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Phytoplankton succession in a coastal area of the NW Adriatic, over a 10-year sampling period (1990–1999)

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Abstract

The distribution of phytoplankton abundance and species composition is described for coastal waters of the NW Adriatic Sea, for the period 1990–1999. Hydrochemical and biological properties were investigated every month, at 48 stations. This coastal system is quite unstable and heterogeneous, due to the influence of several rivers, intense water exchange with the Lagoon of Venice, and complex advective processes. In the vicinity of river plumes, dissolved nitrogen and dissolved silica appear to be in excess, rarely limiting phytoplankton growth. Examining the general trend of phytoplankton over the years, the main limiting factors for phytoplankton growth in the Adriatic coastal system are light, temperature, and the strong influence of meteorological events.

The NW Adriatic coastal area was subdivided into three zones, each characterised by different trophic conditions. In each zone, phytoplankton was similar in terms of community structure and was different only in abundance. Three main periods of growth were observed: February, April and July. As expected in a nutrient-enriched system, the community structure was dominated by diatoms (both micro- and nanoplankton fractions), over most of the year. The importance of dinoflagellates in the communities was generally low, with significant abundances present only in June–July, once the spring bloom of diatoms had left 'nutrient-poor' conditions in the water. These low concentrations of nutrients favoured the growth of dinoflagellates, which have lower nutritional requirements. Over the 10-year study, a decrease in orthophosphate concentrations was observed. This pattern could be explained as a consequence of reduced quantities of phosphorus used in detergents, in the late 1980s. No significant change in any hydrochemical or biological property was observed.

Keywords: Phytoplankton; Chlorophyll *a*; Nutrients; Coastal ecosystem; Seasonality; Northern Adriatic Sea

1. Introduction

Distributions of the abundance, biomass and productivity of phytoplankton in the Northern Adriatic Sea (Fig. 1) have been studied by many authors (Revelante and Gilmartin, 1976a, b; Marzocchi et al., 1979; Socal et al., 1982, 1992; Franco, 1983b; Faganeli et al., 1989; Socal and Bianchi, 1989; Fonda Umani et al., 1992; Malej et al., 1995; Zoppini et al., 1995; Alberighi et al., 1997; Mozetic et al., 1998; Giani et al., 1999; Socal et al., 2002). Each of these studies have described the basin and stressed its complexity. The shallow northern

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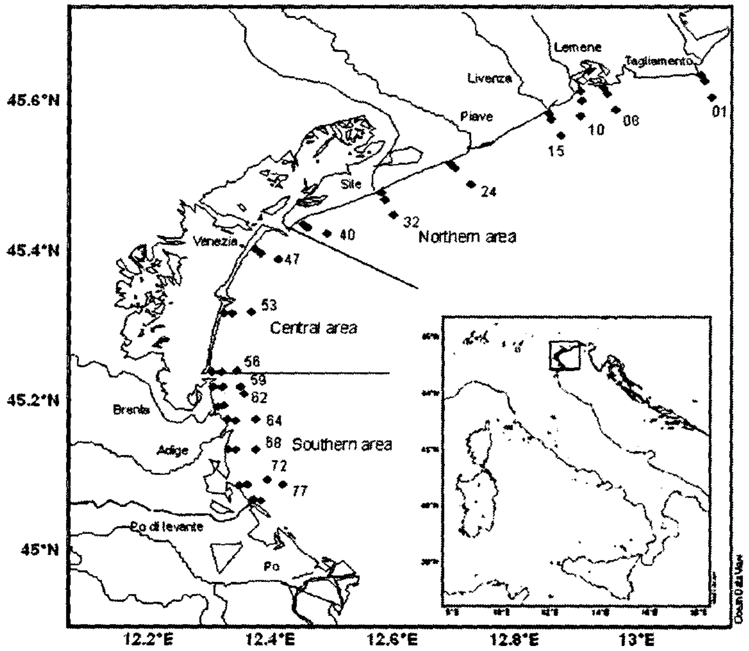

Fig. 1. Study area and the location of the 16 transects in NW Adriatic Sea. Three geographic regions, as described in the text, are defined.

Adriatic (maximum depth 70 m), is influenced on its northwestern end by two important rivers (Po and Adige) whilst, at its southeastern end, it receives highly saline waters from the southern Adriatic basin (Franco, 1970). These features combine to make the ecosystem quite heterogeneous.

Along its western boundary, the study area is characterised by a frontal system, i.e., a transition zone between shallow mesotrophic and saline oligotrophic waters. This frontal system is located 8–16 km from the coast and consists of a dynamic boundary area, between inshore and offshore systems (Franco and Michelato, 1992).

In the Northern Adriatic, dissolved nutrient concentrations depend mainly upon freshwater influx, which is influenced greatly by meteorological conditions. When some water layers become impoverished in nutrients by phytoplankton activity, available regenerative nutrients are controlled mainly by the vertical structure of the water column.

In coastal waters, seasonal stratification of the water column is not as well defined as offshore (Franco, 1989). Advective processes are quite strong, creating a very unstable system (Franco and Michelato, 1992). Chemical and biological processes are influenced by the hydrodynamic regime of this system, which changes strongly changes according to short-term meteorological phenomena. In fact, discharges from the Po and Adige rivers, together with the wind stress, modify local circulation and vertical structure of the water column (Franco, 1983a). The average discharge from the Po is 1500 m^3/s (Franco, 1973), but changes occur within and between years (Degobbis et al., 1995). Discharges show pronounced seasonal variability, with peaks in spring and autumn, in response to mountain snow melting and heavy precipitation (Boicourt et al., 1999). Three geographical areas of the Veneto coastal belt have been defined (Fig. 1), each corresponding to a different horizontal distribution of oceanographic features (Baroni et al., 1998; Bresolin et al., 1999). The northern area, between the mouth of the Tagliamento river and the so-called Lido inlet, is influenced by inputs from small rivers (Tagliamento, Lemene, Livenza, Piave, Sile). In this area, the salinity values are lower compared to the mean values of the basin, and the spatial–temporal variations are low, indicating a weak continental influence. The central area, just outside the Lagoon of Venice, is affected greatly by the tidally-induced southward marine plumes of outflowing lagoonal waters. However, salinity and transparency here appear to be the highest for all of the coastal belt. The southern area is influenced heavily by the large Italian rivers (Po, Adige, Brenta), where nutrients and chlorophyll generally reach high concentrations (Alberighi et al., 1990; Acri et al., 1994; Baroni, 2002).

There is also a general coastal water circulation from the northeast, which constantly displaces water masses to the south, along the entire coastal zone. The mean wind fields are weak (Markgraf, 1961), but episodes of *bora* (NE) or *sirocco* (SE) winds sometimes significantly affect the Adriatic flow field (Kuzmić and Orlić, 1987; Kuzmić et al., 1988; Bergamasco and Gacic, 1996; Zavatarelli et al., 2000).

Observations of the spatial patterns of phytoplankton communities have been made previously on a seasonal basis, to describe their west-to-east distribution along a gradient driven by riverine influences, and to relate their vertical stratification to the stability/instability regimes of the water column (Franco et al., 1979, 1982). Literature published on the annual phytoplankton cycle in offshore waters is scarce (see, e.g., Degobbis et al., 1995), although several papers provide information on the cycle in shallow areas, such as the Gulf of Trieste (Cabrini et al., 1988, 1994; Malej et al., 1995) and coastal waters of the Veneto and Emilia-Romagna regions (Viviani et al., 1985; Bernardi Aubry et al., 1995; Montanari et al., 2000), north and south of the Po river, respectively. Phytoplankton distributions in NW Adriatic coastal waters highlight two decreasing longitudinal and latitudinal gradients, displaying: (a) higher abundance and production near the mouths of the Adige and Po than offshore; and (b) in the southern area, with respect to the more northerly ones (Acri et al., 1994). Moreover, high biomasses are observed generally in summer (June–July), with their minima in winter (December–January; Alberighi et al., 1990).

