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PHYTOPLANKTON DIVERSITY AND LIMITING RESOURCES IN A SEMI-ENCLOSED MARINE ECOSYSTEM (ALEXANDRIA, EGYPT)

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ABSTRACT

To address the mechanisms regulating phytoplankton diversity indices, the relationship with limiting resources (temperature, salinity, pH, oxidizable organic matter (here after OOM), nutrient concentrations and ratios) were analyzed in the Eastern Harbour of Alexandria (Egypt) through an intensive period of sampling (July 2006-September 2007). The environmental heterogeneity in the harbour made an essential contribution to phytoplankton numerical variability and species diversity (94 species). 13 species were able to form blooms ($>1x10^6$ unit l^{-1}), and the number of coexisting species during the bloom periods was generally low. Pulsed nitrogen concentrations enhanced the production of diatoms, and phosphate input between 4.3 and 7.6 µM measured with maximum abundances of dinoflagellates. The diversity index fluctuated between 0.03 and 3.57, with no clear seasonal trend. Highly significant positive correlation was found between diversity and evenness. The sudden increase in nutrient concentrations followed by and/or accompanied by abnormal high phytoplankton densities of specific species indicate the harbour to be subjected to eutrophication processes. The pulses greatly affected the phytoplankton succession, had a strong negative effect on the diversity indices through the dominance of a single species, and can increase the possibility of harmful algal blooms. For a better understanding of the correlation between resources and diversity indices, temperature values and nutrient concentrations were divided into different ranges. The effects of the measured parameters and nutrient ratios on the phytoplankton assemblages and the diversity indices were more obvious at 16-22°C. At this range, the correlation matrix indicates the production to be significantly correlated with temperature, SiO_4^{-2}, NO_3^{-1}, nutrient ratios, and species richness. Evenness (*J*) and diversity (*H'*) correlated significantly with each other and with production, PO_4^{-2}, SiO_4^{-2}, NO_3^{-1}, OOM, nutrient ratios, and species diversity. A significant correlation was found between production and diversity at 1-2 µM, and > 2 µM PO_4^{-2}, and at > 4 µM SiO_4^{-2}, it was strong at > 4 µM NO_3^{-1}, and ammonia concentrations seem of a negligible effect. About 16.4% of the summer's pH data were in the range of 9-9.4, positively significantly correlated with the relative contribution of dinoflagellates.

1. INTRODUCTION

Since the Earth Summit held in Rio de Janeiro, Brazil, in 1992, worldwide interest in species diversity has been increasing, especially in terms of conserving natural ecosystems. The ecology and biodiversity of estuarine and coastal waters in many parts of the world are under threat from increasing anthropogenic inputs of nutrients (Cloern, 2001). The knowledge about ecological succession and diversity in the phytoplankton communities is an important implement to characterize and type different system dynamics (Hillebrand and Sommer, 2000). Variability in diversity can serve as an indicator for the modification of ecosystems under the eutrophication/pollution stress

(Telesh, 2004). The role of biodiversity in the regulation of ecosystem functioning, based primarily on species and functional group richness, has been the focus of much research (Duffy and Stachowicz, 2006).

How community diversity might regulate other ecological properties, like productivity, is the most prominent biodiversity research (Aktan *et al*., 2005). Other research, which has sought to understand the opposing question, or ‘‘what regulates diversity in communities?’’ has been extensive (Interlandi and Kilham, 2001).

Based on "Resource-competition theory" diversity directly proportional to the number of resources at limiting levels within a system, and the predicted species diversity should exactly equal the number of limiting resources when equilibrium conditions are met (Tilman, 1982). However, diversity of phytoplankton communities is often greater than the number of measured limiting resources even when conditions are apparently close to equilibrium, that evaluated both theoretically and experimentally (Siegal, 1998).

This study is an attempt to ascertain the connection between phytoplankton diversity indices and number of ecological resources in the Eastern Harbour ecosystem, which have been characterized extensively during the last two decades (Zaghloul and Halim, 1992; Labib, 1994 a,b; Zaghloul, 1995; Mikhail, 2001; Mikhail, *et al*., 2007), and to see if resources are able to regulate diversity under dynamic conditions, and the possibility to predict the occurrence of an algal bloom. The question "How is productivity related to biodiversity" needs to be answered. The importance of the forcing short-timescale in phytoplankton dynamics, and the linkage between sudden nutrient pulses (anthropogenic influence), phytoplankton blooming, and changes in diversity are discussed. The quantification of the causes of phytoplankton variability in the harbour is still inadequate and many principals of phytoplankton variability and impacts on community structure and species diversity have yet to be elucidated.

2. MATERIALS AND METHODS

The Eastern Harbour of Alexandria (Egypt) is a semi-enclosed coastal marine ecosystem located in the center part of the city (area of 2.53 km^2, average depth of 5 m, water volume of $15.2x10^6$ m^3), and it is connected to the Mediterranean Sea.

Short-term collection for 132 consecutive days between 10 July 2006 and 10 September 2007 was carried out at a fixed station (3 m depth, Figure 1); it was almost daily during the red tide periods. Measurements of physico-chemical parameters were done parallel to the phytoplankton sampling. Surface water temperature and salinity were measured using a thermometer accurate to ± 0.1°C, and salinity refractometer (S/Mill, after calibration). Above bottom temperature and salinity were frequently measured, and pH was determined using *in situ* instrument. Water samples for nutrient analysis were filtered through Whatman GF/F filters and were immediately frozen until further analysis. Dissolved inorganic nutrients (nitrate, nitrite, ammonium, phosphate, and silicate) were measured spectrophotometrically (Grasshoff *et al*., 1999), and oxidizable organic matter (OOM) using a permanganate value test (FAO, 1975). Phytoplankton samples taken from the surface water were first examined under microscope, then fixed with the addition of neutral formalin and a few drops of Lugol's acid solution for cell enumeration and species identification (Tanaka, 2002; Tomas 1997) using an inverted microscope after sedimentation (Utermöhl, 1958). The abundance of phytoplankton species (production) expressed as units per liter (The unit comprised cells, colonies and filaments).

Linear regressions were used to estimate the relationship of one variable to another. Biological diversity (H') and evenness (J) were calculated according to the equations of

Shannon and Weaver (1969) and Pielou (1966). Correlation coefficients between phytoplankton abundance, diversity index, evenness and environmental factors were computed.

