ISSN: 0001-5113
AADRAY

ACTA ADRIAT.,
45 (2): 163-180, 2004

UDC: 595.3 (560)
Original scientific paper

Phytoplankton community composition and distribution in an eutrophic coastal area (Venice lagoon, Italy)

Chiara FACCA, Adriano SFRISO and Pier Francesco GHETTI

Department of Environmental Sciences, University of Venice, Calle Larga Santa Marta 2137, 30123 Venice, Italy
E-mail: sfrisoad@unive.it

We investigated the phytoplankton in the central area of the Venice lagoon in the 1990s. Water samples were collected at 46 sites in June 1993 and June 1998 and at four stations every month from November 1998 to October 1999. Collected data include community composition, cell abundance, and cell bio-volumes, estimated with an inverted light microscope. Cell abundance distribution maps display mean (6.9 x 10^6 and 2.5 x 10^6 cells dm^{-3} in June 1993 and June 1998, respectively) and peak values (151 and 16 x 10^6 cells dm^{-3} in June 1993 and June 1998, respectively). The reasons for differences in blooming taxa were investigated by processing environmental variables of the most abundant taxa by Canonical Correspondence Analysis. The environmental parameters that most affected the species spatial distribution were salinity and temperature in June 1993 and salinity and water transparency in June 1998. Phytoplankton temporal trends confirmed the spatial distribution: the blooming period was in June and the highest cell abundances occurred close to the mainland.

Key words: phytoplankton distribution, cell abundance, biomass, microalgae communities, Venice lagoon

INTRODUCTION

The key role of phytoplankton in the trophic chain is widely recognized. Particular attention has been paid to freshwater (HABIB *et al.*, 1997; NOGUEIRA, 2000; PIIRSOO, 2001) and pelagic (TIMMERMANS *et al.*, 1998; BOYD & HARRISON, 1999; ANDERSEN & PRIEUR, 2000) processes. Phytoplankton are also monitored in estuarine areas (GÓMEZ & BAUER, 1998; SANDERS *et al.*, 2001). However, studies on phytoplankton in protected and shallow coastal areas, such as lagoons and bays, have often been neglected because of the dominance of macrophytes. Microalgae are often estimated by means of chlorophyll *a* concentrations and are of minor interest. Nevertheless, the abundance and distribution of microalgae can be a good indicator of ecosystem conditions, particularly when related to the impact of anthropic activities (fishing, shellfish farming, bathing, etc.).

Environmental conditions in the Venice lagoon have been strictly connected to the human presence since the fourteenth century when the Serenissima Republic of Venice began to transform the lagoon morphology and, consequently, its hydro-dynamics (diversion of main rivers, digging of channels to allow transit of commercial ships, construction of artificial dikes

and breakwaters). During the twentieth century, chemical pollution heavily affected the lagoon ecosystem, triggering noticeable changes in the flora and fauna communities. Before the 1960s, sea grasses were prevalent but, later, eutrophication increased and favored macroalgae colonization, especially in the central lagoon. During that period, phytoplankton bloomed mainly after macroalgae collapse, which usually occurred in late spring.

In the early 1990s, macroalgae started to decrease, mainly because of climatic changes that produced unfavorable growth conditions (SFRISO, 1996; SFRISO & MARCOMINI, 1996). In 1993, the total macroalgae standing crop was about 85000 tons (SFRISO *et al*., 2003), approximately seven times less than the value estimated during the 1980s (about 550000 tons). By 1998, the macroalgae biomass had decreased to about 8700 tons (SFRISO *et al*., 2003). While the macroalgae coverage was decreasing, the bivalve *Tapes philippinarum* Adams and Reeve, introduced to the lagoon for economic reasons, colonized the bottoms that were free of biomass (OREL *et al.*, 2000; SFRISO, 2000) and spread everywhere. The *T. philippinarum* were caught by hydraulic and mechanical dredges causing, among other damages, disruption of the upper microlayer of sediment that prevalently consists of microautotroph organisms. As a result, sediment re-suspension in the last decade increased 5-12 times, preventing the re-colonization of macrophytes, especially sea grasses (SFRISO, 2000).