Most of the above studies were limited to 1 or 2 years of investigations and few of them described the wide-ranging aspect of the work. Wide-range interactions may become important when considering that, in coastal systems, complex land–sea exchanges and high climatic variability (on short spatial and temporal scales) lead to phytoplankton dynamics which are difficult to predict accurately (Zingone et al., 1995). Long-term analyses of data viewed have been carried out recently for whole communities in the northern and middle Adriatic, to examine general trends in the communities, free of occasional events (Degobbis et al., 1995; Malej and Fonda Umani, 1995; Pompei et al., 1995; Cataletto et al., 1996; Solic et al., 1997; Mozetic et al., 1998; Degobbis et al., 2000).

Within the above framework, in order to establish information on phytoplankton dynamics over a long period, we present here the results of 10 years of hydrochemical and biological data (1990–1999) collected in the western Adriatic coastal zone. The objectives of this work were: (i) to identify the principal factors influencing phytoplankton biomass dynamics; (ii) to typify its seasonal pattern and (iii) to analyse long-term variations, in order to highlight or exclude trends in hydrochemical variables and phytoplankton biomass and abundance.

2. Materials and methods

Sampling stations were located along 16 transects, at distances of 0.3, 1.0 and 2.5 nautical miles from the coast (Fig. 1), with a maximum water depth of 15 m. The sampling area was surveyed on a monthly basis. For each station, transparency was measured with a Secchi disk and continuous profiles of temperature, salinity, dissolved oxygen and pH were obtained using a CTD Idronaut profiler (Ocean Seven, Mod. 401). Two samples of nutrients and chlorophyll *a* were collected at each station at the surface and at 1 m above the bottom, using 5 l Niskin bottles. Dissolved inorganic nutrients were analysed according to the methods described by Strickland and Parsons (1972); whilst chlorophyll *a* was assessed according to Holm-Hansen et al. (1965). Hydrochemical and chlorophyll *a* data consisted of more than 10,000 data points. Irradiance data were obtained from the meteorological archive of the Istituto di Biologia del Mare, CNR Venezia.

A total number of 4357 phytoplankton samples were counted. Samples were collected in five transects (08, 24, 40, 56, 72; Fig. 1), stored in 250-cm^3 glass dark bottles, and fixed with 10-cm^3 of 20% hexamethylentetramine-buffered formaldehyde (Throndsen, 1978). Counts were taken according to Utermöhl's (1958) method, using an inverted microscope equipped with phase contrast (model Zeiss Axiovert 35 and Zeiss ICM 405), at a magnification of 400 × (i.e. Ocular 10 ×, Objective 40 ×) after samples had settled in 2–50-ml chambers, for 24–48 h; a variable transect number (0.230 mm height and 25 mm settling chamber diameter width) has been observed at the microscope until, at least 200 (but often more than 500) cells being counted for each sample (Zingone et al., 1990). Species composition for marine phytoplankton was defined according to Hasle and Syvertsen (1996), Steidinger and Tangen (1996), Heimdal (1993), and Throndsen (1993). The taxa examined here fall into the following main groups: diatoms, dinoflagellates (naked and armoured cells), coccolithophorids and other flagellates. This last group is referred to, hereafter, as nanoflagellates and includes the sum of cells belonging to cryptophyceans, crysophyceans, prymnesiophyceans (except coccolithophorids), prasinophyceans and chlorophyceans, whose sizes lie between 4 and 20 μm and often remain undetermined. Other flagellates <4 μm are not considered here. The weight of dictyochophyceans and euglenophyceans, often larger than 20 μm, is generally negligible in our samples (below 1% of total abundances). Cell volume was estimated from cell measurements (Edler, 1979), whilst carbon content was calculated using conversion factors (Strathmann, 1967; Smetacek, 1975).

Statistical analyses (principal component analysis—PCA, one-way ANOVA and linear correlation analysis) were performed using Statistica by Statsoft, after log-transformation of biological data (Cassie, 1962). In order to analyse the spatial pattern of the community structure, a Multi-Dimensional Scaling (MDS) ordination method was used on the species-samples matrix, after a double-square transformation of abundance data (Clarke and Warwick, 1994; Carr, 1996). Undetermined nanoflagellates were excluded, owing the fact that they were ubiquitous in our study. For the interannual trends, a seasonal Kendall-τ non-parametric analysis was applied. This analysis determines the direction of trend (+ or −), goodness of fit (τ) and statistical significance of fit (*p*; Boyer et al., 1999; Hirsch et al., 1991). The rate of change of each variable is quantified by the seasonal Kendall slope estimate, i.e., the median (over all pairs of years for each month) of the change-per-year of the parameter in question (Theil, 1950; Sen, 1968). The seasonal Kendall-τ test requires the data-set to be contiguous; therefore our data prior to 1991 were excluded from the analysis and we mainly considered ten stations, at 1.0 and 2.5 nautical miles from the coast, where, beginning in 1992, sampling was always performed because of the importance of these areas as fishing grounds. Finally, a monthly seasonal Kendall-τ analysis was performed: on the whole stations at 1.0; and on the whole stations at 2.5 nautical miles from the coast. For this test, all the presented variables were a composite (median) of all the stations included in that particular zone.

The statistical significance for the seasonal Kendall-τ test was set at $p<0.01$. For these statistical analyses, WQ2 (release 2.0 by EQMetric, LLC and Virginia Tech Intellectual Properties Inc.) was utilised.

3. Results

The ranges, averages and standard deviations of hydrochemical and biological data for the 10-year period are listed in Table 1. CTD profiles for temperature and salinity indicated unstable conditions in the water column during most of the samplings, suggesting high turbulence and vertical homogeneity induced by strong advective processes. However, significant differences of phytoplankton abundance and biomass between the surface and bottom layer were generally found, with higher values at the surface. In order to

Table 1
Mean statistics for hydrochemicals variables, chlorophyll *a* and total phytoplankton abundance over the whole sampling area (1990–1999)

	N of measures and samples	Mean	Range	Std. dev.
Global irradiance ($\mathrm{kJ\,m^{-2}\,h^{-1}}$)	7700	655	111–3019	404
Secchi disk (m)	7700	3.1	0.1–15	1.7
Temperature (°C)	10,437	17.7	3.4–29.3	6.5
Salinity (psu)	10,436	32.5	5.1–38.2	4.4
Dissolve inorganic nitrogen (DIN, μM)	10,324	14.6	0.03–382.1	19
Si-SiO$_4$ (μM)	10,321	8.1	0.01–67.7	8.1
P-PO$_4$ (μM)	10,319	0.15	0.01–9.40	0.34
Chlorophyll *a* ($\mathrm{\mu g\,dm^{-3}}$)	10,384	2.7	0.01–66.3	2.9
Phytoplankton abundance ($10^3\,\mathrm{cells\,dm^{-3}}$)	4357	3238	64–59166	4821

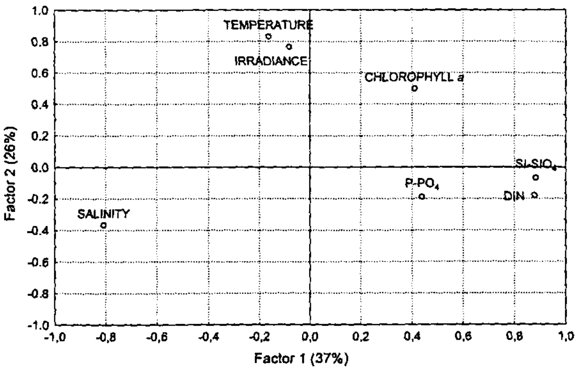

Fig. 2. Loadings of environmental variables on the first two Principal Components extracted (PCA).

summarise the weight of each parameter in an analysis of the dataset, PCA was applied for reduction of dimensionality (Blanco et al., 1998; Fig. 2). From the correlation matrix, two components were extracted with eigenvalues greater than 1, explaining 63% of the total variance.

