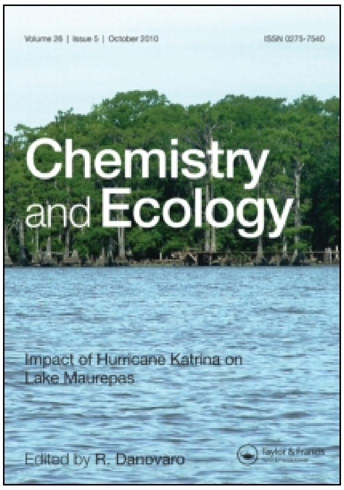

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

Observations on phytoplankton productivity in relation to hydrography in the Northern Adriatic

G. Socal[a]; A. Pugnetti[a]; L. Alberighi[a]; F. Acri[a]
[a] C.N.R., Istituto di Biologia del Mare, Venezia, Italy

Online publication date: 14 September 2010

To cite this Article Socal, G. , Pugnetti, A. , Alberighi, L. and Acri, F.(2002) 'Observations on phytoplankton productivity in relation to hydrography in the Northern Adriatic', Chemistry and Ecology, 18: 1, 61 — 73
To link to this Article: DOI: 10.1080/02757540212686
URL: http://dx.doi.org/10.1080/02757540212686

Chemistry and Ecology, 2002, Vol. 18(1-2), pp. 61–73

OBSERVATIONS ON PHYTOPLANKTON PRODUCTIVITY IN RELATION TO HYDROGRAPHY IN THE NORTHERN ADRIATIC

G. SOCAL*, A. PUGNETTI, L. ALBERIGHI and F. ACRI

C.N.R. Istituto di Biologia del Mare, Castello 1364/A, I-30122 Venezia, Italy

(Received 1 November 2000)

This work, carried out within the framework of the PRISMA II project, aims at evaluating the effects of the Po River flow on primary productivity, measured by ^{14}C with *in situ* sample incubations. A total of four cruises was carried out in late winter and early summer (1996–1998) along transects from the coast offshore. In both seasons, the highest primary productivity was found in the most oligohaline stations. The effects of the Po River inputs were therefore clearly evident in the westernmost area, both in high productivity values and in the shape of productivity profiles. In late winter, extensive blooms of *Skeletonema costatum* and *Pseudo-nitzschia delicatissima* resulted in productivity values that were sometimes higher than in early summer. In early summer 1996, greatly reduced river flow clearly influenced productivity which was much lower than in 1997.

Keywords: Phytoplankton; productivity; Northern Adriatic

INTRODUCTION

The hydrodynamics of the Northern Adriatic are quite complex as a consequence of the large seasonal variations in heat fluxes and volumes of freshwater coming from the Po River. A temporal succession of two different hydrodynamic patterns has been recognized (Franco, 1983; Franco and Michelato, 1992): in winter, from November to March, the westernmost waters are diluted by the Po River outflow and remain separated by offshore water by a frontal system, so that the dissolved and particulate matter from the land remains more or less confined near the coast. The highly saline offshore waters become progressively vertically mixed as a consequence of heat losses and mechanical stirring by winds. For the rest of the year, from April to October, a salinity gradient overlaps the temperature gradient and waters are highly stratified. Warmest waters diluted by fresh water inflow are confined in the surface layer and reach almost the whole northern basin and one or more pycnoclines separate water masses of intermediate density, while high-density water is confined near the bottom.

*Corresponding author. E-mail: socal@ibm.ve.cnr.it

ISSN 0275-7540 print; ISSN 1029-0370 online
DOI: 10.1080/0275754021000001961

These periodic modifications in the structure and dynamics of the density field lead to distinct patterns in the spatial and temporal distribution of phytoplankton species composition, biomass and production, due both to direct effects on the process of horizontal and vertical distribution of organisms and to indirect effects through distribution of nutrients and photo-attenuating materials (Franco, 1984).

It is well known that variations in irradiance, mixing and nutrient availability are of crucial importance for phytoplankton productivity. According to the complex interactions of these three factors, primary productivity in the Northern Adriatic is highly variable in both time and space (Franco, 1984; Smodlaka, 1986; Zoppini *et al.*, 1995; Alberighi *et al.*, 1997; Harding *et al.*, 1999): in winter, a west-to-east decreasing gradient in the phytoplankton standing crop and production occurs; during summer stratification, the lateral advection of river runoff in surface layers and the presence of marked pycnoclines result in vertical heterogeneities and local variations in primary productivity (Franco, 1984).

Data collected until now show that the amount of freshwater inputs and the extension of plume spreading through the frontal systems clearly determine the boundary between low and high productive areas in the Northern Adriatic (Franco, 1984; Smodlaka, 1986; Alberighi *et al.*, 1997). However, relatively few works have dealt with quantification of primary productivity *in situ* along the Italian coastline (Franco, 1984; Alberighi *et al.*, 1997); most observations of primary productivity in the Northern Adriatic consist of simulated *in situ* measurements in artificial light incubators (Harding *et al.*, 1999).

The present work, carried out within the framework of the project PRISMA II (subproject "Biogeochemical Cycles"), aims at describing variations in *in situ* primary productivity in relation to the Po River plume when seasonal and spatial variations in the main physical, chemical and biological characteristics take place.

MATERIALS AND METHODS

In the frame of the project PRISMA II, the R/V "U. D'Ancona" undertook four cruises, in June, 1996 and 1997 and February, 1997 and 1998. During each cruise, two sets of stations, respectively in the Northern and Central Adriatic (Fig. 1), were chosen along transects across the frontal system. The choice of stations was based on the results of physical surveys carried out with the towed undulating vehicle "Sarago", a few days before primary productivity measurements.

