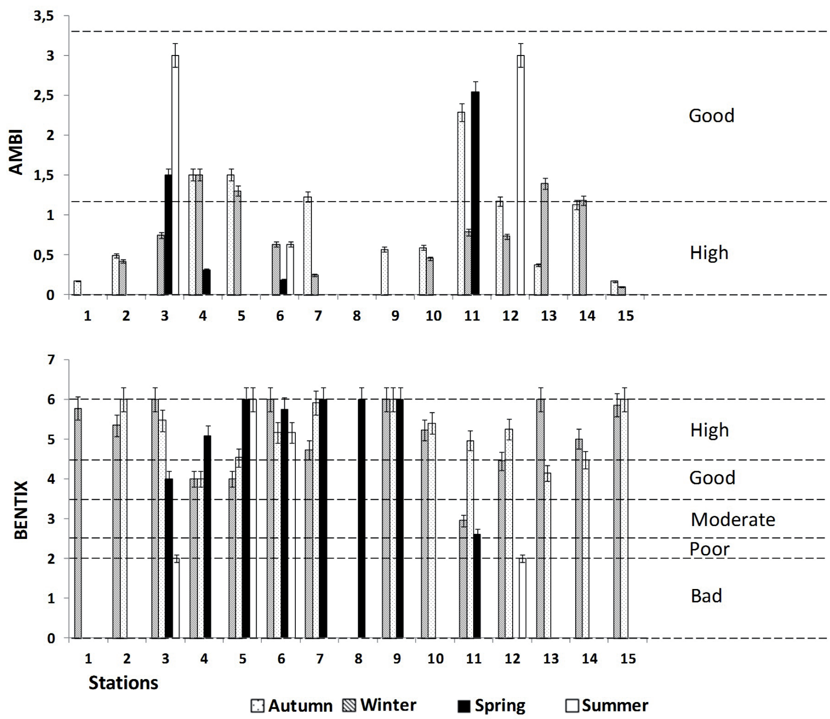


Figure 3. Seasonal variations of the biotic indices used and corresponding ecological statuses (2015-2016). Dotted lines: boundary limits of the ecological statuses.

Table 5. ANOVA, (F) and their significance levels (*P*) for main biotic and abiotic parameters.

Main effects	df	NO^{2-}		NO^{3-}		N-total		PO_4^{3-}		P-total			
		F	*P*	F	*P*	F	*P*	F	*P*	F	*P*		
Stations	14	0.85	0.615	0.532	0.901	4.8	<0.001	0.999	0.47	0.5	0.921		
Seasons	3	6	<0.001	11.13	<0.001	3.245	0.029	6.827	<0.001	1.169	0.33		
Main effects	df	Temperature		Salinity		O_2		pH		Chl*a*			
		F	*P*	F	*P*	F	*P*	F	*P*	F	*P*		
Stations	14	0.003	1	0.279	0.994	0.157	1	1.285	0.245	1.679	0.095		
Seasons	3	3160	<0.001	78.14	<0.001	86.96	<0.001	14.58	<0.001	4.959	0.004		
Main effects	df	S		A		H’		J’		AMBI		BENTIX	
		F	*P*	F	*P*	F	*P*	F	*P*	F	*P*	F	*P*
Stations	14	0.45	0.947	0.611	0.814	0.361	0.979	0.8	0.665	1.738	0.081	0.882	0.582
Seasons	3	16.63	<0.001	4.425	0.007	28.91	<0.001	25.94	<0.001	0.97	0.413	9.92	<0.001