The first principal component (PC1: 37% of variance) is related to river discharge, as indicated by factor loadings, which were negative for salinity and positive for inorganic nutrients. This means that, in this coastal system, the spatial distribution of nutrients is closely linked to river discharge. Consequently, low salinity values generally correspond to high nutrient concentrations.

The second component (PC2: 26% of variance) is mainly due to seasonal variations in temperature and irradiance. Chlorophyll *a* plots in an intermediate position, being correlated to temperature, irradiance and nutrients.

3.1. Spatial variations

The northern area is represented by the stations labelled from 01 to 40, whilst the central and the southern ones are, respectively, represented by stations from 47 to 56 and from 59 to 77 (Fig. 1). Although temperature patterns show similar values along the entire coastal zone, other physical, chemical and biological features distinguish the three areas, as reported in the literature (Baroni et al., 1998; Bresolin et al., 1999; Baroni, 2002); one-way ANOVA confirmed this geographical pattern (Table 2). Salinity varies greatly, with low values in the south, intermediate in the north, and high in the centre, inversely reflecting nutrient concentrations and phytoplankton biomass, the averages of which vary significantly among the three areas. Values for dissolved inorganic nitrogen (DIN: sum of ammonia, nitrite and nitrate) and chlorophyll *a* are highest in the southern area where phytoplankton abundance also reaches its maximum (Table 2, Fig. 3), as a result of frequent blooms, especially in late winter and spring-summer. In fact, more than 30% of the samples collected here over the 10-year period had chlorophyll *a* concentrations of $> 5\,\mathrm{\mu g/dm^3}$.

Phytoplankton composition in the three areas, however, was quite similar throughout the study period, with the mean diatom percentages varying between 61% and 72%, and those of nanoflagellates, between 27% and 36% of total abundance (Fig. 3). The lack of a spatial diversification in phytoplankton community structure was confirmed by the analysis of the MDS plot, obtained

Table 2
Average of main environmental variables calculated on the entire data set

	Secchi disk (m)		Temperature (C)		Salinity (PSU)		DIN (μM)		Si-SiO$_4$ (μM)		P-PO$_4$ (μM)		Chlorophyll *a* (μg/dm^3)		Phytoplankton (10^3 cells dm^{-3})	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
North	3.8*	2.5	17.9	6.4	33.0*	3.5	13.8*	14.0	7.3*	6.3	0.11	0.19	1.8*	1.4	1525*	2552
Centre	3.6*	1.7	17.6	6.6	34.3*	2.5	8.0*	8.0	4.8*	4.2	0.10	0.23	2.0*	1.5	1932*	3370
South	2.5*	1.4	17.5	6.7	30.2*	5.6	21.6*	27.0	12.0*	10.6	0.24*	0.51	4.3*	4.2	6288*	6184

*Significant differences ($p<0.01$, one way ANOVA). The *F* tests for chlorophyll *a* and phytoplankton data have been applied after normalization of the data.

by a Bray–Curtis similarity matrix (Fig. 4). Considering the biomass, the relative contribution of dinoflagellates becomes generally high (from 9% and 16% of total biomass), whilst the contribution of nanoflagellates decreases to 5–7% (Fig. 3). The higher relative phytoplankton abundance in the central waters, characterised by low nutrient contents with respect to the northern ones (Table 2), is mainly due to the samples observed in late winter and early spring periods. During these periods, the Lagoon of Venice exports water, the hydrochemical properties of which are quite different from those of coastal waters. Blooms of *Skeletonema costatum* occur regularly in early spring in the Lagoon as described by several authors, who also demonstrated that large quantities of phytoplankton biomass are subsequently carried to coastal areas by outflowing tides (Voltolina, 1973; Socal et al., 1999a; Tolomio et al., 1999).

3.2. Seasonal variations

Considering that no spatial differences were found in community structure, phytoplankton seasonal cycles from the entire data set were examined: i.e. phytoplankton data were clustered and averaged for each month. For consistency, hydrochemical data were averaged in the same way although some differences among the three areas had been demonstrated.

In different seasons, hydrochemical parameters had different influences on the distribution of phytoplankton abundance.

Late autumn–early winter (December–January) is characterised by low temperatures and low phytoplankton biomass, whereas DIN and silicates are high (Fig. 5). The phytoplankton community is represented mainly by nanoflagellates (62% and 52%) and, secondarily, by diatoms (25 and 47%; Fig. 6). On this period, coccolithophorids reach their relative peak, mainly with *Emiliania huxleyi* (Fig. 7). As winter proceeds, increased irradiance, temperature, and nutrients enhance phytoplankton growth. In February, diatoms grow rapidly (84% of total abundances; Fig. 6), *Skeletonema costatum* being the dominant species (Fig. 7), as an example of small and

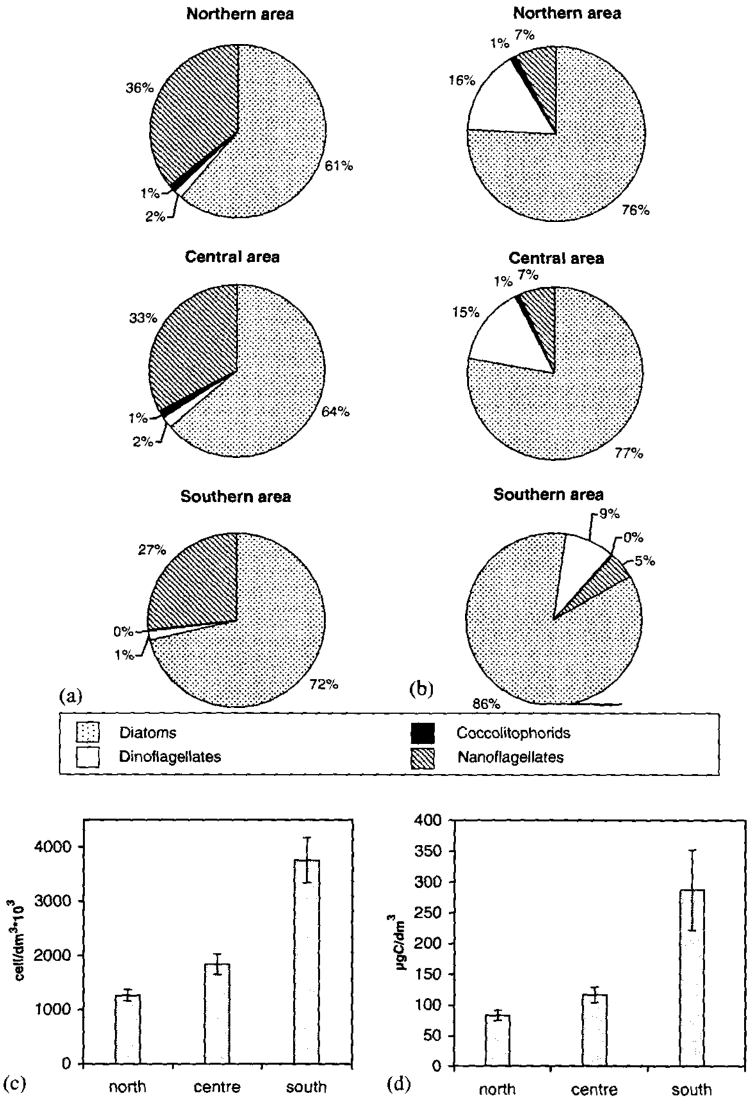

Fig. 3. Average contribution of phytoplankton groups to the total abundance (a) and to the total biomass (b), obtained from 1990–1999 data in three sampling areas: northern area (transect from 08 to 40); central area (from 47 to 56); southern area (from 59 to 77). Mean values of phytoplankton abundance (c) and biomass (d) in the three sampling areas. Confidence limits have been calculated from mean standard errors and multiplied for Student's *t* (95% probability).

opportunistic species, characterised by low carbon content (Mozetic et al., 1998).

