SIFT DESK

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THE CHARACTERISATION AND SEASONAL DISTRIBUTION OF DIATOMS ALONG SFAX NORTHERN AND SOUTHERN COASTS (GULF OF GABES, EASTERN MEDITERRANEAN SEA) IN RELATION TO ENVIRONMENTAL CONDITIONS

Research

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CONFLICTS OF INTEREST

There are no conflicts of interest for any of the authors.

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ABSTRACT

The spatial and seasonal variations of the diatoms communities were examined during four marine cruises conducted between years 2011 and 2012 on 12 stations at the north (restored) and south (not yet restored) coasts. Results revealed a striking difference between the two coasts regarding pH, with strong acidification of seawater in the south, likely caused by industrial activity. Suspended matter was higher in the north than in the south may be reasonably attributed to the recently added soil not yet fully stabilised. The low concentrations of orthophosphate as well as their low values relative to total phosphate show that restoration of the northern part of Sfax coast had positive effects on dissolved inorganic phosphate concentrations. Orthophosphate and total phosphate concentrations were still important in the southern coast. Inverted microscopy analysis of diatoms resolved 31 and 29 taxa in the north and south Sfax coasts respectively. Diatoms dominated community composition in the northern coast (65%), contrary to the southern coast, diatoms do not exceed 40%. Diatoms was characterised by the proliferation of pennate diatoms species (*Amphiprora* sp., *Nitschia longissima*, *Nitschia* sp., *Nitschia ventricosa*, *Plagiotropis* sp. ..) in northern part contrasting a progressive augment of centric diatoms species (*Biddulphia* sp., *Leptocylindricus danicus*, *Leptocylindrus* sp., *Skeletonema costatum*, *Rhizosolenia stolforthii* ..) in the southern part of the coast. The results confirm that restoration had positive effects on the abiotic variables and diatoms assemblage of the north coast. The case for restoration of the city's south coast is also reinforced.

INTRODUCTION

Diatoms represent a major part of the eukaryotic primary production in marine ecosystems (Drira et al., 2009). The seasonal succession of diatoms communities were governed by a combination of physical, chemical and biological variables in marine ecosystems (Meiners et al., 2003). Diatoms tend to have considerably higher maximum uptake rates of nutrients than any other group (Litchman et al., 2006). Indeed, diatoms are the preferred food of many grazers in the upper trophic levels and thus form the basis for many of the productive fisheries (Ben Brahim et al., 2015).

The Eastern Mediterranean Sea is eutrophic to oligotrophic, depending on location and season. The Gulf of Gabes in the Eastern Mediterranean Sea is one of the main harbours and is a highly productive ecosystem

(Hamdi et al., 2015). The Gulf of Gabes, situated in the south-east of Tunisia, is delimited by arid to semi-arid continental shelves and it is surrounded by the Kerkennah Islands in the north-east, Kneiss islands in the south-east, Djerba Island in the south-east, the lagoons of Boughrara and El Bibane (Hattour et al. 2010). Water area is about 100 km long and 100 km wide with depths varying from 20 to 50 m (Sammari et al., 2006).

Sfax coast, a part of the Gulf of Gabes, are surely associated to the two industrial regions of Madagascar and Sidi Salem, the sewage treatment station ONAS (National Sanitation Office). These regions are recognized for generating contaminants released from commercial, agricultural and domestic effluents (Ben Salem et al., 2015). The residue of phosphate treatment, phosphogypsum, has been stocked along the coast at an abandoned dumpsite from the plant which fabricates phosphoric acid (SIAPE) (Rekik et al., 2012). Over years, due to enlarged pressure from industrial activities and fisheries, there has been a reduction in the biodiversity in the Sfax coast (Rekik et al., 2012). Recently, the north coast of Sfax is subject to restoration from pollution by Taparura project (Rekik et al., 2013ab; 2014; 2015ab); on the other side the Sfax south coast is not yet restored (Rekik et al., 2015c; 2016ab).

To determine the impact of restoration work on water quality and biodiversity, the seasonal variation of the diatoms community was studied in a restored ecosystem (north Sfax coast) and a not restored ecosystem (south Sfax coast) at 12 stations (6 stations on each coast). Thus, we studied the diatoms species abundance and diversity together with physical and chemi-cal processes and biological factors along Sfax's coasts. We hypothesized that the diatoms would change from the northern to the southern Sfax coast according to, (i) abiotic proprieties and (ii) the effect of the restoration and pollution.

KEYWORDS: Diatoms, Environmental parameters, Sfax coast, Eastern Mediterranean Sea

2. MATERIALS AND METHODS

2.1. Study site

This research was conducted in Sfax (34°43'N – 10°46'E, Central Eastern Coast of Tunisia), a town with a littoral extends 50 km from the site of Sidi Mansour in the north to Chaffar in the south (Rekik et al., 2012). The north Sfax coast, restored by Taparura project, is described with its geomorphologic polygon. This region includes the phosphate treatment plant (NPK) and the commercial harbour (Rekik et al., 2014). The south Sfax coast, directly exposed to phosphate reject, is a closed ecosystem. This area contains the fishing port, the solar saltern, the SIAPE, the industrial region of Madagascar and Sidi Salem, and commerce locale of Thyna (Rekik et al., 2015c).