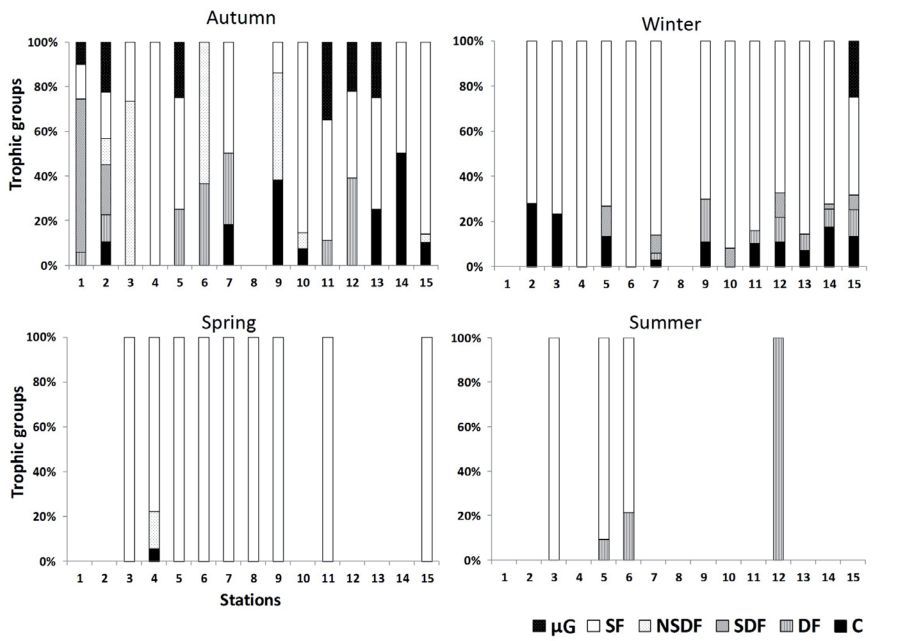


Figure 4. Seasonal variations of trophic groups of the benthic macrofauna in the northern lagoon of Tunis in 2015-2016. µB: micrograzers, SF: suspension-feeders, NSDF : non-selective deposit feeders, SDF: selective deposit-feeders, DF: detritus-feeders and C: carnivores.

1-6). The Shannon index reaches the maximum at station 2 in autumn (2.96 bits.ind^{-1}), and evenness varies in a broad range (0 to 1) but remains relatively high.

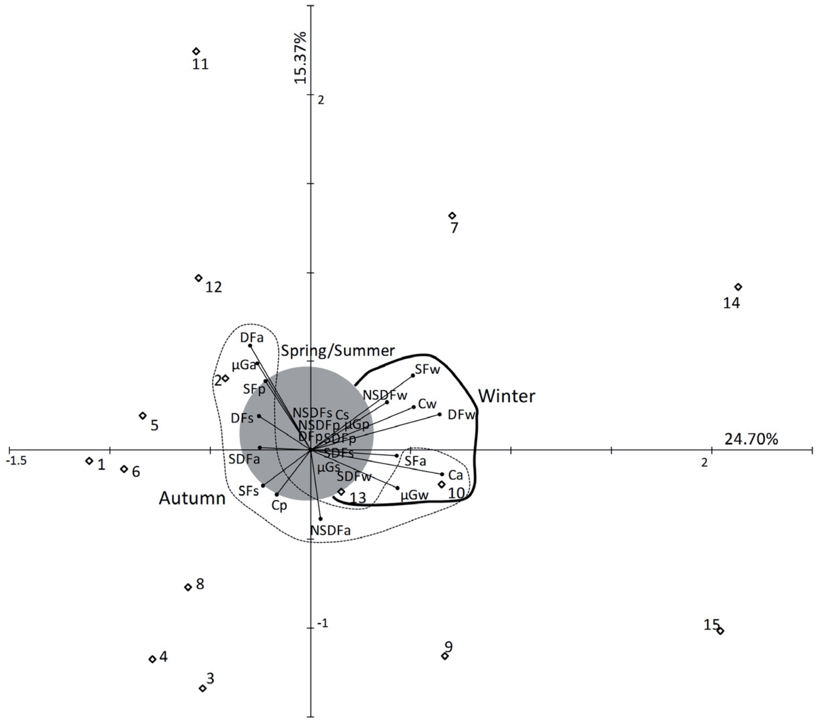
Biotic indices used classify almost all stations at a high and good ecological status, except a few stations classified by BENTIX at poor and moderate ecological status at certain seasons (stations 11 and 12) (Fig. 3).

The trophic structure of the benthic macrofauna is more balanced in autumn, especially facing the channel (stations 1-6) (Fig. 4). This situation changes in the winter with the dominance of suspension feeders (SF) that monopolizes resources in spring and summer.

The ANOVA test shows high significant difference among seasons ($p < 0.001$), but not among stations for most biotic and abiotic variables studied (Table 5). Only N-total shows significant difference among stations ($p < 0.001$), whereas AMBI does not show any significant spatiotemporal variations ($p = 0.081$ and 0.413, respectively).