Spring (March–May) is characterised by low salinity, because of increased river discharge and new increases in phytoplankton abundance, peaking in April. Diatoms are represented by several species such as *Pseudo-nitzschia delicatissima* complex (Hasle, 1965), *Thalassiosira* spp., *Chaetoceros socialis* and *Chaetoceros* sp. (Fig. 7).

In summer, high temperature and salinity values correspond to low river discharge and nutrient concentrations (Fig. 5) because precipitation is generally scarce in this period. In spite of this, nutrients are still sufficient to support a high

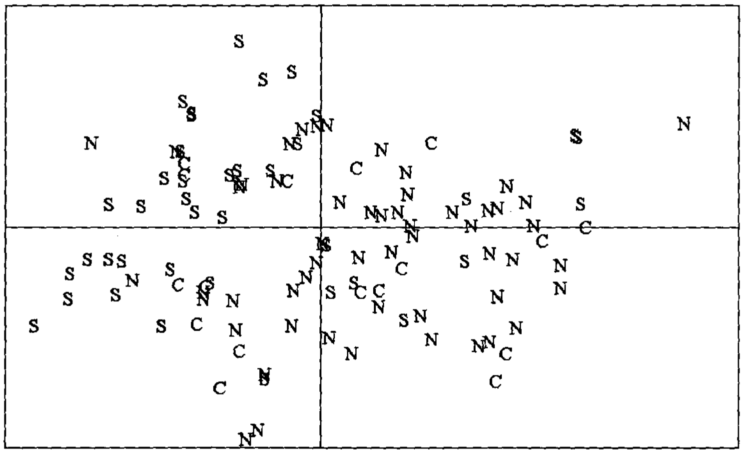

Fig. 4. MDS plot from a matrix of the abundance of 116 taxa, from 117 surface samples, collected at 1 mile from the coast in 1998. N—northern area, C—central area, S—southern area.

biomass. In June, the abundance of diatoms decreased, whereas nano- and dinoflagellates were more frequent. The main dinoflagellates are *Prorocentrum micans*, *P. minimum*, *Gymnodinium* spp. and *Ceratium fusus* (Figs. 7 and 8). In July, diatoms peak again, and include *Proboscia alata*, *Cerataulina pelagica* and *Chaetoceros compressus*, as dominant species (Fig. 8). A discrepancy between the peaks of phytoplankton abundance and biomass was generally observed in late summer mainly due to the presence in August of large diatoms, with relatively high carbon content (Fig. 6).

A nutrient increase is seen in autumn, when the temperature diminishes sharply. A fall in phytoplankton abundance corresponds mainly to decreasing temperature and irradiance (Fig. 5), despite inorganic nutrient availability. The flagellate fraction increases in autumn, diatoms being mainly *Asterionellopsis glacialis*, *Leptocylindrus danicus* and *Lioloma pacificum* (Fig. 8).

3.3. Linear correlations between species abundance and hydrochemical variables

The coefficients of the linear correlations were calculated between the abundance of the main taxa and the hydrochemical variables (Table 3). *Proboscia alata*, nanoflagellates, *Gymnodinium* sp, *Chaetoceros compressus*, *Leptocylindrus danicus*, *Prorocentrum minimum*, *Thalassiosira* sp, *Prorocentrum micans* and *Ceratium fusus* present positive correlations with the temperature values, showing a thermophilic character. In contrast, the inverse correlations between *Emiliania huxleyi*, *Skeletonema costatum*, *Pseudo-nitzschia delicatissima*, *Asterionellopsis glacialis* and temperature indicate the preference of these species for cold waters. A group of species (nanoflagellates, *Skeletonema costatum*, *Thalassiosira* sp., *Cerataulina pelagica*, *Prorocentrum micans*, *Chaetoceros compressus*, *Lioloma pacificum* and *Gymnodinium* sp.) seems to be favoured by the river diluted waters, with their abundance being inversely correlated with salinity (Table 3). Moreover, the positive correlation between the abundance of some of these taxa (i.e. *Skeletonema costatum*, *Thalassiosira* sp., nanoflagellates and *Prorocentrum micans*, Table 3) and nutrients (DIN and Si-SiO_4) confirm this distribution pattern in oligohaline and nutrient rich waters. Only for *Emiliania huxleyi*, *Prorocentrum minimum* and *Proboscia alata* was an affinity for high salinity waters highlighted by the positive correlations between their abundance and the salinity values.

3.4. Inter-annual trends

Statistical tests showed no significant trends in temperature for any station. Only near the

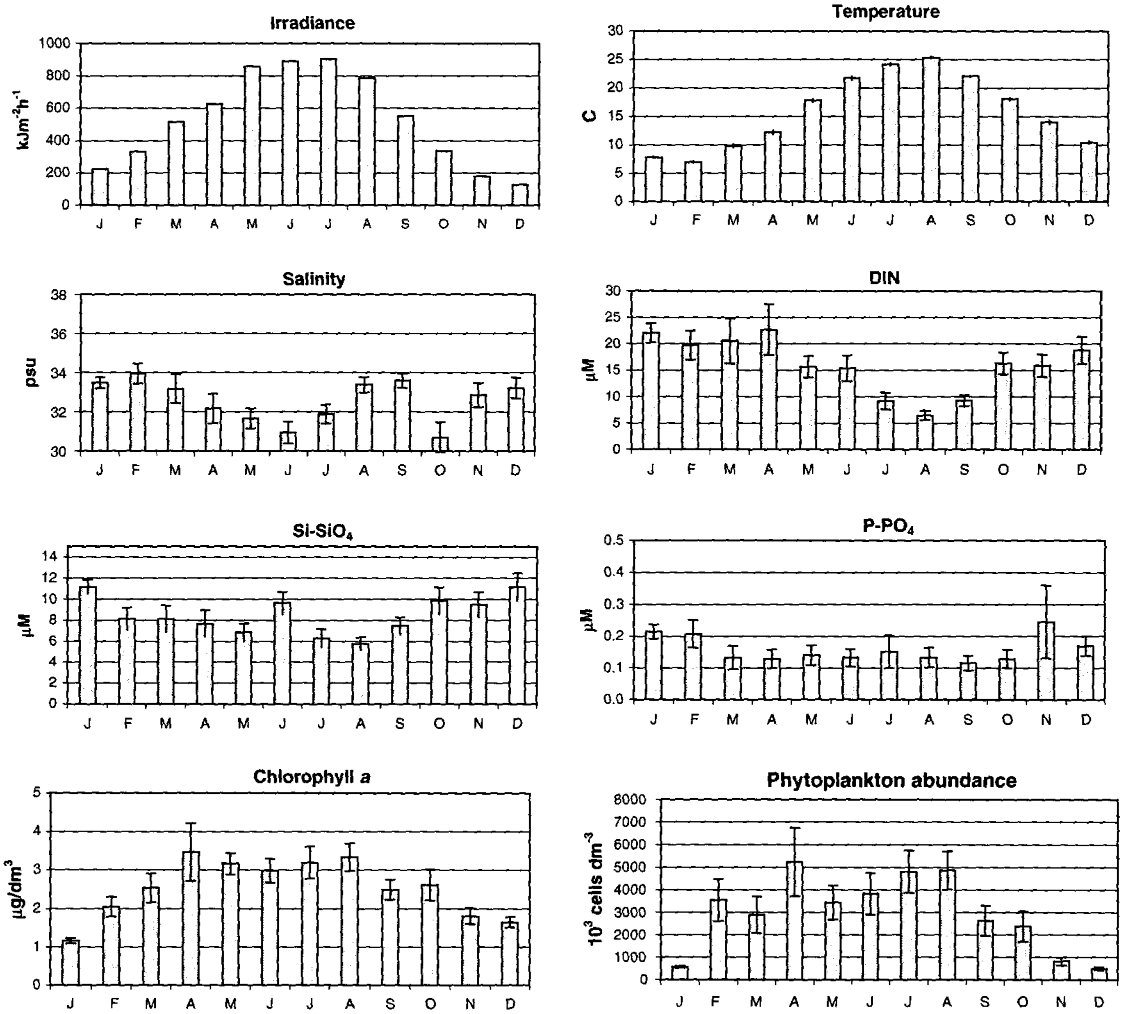

Fig. 5. Annual cycle of the environmental variables, chlorophyll *a* and phytoplankton abundance from the whole of the data set, from 1990 to 1999. Each monthly average has been obtained from the entire data set, clustered for each month. Confidence limits have been calculated from mean standard errors, multiplied for Student's *t* (95% probability).

mouth of the Piave (Station 24, at 1 nm from the coast) were significantly decreasing trends evident in salinity ($-0.35\,\mathrm{yr}^{-1}$) and transparency ($-0.25\,\mathrm{m\,yr}^{-1}$; Table 4).