A CTD probe (Idronaut mod. 801), equipped with a Sea Tech transmissometer, was used to measure temperature, conductivity and transmittance. Photosynthetically available radiation (PAR: 400–700 nm) was measured by a biospherical quantum scalar irradiance metre (PNF 300). The light attenuation coefficient (K_0) was calculated according to Kirk (1983).

Samples for determining pH (pH meter Beckman ϕ 72), carbon dioxide (potentiometric titration; Johannson and Wedborg, 1982), oxygen (Winkler method), dissolved inorganic nutrients (filtered and frozen samples analysed on a Technicon autoanalyser; Strickland and Parsons, 1972), chlorophyll *a* (HPLC, Beckman Gold System 11) and primary productivity (^{14}C incorporation; Steemann Nielsen, 1952) were collected at 0, 1, 5, 10, 15 and 20 m and at 1 m from the bottom (max depth: 50 m), using 5 l Niskin bottles.

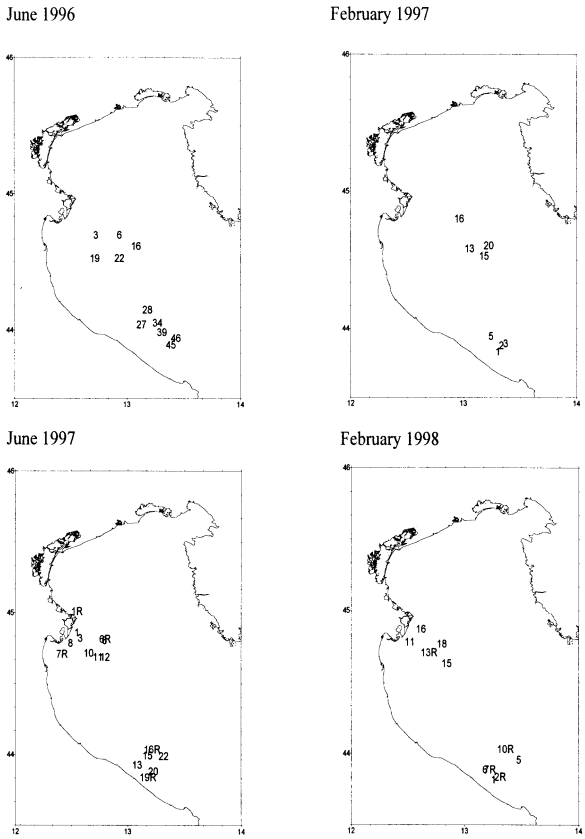

FIGURE 1 Location of sampling stations.

Primary productivity was measured by means of *in situ* incubations following the method of Lewis and Smith (1983), slightly modified, with small sample volumes and short incubation times. At each sampling depth, 20 cm^3 of water were inoculated with 148 kBq of $NaH^{14}CO_3$ and incubated *in situ* for 30 min. After incubation, 1 cm^3 subsamples were acidified (0.5 cm^3 of hydrochloride acid 6N) and stirred under a hood for 1 h. ^{14}C activity was measured after the addition of an Instagel Plus (Packard) cocktail, on a LS6000 Beckman liquid scintillation counter. Time zero samples were used instead of dark bottles.

The statistical analyses were performed by Statgraphics. Biological data were log-transformed for Principal Component Analysis (R-mode).

RESULTS AND DISCUSSION

Hydrological Characteristics

Po River Flow

The flow regime of the Po River is generally characterized by high flows in spring and autumn (data from Magistrato del Po). In comparison with long-term averages (1950–

TABLE I Monthly averages and confidence limits ($p < 0.05$) of Po River flow measured in February and June at Pontelagoscuro (Province of Ferrara) in the study periods, with related long-term averages (data from Magistrato del Po).

	1950–1994	*1996*	*1997*	*1998*
February ($m^3\,s^{-1}$)	1300		1432 ± 59	940 ± 32
June ($m^3\,s^{-1}$)	1800	1080 ± 108	1590 ± 264	

1994) this study was carried out in low flow conditions in June, 1996 and 1997 and in February, 1998, and in high flow conditions in February, 1997 (Tab. I). In June, 1996, particularly low discharge was observed, with minima between 700 and 800 $m^3\,s^{-1}$ during samplings in the northern area.

Late Winter

In February, 1997 in the northern area, fresh water inputs caused a sharp vertical salinity gradient along the water column on the western side: values in the most superficial waters were around 30 and 37–38 in the deeper layers; temperature ranged between 9 and 10.8 C from the surface to the bottom. Moving eastwards, vertical stratification disappeared almost completely and temperature increased (in the water column salinity was around 37–38 and temperature between 10.3–11.6 C). In the southern area, marked vertical salinity (maximum 30–37.5) and temperature (maximum 7.3–11.2 C) gradients were found in all stations from west to east.

In February, 1998 in the northern area, salinity and temperature gradients were very similar to those of February, 1997. In the southern area, the effects of the Po River were limited to a very small area close to the coast, where the lowest salinity (33–35) and temperature (7–8 C) values were found. The other stations were characterized by salinity around 38 and temperature between 10 and 12 C.

The most superficial oligohaline waters were always the coldest, while the deepest and most saline waters were the warmest. Highest light attenuation coefficients (K_0 0.20–0.5 m^{-1}) usually characterized the less saline waters.