Overall, the CFA analysis shows that trophic groups are more diversified in N-E (stations 1-7) in autumn and in S-W in winter (stations 9-15) (Fig. 5). However, spring and summer are grouped together in the center of the graph, and do not show notable trophic diversity. Those established separately on seasons regroup the stations in the center of graphs, except for a few stations because of some characteristic species, station 1 in autumn (*Cerithium vulgatum*), station 11 in spring (*Polititapes aureus* and *Cerastoderma glaucum*) and stations 3 and 5 in summer (respectively *Cerastoderma glaucum* and *Ruditapes decussatus*) (Fig. 6). The CFA analysis established on seasonal surveys shows that stations located at the entry of marine waters (stations 1-7) are clearly separated at certain seasons induced mainly by some characteristic species, as *Cerithium vulgatum* at stations 1 and 2 in autumn, *Cerastoderma glaucum* at station 3 in spring and *Dosinia exoleta* and *Hexaplex trunculus* at station 5 in summer and *Capitella capitata* at station 7 in winter (Fig. 7). The zoomed

Figure 5. CFA established on percentages of trophic groups at sampled stations in 2015-2016. µB: micrograzers, SF: suspension-feeders, NSDF: non-selective deposit feeders, SDF: selective deposit-feeders, DF: detritus-feeders, C: carnivores, p: spring, s: summer, a: autumn and w: winter.



graph shows that autumn surveys are widely dispersed compared with the other seasons, and summer ones are the most consolidated. The temperature and salinity, placed next to summer surveys, seem to play an important role in this seasonal distribution.

Discussion

Physicochemical parameters

The water salinity exceeds in summer 40 inside the lagoon (stations 10-15), and even reached 41.3 at station 12 and 42.6 at station 13. While, it does not exceed at the same season on average 38.5 facing the seawater entrance (stations 1-7). This summer increase in salinity (3.83 on average) is associated with the general rise in temperature whose gradient can reach on average 15°C (11.15°C in winter to 25.95°C in summer). This high gradient of salinity is mainly due to the high values recorded in summer inside the lagoon. The adjacent southern lagoon of Tunis shows also no notable spatial-temporal variation in water temperature as the northern lagoon, but shows a clear difference in salinity that varied during 2001-2009 (after managements) from 36.6 to 37.7, exceptionally to 39 (July 2003) during a period of heat and drought (Ounifi Ben Amor 2016). This results from a restricted water exchange in the northern lagoon, and more active circulation, mixing and renewal of waters in the southern lagoon due to locks and forced exit gates of waters (Trabelsi et al. 2013, Chouari 2015). For this reason, temperature and salinity seem to play a paramount role in the composition and distribution of benthic macrofauna communities in the northern lagoon of Tunis, as shown in the CFA analyzes. In comparison with other Mediterranean lagoons, physicochemical parameters are clearly more homogeneous in the northern lagoon of Tunis, and waters are relatively warmer and more salty. As example, in the lagoon of Smir (Morocco), the temperature and salinity are lower and the dissolved oxygen content is clearly higher (on average 19.17°C, 34.55 and 11.70 mg l^{-1} respectively, versus 19.41°C, 35.64 and 8.27 mg l^{-1} in the northern lagoon of Tunis) (Chaouti and Bayed 2008). In addition, physicochemical parameters are clearly more heterogeneous in the lagoon of Smir, they vary in a wider range of values, 17.78-20.82°C for temperature, 24.88-36.26 for salinity and 7.45-14.80 mg l^{-1} for dissolved oxygen (Chaouti and Bayed 2008).

On the contrary, the grain size of the sediment does not seem to be a primary factor structuring the benthic macrofauna in the northern lagoon of Tunis, since no relationship between the mud rate and the community was observed in the various statistical analyzes carried out. As example, muddy sediments (stations 2, 5, 6, 8 and 14) do not show any notable faunistic affinity between them. It seems that there are other factors more important that govern the community organization according to Afli et al. (2008b), who noted that in the absence of stressors, the organization of the benthic communities depends primarily on the resources (food and space) available and the habitat type (e.g., sediment grain size). However, in a stressed area, this relationship is not always possible because other intrinsic characteristics of the species (resistance, tolerance and opportunism) can play increasing roles (Khedhri et al. 2016b). However, the sediment in the northern lagoon of Tunis became currently clearly more silted compared to 2003-2004 when it was exclusively sandy (fine sand, mean sand and coarse sand) (Diwara et al. 2008, Chouari 2015). The pH values recorded exceed 8.21, which means that it is seawater, and these values are even higher in