DIN, except at Station 24 (at 2.5 nm from the coast) where concentrations rose by $1.2\,\mu\mathrm{M\,yr}^{-1}$, did not change during the study period, whilst the Kendall-τ test indicated a decrease in phosphate concentrations at all ten stations (-0.01 or $-0.02\,\mu\mathrm{M\,yr}^{-1}$). Silicates showed a significant rise only at stations along Transect 24 (0.6 and $0.4\,\mu\mathrm{M\,yr}^{-1}$ at 1 and 2.5 nm from the coast, respectively). Only near the Po di Levante plume (Station 72, at 1 nm from the coast) were increases in phytoplankton abundance and chlorophyll *a* observed ($138 \times 10^3\,\mathrm{cells\,dm}^{-3}$ and $0.20\,\mu\mathrm{g\,dm}^{-3}\mathrm{yr}^{-1}$, respectively). Lastly, the Kendall-τ test revealed no significant trends in irradiance data.

By plotting the average and the confidence limits of nutrients and chlorophyll *a* for each year over the entire data set (Fig. 9), the evidence for a

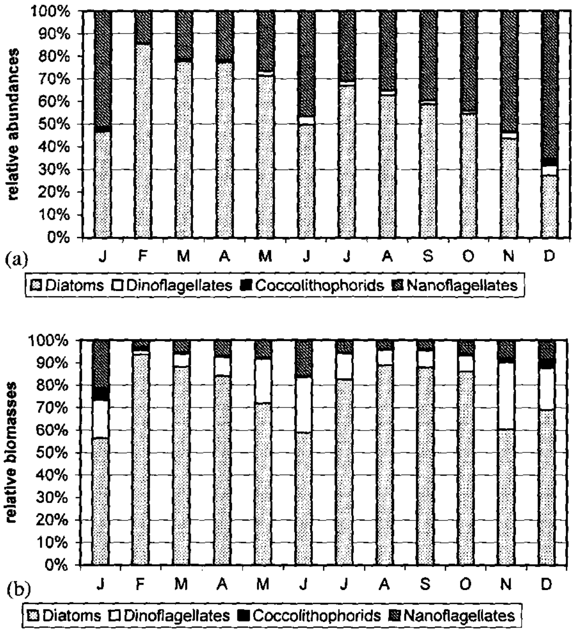

Fig. 6. Average contribution of phytoplankton groups to the total abundance (a) and to the total biomass (b), during the year, from 1990 to 1999. Data have been obtained from the entire data set, clustered for each month.

phosphorus decrease over the years was confirmed, whilst any general trend has not been shown for the other nutrients and clorophyll *a*.

4. Discussion

The complex dynamics of phytoplankton in a coastal system (Zingone et al., 1995) becomes even more complex in areas where estuaries discharge large amounts of freshwater, in small volume basins such as in the NW Adriatic (Franco and Michelato, 1992). In such waters, especially in the vicinity of river plumes, dissolved nitrogen and dissolved silica appear to be in excess, rarely limiting phytoplankton growth. Instead, the distribution of phosphates is low for the entire study period (average around 0.15 μM). For this reason, very high N/P values, far above the Redfield ratio, are observed in the Adriatic Sea, especially in the northern basin (Marchetti et al., 1985). This confirms the hypothesis of nitrogen excess as an intrinsic characteristic of Adriatic waters (Franco et al., 1979; Socal et al., 1999b), whereas the P-limitation described in offshore waters (Degobbis et al., 2000) may be an actual feature of the coastal belt only in time-limited situations. The low availability of phosphorus in the water may be due to efficient removal of phosphorus from the water column and burial within the bottom sediments (Degobbis and Gilmartin, 1990; Giordani et al., 1992). However, in spite of these considerations, the general opinion is that phytoplankton find enough nutrients to grow in the NW Adriatic coastal system for most of the year. Similar results were obtained in Dutch coastal areas (Wadden Sea), where high phytoplankton biomass and primary production values were observed in spite of declining phosphate concentrations (Cadée and Hegeman, 1993). Very low transparency values were observed during our samplings, showing that light generally does not penetrate below the first few meters of water, due to input of particulate matter from rivers and other coastal sources. However, we also believe that resuspension processes, due to active lateral advection in the bottom layer and to storms, play an important role in increasing water turbidity. This has also been supported by observations of the high contribution of suspended matter to sedimentation towards the benthic layer of the Adriatic coastal belt (Giani et al., 2001). Thus, near the bottom, phytoplankton is sometimes subjected to light limitation. Looking at the general trend of phytoplankton over the years, the main limiting factors for phytoplankton growth in the Adriatic coastal system are not only light, but also temperature, together with the strong influence of meteorological events (see also Caroppo et al., 1999). In spite of the extreme environmental variability, a temporal phytoplankton sequence over a yearly period was successfully designed, representing typical mean conditions obtained from 10 years' sampled data. The general trend describes a sudden 'spurt' of growth in late winter (February) and two other slower growth periods in April and July. Each of these abundance increases is followed by a decrease in cell numbers, corresponding to changes in the community structure (Fig. 10). After the last peak in July, cell