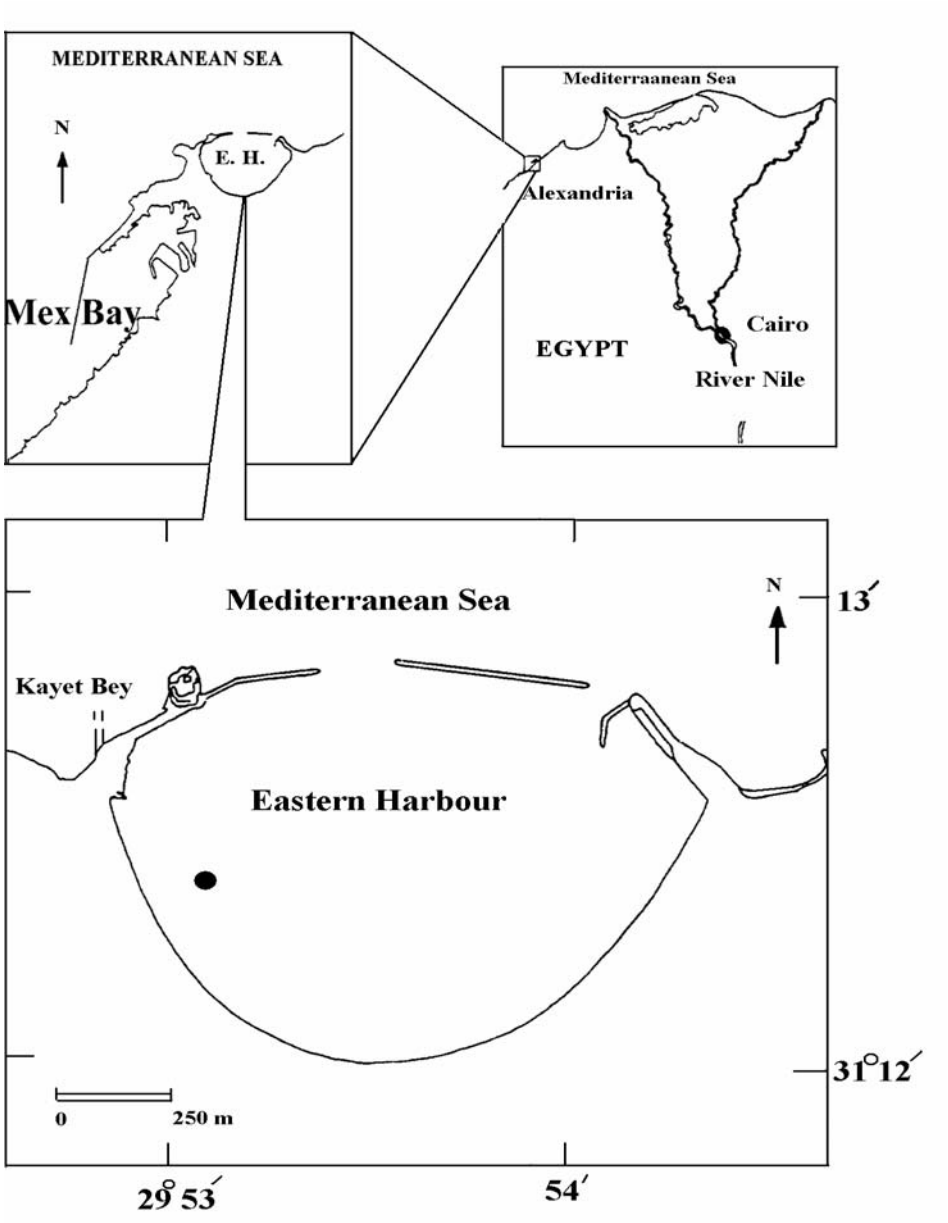

Fig (1): The Eastern Harbour of Alexandria and location of the sampling station (●).

3. RESULTS

3.1. Environmental characteristics during an annual cycle

Surface water temperature (mean 24.04±4.98) fluctuated between 12.4°C in late January and 29°C in early August. The harbour was subjected to mixing processes by wind action from December 2006 to March 2007.The rapid temperature increase in late April-early May (16 to 21.2°C) created a weak thermal stratification (ca 0.9°C) between the warmer surface and the above bottom water layer, which become well established in the summer seasons (difference of 1.1 to 1.5°C).

Generally, 75.76 % of the salinity values (mean 36.7±1.62) ranged between 33 and 37.5, and 24.24% with salinity >37.5 to 39.9. The difference in salinity between the less saline surface water and that above the bottom reached 1.2 to 1.5 in summers.

The OOM concentrations (mean 5.34±4.35) fluctuated between 0.42 and 23.2 mg l^{-1}. The lowest concentrations were measured in winter (average 2.31 mg l^{-1}), and the highest in summer and autumn 2007 (average 7.47 and 9.15 mg l^{-1}). Most of the extreme high concentrations accompanied the phytoplankton bloom periods.

The linear regression analysis (based on all data, n=132) indicates temperature and salinity to have a strong influence on diversity index variability (Fig. 2) and OOM on phytoplankton production (Fig. 3). Diversity index showed significant positive correlation with temperature (r= 0.49, 0.05 level), and strong negative correlation with salinity (r = - 0.39, 0.05 level). A strong positive correlation was found between the phytoplankton density and the corresponding OOM concentration (r= 0.44, n=132).

The exchange of the harbour's water with the adjacent Mediterranean seawater and exhaustion by phytoplankton blooming resulted in rich spectra for the availability and variability of the nutrient concentrations, and might explain the failure of the statistical analyses to predict a significant impact of nutrients on production and diversity. However, by splitting of nutrient concentrations into several ranges more specific and conclusive results could be obtained.

Phosphate concentrations (mean 1.1 µM ±1.64, range 0.04 µM to 8.58 µM) showed remarkable seasonal variations. Three ranges of PO_4^{-2} concentrations are suggested: < 1 µM, 1-2µM and >2µM. The statistical analyses showed different relationships: PO_4^{-2} at <1 µM affects the production (r=0.31, n=95). The effect is stronger on production and diversity at >2 µM (r = - 0.48 and 0.42, n=20, respectively); and is negligible on both production and diversity at 1-2 µM PO_4^{-2} (r = -0.01 and -0.04, n=17, respectively). Meanwhile, a significant negative correlation was found between the production and diversity at the ranges 1-2 µM, and > 2 µM (r= -0.60 & - 0.71).

