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Seasonal and spatial distributions of dinoflagellates in relation to environmental factors along the north and south coasts of Sfax (Tunisia, Eastern Mediterranean Sea)

Amira Rekik, Habib Ayadi, Jannet Elloumi*

Research Unity UR/11ES72 Biodiversity and Aquatic Ecosystem, Department of Sciences of Life, Faculty of Sciences, University of Sfax, Sfax, Tunisia

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ABSTRACT

Objective: To compare the spatial and seasonal distribution of dinoflagellates in relation to environmental factors in north (restored) and south (not yet restored) coasts of Sfax.
Methods: The present study was conducted during the year of 2010 and 2011 at 12 stations for evaluation of the spatial and seasonal distribution of dinoflagellates and abiotic parameters.
Results: Results revealed a striking difference between the two coasts regarding pH with strong acidification of seawater in the south, which may be caused by industrial activity. Suspended matter was more in the north than in the south, which may be reasonably attributed to the recently added soil that has not yet fully stabilised. Inverted microscopy analysis of dinoflagellates showed 35 and 28 taxa in the north and south coasts of Sfax, respectively. Dinoflagellates developed in association with an important proliferation of common species like *Gymnodinium* sp., *Prorocentrum lima* and *Prorocentrum micans*. Two distinct associations of dinoflagellates species were identified: a north association involving an important abundance of *Peridinium* sp. and *Protoperidinium* sp., and a south assemblage concerning mainly *Prorocentum triestinum*. Chlorophyll *a* concentrations on the north [(2.48 ± 2.12) mg/L] and south [(4.95 ± 6.60) mg/L] coasts of Sfax were not correlated with dinoflagellates abundance, probably explained by the fact that an important number of dinoflagellates species are deprived of chloroplasts. The highest heterotrophic dinoflagellates mean abundance was recorded in south Sfax coast (1.64×10^2 cells/L) during summer.
Conclusions: This study shows that environmental variables were in relation with the dinoflagellates community composition which exhibited clear variations over the study area.

1. Introduction

Sfax, located in the Southeastern Mediterranean Sea, is the second largest city in Tunisia after Tunis, one of the main harbours of the Gulf of Gabes and an important industrial centre[1]. Sfax climate is dry (average precipitation: 210 mm), influenced by the hot southerly wind known as the Sirocco. It is bounded by beautiful Kerkennah islands in the northeast[2] and Kneiss islands in the southeast[3].

The north coast of Sfax is subjected to restoration from pollution[4-8]. 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 primary measures of the project consisted of cleaning a sector of 400 ha, eliminating 4 300 000 m^3 of contaminated soil including 1 700 000 m^3 of phosphogypsum. The second, the phosphogypsum was untreated and stockpiled along the coastline, 6 m above sea level in an uncontrolled landfill covering an area of more than 150 ha[4-8].

The south coast of Sfax is marked by salt extraction ponds from solar saltern located over an area of about 1 500 ha (COTUSAL)[9]. In addition, phosphogypsum, the residue of phosphate treatment, has been stored along the south coastline at an uncontrolled dumpsite from the plant which produces phosphoric acid (SIAPE)[1]. The south coastal area is subjected to degradation of water quality[10-12]. The expansion of industrial and commercial activities in the south Sfax coast has become an issue of increasing environmental concern.

After restoration in the north Sfax coast, a larger survey programme including four seasonal sampling campaigns covering environmental variables and biological parameters was conducted at both the surface and bottom[4-8].

On the south coast of Sfax not yet restored, the previous studies focus on the spatial and seasonal distribution of ultraphytoplankton[5], microphytoplankton[5,10,11], ciliates[10,11] and zooplankton[13].

Dinoflagellates represent an important part of the eukaryotic primary production in marine environments and they play a significant role in the carbon cycling and energy flow in the marine planktonic

*Corresponding author: Jannet Elloumi, Research Unity UR/11ES72 Biodiversity and Aquatic Ecosystem, Department of Sciences of Life, Faculty of Sciences, University of Sfax, Sfax, Tunisia
Tel: +216 22 74 11 55
Fax: +216 74 27 44 37
E-mail: jannetelloumi@yahoo.fr
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community[14]. In addition, dinoflagellates are typically considered as autotrophs, heterotrophs and mixotrophic species according to the existence or nonexistence of chloroplast pigments[15]. Heterotrophic and mixotrophic dinoflagellates were the major contributors to total phytoplankton abundance in the marine ecosystems[16]. Some dinoflagellates cause harmful blooms by their ability to produce toxin[17].

To address the restoration problem, in the present study, samples were taken at 12 stations along Sfax's north and south coasts (6 stations on each coast) in order to examine the spatial and seasonal distribution of dinoflagellates coupled with abiotic factors. In addition, by covering the south coast which is not yet restored, we established an additional comparison for the impact of north coast restoration.

2. Materials and methods

2.1. Study site

Sfax (34°43' N and 10°46' E) is located 270 km south of Tunis[18]. The coastal area north of the city stretches for 12 km, from the phosphate treatment plant (NPK) to Sidi Mansour, a zone characterized by its geomorphologic polygon[1]. The south coast includes part of the city, the harbour, the solar saltern, the two industrial areas of Madagascar and Sidi Salem, the SIAPE and business area of Thyna[4,10].

2.2. Field sampling

Nutrients and phytoplankton samples were collected during the years of 2010 and 2011. Water samples were collected on 12 stations along Sfax northern (1, 2, 3, 4, 5 and 6) and southern (A, B, C, D, E and F) coasts (Figure 1). Seawater samples for physico-chemical analyses and phytoplankton examination were collected from the surface water with a Van Dorn-type closing bottle at each station. Nutriment samples (120 mL) were stored immediately in the dark at 20 °C. Phytoplankton samples (1 L) were preserved with Lugol iodine solution (4%) for enumeration[19]. Water samples (1 L) for Chlorophyll *a* analysis were filtered by vacuum filtration onto Whatman GF/F glass fiber filters which were then immediately stored at –20 °C.