Concentrations of nutrients in waters characterized by differing salinities and temperatures were the result of a complex effect due to river inputs, seasonal hydrodynamics and phytoplankton uptake. In all areas, nitrates, *i.e.* the dominant form of dissolved inorganic nitrogen (DIN), showed a significant negative correlation with salinity (Tab. II), their concentrations ranging from 10 to 45 $\mu mol\,dm^{-3}$ and 0.5 to 6 $\mu mol\,dm^{-3}$ in the most oligohaline and in the most saline waters.

Instead, correlations between silicates and salinity were positive in both areas in February, 1997 and only in the northern area in February, 1998 (Tab. II): silicate concentrations increased from below 1 to 4 $\mu mol\,dm^{-3}$ through the increasing salinity gradient. In February, 1998 in the southern area, correlations with silicates were negative (Tab. II): concentrations up to 8 $\mu mol\,dm^{-3}$ could be found in the most oligohaline waters. Orthophosphate concentrations were always very low (below 0.5 $\mu mol\,dm^{-3}$ in all stations) and no significant relationship with river flow or salinity was detected in most cruises.

TABLE II Correlation coefficients between salinity (SAL) and nutrients; correlations are significant at $p < 0.05$ n.s. = not significant

Feb. 1997 North	*n = 26*	*Feb. 1997 South*	*n = 21*	*Feb. 1998 North*	*n = 33*	*Feb. 1998 South*	*n = 30*
Variable	*SAL*	*Variable*	*SAL*	*Variable*	*SAL*	*Variable*	*SAL*
N-NO_3	−0.9	N-NO_3	−0.97	N-NO_3	−0.98	N-NO_3	−0.98
Si-SiO_4	0.7	Si-SiO_4	0.76	Si-SiO_4	0.55	Si-SiO_4	−0.77
P-PO_4	n.s.	P-PO_4	n.s.	P-PO_4	n.s.	P-PO_4	−0.58
June 1996 North	*n = 35*	*June 1996 South*	*n = 40*	*June 1997 North*	*n = 56*	*June 1997 South*	*n = 30*
N-NO_3	0.34	N-NO_3	n.s.	N-NO_3	−0.8	N-NO_3	−0.37
Si-SiO_4	n.s.	Si-SiO_4	0.61	Si-SiO_4	n.s.	Si-SiO_4	n.s.
P-PO_4	0.39	P-PO_4	n.s.	P-PO_4	−0.51	P-PO_4	n.s.

Early Summer

The marked differences in the Po River discharge which characterized the two sampling years (Tab. I) resulted in very different hydrology. In June, 1996, the northern and southern areas showed very similar values. Vertical and horizontal salinity gradients ranged between 34 and 38, with marked thermal stratification (from 24 to 10 C from the surface to the bottom). Nitrates were low ($< 1\,\mu mol\,dm^{-3}$) and tended to increase slightly with depth, whereas the dominant form of DIN was often ammonium (up to $1.4\,\mu mol\,dm^{-3}$). Silicates were characterized by two peaks, one (from 1 to $5\,\mu mol\,dm^{-3}$) in the most superficial waters and the other (up to $10\,\mu mol\,dm^{-3}$) close to the bottom. Phosphates were always below $0.1\,\mu mol\,dm^{-3}$. In the northern area, nitrates and phosphates correlated positively with salinity; in the southern area, only silicates correlated with salinity (Tab. II); the ammonium did not show any significant correlation with salinity.

In June, 1997, in the northern area, the effects of the Po River outflow were evident near the coast, where the most superficial waters had very low salinity (25–30). Strong salinity gradients overlapped temperature gradients: over a depth of 30 m, salinity could range from 21 to 37.5 and temperature from 25 to 12 C. Nitrates were the dominant form of DIN, with concentrations ranging from 11 to $27\,\mu mol\,dm^{-3}$ in the most superficial waters and from 1 to $3\,\mu mol\,dm^{-3}$ in the deepest ones; phosphates were usually below $0.2\,\mu mol\,dm^{-3}$, with the exception of a few isolated peaks, from 1 to $3\,\mu mol\,dm^{-3}$, in the most oligohaline waters.

The vertical distribution of silicates was generally characterized by two peaks, from 10 to $30\,\mu mol\,dm^{-3}$: one was found in the most superficial waters and was related to Po River inputs; the other one was close to the bottom and was probably due to regeneration processes. Photoattenuation was high, and the maximum thickness of the euphotic zone never exceeded 15 m. Going eastwards, stations were characterized by salinity between 35 and 37 and the lowest nitrate concentrations ($< 2\,\mu mol\,dm^{-3}$). Vertical distribution of silicates showed a near-bottom peak (10–$30\,\mu mol\,dm^{-3}$). In the northern area, nitrates and phosphates correlated negatively with salinity; no correlation was found between silicates and salinity (Tab. II).

In June, 1997 in the southern area, the effects of riverine inputs could be slightly detected in the westernmost stations, where salinity ranged between 35 and 37 from the surface to the bottom; in the other stations, water-column stratification was mainly due to the vertical temperature gradient (up to 10 C from the surface to the bottom; salinity around 37). Attenuation of irradiance was low, so that the euphotic layer always reached the bottom. Nitrates were below 0.6 μmol dm^{-3}, with variations which could not be correlated with salinity; ammonium nitrogen was around 0.3 μmol dm^{-3}, with near bottom peaks up to 15 μmol dm^{-3}. Also the silicates tended to increase with depth, from around 2 μmol dm^{-3} to 8 μmol dm^{-3}. Phosphates were always below 0.1 μmol dm^{-3}.