Many papers describe the distribution of macrophytes and their interaction with environmental variables in the central part of Venice lagoon (SFRISO and MARCOMINI, 1999; SFRISO *et al*. 2003 and references therein). From the 1970s to the 1990s, the macroalgae biomass (especially *Ulva rigida* C. Ag.) was so high that it regulated the bio-geochemical cycles, often leading to anoxic crises that killed macrofauna and fishes. On the contrary, studies on phytoplankton are poor, scarcely comparable, and only of a systematic nature (ANDREOLI & TOLOMIO, 1988a,b; SOCAL *et al*., 1999; TOLOMIO *et al.*, 1999). It is possible that, after the disappearance of macroalgae, phytoplankton become the main primary producer and its abundance increases.

The present work describes the composition, abundance, and distribution of phytoplankton in the central part of the Venice lagoon, paying particular attention to environmental variables that favor or hamper microalgae primary production. The emphasis is on changes in the phytoplankton community resulting from marked environmental modifications. During the 1990s, the macroalgae biomass declined and high sediment fluxes, caused mainly by clam fishing, regulate bio-geochemical processes, especially in the central and northern areas of the lagoon.

MATERIALS AND METHODS

The study area

The Venice lagoon is a semi-enclosed water basin with a depth of about 1.2 m. It is connected to the northern Adriatic Sea by three inlets, exchanging some 60% of its entire water body at every tidal cycle (12 h). The study was conducted in the central part of the lagoon, situated between the Malamocco-Marghera canal in the south and the Burano-Torcello tidal lands in the north (Fig. 1). This area receives untreated wastewater from the Venice historical center and untreated and treated sewage from the city of Mestre, its hinterland, and the islands of Lido, Murano, and Burano. Pollutants of a different nature and cooling waters from the Porto Marghera industrial zone also flow into the lagoon. Naval traffic is rather heavy as two large deep canals (the Malamocco-Marghera and the Vittorio Emanuele; width 100-200 m; depth 12-20 m) were dug to allow transit of commercial ships. Seawater flows into this area through the Malamocco and Lido inlets.

Samples were taken at 46 stations in June 1993 to investigate the trophic conditions of the Venice lagoon. The same measurements were repeated in June 1998. Phytoplankton was monitored together with macrophyte biomass and physical variables of the water column