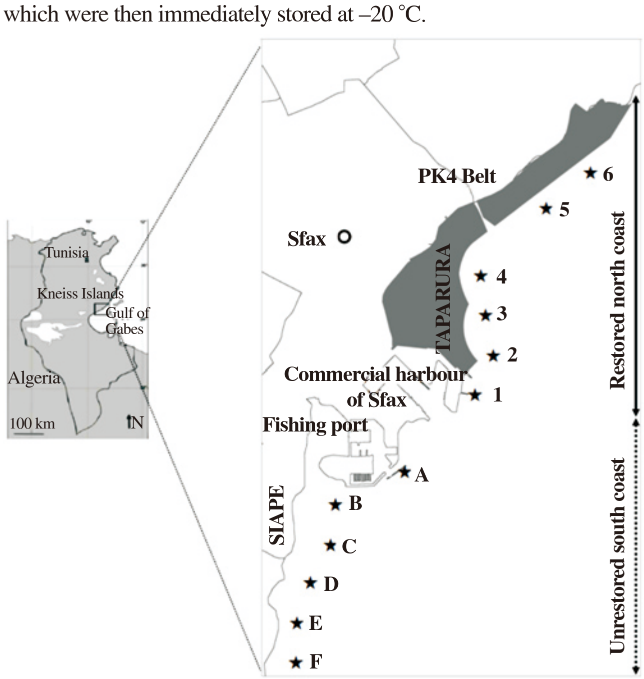

Figure 1. Location of sampling stations on the north and south coasts of Sfax.

2.3. Physico-chemical variables

Physical parameters (temperature, salinity, and pH) were measured immediately after sampling using a multi-parameter kit (Multi 340 i/SET). Suspended matter concentrations were measured using the dry weight of the residue after filtration of 0.5 L of seawater onto Whatman GF/C membrane filters. Chemical parameters (nitrite, nitrate, ammonium, orthophosphate, silicate, total nitrogen and total phosphate) were analyzed with a Bran and Luebbe type 3 autoanalyzer.

2.4. Phytoplankton enumeration

Phytoplankton samples (50 mL) were analysed under an inverted microscope after 24 to 48 h of settling using the Utermöhl method[20]. Phytoplankton species were identified according to various keys[1,4,5,7,8,10].

2.5. Chlorophyll a

Chlorophyll *a* was estimated by spectrometry, after extraction of the pigments in acetone (90%). The concentrations were then estimated using the equations of SCOR-UNESCO[21].

2.6. Statistical analysis

The data recorded in this study were submitted to a normalized principal component analysis (PCA)[22]. Simple log (x+1) transformation was applied to data in order to correctly stabilize variance[23]. Means and standard deviations (SD) were reported when appropriate. The potential relationships between variables were tested with Pearson's correlation coefficient.

3. Results

3.1. Physical parameters

3.1.1. North coast of Sfax

The average water temperature ranged between 13 and 36 °C (Figure 2) at station 1, with the lowest temperature in winter and the highest in summer. The seasonal fluctuation of temperature at all stations revealed higher values from spring to autumn. While, in winter, the coastal water temperatures were lower. Thermal stratification did not develop because of the shallowness at the sampled stations (< 10 m). Salinity varied from 37.33 p.s.u. in winter to 39.17 p.s.u. in summer at station 2, and the seasonal variations of salinity were important in winter, following roughly those of temperature (Figure 2). Salinity changes in winter may be due to rainfall and water runoff. The highest values were recorded in summer, intensified by evaporation. The pH values varied from 7.81 (station 2, autumn) to 8.73 (station 5, spring) (Figure 2). The mean pH value (8.30) was usually alkaline, suggesting an important photosynthetic activity. Seasonal distribution of suspended matter concentrations showed low value (48.20 mg/L) in autumn at station 2 and high value (201.56 mg/L) in winter at station 6 (Figure 2).

3.1.2. South coast of Sfax

Temperature varied between stations and seasons. The temperature was in the range of 14.97–32.33 °C, with the lowest value observed at station A in winter and the highest at station D in summer (Figure 2). At every station, the temperature tended to increase from winter