Primary Productivity

Late Winter

In each area and cruise, samples were grouped with respect to their salinity, as shown in Table III. Oligohaline waters, that were the coldest in winter and the warmest in

TABLE III Mean values of primary productivity (PP: mg C m^{-3} h^{-1}), chlorophyll *a* (CHL: μg dm^{-3}), temperature (TEMP: °C), nitrates (N-NO$_3$: μmol dm^{-3}), phosphates (P-PO$_4$: μmol dm^{-3}), silicates (Si-SiO$_4$: μmol dm^{-3}) in water masses of low (LS), intermediate (IS) and high (HS) salinity

	PP	*CHL*	*TEMP*	*N-NO$_3$*	*P-PO$_4$*	*Si-SIO$_4$*
FEB97N						
LS (30–32)	32.1	1.0	9.1	29.0	0.06	0.7
IS (32–37)	4.9	0.7	10.2	5.1	0.04	2.0
HS (> 37)	1.9	0.4	10.8	2.1	0.05	3.5
FEB97S						
LS (28–30)	44.9	1.9	7.4	36.5	0.03	0.8
IS (30–36)	24.7	1.4	9.0	19.9	0.07	0.8
HS (> 36)	1.8	0.9	11.1	2.4	0.05	2.6
FEB98N						
LS (30–32)	44.2	4.0	8.7	20.2	0.03	0.6
IS (32–37)	5.1	2.1	9.2	4.1	0.02	0.8
HS (> 37)	1.1	0.9	10.4	1.3	0.03	2.5
FEB98S						
LS (32–35)	16.6	7.3	7.5	17.5	0.07	4.6
IS (35–38)	3.7	1.1	10.1	1.4	0.03	2.6
HS (> 38)	1.5	0.5	11.8	0.7	0.03	2.6
JUN96N						
IS (35–37)	1.5	0.5	23.2	0.02	0.05	1.8
HS (> 37)	0.7	0.4	15.8	0.3	0.06	3.2
JUN96S						
IS (35–37)	3.0	0.6	20.6	0.5	0.06	2.0
HS (> 37)	2.4	1.3	15.6	0.5	0.07	5.5
JUN97N						
LS (21–23)	279.2	2.2	26.0	12.9	1.19	19.3
IS (23–30)	33.3	4.7	24.3	12.4	0.25	9.4
HS (> 30)	2.5	0.8	17.6	1.2	0.1	6.5
JUN97S						
IS(35–37)	2.0	0.5	21.5	0.5	0.02	3.0
HS (> 37)	1.5	0.4	15.9	0.2	0.03	3.0

TABLE IV Correlation coefficients between primary productivity and temperature (TEMP), salinity (SAL), nitrates (N-NO_3), silicates (Si-SiO_4) and phosphates (P-PO_4); Units as in Table III. Correlations are significant at $p < 0.05$; n.s. = not significant

Feb. 1997 North	*n = 26*	*Feb. 1997 South*	*n = 21*	*Feb. 1998 North*	*n = 33*	*Feb. 1998 South*	*n = 30*
Variable	*PP*	*Variable*	*PP*	*Variable*	*PP*	*Variable*	*PP*
TEMP	−0.70	TEMP	−0.72	TEMP	−0.6	TEMP	−0.67
SAL	−0.81	SAL	−0.79	SAL	−0.95	SAL	−0.74
N-NO_3	0.60	N-NO_3	0.74	N-NO_3	0.92	N-NO_3	0.72
Si-SiO_4	−0.50	Si-SiO_4	−0.56	Si-SiO_4	−0.47	Si-SiO_4	0.74
P-PO_4	n.s.	P-PO_4	n.s.	P-PO_4	n.s.	P-PO_4	n.s
June 1996 North	*n = 35*	*June 1996 South*	*n = 40*	*June 1997 North*	*n = 56*	*June 1997 South*	*n = 30*
TEMP	0.41	TEMP	n.s.	TEMP	0.4	TEMP	n.s.
SAL	−0.54	SAL	n.s.	SAL	−0.81	SAL	n.s
N-NO_3	−0.35	N-NO_3	n.s.	N-NO_3	0.6	N-NO_3	n.s
Si-SiO_4	n.s.	Si-SiO_4	n.s.	Si-SiO_4	0.32	Si-SiO_4	n.s.
P-PO_4	n.s.	P-PO_4	n.s.	P-PO_4	0.71	P-PO_4	n.s.

summer, clearly had the highest primary productivity (PP) and chlorophyll *a* concentrations (Tab. III). Productivity was in fact negatively correlated with salinity (Tab. IV). Moreover, PP was positively correlated with nitrates and negatively with silicates, with the only exception of February, 1998 in the southern area, when correlations with silicates were positive; no significant correlations with phosphates could be detected (Tab. IV). The relations between production and nitrates suggest that riverine inputs of nitrates greatly exceed phytoplankton requirements; instead, the supply of silicates from the Po appears to be markedly reduced by phytoplankton uptake, characterized in this period by large blooms of the diatom *Skeletonema costatum*. In February, 1998 in the southern area, during an early growth phase of *Pseudo-nitzschia delicatissima*, the most oligohaline waters, although having the highest productivity, still showed the highest silicate concentrations.