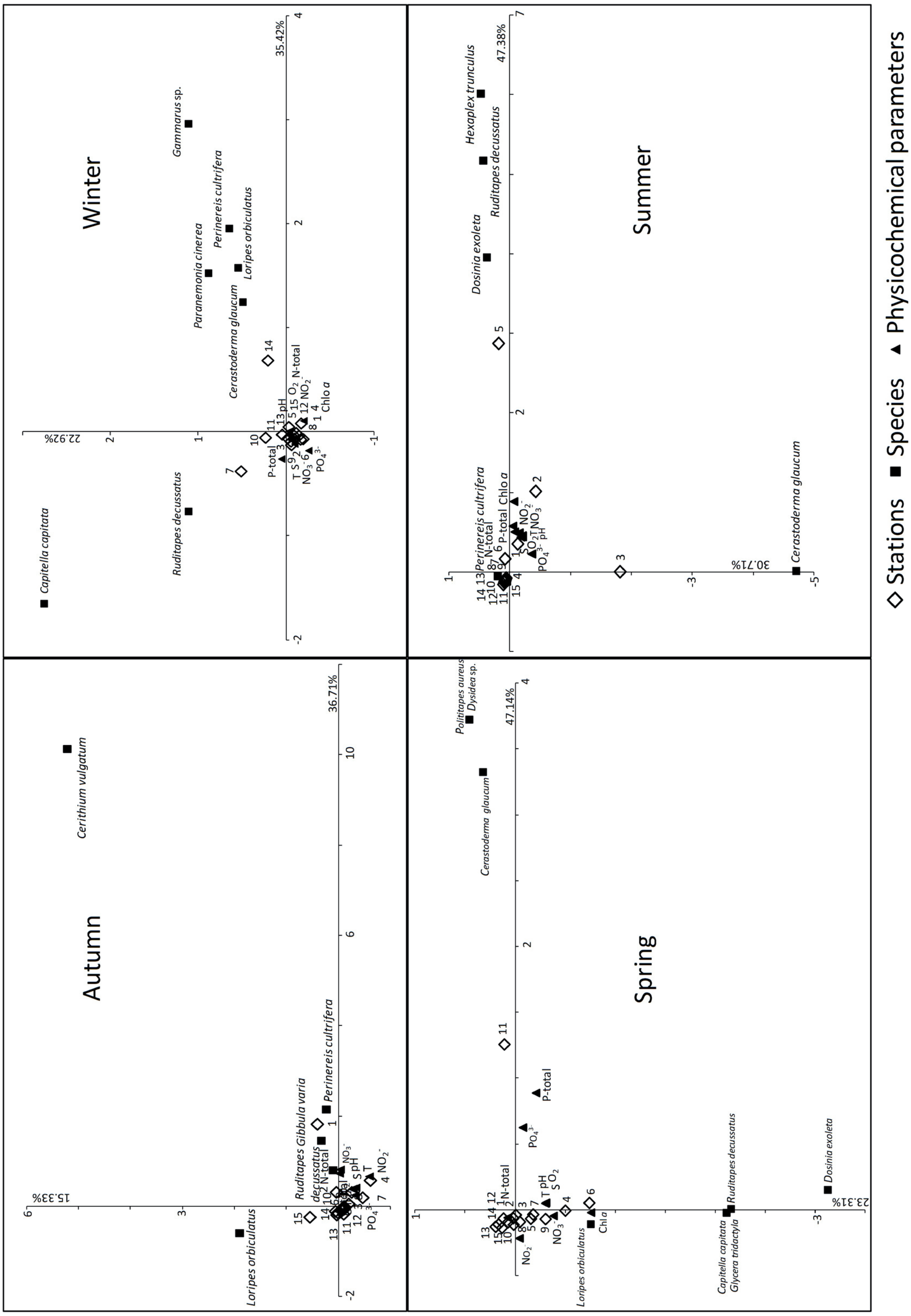


Figure 6. CFA established on macrofauna abundances, main physicochemical parameters and chlorophyll *a* at sampled stations in 2015-2016. T: temperature, S: salinity, O_2: dissolved oxygen, NO_2^-: nitrites, NO_3^-: nitrates, N-total: total nitrogen, PO_4^{3-}: phosphate, P-total: total phosphorus, Chl *a*: chlorophyll *a*.