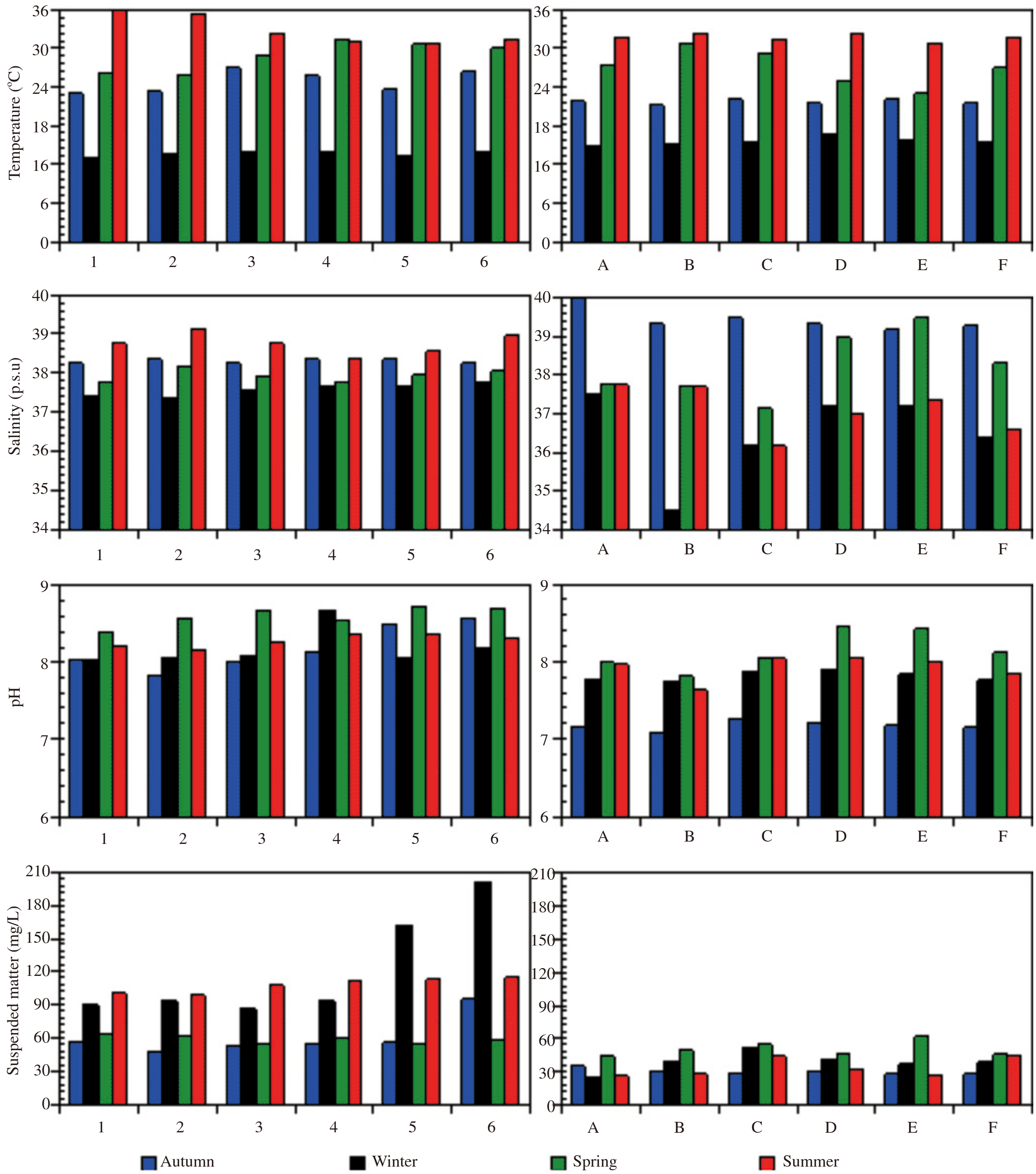

Figure 2. Spatial and seasonal variation of physical parameters (temperature, salinity, pH and suspended matter) at sampled stations.

to summer and showed a small decline in autumn compared to summer. The observed temperatures were the lowest in winter. Salinity varied from 34.53 p.s.u. (winter, station B) to 40 p.s.u. (autumn, station A) (Figure 2). The transition from autumn to winter exhibited a net decrease in salinity, whereas the salinity increase from summer to autumn was more pronounced. The value of pH was higher in spring (7.82–8.45) than that in winter (7.75–7.90) (Figure 2). Concentrations of suspended matter varied between 23.87 mg/L (winter, station A) and 61.44 mg/L (spring, station E) (Figure 2).

3.2. Chemical parameters

3.2.1. North coast of Sfax

Both NO_3^- and NH_4^+ concentrations were more available, whereas NO_2^- concentrations showed low values throughout the study period (Figure 3). Total nitrogen (T-N) concentrations varied between 13.26 μmol/L in autumn at station 6 and 23.06 μmol/

L in spring at station 2 (Figure 3). PO_4^{3-} concentrations were low [(0.16 ± 0.02) μmol/L] during autumn, but reached maximum level [(1.83 ± 0.48) μmol/L] during winter (Figure 3). When considering total phosphate concentrations, values were three times that of orthophosphate concentration in the winter and spring and ten times in the autumn and summer (Figure 3). The N/P: DIN (DIN = NO_2^- + NO_3^- + NH_4^+) to DIP (DIP = PO_4^{3-}) ratio ranged from 1.95 in winter to 15.76 in autumn at station 2. This average was less than the Redfield ratio (16), suggesting a potential nitrogen limitation. In contrast, the N/P ratio was higher in summer particularly at stations 1 and 2 with values of 30.15 and 32.88 (Figure 3). $Si(OH)_4$ concentrations were more important during winter [(22.76 ± 11.09) μmol/L] than during autumn [(2.21 ± 0.50) μmol/L]. The highest concentration of $Si(OH)_4$ was recorded at station 4 (40.09 μmol/L, winter), and the lowest (1.41 μmol/L, autumn) at station 1 (Figure 3).

3.2.2. South coast of Sfax

NO_2^- concentrations varied between 0.17 and 6.56 μmol/L in the study area, with the highest (6.56 μmol/L) concentration observed at station E in autumn, whereas the lowest concentration (0.17 μmol/L) was also observed at station E in summer (Figure 3). NO_3^- concentrations were more important than NO_2^- and NH_4^+ concentrations over the seasons and its mean value varied between (3.39 ± 2.04) μmol/L during summer and (10.69 ± 5.06) μmol/L during autumn (Figure 3). NH_4^+ concentrations were low (2.01 μmol/L) in summer (station C), but reached maximum value (11.33 μmol/L) during autumn at station A. The largest variations of total nitrogen (T-N) concentrations (13.83–33.92 μmol/L) were observed in summer. Total nitrogen concentrations were low (13.83 μmol/L, station C) in summer, and high (45.43 μmol/L, station E) in autumn (Figure 3). Total phosphate (T-P) concentrations varied between (10.61 ± 0.84) μmol/L (winter) and (29.70 ± 8.29) μmol/L (spring), whereas orthophosphate concentrations varied between (2.51 ± 1.04) μmol/L (winter) and (11.41 ± 1.94) μmol/L (spring), representing only 20%–38% of total phosphate (Figure 3). The mean value of the N/P ratio was less than that of the Redfield ratio (16) during the four seasons of study, but its whole range of variation (0.75–34.12) was large (Figure 3). $Si(OH)_4$ concentrations were higher during spring and autumn. In spring, $Si(OH)_4$ concentrations were 23.08 and 36.27 μmol/L at stations E and F respectively (Figure 3).