Silicate concentrations (mean 4.33 µM±5.22, minimum 0.37 µM and maximum 32.23 µM) was highest in autumn 2006 (average 11.23 µM) and lowest in summer 2007 (average 1.66 µM). The concentrations were divided into 2 ranges: <4 µM and >4 µM. A negative strong insignificant correlation existed between production and diversity at < 4 µM (r =-0.36, n = 92), and it was significant at > 4 µM (r = 0.49, n = 40).

Nitrate concentrations (mean 2.31 µM±1.76, minimum 0. 41 µM and maximum 10.25 µM) were relatively high in autumn 2006 and low in summer 2007 (average 3.46 and 1.56 µM, respectively). The concentrations were divided into 3 ranges: <2 µM, 2-4 µM, and >4 µM. No significant correlation was found between production, diversity and NO_3^{-1} at <2 µM, nevertheless, production and diversity were significantly inversely correlated (r = - 0.53, n=78). Levels of 2-4 µM seem to cause no effect on production and diversity, and at > 4 µM were

more effective (r = 0.34, and 0.22, n =14, insignificant at 0.05 level).

Ammonia concentrations (mean 2.33 µM ±1.48, minimum 0.1 µM, and maximum 8.19 µM) showed almost similar average values during most of the year (2.09 -2.81 µM), that relatively lower in summer 2006 (1.63 µM). Its concentrations were divided into 2 ranges: < 2 µM and > 2 µM. The statistical analyses showed ammonia concentrations to have a negligible effect on production and diversity variations. However, much stronger correlation was found with increased concentrations (r = - 0.37 and - 0.45, n=62).

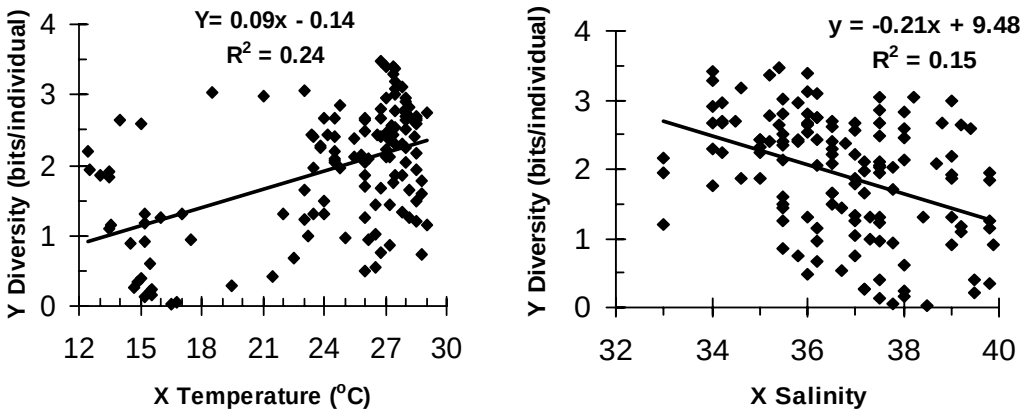

Fig. (2): Linear relationship between temperature, salinity and diversity.

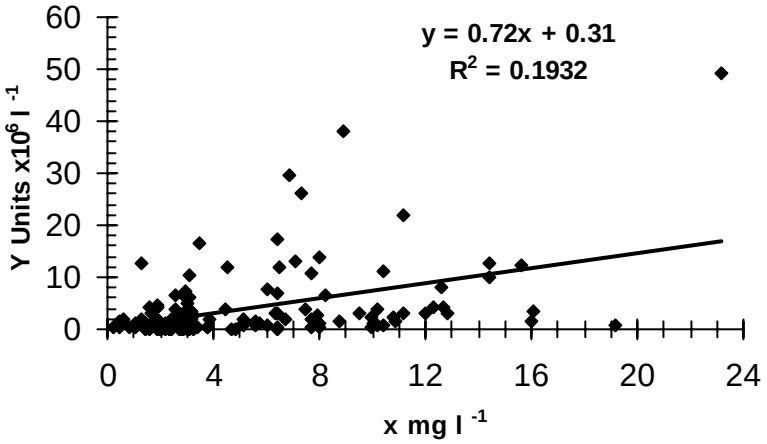

Fig (3): Linear relationship between oxidizable organic matter and phytoplankton density.

3.2. Temporal distribution of phytoplankton abundance and structure

The phytoplankton community in the harbour appeared to be highly diversified (94 species), mainly represented by marine forms. Regardless of this large, only 20 species were abundant, among them 13 species were able to form blooms (>1x10^6 unit l^{-1}), and the number of coexisting species within the bloom periods was generally low. The annual average of the standing stock was estimated as 3.93x10^6 unit l^{-1}. Based on average data considering difference in sampling frequency, the production by number was arranged by order of magnitude as: autumn 2007 (10.24x10^6 units l^{-1}, 8 samples) > spring 2007 (8.54x10^6 units l^{-1}, 23 samples) > summer 2007 (4.7x10^6 units l^{-1}, 39 samples) > autumn 2006 (2.22 x10^6 units l^{-1}, 24 samples) > summer 2006 (1.19x10^6 units l^{-1}, 28 samples), and the lowest in winter 2006-2007 (0.56x10^6 units l^{-1}, 10 samples). The distribution of the phytoplankton groups showed usually high relative abundance of diatoms (average 1.83x10^6 cells l^{-1}, 46.56% of the total, 44 species), followed by unidentified microflagellate species (1.01x10^6 cells l^{-1}, 25.7%), and dinoflagellates (0.95x10^6 cells l^{-1}, 24.17%, 32 species), while euglenophytes (0.097x10^6 cells l^{-1}x10^6, 5 spp.), raphidophytes (0.04x10^6 cells l^{-1}, 2 spp.), chlorophytes (4 spp.), cyanophytes (2 spp.) and silicoflagellates (2 spp.) contributed together 3.57% to the total standing crop. The most diverse genus was *Protoperidinium* (9 species).