Table V shows integrated and maximum primary productivity and some related parameters for each cruise and each station. Total incident PAR was quite variable during each cruise; a general pattern of relation between PAR and PP could not be found, as the highest incident PAR could correspond to a high, median or low PP. PP

TABLE V Integrated (ΣPP: mg C m^{-2} h^{-1}) and maximum (MPP: mg C m^3 h^{-1}) primary productivity in water column and some related parameters. SAL: mean salinity in the water column; ΣCHL: integrated chl *a* (mg chl m^{-2}); MCHL: maximum chl *a* (mg chl m^{-3})

	SAL	*ΣPP*	*MPP*	*ΣPP/MPP*	*ΣCHL*	*MCHL*
FEB97N						
st. 16	35.9	259.1	57.0	4.6	19.6	0.5
st. 20	37.1	107.4	6.8	15.7	16.7	0.4
st. 13	35.3	55.4	17.5	3.2	28.6	0.8
st. 15	37.3	101.3	9.3	10.9	12.4	0.3
FEB97S						
st. 2	35.3	139.5	42.4	3.3	9.8	0.5
st. 5	33.2	298.3	84.8	3.5	53.0	3.8
st. 3	36.2	93.9	33.6	2.8	9.4	0.4
st. 1	34.7	95.3	26.2	3.6	12.0	0.9

TABLE V (*Continued*)

	SAL	Σ*PP*	*MPP*	Σ*PP*/*MPP*	Σ*CHL*	*MCHL*
FEB98N						
st. 11	35.0	137.3	38.5	3.6	52.7	2.3
st. 15	37.8	17.5	1.8	9.5	17.6	0.5
st. 13	37.3	75.9	8.8	8.6	32.3	1.1
st. 16R	35.7	174.9	51.3	3.4	46.9	1.8
st. 18R	37.3	30.2	3.0	6.4	33.2	1.1
FEB98S						
st. 1	34.0	92.7	32.8	2.8	88.4	8.0
st. 5	38.4	68.0	4.6	14.7	27.3	0.5
st. 6	34.8	155.9	33.2	4.7	68.2	6.2
st. 2R	37.8	45.4	5.8	7.8	21.2	1.4
st. 7R	38.0	45.1	6.0	7.5	11.3	0.8
st. 10R	38.4	95.0	2.3	18.6	19.4	0.4
JUN96N						
st. 3	36.2	35.9	3.0	12.1	26.3	0.8
st. 6	37.4	32.2	1.3	25.6	14.0	0.4
st. 22	37.7	20.7	1.3	15.6	6.2	0.2
st. 19	36.9	23.9	1.4	12.0	14.6	0.4
st. 16	37.1	40.7	3.2	12.9	10.0	0.3
JUN96S						
st. 28	36.9	213.6	7.9	24.3	30.1	0.6
st. 34	36.9	119.1	3.6	33.3	36.9	0.8
st. 39	37.3	50.5	2.2	22.5	53.2	1.7
st. 46	37.4	108.7	2.5	20.5	28.6	0.6
st. 45	37.1	85.6	8.0	10.8	36.2	1.3
st. 27	36.8	26.6	1.7	15.9	21.2	0.7
JUN97N						
st. 2	32.1	37.6	5.9	6.4	40.8	1.8
st. 1	32.5	246.7	70.6	3.5	33.8	2.0
st. 3	36.8	108.0	6.7	16.1	16.5	0.6
st. 6	36.8	66.3	3.5	18.8	22.6	0.7
st. 11	36.8	10.6	2.7	3.9	17.2	0.5
st. 10	36.2	94.5	10.1	9.3	20.0	0.7
FEB97N						
st. 8	34.9	282.0	94.7	3.0	25.5	1.0
st. 1R	29.7	629.3	341.0	1.8	34.7	2.0
st. 12R	36.4	24.7	3.7	6.7	20.0	0.6
st. 6R	36.6	97.6	4.4	23.3	11.2	0.3
st. 7R	33.2	71.8	14.9	4.8	34.3	1.9
JUN97S						
st. 13	36.0	55.6	6.1	9.1	11.4	0.9
st. 15	37.1	35.3	3.8	9.3	8.2	0.3
st. 22	37.5	77.2	4.0	19.2	20.2	0.5
st. 20	36.2	15.0	1.5	9.8	8.2	0.5
st. 16R	37.3	51.9	3.4	15.3	6.5	0.2
st. 19R	36.5	22.7	3.4	6.6	7.3	0.7

variations among the stations were much better explained by the differences in salinity: the highest integrated and/or maximum productivity was found in the stations nearest the coast in each area, characterized by the lowest mean salinity and highest nutrient concentrations. Not only maximum and integrated PP values but also different vertical productivity profiles were found in stations with different salinities: PP decreased with depth sharply in the coastal stations (Fig. 2) and much more gently in the offshore