3.3. Dinoflagellates structure and dynamics

3.3.1. North coast of Sfax

Chlorophyll *a* concentrations were low (lower than 10 mg/L) over seasons. The pigment concentrations were low in autumn except at station 1 (9.84 mg/L). In contrast, an important increase of Chlorophyll *a* concentration was observed in spring [(3.10 ± 1.32) mg/L] (Figure 4). The total phytoplankton abundance varied from 16.42 × 10^2 cells/L (station 5, spring) to 260.41 × 10^2 cells/L (station 6, summer), with the highest mean abundance recorded in winter [(135.46 ± 80.73) × 10^2 cells/L]. Abundances of phytoplankton community peaked at the same time, in winter at stations 4, 5 and 6. Low densities of phytoplankton were recorded during spring (Figure 4). Dinoflagellates abundance ranged from (4.24 ± 1.03) × 10^2 cells/L in winter to (30.81 ± 31.63) × 10^2 cells/L in summer, showing a remarkable increase in spring and summer. The highest dinoflagellates abundance was observed in station 2 during summer, associated with an important proliferation of *Prorocentrum rathymum* (35.34 × 10^2 cells/L) and *Prorocentrum lima* (44.67 × 10^2 cells/L) (Figure 5). The species composition of the dinoflagellates community changed dramatically throughout the study period, shifting from a predominance particularly of *Peridinium* sp. during autumn and *Gymnodinium* sp. during winter, to a massive proliferation of *Protoperidinium* sp., *P. triestinium* and *P. micans* in spring and *P. lima* in summer (Figure 5). Dinoflagellates abundance and diversity fluctuated in the four seasons under study and showed a significant seasonal variability (Figures 4 and 5). In the present study, 35 dinoflagellates taxa were observed, with 24 identified to the species level (Table 1). Dinoflagellates diversity varied significantly with respect to seasons, decreasing in winter (10 species) and exhibiting a remarkable increase in autumn (20 species) (Table 1). The genus *Protoperidinium* (16 species) and *Prorocentrum* (7 species) were the most diverse among dinoflagellates (Table 1).

3.3.2. South coast of Sfax

Chlorophyll *a* concentrations ranged from 0 to 25.89 mg/L [(4.95 ± 6.60) mg/L] and had a tendency to increase in autumn and spring (Figure 4). The seasonal mean total phytoplankton abundance varied from 8.00 × 10^2 cells/L (station B, autumn) to 205.00 × 10^2 cells/L (station F, summer) (Figure 4). Total phytoplankton abundance was observed to be significant during summer [(105.00 ± 64.46) × 10^2 cells/L], whereas it was poorly represented during winter [(32.00 ± 10.54) × 10^2 cells/L] (Figure 4). Abundance of total phytoplankton peaked in the same season (summer) at station A (151 × 10^2 cells/L), station B (90 × 10^2 cells/L), station C (73 × 10^2 cells/L) and station F (205 × 10^2 cells/L) (Figure 4). Dinoflagellates abundance ranged from (6.00 ± 4.31) × 10^2 cells/L to (41.00 ± 45.32) × 10^2 cells/L. The highest dinoflagellates abundance (118 × 10^2 cells/L) was recorded during summer at station F (Figure 4); however, the highest number of dinoflagellates taxa was observed during spring (20 taxa). Clear differences in dinoflagellates composition were found from station to station and from season to season (Figure 5). Medium-size dinoflagellates essentially represented by *Gymnodinium* sp. were observed particularly during autumn and winter. Small dinoflagellates consisted of *P. micans* and *P. lima* in spring and *P. triestinium* and *P. lima* in summer (Figure 5). A summary of the dinoflagellates taxa observed during the entire study period at the 6 sampling stations is given in Table 1. The dinoflagellates community consisted of 28 taxa (16 taxa in autumn, 8 taxa in winter, 20 taxa in spring and 13 taxa in summer) belonging to 14 genera (Table 1). The genus *Protoperidinium* was dominant among dinoflagellates (9 species), followed by *Prorocentrum* (5 species) (Table 1).