3.3. Phytoplankton variation, resources use, evenness and diversity with temperature ranges

Despite the fact that the surface water temperature reflects seasonality in Alexandria Mediterranean waters, the sudden changes in temperature particularly in early spring, and early autumn by unusual hot weather, hindered specific definition of seasonality on the basis of absolute temperature records. To better understanding the phytoplankton dynamics in the harbour three temperature ranges are suggested (Table 1).

Table (1): Physico-chemical conditions, phytoplankton groups, diversity and evenness indices at temperature ranges.

	< 16°C			16-22°C			> 22°C		
Tem. °C	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
	14.50±1.07	12.40	16.00	19.62±2.47	16.50	23.00	26.65±1.65	23.0	29.0
Salinity	39.03±0.79	37.20	39.90	37.78±0.75	36.20	39.00	36.07±1.27	33.0	38.8
PO_4^{-2} µM	0.2 ±0.12	0.04	0.56	0.89±0.49	0.27	1.61	1.33±1.82	0.1	8.58
SiO_4^{-2} µM	2.35±0.91	1.27	4.80	4.38±1.89	2.20	6.88	4.76±5.91	0.37	32.23
NO_2^{-1} µM	0.35±0.08	0.20	0.52	0.28±0.08	0.14	0.41	0.34±0.21	0.01	1.48
NO_3^{-1} µM	2.89±0.97	1.38	6.42	1.46±0.41	1.05	2.38	2.27±1.95	0.41	10.25
NH_4^{-1}µM	2.11±0.82	1.07	4.51	2.21±0.61	0.94	2.84	2.39±1.65	0.1	8.19
OOM mgl^{-1}	2.62±0.39	1.88	3.21	6.63±3.72	2.82	15.60	5.80±4.66	0.42	23.2
Total density*	1.53±2.13	0.02	6.66	14.14±12.68	0.19	38.25	3.63±6.12	0.06	49.27
Species No.	11.45±3.42	4.00	17.00	17.18±4.38	9.00	23.00	18.57±4.07	9.00	33.00
Diatoms**	87.81±22.28	9.34	99.98	67.64±36.33	3.24	99.91	34.83±29.26	0.54	99.30
Dinoflage.**	8.48±19.38	0.02	85.67	22.66±29.99	0.09	77.85	45.03±29	0.36	98.65
Raphidophy.**	0.00	0.00	0.00	0.00	0.00	0.00	2.68±6.43	0.00	38.76
Microflag.**	2.47±5.46	0.00	19.59	3.02±8.09	0.00	27.22	14.94±23.53	0.00	93.28
Chlorophy.*	0.03±0.09	0.00	0.30	0.06±14.0	0.00	0.45	0.46±0.94	0.00	5.51
Cyanphy.*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.001	0.13
Silicoflag.**	0.00	0.00	0.00	0.00	0.00	0.03	0.05±0.45	0.00	4.44
Euglenop.**	1.20±3.37	0.00	15.47	6.62±12.95	0.00	41.67	2.0±8.95	0.00	83.80
J	0.33±0.23	0.04	0.80	0.3 ±0.27	0.01	0.71	0.52±0.16	0.12	0.80
H'	1.14±0.81	0.14	2.65	1.28±1.20	0.03	3.05	2.16±0.7	0.49	3.47
Number of samples	22			11			99		

* unitsx10^6 l^{-1} ** cellsx10^6 l^{-1}

3.4. Phytoplankton peaks at <16°C

Asterionella glacialis dominated the community from early December to late February and *Skeletonema costatum* during the last week of March, and the second week of April (Table 2). The peaks of *A. glacialis* occurred at high salinity (>39), and much reduced PO_4^{-2}, and under homogenous thermo-haline condition of the water column. *S. costatum* achieved its peaks with relatively higher NO_3^{-1}, and its last bloom occurred under weakly stratified condition with a difference in temperature and salinity of 0.4°C, and 0.9, respectively, between the warmer-less saline surface water and the above bottom water layer. *S. costatum* blooms between 23-24 March took place after supply of SiO_4^{-2} pulses between16 and 21 March (3.43 to 4.8µM), and with a noticeable increase in NO_3^{-1} (ca 3.1 µM), and the bloom on 12 April followed SiO_4^{-2} pulse on 10 April (4.74 µM). The decreased salinity with the bloom peaks indicates input of freshwater.

Evenness and diversity indices showed the highest values on 29 January (0.54, and 2.19 bits/individual) when the standing crop, in spite of its low number ($0.035x10^6$ unit l^{-1}) consisted of 17 species, and the lowest values (0.07 and 0.22; 0.05 and 0.14) on 24 March and 12 April with the sole blooms of *S. costatum*, and much reduced number of the accompanied phytoplankton species (10 and 8, respectively).

Linear relationship between temperatures, evenness and diversity at <16°C is shown in Figure (4). The matrix correlation showed temperature to be significantly correlated with phytoplankton production, evenness and diversity (r = 0.49, - 0.61 & – 0.66, 0.05 level, n = 22). A strong relation was found between OOM and production (r = 0.34). Evenness and diversity were significantly correlated with each other (r = 0.98), and with the production (r = - 0.57, and - 0.55), strongly linked with salinity (r = 0.43 and 0.45), and OOM (r = - 0.38, and - 0.47). Nitrate and ammonia seem to have some impacts on the diversity indices (r = 0.3 and 0.23, insignificant at 0.05 level).

Table (2): Accompanied physical and chemical conditions with the phytoplankton peaks at < 16°C (D: density, cells x 10^6 l^{-1}).