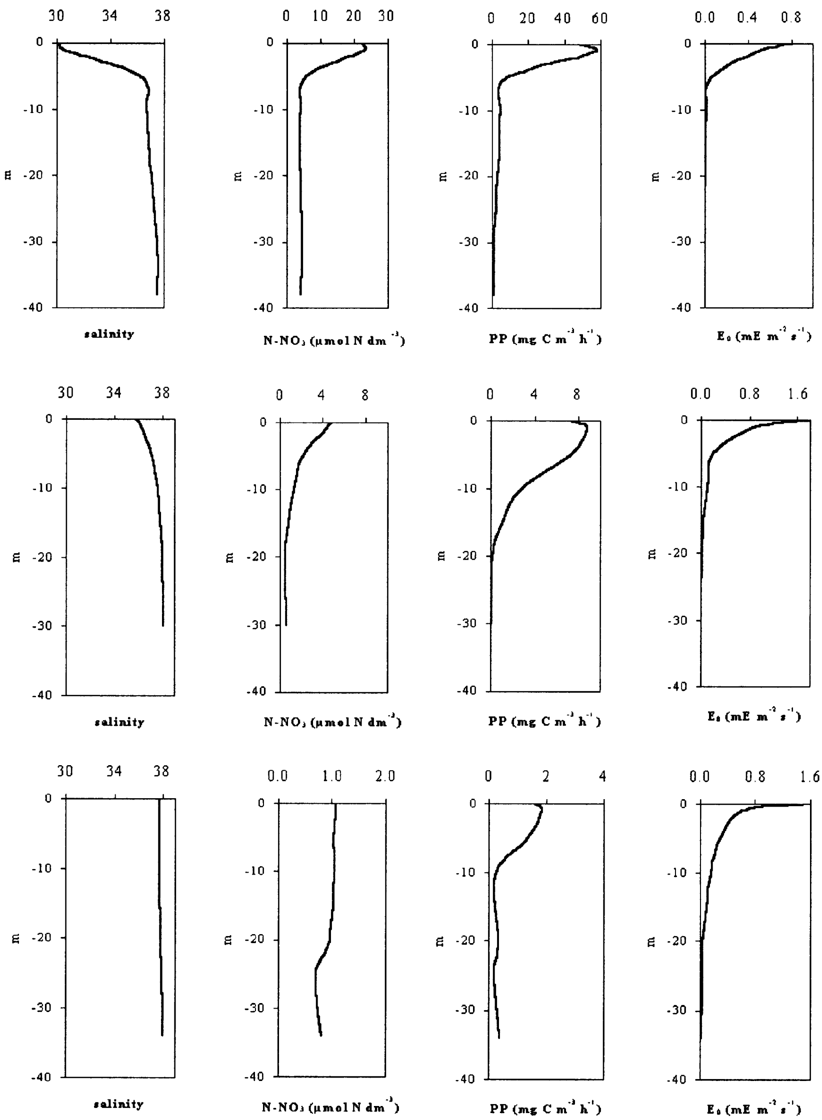

FIGURE 2 Vertical profiles of salinity, nitrates, primary productivity and PAR in areas characterized by low (top), intermediate (centre) and high (bottom) salinity in late winter. Notice the different scales for nitrates, productivity and irradiance.

ones. The first kind of profile, with the lowest ratio between integrated PP and maximum PP (Fig. 2 and Tab. V), is typical of eutrophic waters where self-shading and therefore K_0 are generally high; the second one is more typical of oligotrophic, well-irradiated waters.

Early Summer

The influence of the Po River was greatest in June, 1997 in the northern area, with lowest salinities and highest productivity and chlorophyll *a* (Tab. III). As in February, 1997, PP showed negative correlations with salinity and positive ones with nutrients (nitrates, silicates and phosphates; Tab. IV). Correlations between maximum productivity in the water column and salinity were also negative, indicating that areas of high productivity closely depend on the Po River outflow.

Both areas in June, 1996 and only the southern area in June, 1997 were much less influenced by the Po River: they had the highest salinity and were the most oligotrophic, with respect to nutrients, chlorophyll *a* and primary productivity (Tab. III). Moreover, in the southern areas productivity was not significantly correlated with salinity or nutrients (Tab. IV); however, in these stations correlations between maximum superficial PP and salinity were negative, although not significantly.

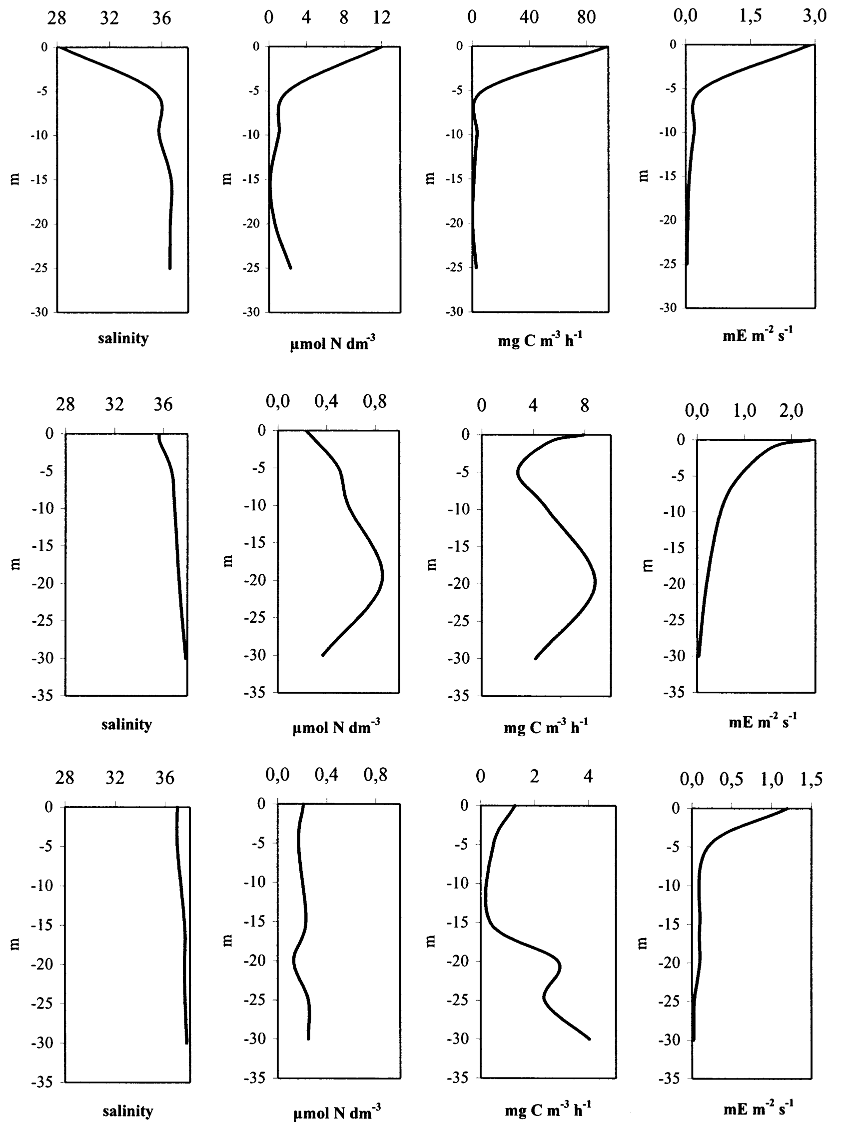

FIGURE 3 Vertical profiles of salinity, nitrates, primary productivity and PAR in areas characterized by low (top), intermediate (centre) and high (bottom) salinity in early summer. Notice the different scales for