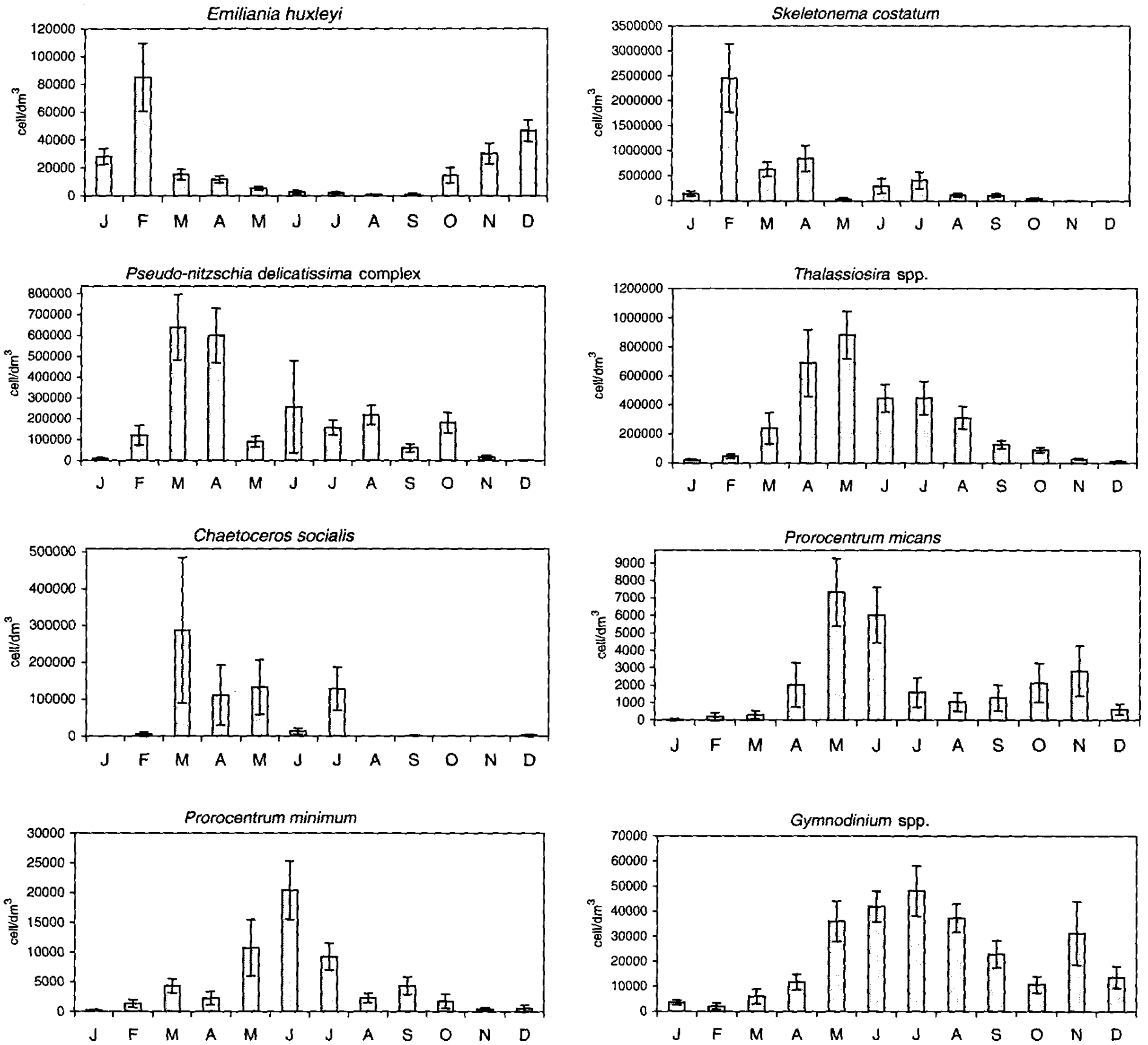

Fig. 7. Annual cycle of main phytoplankton species abundance from 1990 to 1999 data. Data have been obtained from the entire data set, clustered for each month. Confidence limits have been calculated from the mean standard errors, multiplied for Student's *t* (95% probability).

abundance decreases progressively, until the December minimum. As expected in a nutrient-enriched system, the community structure is dominated generally by diatoms (both micro- and nanoplankton fractions), for most of the year. However, the classic drop in phytoplankton abundance in late summer is not so evident as in temperate seas, because nutrients are still sufficient to sustain high phytoplankton biomass. In fact, river discharges and nutrient contents are low only after prolonged dry weather, so that only in a very few cases the lack of nutrients dramatically can limit phytoplankton metabolism. Therefore, one summer storm may be adequate to increase river runoff, and with these new pulses of nutrients, summer phytoplankton blooms may

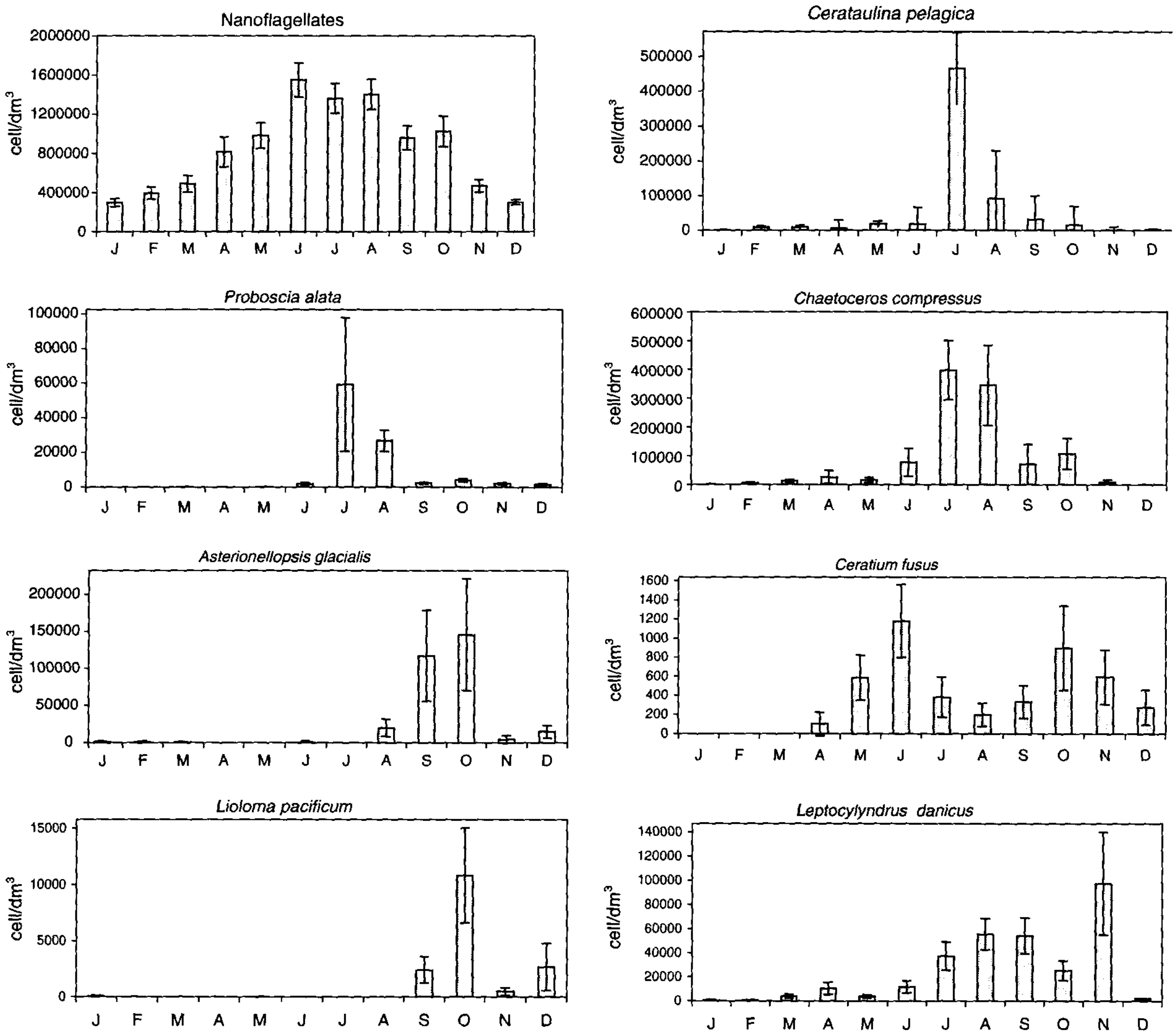

Fig. 8. Annual cycle of main phytoplankton species abundance, from the 1990 to 1999 data. Data have been obtained from the entire data set, clustered for each month. Confidence limits have been calculated from the mean standard errors, multiplied for Student's *t* (95% probability).

occur, especially when a calm period with weak winds follows a stormy phase.