Date	Species	D	%	T°C	Sal.	pH	PO_4^{-2}	SiO_4^{-2}	NO_2^{-1}	NO_3^{-1}	NH_4^{-1}	OOM
2006 7 Dec.	*A glacialis*	1.61	64.54	16.0	39.3	8.24	0.22	2.43	0.32	3.58	2.26	2.68
2007 4 Jan.	*A glacialis*	0.51	86.36	14.5	39.5	8.25	0.31	2.43	0.42	2.16	3.2	1.95
26 Feb.	*A. glacialis*	1.07	61.04	13.6	39.3	8.37	0.23	2.26	0.35	2.71	1.44	2.41
	S.costatum	0.64	36.38									
21 March	*S.costatum*	0.41	71.23	15.2	39.0	8.35	0.04	3.42	0.27	3.12	1.8	2.35
23 March	*S.costatum*	5.50	82.50	15.2	38.2	8.31	0.56	2.13	0.35	3.47	1.54	2.59
	Micof. spp.	0.92	13.75									
24 March	*S.costatum*	6.12	97.14	15.5	38.0	8.31	0.05	1.81	0.31	3.26	1.37	2.97
26 March	*S.costatum*	2.35	94.69	15.0	38.0	8.29	0.06	1.83	0.38	3.14	2.09	2.91
28 March	*S.costatum*	3.30	95.15	14.9	39.0	8.35	0.08	2.88	0.42	2.09	2.0	2.94
29 March	*S.costatum*	2.72	98.44	15.6	38.0	8.27	0.12	1.56	0.37	2.16	2.13	2.85
30 March	*S.costatum*	0.63	91.14	15.5	37.8	8.31	0.16	1.67	0.32	2.7	2.1	2.73
12 April	*S.costatum*	5.08	98.45	15.9	37.5	8.3	0.21	1.6	0.25	2.87	2.03	3.02

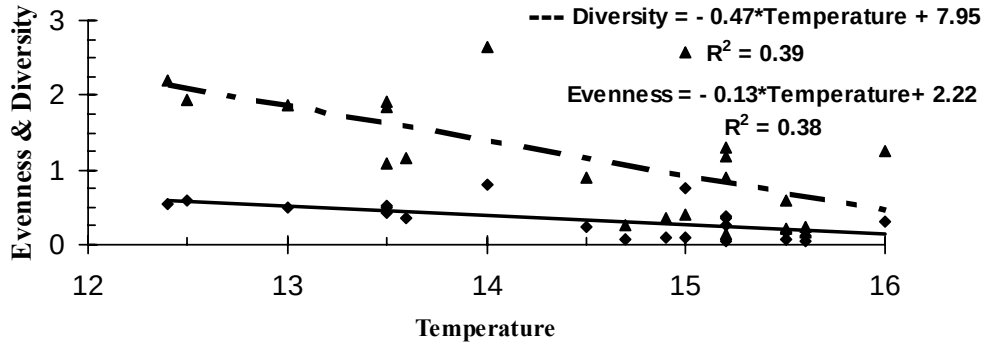

Fig (4): Linear relationship between temperatures, evenness and diversity at <16°C.

3.5. Phytoplankton peaks at 16-22°C

Several massive phytoplankton peaks were observed in April and May, causing water discoloration, and attributed mainly to the proliferation of *S. costatum* and the dinoflagellate, *Prorocentrum triestinum* (Table 3). Others such as; *Euglena gracilis*, microflagellate species and *Chaetoceros pseudocurvisetus* shared actively the degree of dominance. The intensive blooms of *S. costatum* on 14 and 16 April occurred at low salinity (37- 37.5), and high SiO_4^{-2} (Table 3), such increased SiO_4^{-2} also accompanied its blooms in May. The dense bloom of *P. triestinum* on 30 April followed in succession the blooms of *S. costatum*, and pulses of nutrients, which dropped severely. The different blooms occurred at high OOM concentrations.

Diversity index fluctuated from 0.03-0.04 bits/individual on 14 and 16 April (accompanied species were 9 and 16, respectively) to 1.32 bits/individual on 25 May (20 species). Correlations were generally strongest when using the present 11-day physical, chemical and biological data, stressing the importance of short-term measurements of these drivers in phytoplankton studies. The correlation matrix indicates the production to be significantly correlated with temperature, SiO_4^{-2}, NO_3^{-1}, N/P, S/N ratios, and species diversity. Evenness (*J*) and diversity (*H'*) correlated significantly with each other and with production, PO_4^{-2}, SiO_4^{-2}, NO_3^{-1}, OOM, nutrient ratios, and species richness (Table 4, Figure 5). The multiple regression analyses shows that nutrient concentrations seems able to explain about 86% of the variability in diversity at 16-22°C.

3.6. Phytoplankton peaks at > 22°C

The phytoplankton production exhibited a very wide range of variation between $0.06x10^6$ and $49.27x10^6$ units l^{-1}. 17 causative species (mainly 7 diatoms and 6 dinoflagellates) were responsible for the phytoplankton peaks in summer and fall (Table 5). The bloom of *Euglena acus* followed NO_3^{-1} supply (4.37 µM) on 12 July. *Nitzschia longissima* achieved its maximum occurrence at extremely high SiO_4^{-2}, NO_3^{-1}, NH_4, and intermediate PO_4^{-2} (3.6 µM). The great fluctuations of the last parameter (0.1-7.62 µM) seem to limit the occurrence of the different bloom species. High levels of OOM accompanied peaks of *Gymnodinium catenatum*, *Gymnodinium mikimotoi*, and *Prorocentrum minimum*, and high NH_4^{-1} with *Alexandrium ostenfeldii*. Increased abundance of flagellate groups resulted in decreased species diversity. The denser

bloom of microflagellate species in early September 2007 associated with water discoloration, and maintained high nutrients, except for PO_4^{-2}, and the maximum OOM concentration.

The correlation matrix failed to predict any significant relation between diversity indices and the inherent physical, chemical conditions and nutrient ratios. However, production seems to be strongly affected by OOM (r = 0.47), and evenness and diversity were highly significantly correlated with each other (r = 0.97), and strongly inversely correlated with production (r = - 0.35 and - 0.31).

Table (3): Accompanying physical and chemical conditions with the phytoplankton peaks at 16 - 22°C (D: cellsx10^6 l^{-1}).