2.2. Field sampling

Abiotic and biological samples were collected in 2010 and 2011 on 12 stations at the north (1, 2, 3, 4, 5 and 6) and south (A, B, C, D, E and F) coasts of Sfax (Fig. 1). Physico-chemical and phytoplankton samples determination were collected with a Van Dorn-type closing bottle. Nutriment samples (120 ml) were stored directly at 20 ° C in the dark. Phytoplankton samples (1 l) were conserved for enumeration with Lugol iodine solution (4%) (Bourrelly, 1985). Chlorophyll-*a* samples (1 l) were filtered onto Whatman GF/F glass fiber filters via vacuum filtration which were after that directly preserved at −20°C.

2.3. Physico-chemical variables

Physical factors were determined instantly after sampling using a multi-parameter kit (Multi 340 i/SET). Suspended matter concentrations were determined using the dry weight of the residue after filtration of 0.5 L of seawater onto Whatman GF/C membrane filters. Chemical factors were determined with a Bran and Luebbe type 3 autoanalyzer.

2.4. Phytoplankton enumeration

Phytoplankton samples (50 mL) were identified under an inverted microscope using the Utermöhl method (Utermöhl, 1958). Phytoplankton species determination was made according to different books (Rekik et al., 2012; 2013ab; 2015abc).

2.5. Chlorophyll-*a*

Chlorophyll-*a* was measured with spectrometry, after extraction of the pigments in acetone (90 %). The concentrations were then determined using the SCOR-UNESCO equations (SCOR-UNESCO, 1966).

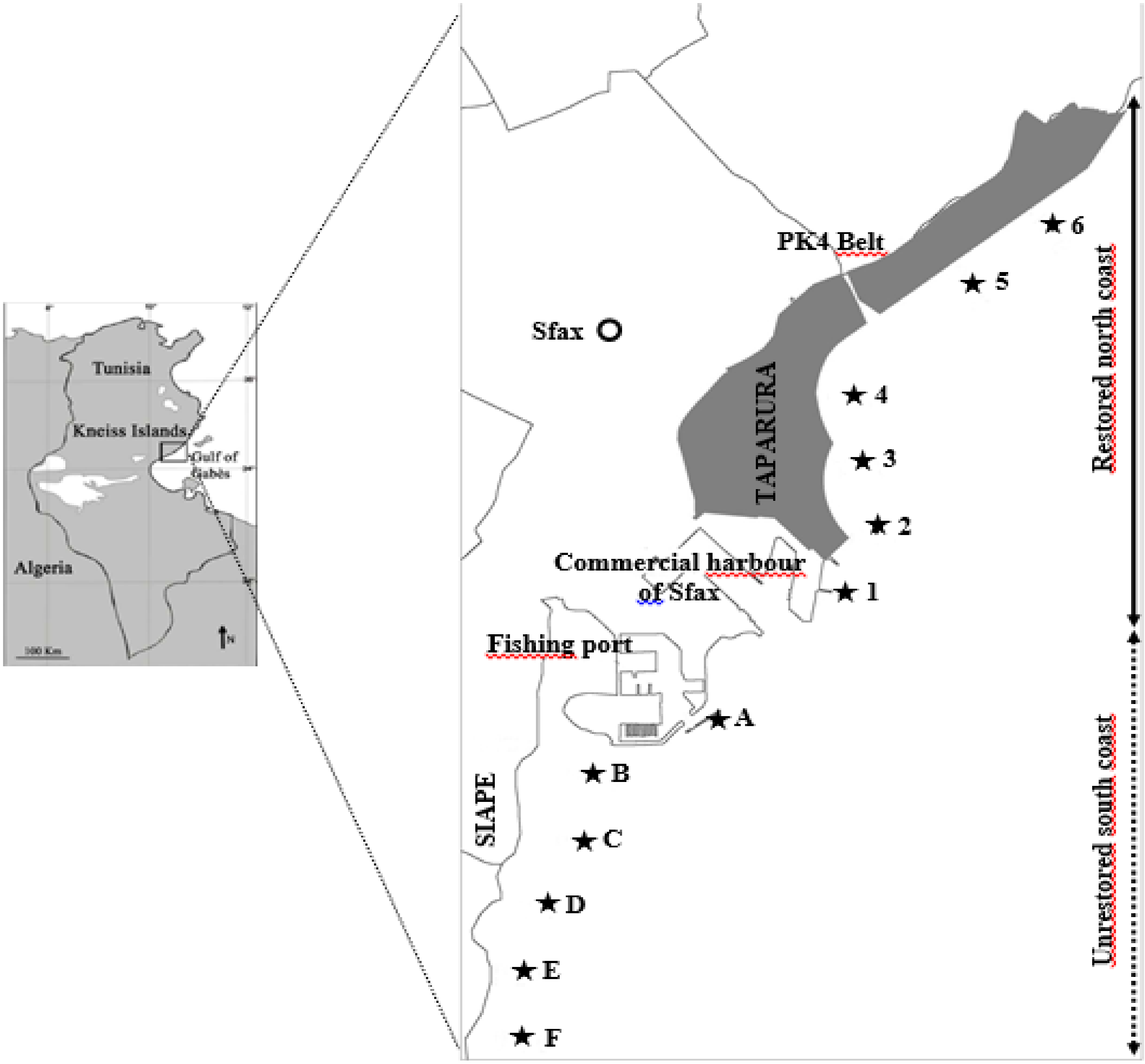

Figure 1

Figure 1. Location of sampling stations on the north and south coasts of Sfax.