The correlation analysis undertaken between the main taxa abundance and temperature has demonstrated the seasonal pattern for most of them; the diatoms *Proboscia alata, Chaetoceros compressus, Leptocylindrus danicus, Cerataulina pelagica* can be considered thermophilic species, whilst *Skeletonema costatum, Pseudo-nitzschia delicatissima, Asterionellopsis glacialis* are typical of cold waters. Species succession, over the year, highlights the low number of dinoflagellates in the communities (2% of total abundance); only in June-July are dinoflagellates present in significant abundances, as observed for *Prorocentrum micans, P. minimum, Gymnodinium* sp and *Ceratium fusus* (Figs. 7 and 8). This occurs when nutrient-poor waters, after the previous spring bloom of diatoms, favour the

Table 3
Linear correlation coefficients between taxa and hydrochemical parameters

	Temperature df = 4076	Salinity df = 4076	DIN df = 4085	Si-SiO$_4$ df = 4081	P-PO$_4$ df = 4079
Prorocentrum micans	0.07	−0.14	0.09	0.10	n.s.
Prorocentrum minimum	0.13	0.12	n.s.	n.s.	n.s.
Gymnodinium sp.	0.30	−0.05	−0.15	−0.06	n.s.
Ceratium fusus	0.05	n.s.	n.s.	n.s.	n.s.
Emiliania huxleyi	−0.43	0.24	−0.09	−0.11	−0.05
Skeletonema costatum	−0.22	−0.28	0.25	0.22	0.07
Thalassiosira sp.	0.13	−0.24	0.18	0.16	n.s.
Leptocylindrus danicus	0.19	n.s.	−0.09	−0.09	−0.05
Proboscia alata	0.37	0.05	−0.16	−0.14	n.s.
Chaetoceros compressus	0.22	−0.11	−0.06	−0.08	−0.09
Chaetoceros socialis	n.s.	n.s.	0.06	n.s.	0.07
Cerataulina pelagica	0.36	−0.15	−0.09	−0.07	n.s.
Lioloma pacificum	n.s.	−0.06	n.s.	0.06	n.s.
Asterionellopsis glacialis	−0.05	n.s.	n.s.	n.s.	n.s.
Pseudo-nitzschia delicatissima	−0.07	n.s.	n.s.	−0.13	−0.12
Nanoflagellates	0.30	−0.29	0.09	0.17	n.s.

All values correspond to a level of significance for $p < 0.01$ except for those indicated n.s. (not significant).

Table 4
Hydrochemical and biological data: results of seasonal Kendall τ-test. τ values, significance of trend (p) and seasonal Kendall slope estimate (SE) in units yr^{-1} are reported

	8			24			40			56			72			All data		
	τ	p	SE	τ	p	SE	τ	p	SE	τ	p	SE	τ	p	SE	τ	p	SE
Distance from coast = 1.0 nm																		
Temperature (°C)	0.04	0.72	0.00	−0.02	0.81	−0.05	0.01	0.91	0.01	−0.03	0.73	−0.03	0.09	0.33	0.10	0.03	0.73	0.03
Salinity (PSU)	−0.19	0.04	−0.17	**−0.31**	**0.00**	**−0.35**	−0.06	0.54	−0.05	−0.11	0.22	−0.13	−0.07	0.44	−0.17	−0.02	0.88	−0.02
Secchi disk (m)	−0.13	0.21	0.00	**−0.30**	**0.00**	**−0.25**	−0.02	0.84	0.00	0.00	1.00	0.00	−0.10	0.30	−0.01	−0.10	0.53	0.00
DIN (μM)	0.21	0.02	0.74	0.20	0.03	1.38	0.04	0.70	0.13	0.05	0.61	0.09	0.07	0.42	0.34	−0.03	0.82	−0.05
P-PO$_4$ (μM)	**−0.39**	**0.00**	**−0.01**	**−0.31**	**0.00**	**−0.01**	**−0.33**	**0.00**	**−0.01**	**−0.44**	**0.00**	**−0.01**	**−0.35**	**0.00**	**−0.02**	**−0.53**	**0.01**	**−0.01**
Si-SiO$_4$ (μM)	0.19	0.04	0.24	0.26	0.00	0.56	−0.01	0.97	−0.02	0.07	0.46	0.10	−0.07	0.42	−0.37	−0.09	0.27	−0.12
Chlorophyll *a* (μg dm^{-3})	−0.03	0.81	−0.02	0.20	0.02	0.12	0.06	0.49	0.04	0.03	0.73	0.03	**0.22**	**0.01**	**0.20**	−0.09	0.54	−0.04
Phytoplankton (10^3 cell dm^{-3})	0.20	0.03	62.88	0.22	0.02	62.10	0.11	0.22	30.48	0.12	0.19	59.00	**0.23**	**0.01**	**138.04**	−0.06	0.66	−19.22
Distance from coast = 2.5 nm																		
Temperature (°C)	0.08	0.38	0.07	−0.03	0.78	−0.01	0.03	0.79	0.03	0.04	0.70	0.03	0.08	0.39	0.08	0.03	0.82	0.02
Salinity (PSU)	−0.15	0.10	−0.09	−0.18	0.05	−0.20	−0.17	0.06	−0.14	−0.17	0.06	−0.13	−0.08	0.39	−0.17	0.01	0.97	0.01
Secchi disk (m)	−0.01	0.97	0.00	−0.19	0.04	−0.20	−0.13	0.19	−0.02	−0.04	0.72	0.00	−0.07	0.47	0.00	0.00	1.00	0.00
DIN (μM)	0.18	0.05	0.45	**0.28**	**0.00**	**1.16**	0.20	0.02	0.65	0.05	0.56	0.14	0.11	0.20	0.73	−0.01	0.91	−0.03
P-PO$_4$ (μM)	**−0.55**	**0.00**	**−0.01**	**−0.45**	**0.00**	**−0.01**	**−0.35**	**0.00**	**−0.01**	**−0.52**	**0.00**	**−0.01**	**−0.35**	**0.00**	**−0.02**	**−0.60**	**0.01**	**−0.01**
Si-SiO$_4$ (μM)	0.12	0.18	0.18	**0.25**	**0.00**	**0.38**	0.13	0.15	0.16	0.03	0.79	0.03	−0.01	0.97	−0.01	−0.09	0.28	−0.06
Chlorophyll *a* (μg dm^{-3})	−0.07	0.47	−0.02	0.15	0.10	0.07	0.03	0.76	0.02	0.18	0.05	0.15	0.20	0.02	0.27	−0.18	0.20	−0.10
Phytoplankton (10^3 cell dm^{-3})	−0.01	0.97	−1.00	0.13	0.15	36.50	0.16	0.07	47.06	0.16	0.07	91.25	0.15	0.10	175.00	−0.04	0.78	−14.02

Bold face indicates results significant at $p < 0.01$.

growth of dinoflagellates, which typically have lower nutritional requirements (Thingstad and Sackshaug, 1990). However, in our system, "red tides" never occurred during the period 1990–1999, confirming that dinoflagellate development is hindered by high-variability hydrodynamic

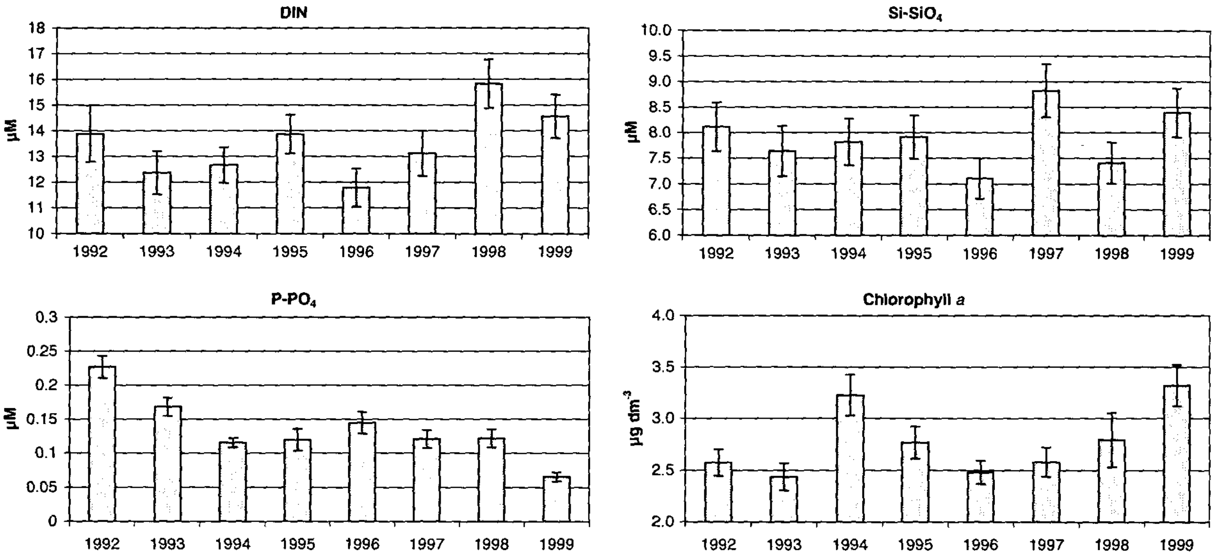

Fig. 9. Annual average of the nutrients and chlorophyll *a*, from 1992 to 1999. Confidence limits have been calculated from the mean standard errors, multiplied for Student's *t* (95% probability).