The peculiarity of the northern area in June, 1996 is highlighted by comparisons with June, 1997 (Tabs. III, IV and V). In June, 1996, primary productivity correlated negatively with salinity and nitrate (Tab. II), that is, the highest PP occurred in the least saline and most nutrient-depleted waters, indicating that, in low flow conditions, nitrate depletion by phytoplankton becomes evident.

The characteristics outlined above are again emphasized when stations in each cruise were compared (Tab. V). The highest PP values were found in oligohaline stations close to the coast in the northern area in June, 1997. In these stations, vertical PP distribution showed a peak close to the surface followed by a sharp decline (Fig. 3). In the other stations in June, 1997 and in all stations in June, 1996, PP showed more peaks along the water column, one (or more) closest to the surface and one (or more) around or below the thermocline. Moreover, maximum PP was not always found in the more superficial layers, but often in deeper ones (Fig. 3). It is very probable that the good penetration of irradiance (K_0 around $0.1\,\mathrm{m}^{-1}$) allowed photosynthetic activity even in the deepest water layers, where phytoplankton could take advantage of nutrients regenerated close to the bottom.

All the data (June and February, northern and southern areas) were then statistically processed by means of Principal Component Analysis, performed on temperature, salinity, nitrate nitrogen, reactive silica, cholorophyll *a* and primary productivity (Figs. 4 and 5). The first two components of the PCA explain 66% of total variance. The first

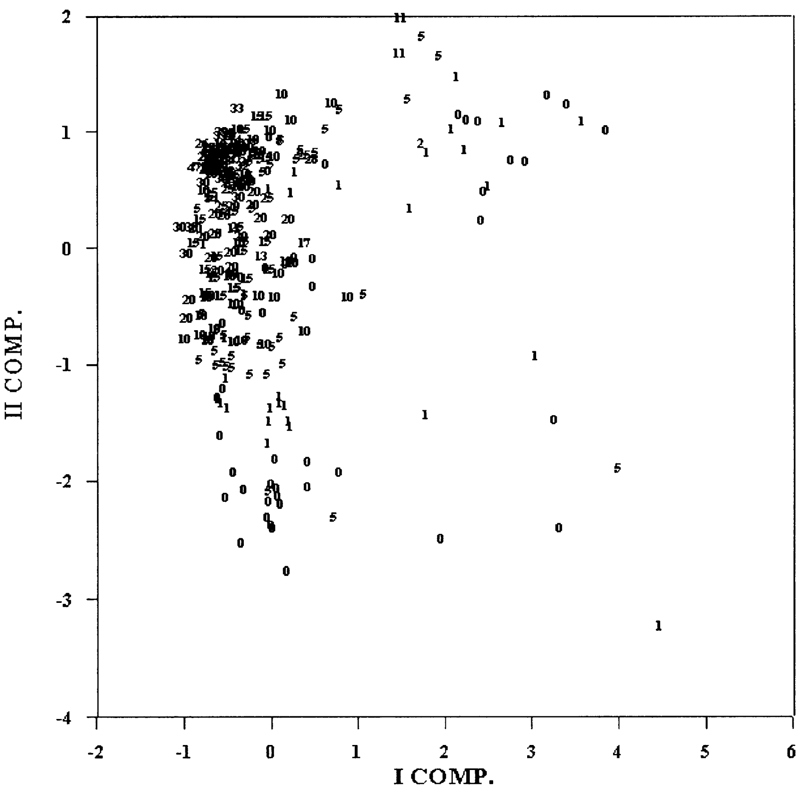

FIGURE 4 Ordering of samples by principal component analysis (see text): the numbers correspond to the sampling depths.