2.5. Statistical analysis

The abiotic and biological variables analysed in our research were presented to a normalised principal component analysis (Doledec and Chessel 1989). Simple log(x + 1) conversion was executed to variables in order to exactly normalize difference (Frontier, 1973). Means and standard variations were recorded when appropriate. The relationships potential among data were experienced by Pearson's correlation coefficient. One-way ANOVA employing XLstat software followed by a *post hoc* evaluation using Tukey's analysis was used to recognize major variations among north and south coasts.

3. RESULTS

3.1. Abiotic variables

3.1.1. North coast of Sfax

The mean temperature values fluctuated between 13.65 ± 0.42 and 32.89 ± 2.21 °C. The seasonal distribution of

temperature illustrated higher values from winter to summer. The water temperature varied between 13.00 and 36.00 °C with the lowest temperature detected in winter and the highest in summer at station 1 (Table 1). The highest and lowest salinity were recorded during winter (37.34 psu) and summer (39.17 psu) respectively at station 2 (Table 1). The pH mean values were typically alkaline varied between 8.16 ± 0.30 to 8.60 ± 0.13 during autumn and spring respectively. Suspended matter concentrations were more varied in winter than in spring where the average value was about 58.63 ± 3.88 mg l^{-1}, whereas in the winter the highest value of suspended matter was 201.56 mg l^{-1} (station 6) and the lowest was 85.78 mg l^{-1} (station 3).
The nitrogen form mean concentrations were more important in spring than in autumn. The dissolved inorganic nitrogen concentrations illustrated a general decrease during autumn. The nitrate, nitrite and ammonium concentrations showed a considerable increase during spring, summer and winter respectively. Overall, total nitrogen concentrations increased significantly from autumn to spring in the coast. The concentration of total nitrogen ranged from 13.26 µM at station 6 to 15.51 µM at station 1 during autumn (Table 1). Total nitrogen concentration was about 20.19 ± 1.84 µM in spring. The mean value of orthophosphate concentration was 1.83 ± 0.48 µM in winter whereas in the autumn it was only 0.16 ± 0.02 µM (Table 1). When considering total phosphate concentrations, values were three times that of orthophosphate concentration in winter and spring and up to twelve times in autumn. The N/P: DIN to DIP ratio varied between 1.95 and 15.76 in winter and autumn respectively at station 2. This average was less than the Redfield ratio (16), indicating a probable nitrogen control. On the contrary, the N/P ratio was more important in summer principally at stations 1 (30.15) and 2 (32.88). Silica concentration was considerably more important in winter (22.76 ± 11.09 µM) than in autumn (2.21 ± 0.50 µM) (Table 1). The maximum concentration of silica was registered at station 4 (40.09 µM), and the minimum (1.41 µM) at station 1 (Table 1).

3.1.2. South coast of Sfax

Water temperature ranged from 14.97 to 32.33 °C (23.99 ± 6.31 °C) (Table 1), tending to augment from winter to summer over the study site. Salinity, which ranged from 34.53 to 40.00 psu (37.82 ± 1.36 psu) (Table 1), was instable through the whole study period fluctuated between 36.51 ± 1.10 psu (winter) and 39.44 ± 0.29 psu (autumn). The pH values ranged from 7.08 to 8.45 (7.76 ± 0.39) (Table 1) augmenting considerably in the coastal site: station B in autumn showed the lowest transparency, stations D and E in spring the highest. Suspended matter values varied significantly during winter and summer, while in autumn and spring suspended matter concentrations were relatively invariable. Suspended matter concentrations ranged from 23.87 mg l^{1} (station A, winter) to 61.44 mg l^{-1} (station E, spring) (38.09 ± 10.08 mg l^{-1}) (Table 1).
Nutrient concentrations were irregularly distributed. The dissolved inorganic nitrogen values were more concentrated in autumn. Nitrate concentrations varied from 2.05 to 19.67 µM, with a mean of 7.31 ± 3.93 µM (table 1), the maximum being observed at station E in autumn. Nitrite concentration was in the range 0.17- 6.56 µM with its maximum value at station E in autumn (table 1). Ammonium concentration ranged from 2.01 µm to 11.33 µM, the peak value being observed at station A in autumn. Total nitrogen concentration ranged from 13.83 µM (station C, summer) to 45.43 µM (station E, autumn) (Table 1). The highest concentration of silica was recorded in autumn (61.51 µM) and the lowest (4.18 µM) in winter at station E (Table 1).