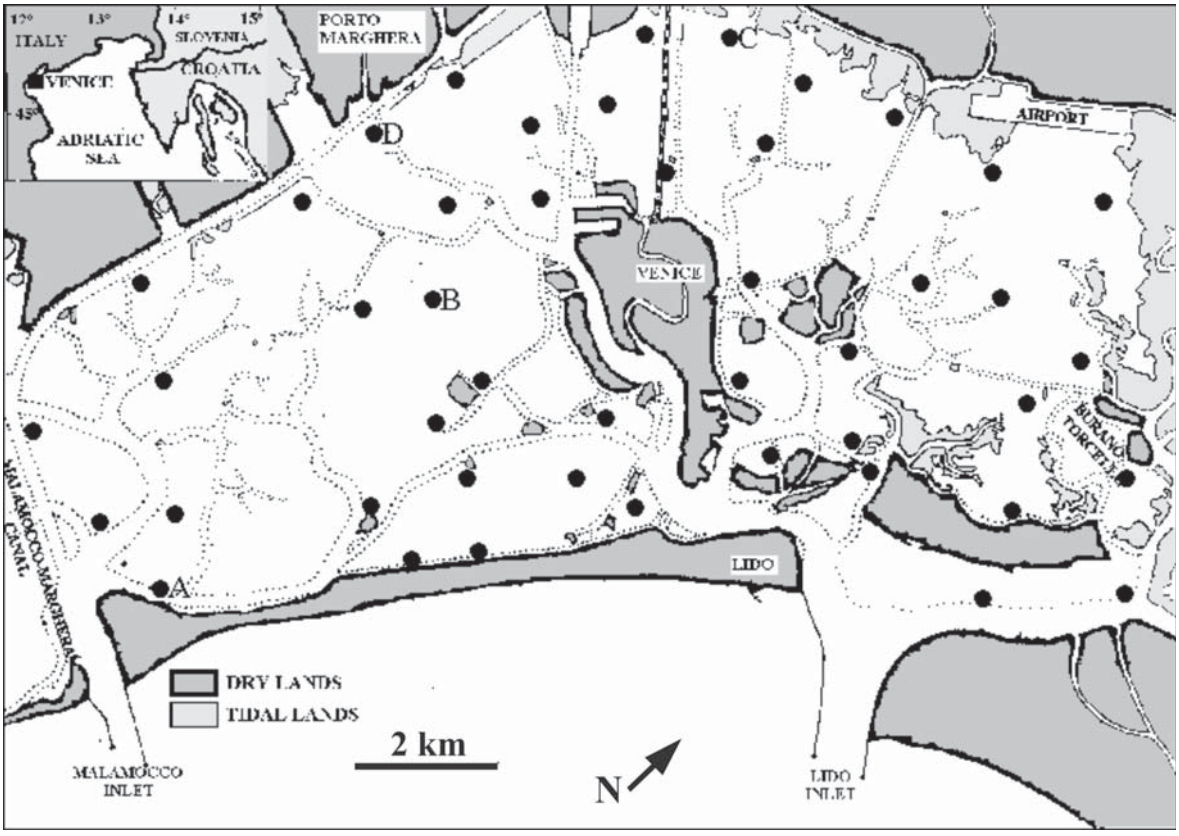

Fig. 1. Map of the central part of the Venice lagoon and sampling stations. Forty-six sites sampled in June 1993 and June 1998 are marked by circles; four sites sampled monthly from June 1998 to June 1999 are marked by letters A-D.

(temperature, chlorinity, pH, redox potential, water transparency, dissolved oxygen). In June 1998, nutrient concentrations were also determined. Four of the 46 stations were monitored monthly from November 1998 to October 1999 to assess phytoplankton peaks and composition during an entire year.

Physico-chemical parameters

Water temperature (to a precision of 0.1°C), pH, and redox potential were measured with a portable pH-meter equipped with a thermocouple sound (model HD 8705, Delta Ohm, Padua, Italy). Water transparency was measured with a SECCHI disk; values are reported as percentages with 100% indicating that the bottom was visible and 50% that the disk was not visible half-way to the bottom. Chlorinity was determined argentometrically by silver nitrate titration according to the modified KNUDSEN method (OXNER, 1962). Dissolved oxygen was measured with an Oximeter (OXI 196, Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany) equipped with a battery stirrer (BR 190). Data were transformed into saturation percentages depending on water temperature and chlorinity.

In June 1998, water column aliquots, after filtration through GF/F WHATMAN glass fiber filters (0.7 µm), were immediately analyzed on board for orthophosphate (RP), ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) according to STRICKLAND & PARSONS (1972). The sum of the nitrogen compounds is expressed as dissolved inorganic nitrogen (DIN). Nutrient concentrations were spectrophotometrically determined in the laboratory on the same day.

Phytoplankton

Phytoplankton was monitored as chlorophyll *a* concentration, cell abundance, and bio-volume. Six to ten samples of the entire water column were collected with a homemade plexiglas bottle (height 150 cm, diameter 4 cm), and mixed together in a tank. Water aliquots, ranging from 100 to 1000 ml, were filtered in situ through GF/F WHATMAN glass fiber filters (0.7 µm). Filters were stored at -20°C until pigment determination according to the spectrophotometric procedure (LORENZEN, 1967).