3.4. Statistical analysis

3.4.1. North coast Sfax

PCA allowed discrimination of four groups around the

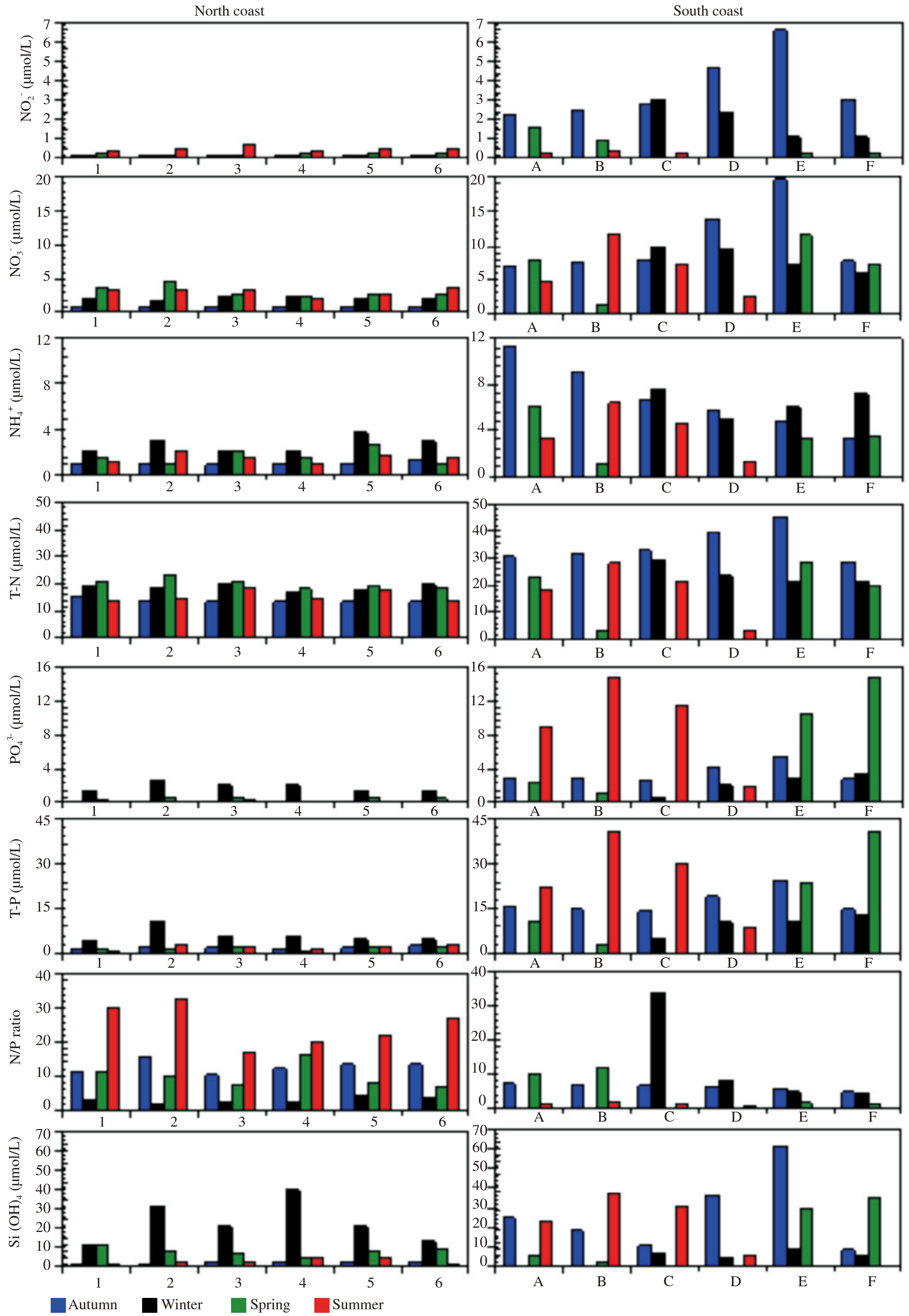

Figure 3. Spatial and seasonal variation of chemical parameters (nitrite, nitrate, ammonium, total nitrogen, orthophosphate, total phosphate, N/P ratio and silicate) at sampled stations.

Table 1

List of the dinoflagellates species observed on the north and south coasts of Sfax.

Species	Mode of nutrition	North coast of Sfax				South coast of Sfax			
		Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer
Alexandrium sp. (Halim, 1960)	Mixo-heterotrophic	+	-	-	-	-	-	+	-
Amphidinium sp. (Herdman, 1922)	Mixo-heterotrophic	-	+	+	-	+	+	+	+
Ceratium furca (Claparède and Lachmann, 1859)		-	-	-	+	-	-	-	-
Ceratium fusus (Dujardin, 1841)	Mixo-heterotrophic	-	-	-	+	-	-	-	-
Ceratium lineatum (Cleve, 1899)	Mixo-heterotrophic	-	-	-	-	+	-	-	-
Ceratium sp. (Nitzsch, 1817)	Mixo-heterotrophic	+	-	-	-	-	-	-	-
Dinophysis caudata (Saville-Kent, 1881)		-	-	-	-	+	-	-	-
Dinophysis sp. (Kofoid and Skogsberg, 1928)	Endosymbionts	-	-	-	-	-	-	-	+
Gonyaulax sp. (Claparède and Lachmann, 1859)	Mixo-heterotrophic	-	+	+	+	-	+	+	+
Gymnodinium marinum (Saville-Kent, 1880)		-	-	-	-	+	-	-	
Gymnodinium sp. (Stein, 1878)		+	+	+	+	+	+	+	+
Gyrodinium sp. (Freudenthal and Lee, 1963)	Mixo-heterotrophic	-	+	-	+	+	+	-	+
Noctiluca sp. (Suriray, 1816)		-	-	-	-	-	-	+	
Peridinium sp. (Ehrenberg, 1830)	Autotrophic	+	+	+	+	+	-	+	+
Polykrikos sp. (Bütschli, 1873)	Heterotrophic	-	+	-	-	+	-	+	+
Prorocentrum compressum (Dodge, 1975)		+	-	-	-	-	-	+	-
Prorocentrum gracile (Schütt, 1895)		+	-	+	-	+	-	-	-
Prorocentrum lima (Stein, 1878)		-	-	-	+	+	-	+	+
Prorocentrum micans (Ehrenberg, 1834)	Mixo-heterotrophic	+	+	+	-	-	-	+	+
Prorocentrum rathymum (Sherley and Schmidt, 1979)		-	-	-	+	-	-	-	-
Prorocentrum sp. (Ehrenberg, 1834)		-	-	-	+	-	-	-	-
Prorocentrum triestinum (Schiller, 1918)	Mixo-heterotrophic	+	-	+	-	-	+	+	+
Protoperidinium bipes (Balech, 1974)		-	-	-	-	+	-	+	-
Protoperidinium brevipes (Balech, 1974)		+	-	+	-	-	-	-	-
Protoperidinium cerasus (Balech, 1973)		+	-	-	-	-	-	+	-
Protoperidinium conicoides (Balech, 1973)		-	-	+	-	-	-	+	-
Protoperidinium conicum (Balech, 1974)		-	-	+	-	+	-	-	-
Protoperidinium curvipes (Balech, 1974)	Mixo-heterotrophic	+	+	-	-	-	-	-	-
Protoperidinium depressum (Balech, 1974)	Mixo-heterotrophic	-	-	-	-	-	-	+	-
Protoperidinium diabolum (Balech, 1974)		+	-	-	+	-	-	-	-
Protoperidinium divergens (Balech, 1974)	Mixo-heterotrophic	+	-	-	+	-	-	-	-
Protoperidinium globulum (Balech, 1974)		-	-	-	-	-	-	+	-
Protoperidinium minutum (Loeblich III, 1970)	Mixo-heterotrophic	+	-	+	-	-	+	+	+
Protoperidinium ovatum (Pouchet, 1883)		-	+	-	-	-	-	-	-
Protoperidinium pellucidum (Bergh, 1881)		+	-	-	-	-	-	-	-
Protoperidinium pyriforme (Balech, 1974)	Mixo-heterotrophic	+	-	+	+	-	-	-	-
Protoperidinium steinii (Jorgensen, 1899)	Mixo-heterotrophic	+	-	+	+	+	-	-	-

continued on next page

Table 1 (*continued*)