3.2. Diatoms community

3.2.1. North coast of Sfax

Chlorophyll-*a* concentrations were small during the four seasons, with values being inferior to 10 mg l^{-1}. The spatial and seasonal differences in pigment concentrations were not significant in autumn with the exception of station 1 (9.84 mg l^{-1}). Yet, an important augment of Chlorophyll-*a* concentrations was registered during spring (3.10 ± 1.32 mg l^{-1}) (Fig. 2). Abundance of phytoplankton community fluctuated from 16.42 × 10^{2} cells l^{-1} to 260.41 × 10^{2} cells l^{-1} at station 5 and 6 during spring and summer respectively (Fig. 2), with the important mean abundance being registered in winter (135.46 ± 80.73 × 102 cells l^{-1}). The total phytoplankton abundance peaked at the same time, at stations 4, 5 and 6 in winter, however, abundance was low in spring (Fig. 2). Diatoms abundance changed significantly over the study period, with a maximum of 235.71 × 10^{2} cells l^{-1} in winter and a minimum of 4.34 × 10^{2} cells l^{-1} in spring (Fig. 2). The maximum individuals number was registered at station 6 bloom of diatoms species such as *Navicula* sp. (145 × 10^{2} cells l^{-1}), *Grammatophora* sp. (43.67 × 10^{2} cells l^{-1}), *Licmophora* sp. (24.67 × 10^{2} cells l^{-1}) and *Pleurosigma* sp. (13 × 10^{2} cells l^{-1}) (Table 2).

Diatoms species composition varied considerably throughout our research (Table 2), with a particularly predominance of *Navicula* sp. fluctuated from 37% and 63% of total abundance of diatoms during summer and autumn respectively (Fig. 2). Among diatoms, there are taxa which are exclusively observed in the north Sfax coast like *Chaetoceros* sp., *Guinardia* sp., *Hemiaulus sinensis*, *Hermesinum* sp., *Leptocylindricus mediterranus*, *Licmosphenia* sp., *Melosira italica*, *Nitschia* sp., *Plagiotropis* sp. and *Surirella* sp. (Table 2).

	North coast of Sfax			South coast of Sfax				
	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD	*F*-values	p
Physical variables								
Temperature (° C)	13.00	36.00	25.02 ± 7.51	14.97	32.33	23.99 ± 6.31	89.82	3.24×10^{-19}***
Salinity (p.s.u.)	37.34	39.17	38.13 ± 0.49	34.53	40.00	37.82 ± 1.36	14.46	2.58×10^{-8}***
pH	7.81	8.73	8.30 ± 0.27	7.08	8.45	7.76 ± 0.39	24.98	2.89×10^{-11}***
Suspended matter (mg l^{-1})	48.20	201.56	86.92 ± 37.47	23.87	61.44	38.09 ± 10.08	15.40	1.23×10^{-8}***
Chemical variables								
NO_3^- (µM)	0.87	4.81	2.37 ± 1.06	2.05	19.67	7.31 ± 3.93	20.07	4.83×10^{-10}***
NO_2^- (µM)	0.07	0.69	0.24 ± 0.15	0.17	6.56	1.45 ± 1.66	12.24	1.71×10^{-7}***
NH_4^+ (µM)	0.82	3.68	1.67 ± 0.78	2.01	11.33	5.35 ± 2.55	6.66	6.75×10^{-5}***
Total-N (µM)	13.25	23.06	17.05 ± 2.98	13.83	45.43	24.34 ± 8.20	13.60	5.24×10^{-8}***
PO_4^{3-} (µM)	0.20	2.60	0.69 ± 0.73	0.61	14.82	5.22 ± 3.93	64.24	4.88×10^{-17}***
Total-P (µM)	0.78	11.12	2.96 ± 2.23	5.37	40.85	17.76 ± 8.99	33.07	6.60×10^{-13}***
N/P ratio	1.95	32.88	12.63 ± 8.82	0.75	34.12	4.90 ± 6.67	35.92	2.10×10^{-13}***
Si $(OH)_4$ (µM)	1.41	40.09	9.01 ± 9.97	4.18	61.51	21.78 ± 15.06	6.52	8.17×10^{-5}***
Biological variables								
Chlorophyll-*a* (mg l^{-1})	0.01	9.84	2.48 ± 2.12	0.01	25.89	4.95 ± 6.60	8.09	1.18×10^{-5}***
Phytoplankton ($\times 10^2$ cells l^{-1})	16.42	260.41	84.13 ±	7.67	204.72	58.33 ± 46.79	2.63	0.03*
Diatoms ($\times 10^2$ cells l^{-1})	4.34	235.71	54.30 ± 60.97	4.67	44.66	23.45 ± 12.74	9.69	2.02×10^{-6}***

Table 1. Min, Max and Mean ± SD of physico-chemical and biological parameters on the north and south coasts of Sfax and results of ANOVA analysis to identify the significant differences between the sampled north and south stations.
F-values were determined by a one-way ANOVA test, P values for differences among coasts within each variable. (*P <0.05, ** <0.01, *** <0.001)

3.2.1. South coast of Sfax

Chlorophyll-*a* concentrations varied from 0 to 25.89 mg l^{-1} (4.95 ± 6.60 mg l^{-1}) and have a tendency to augment in autumn and spring (Figure 2). Phytoplankton abundance fluctuated from 8.00×10^2 cells l^{-1} (station B, autumn) to 205.00×10^2 cells l^{-1} (station F, summer) (Fig. 2). Total phytoplankton were abundant in summer ($105.00 \pm 64.46 \times 10^2$ cells l^{-1}) whereas they were poorly represented in winter ($32.00 \pm 10.54 \times 10^2$ cells l^{-1}) (Fig. 2). Abundance of total phytoplankton peaked during summer at station A (151×10^2 cells l^{-1}), station B (90×10^2 cells l^{-1}), station C (73×10^2 cells l^{-1}) and station F (205×10^2 cells l^{-1}) (Fig. 2). The highest diatoms abundance was recorded in spring at station D (45×10^2 cells l^{-1}) (Fig. 2), associated with an important proliferation of *Navicula* sp. (24×10^2 cells l^{-1}). *Navicula* sp., considered as a whole, were more abundant in spring than in autumn, with average abundance values , 12.90×10^2 and 3.00×10^2 cells l^{-1} in spring and autumn respectively