Unfiltered water aliquots were preserved with 4% formaldehyde neutralized with hexamethylenetetramine. Cell count and taxonomic identification were performed under an inverted light microscope provided with phase contrast optics and a 40x objective (Axiovert 10 ZEISS, Oberkochen, Germany), using settling chambers according to the method of UTHERMÖL (1958). A minimum of 200 cells was counted in each sample. Taxonomic identification was carried out using the taxonomic keys reported by PERAGALLO & PERAGALLO (1897-1908), ROUND et al. (1990), and TOMAS (1993, 1996). The nomenclature was updated using VAN LANDINGHAM (1967-1979). Cell size was measured under the microscope to determine the bio-volume according to EDLER (1979). Community diversity was estimated using the SHANNON Index (log_2). The formulation of SHANNON & WEAVER (1948) was applied to the taxa identified at least to the genus level. Groups identified to the class level could have contained several different species, whose individual contributions could not be clearly isolated. Maps were drawn using the Surface Mapping System program (Surfer Version 7.02. 1993-2000. Surface Mapping System. Golden Software Inc., Golden, Colorado).

Macrophyte biomass

Macrophyte biomass, if present, was estimated according to the procedures of SFRISO et al. (1991) for macroalgae and of SFRISO & GHETTI (1998) for sea grasses. Six sub-samples of 0.5 and 0.05 m² for macroalgae and sea grasses, respectively, were collected using special sampling frames to allow determination of the biomass to an accuracy >95%.

Statistical analyses

A numeric matrix per year was built with all available data. Biological variables were $log_{10}(x+1)$ transformed. Application of the PEARSON correlation matrices provided evidence of the most significant environmental variables that determined the spatial distribution of phytoplankton. Significant correlations occurred per $r>\pm0.30$ when $p<0.05$. Principal Component Analysis (PCA) was used to describe the ecosystem variance. Significant loadings ($r>\pm0.70$, $p<0.05$) are reported. Canonical Correspondence Analysis (CCA) allowed correlation between variation in the phytoplankton species and environmental variables. Taxa with an abundance of at least 4% per sample were used. The software CANOCO v4 (TER BRAAK & SMILAUER, 1998) was used to process data.

RESULTS

Environmental variables

Environmental parameters for June 1993 and June 1998 are given in Tables 1 and 2. In June 1993 most of the stations had good water transparency. The bottom was not visible in a restricted area near the airport. In June 1998 conditions were markedly different and water turbidity was significantly higher in the area south of Venice. The number of stations with clear water decreased progressively, confirming a trend already observed (SFRISO, 2000; FACCA *et al.*, 2002a; SFRISO *et al.*, 2003; SFRISO *et al.*, submitted to Environ. Int.). Nitrogen and phosphorus were highest along the lagoon boundaries, especially near the industrial district of Porto Marghera and the airport where the fresh waters of the Dese and Siloncello Rivers inflow.

In June 1993 the macroalgae biomass was about five times higher than in June 1998. However, attention should be focused on the spatial distribution of the biomass rather than on the total standing crop. In 1993, only 17 of the 46 stations were free of biomass whereas in 1998, except for the station near Lido Island, macroalgae were absent in the entire study area. The reason for the disappearance of the macroalgae has been widely investigated (SFRISO, 1996, 2000; SFRISO and MARCOMINI, 1996; SFRISO *et al.*, 2003).