Date	Species	D	%	T°C	Sal.	pH	PO_4^{-2}	SiO_4^{-2}	NO_2^{-1}	NO_3^{-1}	NH_4^{-1}	OOM
2007 14/4	*S. costatum*	25.92	99.73	16.5	37.5	8.17	1.46	6.25	0.30	1.32	2.84	7.3
16/4	*S. costatum*	28.30	99.61	16.8	37	8.1	0.92	6.10	0.41	1.29	2.75	8.9
29/4	*P. triestinum*	7.95	76.18	17	38.4	8.15	2.71	2.34	0.17	2.86	3.94	7.1
	S. costatum	1.32	10.12									
30/4	*P. triestinum*	20.18	77.76	17.5	37.8	8.25	0.83	6.88	0.35	0.95	0.63	6.9
	E. gracilis	5.62	18.90									
	S. costatum	0.64	2.16									
14/5	*S. costatum*	6.48	96.97	19.5	37.2	8.25	1.43	4.56	0.32	1.27	1.87	8.2
19/5	*S. costatum*	10.20	95.39	21.5	37.5	8.25	1.61	5.58	0.24	1.12	1.61	6.5
25/5	*S. costatum*	11.45	80.49	22	37.5	7.89	0.74	6.15	0.14	1.05	2.74	7.5
	E. gracilis	0.71	4.24									
	Micoflagellates	0.57	3.41									
	C.pseudocurvisetus	0.40	2.38									

Table (4): Correlation coefficient (r) at 16-22°C (Density: unitsx10^6 l^{-1}).

Parameter	Density	*J*	*H'*
Temperature	-0.60*	0.37	0.38
Salinity	-0.03	0.35	0.35
pH	-0.31	0.13	0.12
PO_4^{-2}	0.40	-0.90*	-0.89*
SiO_4^{-2}	0.76*	-0.81*	-0.83*
NO_2^{-1}	0.36	-0.13	-0.14
NO_3^{-1}	-0.54*	0.72*	0.74*
NH_4^{-1}	0.40	-0.05	-0.04
OOM	0.38	-0.67*	-0.67*
Total nitogen	0.07	0.34	0.36
N/P	-0.58*	0.91*	0.93*
S/N	0.57*	-0.83*	-0.84*
S/P	-0.05	0.64*	0.63*
Species No.	-0.59*	0.64*	0.67*
Density		-0.72*	-0.73*
J			0.998*

* significant at 0.05 level, n=11

Table (5): Accompanying physical and chemical conditions with the phytoplankton peaks at > 22°C (D: density, cells x 10^6 l^{-1}).

Date	Species	D	T °C	Sal.	pH	PO_4^{-2}	SiO_4^{-2}	NO_2^{-1}	NO_3^{-1}	NH_4^{-1}	OOM
2006 15/7	*E. acus*	3.07	26.8	35.8	8.7	0.10	11.27	0.01	2.80	1.65	1.80
1/8	*G. catenatum*	1.12	28.2	35.5	8.4	0.62	1.75	0.30	1.45	3.81	7.49
19/8	*C. antiqua*	1.22	27.4	34	8.6	0.36	1.85	0.20	1.28	0.32	1.66
24/10	*N. longissima*	1.84	23.4	35	9.0	3.60	16.42	0.83	8.62	6.11	4.50
2007 11/6	*P. minimum*	3.25	24	36.5	8.8	2.67	4.0	0.14	1.56	1.59	11.20
2/7	*S. costatum*	9.12	26.5	37	8.4	0.32	1.34	0.15	0.47	0.62	7.68
12/7	*P. triestinium*	2.25	27	37.2	8.1	0.18	3.88	0.41	2.97	2.60	1.92
21/7	*R. delicatula*	1.45	26	37	8.2	0.31	1.29	0.21	1.27	2.11	1.92
31/7	*A. ostenfeldii*	0.52	28	37.5	8.3	0.40	0.64	1.48	2.18	6.05	1.28
	T. pseudonana	2.35									
11/8	*G. mikimotoi*	1.32	28.5	34.2	8.2	7.62	0.62	0.45	1.14	1.46	12.30
20/8	*C.closterium*	0.43	29	36.2	8.0	4.80	0.37	0.48	0.86	4.21	3.20
	N. longissima	0.43									
22/8	*Heterosigma* sp.	0.16	27.5	36	8.0	1.36	3.18	0.21	4.53	5.36	19.20
3/9	Micoflagellates	39.5	27.2	35.5	8.1	0.37	5.22	0.21	3.60	4.25	25.20
21/9	*R. setigera*	0.93	26	37.5	8.2	1.05	3.18	0.17	1.95	1.62	6.40
2/10	*N. pungens.*	2.33	24	37.3	7.9	0.58	1.62	0.16	1.56	2.67	11.20

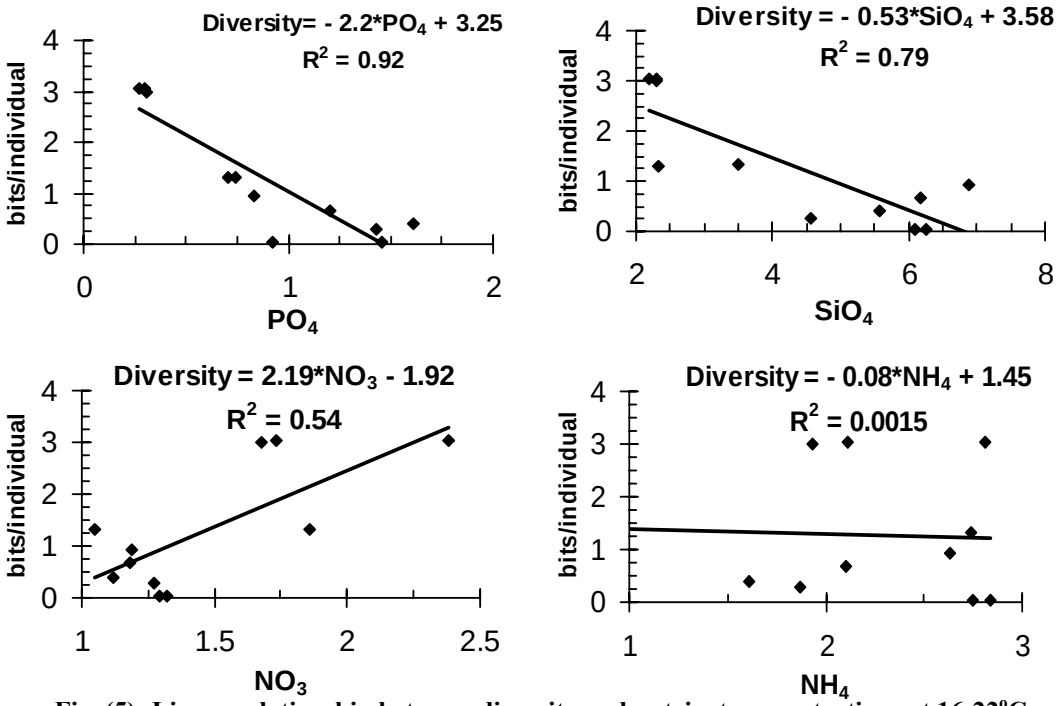

Fig. (5): Linear relationship between diversity and nutrient concentrations at 16-22°C.