(Fig. 2). Average diatoms abundance was low during autumn, with mean values being lower than 18.00 × 10^2 cells l^{-1}. Among the species collected, *Bellarochea* sp., *Diploneis* sp., *Epithemia* sp., *Leptocylindricus danicus*, *Leptocylindrus* sp., *Lithodesmium* sp., *Lithodesmium undulatum*, *Rhizosolenia stolforthii* and *Skeletonema costatum* were found only in the south Sfax coast (Table 2). A number of species were particularly prominent at specific seasons, and among these diatoms, *Amphiprora* sp., *Epithemia* sp., *Leptocylindricus danicus*, *Leptocylindrus* sp., *Lithodesmium* sp., *Skeletonema costatum* and *Skeletonema* sp. were found in spring and *Rhizosolenia stolforthii*, *Synedra* sp. and *Synedra ulna* were collected in autumn (Table 2).

3.3. Statistical analysis
3.3.1. North coast of Sfax

PCA distinguished between four groups surrounding the F1 and F2 component axes thus explaining 56.66% of the variance in the Sfax north coast. The axes selected a group G1 comprising total phytoplankton and diatoms linked to salinity, suspended matter, NH_4^+ and NO_2^- concentrations, at stations 5 and 6. F1 component axis which extracted 29.07% of the variability, selected negatively the group G2, with temperature and pH at station 4. G3 formed by chlorophyll-a concentrations, witch were mostly influenced by silica content in station 1. G4 selected, NO_3^-, T-N, PO_4^{3-}, T-P and N/P ratio (stations 2 and 3) (Fig. 3).

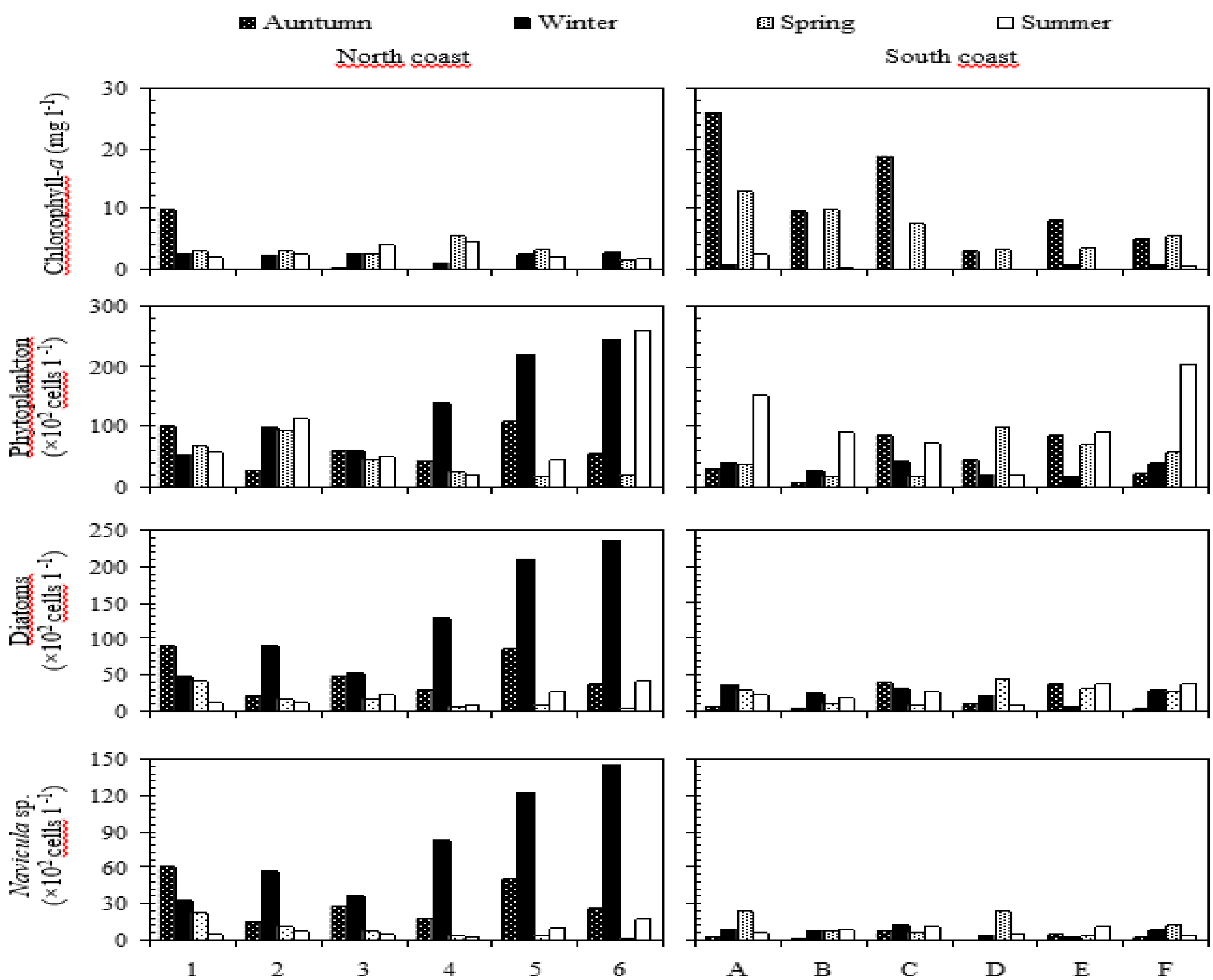

Figure 2. Spatial and seasonal variation of chlorophyll-*a* concentration and abundance of phytoplankton, dinoflagellates and *Navicula* sp. at sampled stations.