systems. In contrast, other Adriatic coastal systems (e.g., south of the Po) are exposed to lesser hydrodynamic variability, and red tides have often been described in those environments (Viviani et al., 1985). In the same way, toxic events in our sampled waters are rarer than in other coastal Adriatic waters (Bernardi Aubry et al., 2000). Coccolithophorids reach their relative peak maximum mainly in winter with *Emiliania huxleyi*, whose distribution appears to be connected with higher salinity, cold and "oligotrophic waters", as shown by the positive correlation between this species and salinity and by the negative one with temperature and nutrients. In contrast, our results highlight the positive influence of low salinity and high nutrients over the growth of several taxa (for example, over *Skeletonema costatum*, *Thalassiosira* sp, *Cerataulina pelagica* and *Prorocentrum micans*). With respect to spatial variability, the wide salinity and nutrient fields highlight the fact that the three areas differ mainly in their phytoplankton abundance and biomass, but not in community structure, indicating that this structure is composed of neritic species which must cover a large ecological spectrum; that is in order to survive in such greatly differing hydrodynamic conditions. Thus, we may typify the spatial distribution of phytoplankton standing stock as follows:

(i) the southern area, characterised by low salinity and high nutrient values, i.e., an area in which hydrodynamic properties favour frequent phytoplankton blooms, spreading the phytoplankton biomass to the eastern (oligotrophic) part of the basin through a cyclonic gyre (Franco and Michelato, 1992);
(ii) the central area, located off the Lagoon of Venice, not influenced greatly by river discharge and, thus, characterised by higher salinity and lower nutrients; phytoplankton biomass is not as low as expected, because outflowing lagoonal waters often contain higher abundances of *Skeletonema costatum* (a typical species of the winter Adriatic phytoplankton; Caroppo et al., 1999) than found in the coastal waters;
(iii) and the northern area, influenced by minor river discharge, with intermediate salinity and nutrients and lower phytoplankton biomass (Table 2).

Long-term trends observed over the entire sampling period did not reveal significant patterns for most of the hydrochemical parameters, since

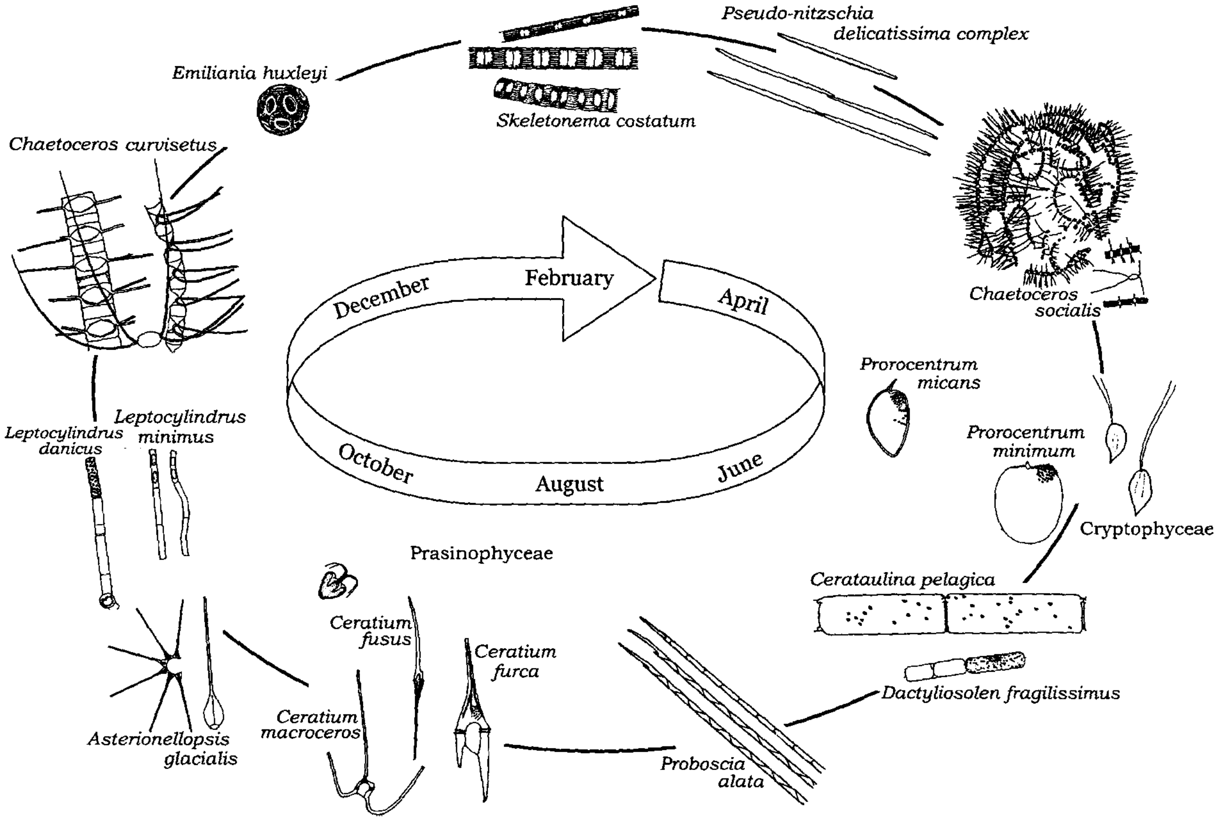

Fig. 10. Schematic representation of species succession, over an annual cycle, obtained from the 1990–1999 data.

the interference produced by the high variability of the data-set probably masked significant increases or decreases, in the values over the 1992–1999 period. In contrast, a recent publication (e.g., Russo et al., 2002) has demonstrated significant increases in water temperatures in the offshore Adriatic waters, when 1985–1988 data are compared with those for 1995–1998. Throughout the whole of the sampling area described here, significant changes were found only for decreasing orthophosphate concentrations (Fig. 9). This pattern can be explained as being due to reduced quantities of phosphorus in detergents, in the late 1980s. In relation to this tendency, the unbalanced N/P ratio described for the offshore Adriatic waters (Vollenweider, 1995) could become a new signal of phosphorus limitation for phytoplankton in Adriatic coastal waters; until now, this process has never been described. Moreover, an increase in the N/P ratio might also have consequences on the phytoplankton excretion rate, promoting mucilage events (Degobbis et al., 2000). In addition, a local trend was observed, with decreasing salinity and transparency being correlated with increased DIN and orthosilicates at a station off the mouth of the Piave. This trend is related probably to a change in the course of the river plume, around 1994–1995, due to two different factors: (i) the effects of a flood in November 1994, which locally altered bottom morphology around the river mouth; and (ii) an increase of the erosive processes in the area, which could compress the plume path to closer to the coast (Consorzio Venezia Nuova, personal communication).

The final analysis relating to long-term trends was made in relation to phytoplankton biomass and group abundance data, the patterns of which did not reveal significant changes of phytoplankton biomass, or abundance, in the Northern Adriatic coastal system during the 10-year period (1990–1999). We suggest that an improved interpretation of the decreased phosphate levels and the phosphate limitation, which do not seem to produce significant changes in the phytoplankton communities structures, probably requires multidecadal data; this leads us to stress the importance of continuous monitoring activities, in order to obtain long and uninterrupted time-series.

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