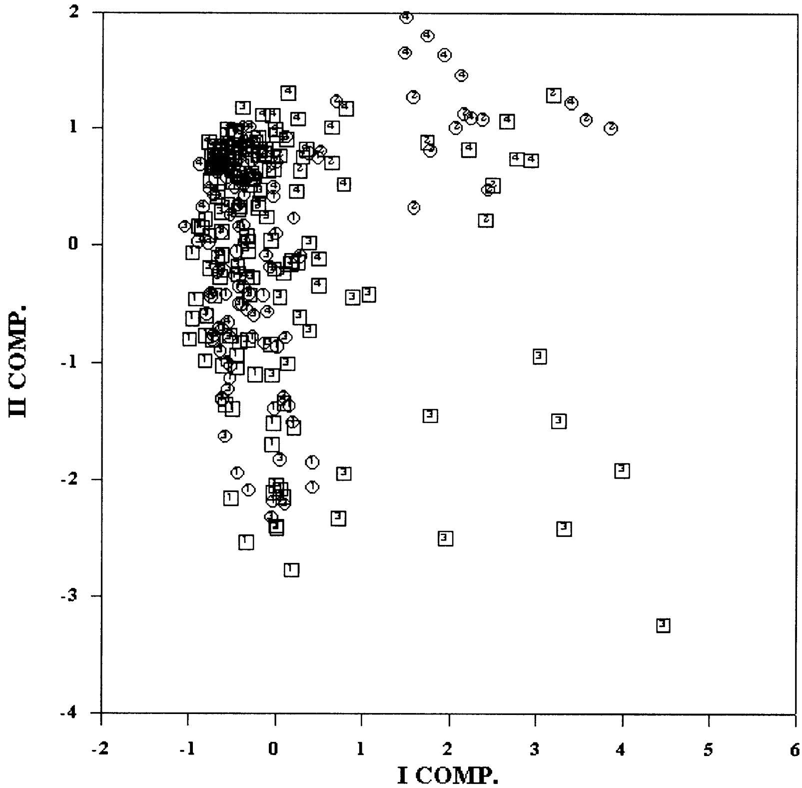

FIGURE 5. Ordering of samples by principal component analysis (see text): cruises (1 = June, 1996; 2 = February, 1997; 3 = June, 1997; 4 = February, 1998; squares = north; circles = south).

eigenvector correlates positively with productivity, nitrate nitrogen, and chlorophyll *a* and negatively with salinity; the second one correlates positively with nitrate, chlorophyll *a* and salinity, and negatively with temperature and irradiance. As described above, the scatterplot of the first two components identifies four groups of samples on the basis of seasonality and different effects of the Po River on hydrology and primary productivity: i) surface samples of June, 1997, northern area; ii) all surface samples of February, 1996 and 1997; iii) all samples of June, 1996 and those of the southern stations of June, 1997; iv) all deep-water samples of winters 1997 and 1998.

CONCLUSIONS

The effect of the Po River on primary productivity in the North-Western Adriatic were quite evident: the station with the lowest salinity had the highest primary productivity. Not only did the highest absolute values of primary productivity differentiate the most oligohaline stations from the others, but also the shape of the productivity profile was clearly different, due to a different photoattenuation. Nutrient inputs from the Po allowed a bloom of the diatoms *Skeletonem costatum* and *Pseudo-nitzschia delicatissima* in late winter; as a consequence, productivity in late winter could be as high as or higher than in early summer. The effects of the Po River on productivity are again emphasized by comparisons between the northern areas in June, 1996 and June, 1997: in low flow conditions (June, 1996) primary productivity values were much lower than during high ones (June, 1997).

Primary productivity, representing the immediate result of interactions among physical, chemical and biological variables, gives a dynamic overview of the ecosystem and therefore it is a valuable tool to follow the complex effects of freshwater inputs in the Northern Adriatic system, although the marked interannual and spatial variability of primary productivity, related to hydrology, should be stressed. In order to evaluate the generality or specificity of these data, and therefore their use as a predictive tool, processing of long-term series of data will prove invaluable.

Acknowledgements

This work was supported by the Italian Ministry of University and Research (MURST) and the National Research Council (CNR), in the framework of the PRISMA II – Biogeochemical Cycles Research Project. Dr. Paolo Franco headed this research on primary productivity and he prepared and processed the whole data-base. We thank M. Bastianini, F. Bernardi Aubry, A. Berton, F. Cioce, L. Craboledda, A. Locatelli, G. Penzo and R. Bullo for their helpful assistance in the field. G. Walton revised the English text.

References

Alberighi, L., Franco, P., Bastianini, M. and Socal, G. (1997) "Produttività primaria, abbondanza fitoplanctonica e campo di irradianza in due stazioni dell'Adriatico Settentrionale. Crociere Marzo e Giugno 1994", *Biol. Mar. Medit.* **4**, 17–23.

Franco, P. (1983) "L'Adriatico Settentrionale: caratteri oceanografici e problemi". In: *Atti del V Congresso dell' Associazione Italiana di Oceanologia e Limnologia (AIOL)*, Stresa (Italy), May 19–22, 1982: 1–27.

Franco, P. (1984) "Fattori influenti sulla produttività primaria dell'Adriatico Settentrionale", *Bollettino di Oceanologia Teorica e Applicata* **22**, 125–140.

Franco, P. and Michelato, A. (1992) "Northern Adriatic Sea: oceanography of the basin proper and of the western coastal zone", *Sci. Tot. Environ.* Supplement, 35–62.

Harding, L.W., Degobbis, D. and Precali, R. (1999) "Production and fate of phytoplankton: annual cycles and interannual variability", *Coast. Est. Stud.* **55**, 131–172.

Johansson, D. and Wedborg, M. (1982) "On the evaluation of potentiometric titrations of seawater with hydrochloric acid", *Oceanol. Acta* **5**, 209–218.

Kirk, J.T.O. (1983) *Light and Photosynthesis in Aquatic Ecosystems* (Cambridge University Press: pp. 401).

Lewis, M.R. and Smith, J.C. (1983) "A small volume, short-incubation-time method for measurements of photosynthesis as a function of incident irradiance", *Mar. Ecol. Prog. Ser.* **13**, 87–94.

Smodlaka, N. (1986) "Primary production of the organic matter as an indicator of the eutrophication in the Northern Adriatic Sea", *Sci. Tot. Environ.* **56**, 211–220.

Steeman-Nielsen, E. (1952) "The use of radioactive carbon (C^{14}) for measuring organic production in the sea", *J. Cons. Int. Explor. Mer.* **18**, 117–140.

Strickland, J.D.H. and Parsons, T.R. (1972) "A Practical handbook of seawater analysis", *Bull. Fish. Res. Bd. Canada* **167**, pp. 311.

Zoppini, A., Pettine, M., Totti, C., Puddu, A., Artegiani, A. and Pagnotta, R. (1995) "Nutrients, standing crop and primary production in western coastal waters of the Adriatic Sea", *Estuar. Coast. Shelf Sci.* **41**, 493–513.