	North coast of Sfax				South coast of Sfax			
	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer
Achnantes sp. (Hustedt, 1933)	-	+	+	+	+	+	-	+
Amphiprora sp. (Ehrenberg, 1843)	+	+	+	-	-	-	+	-
Amphora sp. (Kützing, 1844)	+	-	+	+	+	+	+	-
Bellarochea sp. (Crawford, 1990)	-	-	-	-	+	+	-	+
Biddulphia sp. (Gray, 1821)	+	+	+	-	+	+	+	+
Chaetoceros sp. (Ehrenberg, 1844)	+	+	+	+	-	-	-	-
Climacosphenia sp. (Ehrenberg, 1843)	+	-	+	-	+	+	+	-
Cocconeis sp. (Ehrenberg, 1836)	+	+	+	+	-	+	+	+
Coscindiscus sp. (Ehrenberg, 1839)	+	+	+	+	-	+	+	+
Diploneis sp. (Cleve, 1894)	-	-	-	-	+	-	+	-
Epithemia sp. (Kützing, 1844)	-	-	-	-	-	-	+	-
Grammatophora marina (Kützing, 1844)	+	+	+	+	+	+	+	+
Guinardia sp. (Peragallo, 1892)	+	-	-	-	-	-	-	-
Hemiaulus sinensis (Greville, 1865)	-	-	-	+	-	-	-	-
Hermesinum sp. (Zacharias 1906)	+	-	-	-	-	-	-	-
Leptocylindricus danicus (Cleve, 1889)	-	-	-	-	-	-	+	-
Leptocylindricus mediterranus(Cleve, 1889)	-	-	+	-	-	-	-	-
Leptocylindrus sp. (Cleve, 1889)	-	-	-	-	-	-	+	-
Licmophora sp. (Agardh, 1831)	+	+	+	+	+	+	+	-
Licmosphenia sp. (Hustedt, 1931)	-	-	-	+	-	-	-	-
Lithodesmium sp. (Ehrenberg, 1839)	-	-	-	-	-	-	+	-
Lithodesmium undulatum (Ehrenberg, 1839)	-	-	-	-	+	-	+	-
Melosira italica (Kützing, 1844)	-	+	-	-	-	-	-	-
Navicula sp. (Bory de St Vincent, 1822)	+	+	+	+	+	+	+	+
Nitschia longissima (Ralf, 1861)	+	+	+	+	+	-	+	-
Nitschia sp. (Hassall, 1845)	+	+	+	+	-	-	-	-
Nitschia ventricosa (Hassall, 1845)	-	-	+	+	-	-	-	-
Pinnularia sp. (Ehrenberg, 1843)	+	+	+	+	-	+	+	+
Plagiotropis sp. (Czarnecki and Blinn, 1978)	-	-	+	+	-	-	-	-
Pleurosigma sp. (Smith, 1852)	+	+	+	+	+	+	+	+
Rhabdonema sp. (Ehrenberg, 1832)	-	+	-	-	+	+	-	-
Rhizosolenia sp. (Brightwell, 1858)	+	-	-	-	+	+	-	-
Rhizosolenia stolforthii (Cupp, 1943)	-	-	-	-	+	-	-	-
Skeletonema costatum (Cleve, 1873)	-	-	-	-	-	-	+	-
Skeletonema sp. (Cleve, 1873)	+	-	+	-	-	-	+	-
Striatella unipunctata (Agardh, 1832)	+	+	+	+	-	+	-	+
Surirella sp. (Hustedt, 1911)	-	+	+	-	-	-	-	-
Synedra sp. (Greville, 1833)	-	+	-	+	+	-	-	-
Synedra ulna (Ehrenberg, 1832)	-	+	-	-	+	-	-	-
Thalassiosira sp. (Lebour, 1930)	+	-	-	-	+	-	+	-

Rhizosolenia sp. (Brightwell, 1858)	+	-	-	-	+	+	-	-
Rhizosolenia stolforthii (Cupp, 1943)	-	-	-	-	+	-	-	-
Skeletonema costatum (Cleve, 1873)	-	-	-	-	-	-	+	-
Skeletonema sp. (Cleve, 1873)	+	-	+	-	-	-	+	-
Striatella unipunctata (Agardh, 1832)	+	+	+	+	-	+	-	+
Surirella sp. (Hustedt, 1911)	-	+	+	-	-	-	-	-
Synedra sp. (Greville, 1833)	-	+	-	+	+	-	-	-
Synedra ulna (Ehrenberg, 1832)	-	+	-	-	+	-	-	-
Thalassiosira sp. (Lebour, 1930)	+	-	-	-	+	-	+	-

Table 2. List of the diatoms species observed on the north and south coasts of Sfax. Present (+), not detected (-).