Species	Mode of nutrition	North coast of Sfax				South coast of Sfax			
		Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer
Protoperidinium subcurvipes (Balech, 1974)		-	-	+	-	-	-	-	-
Protoperidinium subinerme (Loeblich III, 1969)		-	-	+	-	-	-	-	-
Protoperidinium thorianum (Paulsen, 1905)		-	-	+	-	-	-	-	-
Protoperidinium sp. (Balech, 1974)		+	+	+	+	+	+	+	+
Pyrophacus sp. (Stein, 1883)		+	-	-	-	+	-	-	-
Scrippsiella trochoidea (Stein, 1883)	Mixo-heterotrophic	+	-	-	+	+	+	+	+

+: Present; -: Not detected

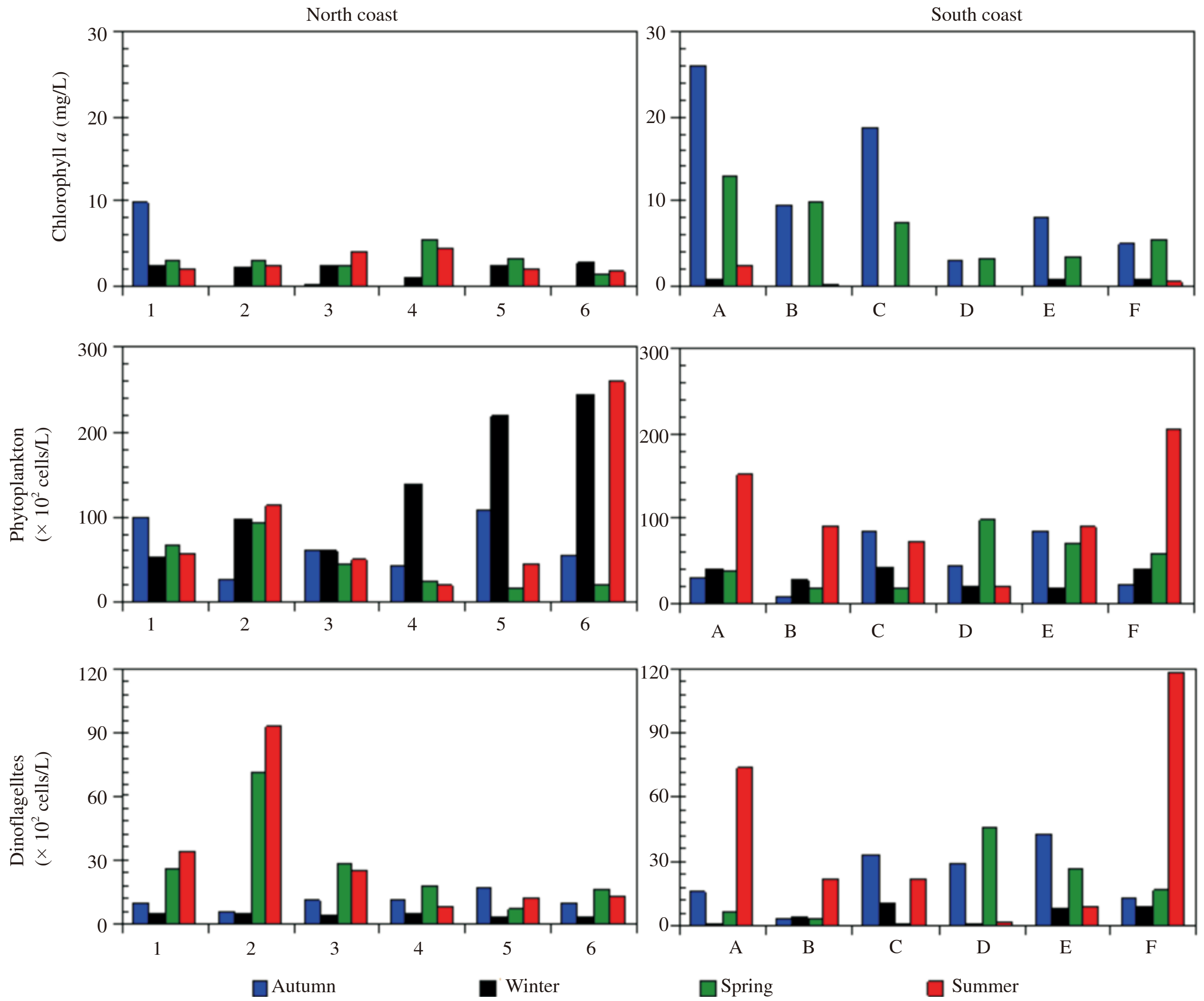

Figure 4. Spatial and seasonal variation of chlorophyll *a* concentration and abundance of phytoplankton and dinoflagellates at sampled stations.

components of the F1 and F2 axes (Figure 6), explaining 58.66% of the variance. The F1 axis, explaining 32.85% of the variability of abiotic and biotic parameters, positively selected group G1 composed of NO_3^-, T-N, N/P and dinoflagellates selected in station 1. The F2 axis, representing 25.81% of the variability, positively selected group G2 comprising environmental factors such as salinity, NO_2^-, NH_4^+, PO_4^{3-} and T-P correlated with total phytoplankton abundance selected in stations 2 and 3. G3 comprised temperature, pH and suspended matter concentrations. The group G4 was formed by chlorophyll *a* and $Si(OH)_4$ (Figure 6).

3.4.2. South coast of Sfax

The PCA distinguished between four groups surrounding the F1 and F2 component axes thus explaining 69.32% of the variance. The group G1 was formed by salinity, NO_3^-, NH_4^+ and T-N. F1 component axis, which extracted 43.43% of the variability, selected positively the group G2, with pH, NO_2^-, PO_4^{3-}, T-P and $Si(OH)_4$.