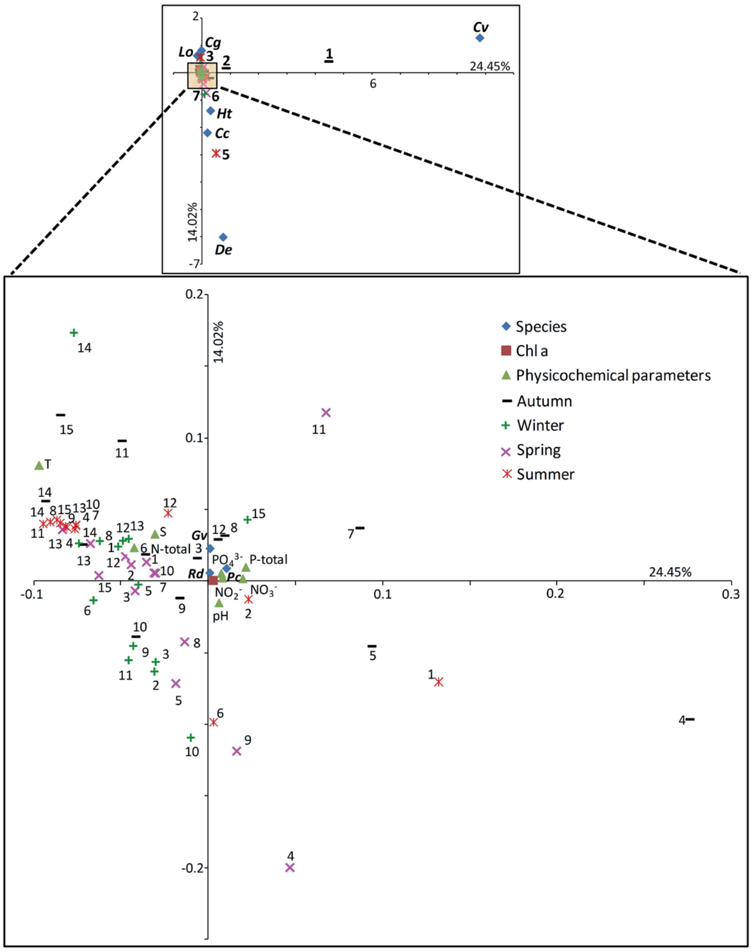


Figure 7. CFA established on seasonal surveys using macrofauna abundances, main physicochemical parameters and chlorophyll *a* in 2015-2016. T: temperature, S: salinity, O_2: dissolved oxygen, NO_2^-: nitrites, NO_3^-: nitrates, N-total: total nitrogen, PO_4^{3-}: phosphate, P-total: total phosphorus, Chl *a*: chlorophyll *a*. *Cc*: *Capitella capitata, Cg*: *Cerastoderma glaucum, Cv*: *Cerithium vulgatum, De* :*Dosinia exoleta* , *Gv*: *Gibbula varia, Ht*: *Hexaplex trunculus, Lo*: *Loripes orbiculatus, Pc*: *Perinereis cultrifera, Rd*: *Ruditapes decussatus*.

summer/autumn (stations 10, 11, 14 and 15) with the rainfall, the freshwater flow loaded of nutrients of continental origin and the vegetal development that consumes CO_2 and increases the pH. On average, these recorded values are comparable with those registered in the southern lagoon of Tunis (Ounifi Ben Amor 2016) and the lagoon of Boughrara (South of Tunisia) (Khedhri et al. 2016a) where spatial-temporal variations are greater, ranging respectively from 7.13 to 8.80 and from 7.03 to 9.2. Compared with the situation in 2003-2004, the temperature and salinity are currently slightly lower and the dissolved oxygen and pH do not show notable variations (Diawara et al. 2008).