3.3.2. South coast of Sfax

PCA allowed discrimination of four groups around the components of the F1 and F2 axes explaining 69.23% of the variance in the Sfax south coast. These axes positively selected group G1, formed by diatoms correlated to salinity, NO_3^-, NH_4^+ and T-N (station A). The F1 component axis, which extracted 43.59% of the variability, positively selected group G2, a group selected in station D and comprised of pH, NO_2^-, PO_4^{3-}, T-P and $Si(OH)_4$. The PCA plots illustrate that, in G3 selected in stations B, C and F, temperature and suspended matter concentrations. The last group, G4, was mainly related to N/P ratio and correlated to total phytoplankton and chlorophyll-*a* concentrations (Fig. 3).

4. Discussion

The present study is the first attempt to investigate the distribution of diatoms assemblage through high spatial resolution sampling in the shallow coastal waters of Sfax during four seasons. Our results demonstrated distinct spatial and seasonal contrasts. The north coast of Sfax is subject to restoration from pollution. The Taparura Project is part of an environmental policy and management program aimed at tackling the pollution threatening the north Sfax beaches and coastal waters. The south coast of Sfax is subject to degradation of water quality. The expansion of industrial and commercial activities in the south Sfax coastal area has become an issue of increasing environmental concern. In order to distinguish between variations provoked by the coast restoration and those of other origin, it was also important to compare the north coast situation to that of the south which is still subject to the same industrial pollution linked to the phosphate and fertilizer industry.

Our results agree with and complement other research performed in arid to semi-arid Mediterranean ecosystems, which illustrated important values for both temperature and salinity starting in spring and arriving at its maximum in summer, followed by a cooling trend with its minimum in winter (Rekik et al., 2013a; 2014; 2015ab). The mean water temperature and salinity registered at the 6 sampling north stations (from station 1 to 6) were significantly higher than those registered at the southern stations (from station A to F). Significant differences were observed in water temperature ($r = 3.24 \times 10^{-19}$, $p<0.001$, $n = 15$) and salinity ($r = 2.58 \times 10^{-8}$, $p<0.001$, $n = 15$) between northern and southern stations. Results revealed a striking difference between the two coasts about pH, with high acidification of seawater in the south, probably generated by industrial activity (Rekik et al., 2013b). Suspended matter was more important in the north (48.20 – 201.56 mg l^{-1}) than in the south (23.87 – 61.44 mg l^{-1}). The high suspended matter values may be attributed to the shallowness of the sampled north stations, the spatial distribution of tiny particles and tidal action and to the recently added soil, not yet fully stabilised (Rekik et al., 2013b). The low concentrations of orthophosphate as well as their low magnitude relative to total phosphate show that restoration of the northern part of Sfax coast had positive