G3 selected temperature and suspended matter concentrations. The axes selected a group G4 comprising the biological parameters (total phytoplankton, dinoflagellates, chlorophyll *a*) and N/P ratio. This combination was selected in station A (Figure 6).

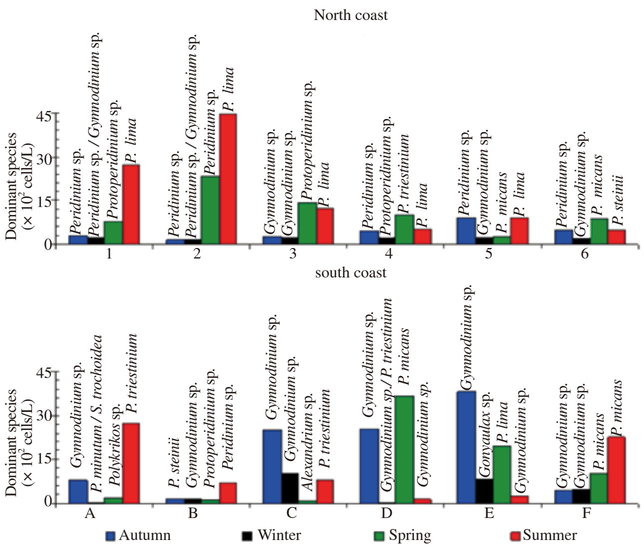

Figure 5. Spatial and seasonal variation of dominant species at sampled stations.

4. Discussion

This study is the first attempt to examine, with high spatial resolution, the seasonal changes in dinoflagellates community composition in relation to abiotic factors in north coast as subject to phosphogypsum restoration and south coast which is still subjected to the same industrial pollution related to the fertilizer and phosphate industry. Yet, in order to distinguish among variations induced by the coast restoration and those of a diverse source, it was also imperative to evaluate the north coast situation to that of the south of Sfax.

This study indicates that spatial and seasonal variations in temperature were characteristic of a semi-arid to arid Mediterranean climate[24]. The seasonal cycle in temperature at 12 stations along Sfax northern and southern coasts (6 stations on each coast) showed a warming trend starting in spring and reaching its maximum in summer, followed by a cooling trend reaching its minimum in winter. Water salinity decreased along with the decrease in temperature in winter (r = –0.84, P < 0.05, n = 15). The average pH value in the north (8.30) was largely higher than the value found in the southern Sfax coast (7.76). The low pH values can reasonably be attributed to the industrial activity still in function in the southern coast while it has been finished in the north[5]. The pH augment in the north since restoration suggests that equilibrium had not been attained yet at the southern Sfax coast and that pH restoration had been more important than the sea acidification induced by global alteration[5]. A striking difference between the north and south coasts is seen in suspended matter concentrations with lower values in the south (23.87–61.44 mg/L), contrasted with the higher concentrations in the north (48.20–201.56 mg/L). The high suspended matter concentration levels may reasonably be attributed to the shallowness of the sampled north stations, the spatial distribution of tiny particles and tidal action[13] and to the recently added soil, not yet fully stabilised.

We found low orthophosphate concentrations follow-on phosphogypsum restoration in the north coast of Sfax (0.18–2.60 μmol/L). A major difference with the south coast concerns the high orthophosphate concentrations (average value: 2.51–11.41 μmol/L), which was 5 times higher than the north Sfax coast. Total phosphate concentrations presented the same pattern as orthophosphate, increasing from the north to the south Sfax coast. Indeed, the average north coast concentration of phosphate was about 4 times lower than it was in south coast of Sfax. The closing of the phosphate processing industry on the north Sfax coast restored phosphate concentrations to normal values for a marine environment[7]. Accordingly, the N/P–DIN to DIP ratio was less than the Redfield ratio (16), suggesting potential dissolved inorganic phosphate excess

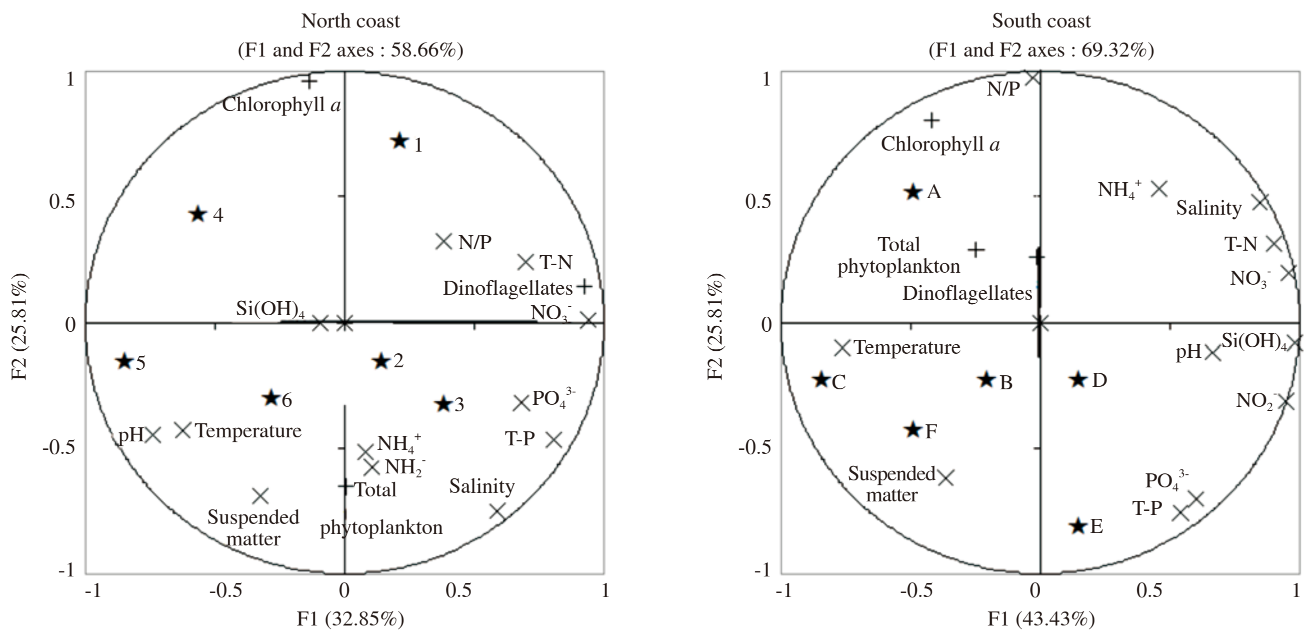

Figure 6. Principal component analysis (PCA) (Axis I and II) of biological parameter abundance and selected environmental variables at sampled stations on the north and south coasts of Sfax.