The nutrient contents in general have not changed in the northern lagoon of Tunis since the implementation in 1988 of the new water circulation system (Ben Charrada 1992, Armi et al. 2012). Contrary to what the supposed sources of nuisance surrounding suggest, the nitrogen and phosphorus nutrients are relatively low in the study site compared with other Tunisian lagoons. As example, in the southern lagoon of Tunis, nitrates, N-total and P-total exceeded in 2008-2009 respectively 100 µg l^{-1}, 1000 µg l^{-1} and 90 µg l^{-1} at some locations/seasons (Ounifi Ben Amor 2016). Likewise, in the Bizerte lagoon, nitrites, nitrates and phosphates are clearly higher, often reaching 218 µg l^{-1}, 399.2 µg l^{-1} and 32.3 µg l^{-1} respectively (Afli et al. 2009a).

Benthic macrofauna

Macrofauna abundances in the northern lagoon of Tunis exceed rarely 100 ind.m^{-2} and distributed among 25 species only. Moreover, at certain stations/seasons no species was collected, mainly at station 8 which is sheltered from currents and facing an urban neighborhood (Lac 1) and where only one species (*Ruditapes decussatus*) was collected solely in spring with a low abundance (3 ind.m^{-2}). It is also the case of the station 1 where only 4 species were collected in autumn, and the reasons seem to be the same as at station 8. Compared with other Tunisian and Mediterranean lagoons, the study site seems to be very impoverished. As examples, in the adjacent southern lagoon of Tunis and during 1996-1997, a total of 67 macro-benthic species, mainly molluscs, were recorded, with seasonal average abundances ranging from 1279 to 7547 ind.m^2 and reaching locally 31483 ind.m^2 (Afli et al. 2009b). Fifteen years after (2012-2015), 44 crustacean species, mainly decapods, isopods and amphipods, were identified in this site (Ounifi Ben Amor et al. 2016). In the lagoon of Ghar El-Melh (North of Tunisia), 68 species were recorded in 1998-1999, with an average abundance of 542 ind.m^2 and reaching locally 5092 ind.m^2 (Afli et al. 2009c). In the lagoon of Boughrara (South of Tunisia), 65 species, mainly molluscs, were reported in 2012-2013, with abundances reaching locally 2534 ind.m^2 (Khedhri et al. 2016a). In the lagoon of Bizerte (North of Tunisia), 49 species whose 60% are polychaetes were recorded in 2001, but mollusks dominate at 60% in term of abundance which reaches locally 470 ind.m² (Afli et al. 2008b). While in the Mediterranean lagoon of Smir (Morocco), 22 macrofauna species were reported in 2000 with abundances clearly higher, ranging from 1236 to 3810 ind.m² (Chaouti and Bayed 2008).

The extreme conditions, mostly salinity and temperature and the continuous silting of the sediment (Chouari 2015) seem to be the major factors structuring macrofauna community in the northern lagoon of Tunis, since species are more present inside the lagoon in winter and facing the channel at the entry of seawaters in summer.

Although the environmental variables and fauna biodiversity parameters show a high significant difference among seasons only and not stations, the community shows a rather clear difference between the entrance of seawaters and inside the lagoon. Indeed, it seems that this difference resides more in the quality of the species present than in the biodiversity parameters of the community, which nevertheless remain low and comparable. In fact, even a slight variation in temperature or salinity is easily perceived by certain species, and the entrance of cleaner and cooler seawaters in summer can only be favorable to the community. This is the case, for example, of the station 2 in autumn where the species richness is relatively high (9 species), the abundance is low (67 ind.m⁻²) and H' and J' are relatively high. This means that the community is relatively diversified and not dominated by its leader species, which is confirmed by the trophic organization more balanced (presence of the 6 trohpic groups). Thus, CFA graphs are stretched more by species than by physicochemical parameters. As examples, station 11 is isolated in spring due to *Polititapes aureus* and *Cerastoderma glaucum*, station 3 in summer due to *Cerastoderma glaucum*, station 5 in summer due to *Ruditapes decussates*, *Dosinia exoleta* and *Hexaplex trunculus*, stations 1 and 2 in autumn due to *Cerithium vulgatum* and station 7 in winter and station 4 in spring due to *Capitella capitata*. This species distribution seems to be related to spatial differences along the longitudinal axis of the lagoon. Indeed, *Cerastoderma glaucum* has a wide distribution (stations 1, 2 and 3 in the East and station 4 in the West). It is a euryhaline and eurythermal species that tolerates very large variations of water's temperature and salinity (Derbali et al. 2012). However, most other species prefer reduced salinity muddy sediment as *Capitella capitata* (Afli 1999) and *Dosinia exoleta* (Tunberg 1983).