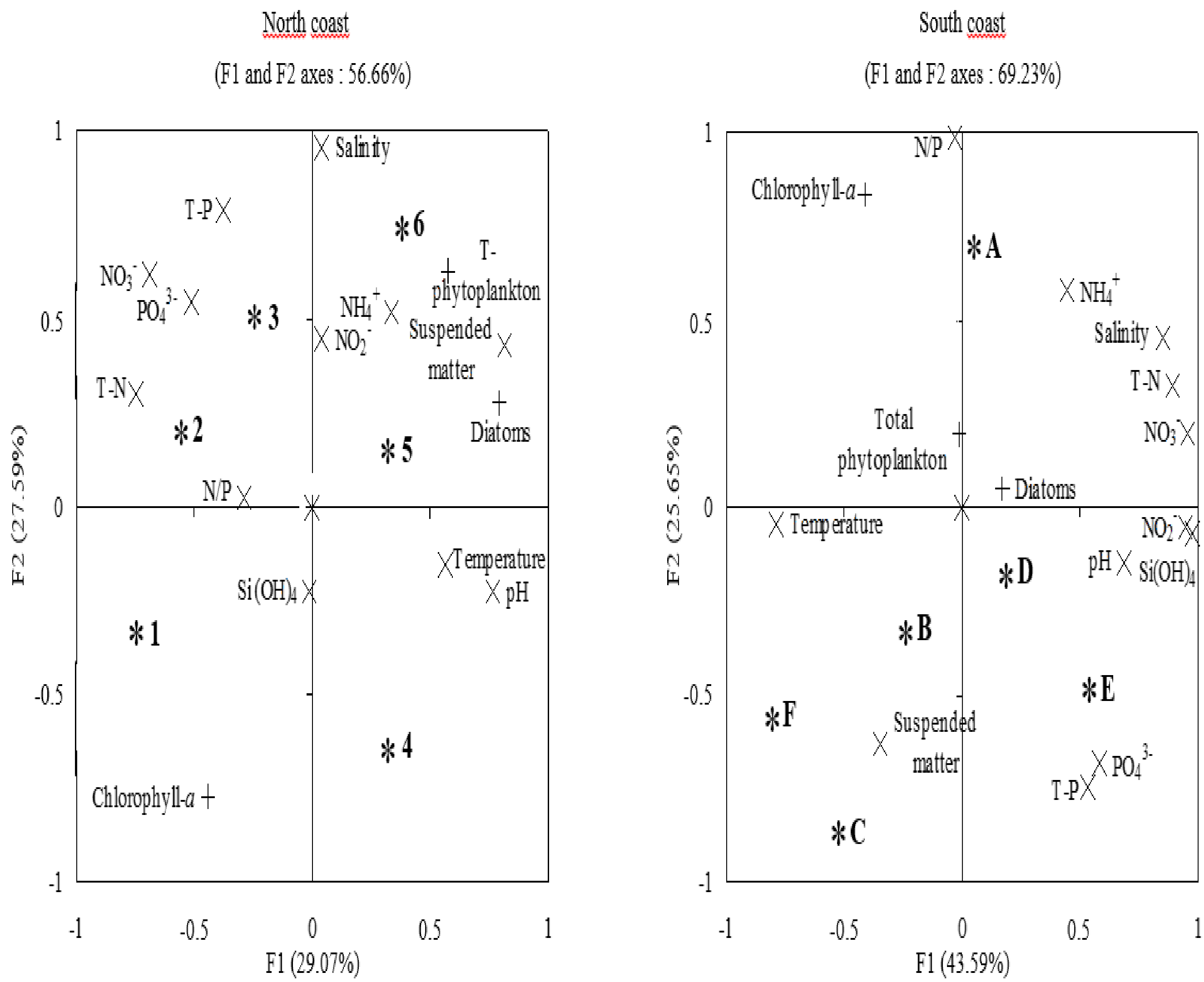

Figure 3. Principal component analysis (PCA) (Axis I and II) of biological parameter abundance and selected environmental variables at sampled stations on the north and south coasts of Sfax.

effects on dissolved inorganic phosphate concentrations. Orthophosphate and total phosphate concentrations were still prevalent in the south. Accordingly, the N/P–DIN to DIP ratio (12.63 ± 8.82) was close to the Redfield ratio (16) in the north coast of Sfax. This result clearly shows that the phosphogypsum restoration had been indispensable with, however, phosphate values still elevated enough to quality an oligotrophic status to the north Sfax coast. A major difference with respect to the not restored south coast concerns the high phosphate concentration and which was 6 times higher compared to the north coast. It is noteworthy that phosphogypsum was dumped only on the north coast. Analysis of nutrient concentrations indicates that south coast was not nutrient limited during the four seasons.

Our study explained two key results: (i) phytoplankton was strongly abundant in the north part compared to the south part of our site, indicating favorable growing conditions after the restoration work on the north coast of Sfax, and (ii) diatoms generally dominated community composition in the northern coast (65%) and particularly during winter (94%) and autumn (80%), contrary to the south coast, diatoms do not exceed 40%. Diatoms are important indicators of ecological quality as they react quickly to several physical, chemical and biological factors in marine environment (Davies and Ugwumba 2013). The physicochemical variables such as temperature, pH, suspended matter and ammonium concentrations were found to control the occurrence of diatoms. Our results showed an increase of diatoms in the north Sfax coast correlated with ammonium concentrations ($r = 0.66$, $p<0.05$, $n = 15$). In particular, suspended matter concentrations seemed to be the most important parameter in the north coastal site which may affect the abundance and distribution of diatoms ($r = 0.89$, $p<0.05$, $n = 15$). Lauria *et al.* indicated that diatoms reacted positively to turbulence, showing enhanced development rates with increased stirring and aeration in laboratory experiment, probably due to the increase of suspended matter during water movement (Amari, 1984). Water temperature seems also to be an important factor that explains the abundance of diatoms in the south coast of Sfax ($r = 0.66$, $p<0.05$, $n = 15$). The low pH values are likely the most important predictor among the physical factors and its negative influence on diatoms abundance ($r = -0.64$, $p<0.05$, $n = 15$) in southern part of the coast. The low pH values can reasonably be attributed to the industrial activity still in function in the south coast while it has been finished in the north Sfax coast (Rekik et al., 2013b). The seasonal variability shows that the littoral of Sfax is subjected to a clear seasonal cycle deference north coast species to south coast species. This was related to the increase of pennate diatoms species (*Amphiprora* sp., *Nitschia longissima*, *Nitschia* sp., *Nitschia ventricosa*, *Plagiotropis* sp. ..) abundance in northern part contrasting a progressive augment of centric diatoms species (*Biddulphia* sp., *Leptocylindricus danicus*, *Leptocylindrus* sp., *Skeletonema costatum*, *Rhizosolenia stolforthii* ..) in the southern part of the coast. Nygaard (1949) showed that centric diatoms are usually found in eutrophic conditions, whereas pennate diatoms are usually found in non-polluted conditions. Several species of *Navicula* were dominant taxa strongly growing in that coast and belonging to diatoms. They are conventionally considered as benthic (Welker et al., 2002) and euryhaline species (Mikhail, 2008). Dominance of *Navicula* species has been previously recorded in many studies in the coastal Sfax water, although they did not reported their dominance over the seasons (Rekik et al., 2013a; 2015ac). This could be explained by the adaptability of this taxonomic group to different nutrition regimes and environmental conditions.

The results confirm that restoration had positive effects on the abiotic factors and diatoms assemblage of the north coast; they also highlight the strong acidification still prevalent in the south that may be responsible for the lower development and occurrence of phytoplankton. The case for restoration of the city's south coast is also reinforced.

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