in autumn and winter along Sfax north and south coasts. Relatively high dissolved inorganic phosphate concentration compared to dissolved inorganic nitrogen can be a result of orthophosphate fast regeneration[25]. Contrasting with the results we found in autumn and winter, the average value of the N/P ratio was more important to the Redfield ratio (16) in spring and summer both along the north and south coasts of Sfax. This means that restoration did not change the overall N/P ratio.

A total of 43 dinoflagellates taxa representing 14 different genera were identified during our study, relatively the minority of which could be considered as rare, observed at only one or two stations. The data-base was performed in order to collect enough information linked to the dinoflagellates variations for two scales: spatial and seasonal dynamics. Our results showed an increase of dinoflagellates abundance during summer and spring both in the north and south coast of Sfax with the maximum 92.37×10^2 cells/L and 118×10^2 cells/L was reached in station 2 and F respectively. Dominance of dinoflagellates in summer has been already observed in previous studies in the coastal water of the Gulf of Gabes[14] and in other Mediterranean sea[26]. The decrease in water instability is expected to increase dinoflagellates growth[27]. They favour a stable water column and high temperature[28]. Therefore, the stability of the water column during summer provides the opportunity to take full advantage of these abilities. Nitrogen seemed to be the most important factors in the coastal environments which could control the seasonal distribution of dinoflagellates[15]. Dinoflagellates were founded when the water column was characterized by elevated values of inorganic nitrogen[29]. The fact that inorganic nitrogen had the greatest influence on dinoflagellates abundance in our study area was clear from the strong positive correlation between their abundance and NO_3^- ($r = 0.82$, $P < 0.05$, $n = 15$). Dinoflagellate abundance was not correlated with chlorophyll-a concentration, neither in the north coast nor in the south coast of Sfax. Thus, dinoflagellates were not probably linked to the recent episodes of primary production. This could be explained by the fact that an important number of dinoflagellates species in marine phytoplankton were deprived of chloroplasts[30]. Some mixotrophic and heterotrophic dinoflagellates species, like *Polykrikos* sp., *Ceratium lineatum*, *Protoperidinium curvipes*, *Protoperidinium depressum* (*P. depressum*), *Protoperidinium divergens* and *Protoperidinium steinii* attained high numbers in our coastal area. Similar observation was shown by Ben Ltaief *et al.*[16] in the Gulf of Gabes where important proliferation of heterotrophic and mixotrophic dinoflagellates were the distinctive characteristic of the summer cruise. Overall dinoflagellates, the abundance of harmful species (*Alexandrium* sp., *Amphidinium* sp., *Dinophysis caudata*, *P. lima*, *Protoperidinium brevipes*, *P. depressum* and *Protoperidinium steinii*) were not important in both coasts. Except, *P. lima*, which achieved a maximum bloom during the summer in the north part (stations 1, 2, 3, 4 and 5) and in the south part (station F) of Sfax coast, coinciding with the highest temperature. Two distinct associations of dinoflagellates species were identified: a north association involving *Ceratium lineatum*, *Dinophysis caudata*, *Dinophysis* sp., *Gymnodinium marinum*, *Noctiluca* sp., *Protoperidinium bipes*, *P. depressum* and *Protoperidinium globulum*, and a south assemblage concerning *Ceratium furca*, *Ceratium fusus*, *Ceratium* sp., *Prorocentrum rathymum*, *Prorocentrum* sp., *Protoperidinium brevipes*, *Protoperidinium curvipes*, *Protoperidinium diabolum*, *Protoperidinium divergens*, *Protoperidinium ovatum*, *Protoperidinium pellucidum*, *Protoperidinium pyriforme*, *Protoperidiniun subcurvipes*, *Protoperidiniun subinerme* and *Protoperidiniun thorianum*. Dinoflagellates assemblages consisted of an important density of *Gymnodinium*. This genus has been reported to occur under elevated phosphate accessibility[31]. Yet, *Gymnodinium* showed that phosphate concentrations were low and nitrogen resources were important in the northern and southern coasts of Sfax, suggesting that the growth of dinoflagellates was mostly nitrogen-driven. Among the epiphytic dinoflagellates, the genus *Prorocentrum* was the most abundant in spring and summer. *P. lima* is a weakly swimming dinoflagellate that primarily inhabits sandy sediments. It can fix itself by a covering of mucus or by free-living within the interstices of macroalgal thalli, making it exposed to environmental instability. Such groups are mostly reported in small or moderately energy milieu[32]. *Prorocentrum triestinum* formed surface aggregation during the stability of the water column[33] and manifest a diurnal cycle migration[34]. Our study agreed with this finding since the highest abundance of *P. micans* and *Peridinium* sp. was registered mainly during the stable water column[2].

The restoration of the north Sfax coast appears to have a beneficial impact on the ecosystem achieved by the Taparura Project. The highest heterotrophic dinoflagellates mean abundance was recorded in south part of Sfax coast. This increase was justified by the nutrient accessibility. Harmful dinoflagellates were not important, except, *P. lima* which achieved important abundance during the summer bloom in both coasts. Results reported strong values of suspended matter in the north in comparison to the south may be in relation to the lately added soil, not yet fully stabilised and that may effect the resuspension of tiny elements with, for example, tidal action. The important acidification of seawater in the south likely results from industrial activity. The restoration of the south coast should alleviate this high acidification.

Conflict of interest statement

We declare that we have no conflict of interest.

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