The biotic indices used, AMBI and BENTIX, are both based on the same ecological model of sensitivity/tolerance of species to increasing organic matter (Afli et al. 2008b, Aloui-Béjaoui and Afli 2012). But AMBI which is one of the most widely used biotic indices in European countries (Borja et al. 2007) seems to be less sensitive than BENTIX due to the different design of each index (Salas et al. 2006, Pranovi et al. 2007, Blanchet et al. 2008). That prompted some authors to recommend readjustment of BENTIX threshold boundaries for quality classification to be more consistent with the other biotic indices (Equbal et al. 2017). Even more, AMBI robustness could be reduced in case of low number of species and/or individuals (Afli et al. 2008b), such as the case of the northern lagoon of Tunis. In this study, the two biotic indices used seem to be overall consistent in classifying all stations as having a high and good ecological status, except BENTIX index which appears to show more severe conditions. It classifies a few stations inside the lagoon (stations 11 in spring and 12 in summer) or sheltered from currents (station 3 in summer) at poor and moderate ecological status in warm seasons. This is confirmed by the decline, or even the disappearance at these intralagoon stations, of the macro-zoobenthic community in this period of the year reflected mainly by low S and A values, and also by the net dominance of SF. The other trophic groups are discretely present in winter, but the trophic structure becomes more balanced in autumn, mainly at the entrance of seawaters (stations 1 and 2). The same results are given by the CFA analyses, trophic groups are more diversified at the seawater entrance in autumn and inside the lagoon in winter. However, spring and summer are grouped together and do not show notable trophic diversity, which means that warm seasons do not offer favorable conditions to the macrobenthic community. In general, Mediterranean lagoons are often dominated by one or two trophic groups, as the lagoon of Bizerte dominated widely by carnivores (Afli et al. 2008a), the southern lagoon of Tunis by micrograzers, the lagoon of Ghar El-Melh by selective deposit feeders (Afli et al. 2009c) and the lagoon of Smir by detritus feeders (Chaouti and Bayed 2011). The trophic organization in the northern lagoon of Tunis in autumn is comparable to that in the lagoon of Boughrara which seems to be more balanced, with total absence of the NSDF (Khedhri et al. 2016c). This should be related to the sedimentary dynamic that allows organic matter to be inserted in-depth where the trophic group feeds (Afli et al. 2008a).

Currently, the northern lagoon of Tunis does not seem to suffer from nutrient pollution (Chouari 2015), and the very low abundance of the community seems to be related more to extreme temperature and salinity and perhaps to sediment silting and a low availability of food resources. Nevertheless, even if biotic indices do not show strong signs of disturbance, the presence of the opportunistic polychaete *Capitella capitata* and pollution-tolerant species as *Cerastoderma glaucum*, *Perinereis cultrifera* and *Notomastus latericeus* (Pearson and Rosenberg 1978, Hily 1984, Afli 1999, Glémarec and Grall 2000, Afli et al. 2008b) presages a threat of pollution in the future if conditions deteriorate.

In conclusion, the southern lagoon of Tunis seems to be confronted to several environmental/anthropogenic constraints, since the macrofauna community is clearly impoverished with the presence of opportunistic/tolerant species. However, the physicochemical parameters measured do not exceed generally the thresholds tolerated. On the contrary, they are below levels recorded in other Tunisian and Mediterranean lagoons. Besides, in this study, physicochemical parameters show significant differences only among seasons, but not among stations. This allows noting that primarily the temperature and salinity whose seasonal fluctuations are remarkable seem to play an important role in this spatial-temporal distribution of species, for three main reasons;

Firstly, the benthic macrofauna community is more poorly diversified and impoverished in summer and spring when the temperature and salinity are higher. While in autumn, and especially in winter, the community seems to be less impoverished in species and individuals with the rainfall and the freshwater flow. Secondly, the macro-zoobenthic community shows important differences in its species composition between the entrance of seawaters and inside the lagoon, peculiarly in hot seasons when waters coming from the open sea are less salty and colder. Finally, statistical analyses, mainly CFA, show an important role of the temperature and salinity in the macrofauna structure among physicochemical parameters measured. As for the general silting of sediments that has certainly an important role in the community structure, the impact is slowly and continuously over time which does not allow highlighting it in the statistical analyzes over a short period.

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