4. DISCUSSION

The significant fluctuation in the measured physical and chemical conditions of the harbour hindered the establishment of particular annual distribution pattern of the phytoplankton. However, some characteristic seasonal features could be recognized as the low production in winter, the spring blooms, and the increased frequency of recurrent phytoplankton blooms in summer-early autumn periods. The environmental heterogeneity in the harbour made an essential contribution to phytoplankton numerical variability and species diversity, favoring or limiting the growth of the different groups of phytoplankton, coinciding with other results (Telesh, 2004; Ferreira *et al*., 2005). Comparing with studies during early 1990_s (Labib, 1994 a,b) strong modification of the production and the phytoplankton communities could be observed.

The absolute values of the diversity index displayed remarkable temporal variations indicating the instability of the area, its range is wider than that recorded in the harbour (0.1-2.84 bits/individual) between 1986 and 1992 (Zaghloul, 1995). Temporal instability of the environment could be an important factor allowing species diversity (Odum *et al*., 1995), which is closely related to the trophic state of the water body (Telesh, 2004).

The temporal variations in species diversity illustrated the importance of the short-term sampling in understanding ecological systems; succession in phytoplankton communities in the highly dynamic system of the harbour could be rapidly changed in a couple of days. The limited number of species with high relative abundance, classed as important in ecosystem function contributed 88% of the phytoplankton stock in the harbour and reflected a sign of eutrophication (Domingues *et al*., 2005).

Despite the growing evidence that productivity can be significantly related to the species richness (Kinzig *et al*., 2002), the study hardly found a relation between production and number of species. It was significant but only at 16-22°C ($r = 0.59$, $n = 11$). The analysis also showed that evenness and the diversity index were positively significantly correlated with the species richness at this temperature range ($r = 0.64$, and 0.67, $n= 22$). The data showed the species richness controls resource use and production, in agreement with Gross and Cardinale (2007).

Based on the whole year data, the positive highly significant correlation between evenness and diversity ($r = 0.98$, $n = 132$, $p<0.01$) was congruent with other results (Wilsey and Stirling, 2007).

4.1. Physical condition and diversity

Based on the three temperature ranges, the response of phytoplankton assemblage structure and the diversity index explained different relations with the different parameters, and the effect of the measured physical and chemical conditions were obvious at 16-22 ^{o}C. Nutrient concentrations at this range largely affected the diversity. The decreased water temperature in winter represents a reason for the changed diversity (Bruno *et al*., 2003).

The strong correlation between evenness, diversity and salinity might support their importance for changes in species diversity. Changes in salinity is considered as indicator of the volume variability of the discharged wastes entering the harbour from the west (Abdallah, 1979) and consequently might explain the changes in the nutrient levels and the corresponded changes in phytoplankton.

Despite the shallowness of the sampling station, the magnitude of the production, species composition and succession might be linked to changes in the stratification degrees of the water-column (Estrada *et al*., 1988)

and the observed temporal differences in diversity within and between the two years might be driven by variability in mixing/stable condition regimes. Diatoms, the most abundant category overwhelmingly dominated when the water was mixing, and/or stratified. Phytoplankton abundances, in particular flagellates were favored by increased stratified conditions, and this group contributed 59.97% of the community at >22^{o}C. Euglenophyta reached 3 major peaks (1.02 x 10^6 to 5.62 x 10^6 cells l^{-1}) with the partial development of the stratification in late April, and under well stratified condition in the middle of July. The predominance of diatoms when the water column has no vertical density structure, and the critical role of the cessation of mixing in summer for the predominance of flagellates in marine ecosystems were discussed (Wirtz and Wiltshire, 2005). The correlation matrix indicated diatoms significantly correlate with evenness and diversity at 16-22°C (r = - 0.57 and - 0.54), and the relation was strong with variations in abundance of microflagellates (r = 0.48 and 0.47), and dinoflagellates (r = - 0.38 and - 0.33).

Based on the all data, there appears to be no definite correlation between production, evenness, diversity and pH levels. However, the production seems to be strongly affected by pH variations at 16-22°C (r = - 0.31, n = 11) indicating pH an environmental factor might accelerates the production. About 4.54% of the pH data were in the range of pH at 7.2-7.9 and the majority (86.36%) at 8-8.9. The pH values were driven to greater extremes under the observed eutrophic conditions in warm seasons, allowing changes in algal species, in particular flagellates to grow and dominate communities, and to potentially form algal blooms. A significant positive correlation (r = 0.49, n = 61) was found between the relative contribution of dinoflagellates and pH in summer 2006 and 2007 (Figure 6) when 16.4% of the pH data were in the range of 9-9.4. Such influence of pH as a forcing factor has been considered (Rost *et al*., 2003), and high pH values with phytoplankton blooms were reported (Macedo *et al*., 2001). Among the most common marine phytoplankton species found to co-occur with high pH in nature are the dinoflagellates *Prorocentrum* spp., and the diatom *S. costatum* (Macedo *et al*., 2001, Hansen, 2002); the species *P. triestinum*, *P. minimum* and *S. costatum* were major constituents of the community during the present study.

4.2. Nutrient enrichment and diversity

The dynamic relationship between phytoplankton and nutrients has long been of great interest in field, experimental and mathematical ecology (Chattopadhyay *et al*., 2003). The study supports the view that continuous nutrients input (human activities) had a beneficial effect on the functioning of this coastal ecosystem, stimulating the taxonomic diversity through the growth of different taxonomic groups and taxa (Bruno *et al*., 2003).

The sudden high nutrient concentrations followed and/or accompanied abnormal high phytoplankton densities of specific species indicate the harbour is subjected to eutrophication. The pulses greatly affected the phytoplankton succession of organisms, had a strong negative effect on the diversity indices through the dominance of a single species, and can increase the possibility of a harmful algal bloom development. This was congruent with the results obtained by Gao and Song (2005), where clearly the low diversity index corresponded to the sites in which red tide bloom were present. The data suggests a relation between changes in diversity index and anthropogenic eutrophication (Gao and Song, 2005), which may drastically alter biodiversity (Marques *et al*., 1997).

The present work also emphasized the importance of pulsed nutrient supply on coexistence of species (species diversity) in summers to be maintained longer. Experimentally, pulsed supply with the same total amount of nutrients allowed *G.*

catenatum to coexist with *C. antiqua* and *S. costatum*, corresponding to the observations by Padisak (1993). The dominance of dinoflagellates and *Chattonella antiqua* at >22°C, which represent newly introduced species into the harbour (Mikhail, 2003a;c), severely reduced the diversity indexes through the decreasing in number of other accompanied phytoplankton species during their bloom periods, in accordance with Anil *et al* (2002). Toxicity of the major dinoflagellates and *C. antiqua* in summers, if present, is likely considered a pollution stress often manifested as biodiversity loss (Ptacnik *et al*., 2008).

4.3. Production and diversity

Production was negatively correlated with the diversity index values (Figure 7). The linkage was strong for all data, and > 22°C (r = - 0.37, n=132, and r = - 0.31, n = 99), and it was significant for the data of < 16°C, and 16-22°C (r = - 0.55, n=22, and r = - 0.73, n= 11, respectively). Hypothesized production-diversity relationships can be positive (Abrams, 1995), negative (Pedro *et al*., 2006) or unimodal (Tilman and Pacala, 1993). The inverse relation between production and diversity index might be influenced by factors as the proliferation of a limited species number and sampling effect.

The relation between production and diversity was also controlled by specific nutrient concentrations; the significant negative/positive correlation between the production and diversity index at PO_4^{-2} ranges 1-2 µM, and > 2 µM, and at SiO_4^{-2} > 4 µM supports this conclusion. Their correlation became much stronger with increasing concentrations of NO_3^{-1} and NH_4^{-1}. The sharp reduction in silicate stays behind the dissipation of diatom blooms in winter 2006.

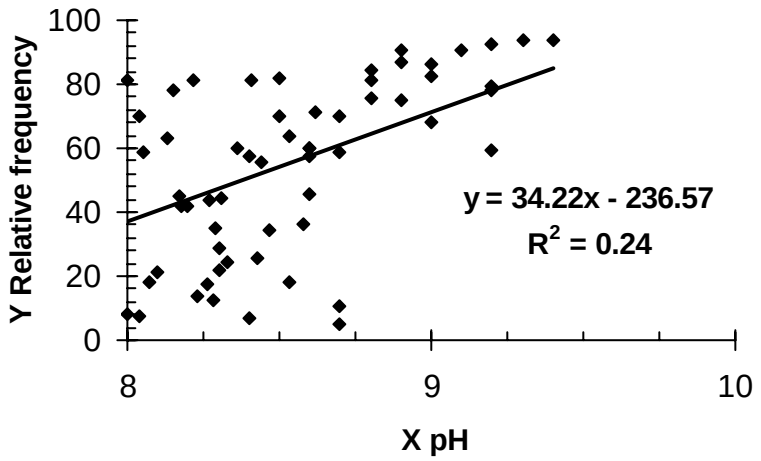

Fig. (6): Linear relationship between the relative frequency of dinoflagellates and pH in summer 2006 and 2007.

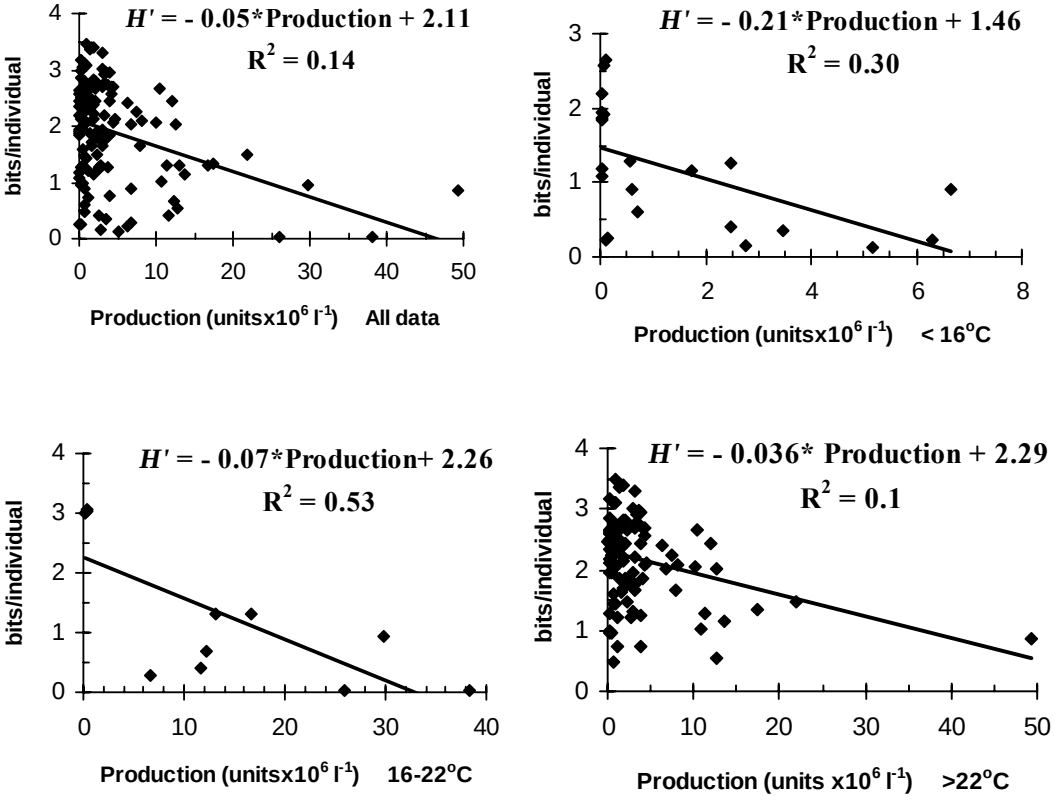

Fig. (7): Linear relationship between production and diversity.

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