Table 1. Environmental parameters measured in June 1993

	Temperat.	SECCHI Disk	Chlorinity	Dissolved Oxygen	pH	Eh	Macrophyte Biomass	Chlorophyll *a*
	°C	%	g dm^{-3}	% saturation		mV	kg m^{-2} fwt	µg dm^{-3}
Mean	25,8	89,5	17,2	134	8,48	366	0,65	4,33
Std Dev	1,71	13,6	1,13	30,2	0,15	20,6	2,18	5,81
Max	29,6	100	19,3	226	8,90	411	12,50	32,0
Min	22,7	40,0	13,7	76,0	8,21	323	0,00	0,43
Significant Pearson correlation with phytoplankton								
Abundance	-	-0,64	-0,80	0,47	0,55	0,36	-	0,79
Diversity	-	-	-	-	-	-	-	-
Results of Principal Component Analysis								
Component 1	-	-0,76	-0,88	-	0,70	-	-	0,91
Component 2	0,74	-	-	-	-	-	0,76	-
Component 3	-	-	-	-	-	0,72	-	-

Table 2. Environmental parameters measured in June 1998

	Temp.	Secchi Disk	Chlorinity	Dissolved Oxygen	pH	Eh	Nutrient concentration					DIN /RP	Macrophyte Biomass	Chlorophyll *a*
							RP	NO_3	NO_2	NH_4	DIN			
	°C	%	g dm^{-3}	% saturation		mV	µmol dm^{-3}						kg m^{-2} fwt	µg dm^{-3}
Mean	24,6	74,5	16,3	112	8,01	296	0,45	10,7	1,01	10,1	21,9	60,4	0,12	3,55
Std Dev	2,52	23,2	1,62	23,7	0,12	27,0	0,21	7,99	0,54	5,17	10,1	43,8	0,81	4,86
Max	29,7	100	19,3	202	8,27	367	1,00	31,0	2,85	24,0	47,0	243	5,50	29,1
Min	20,7	26,0	12,3	70,0	7,65	238	0,09	1,62	0,23	1,19	5,38	9,78	0,00	0,30
Significant Pearson correlation with phytoplankton														
Abundance	-	-0,41	-0,53	0,53	-	0,31	-	-	-	-	-	-	-	0,52
Diversity	-	0.42	-	-	-	-	0,31	-	-	-	-	-	-	-
Results of Principal Component Analysis														
Comp. 1	-	-	-0,83	-	-	-	-	-	-	-	As these values are not indipendent, they were not inserted in PCA		-	0,74
Comp. 2	-	-	-	-0,79	-	-	-	0,73	0,82	-			-	-
Comp. 3	-	-	-	-	-	-	-	-	-	-			-	-

Phytoplankton: taxa

Fifty-one taxa were identified in June 1993 and 54 in June 1998 (Table 3). There were 29 Bacillariophyceae in June 1993 and 40 in June 1998. Dinophyceae decreased from 11 taxa in June 1993 to seven in June 1998. The remaining phytoplankton community consisted of micro- and nanoflagellates.

Table 3a. Bacillariophyceae. *Maximum cell abundance values are reported (x 10^5 cells dm^{-3})*

Taxa	1993	1998	1998-99	Taxa	1993	1998	1998-99
Amphipleura micans Cleve			0,07	*Navicula anglica* Ralfs			0,11
Amphipleura rutilans Cleve			0,05	*Navicula arenaria* Donkin			0,11
Amphiprora alata Kützing	0,05			*Navicula arenicola* Grunow		0,21	
Amphiprora paludosa Smith	0,22			*Navicula cancellata* var. *retusa* Cleve			0,04
Amphiprora sp.			0,11	*Navicula cincta* Ralfs		0,05	0,11
Amphora cymbelloides Grunow			0,06	*Navicula cincta* var. *heuflrei* Grunow			0,16
Amphora exigua Gregory	0,05		0,22	*Navicula complanata* Grunow	0,22		
Amphora fluminensis Grunow			0,11	*Navicula crucifera* Grunow			0,02
Amphora laevis Gregory			0,42	*Navicula cryptocephala* Kützing	0,83	2,23	13,2
Amphora lineolata Ehrenberg		0,05		*Navicula cryptocephala* var. *veneta* Rabenhorst	11,5		
Amphora proteus Gregory			0,11	*Navicula forcipata* Greville			0,02
Amphora pusio Cleve			0,04	*Navicula inflexa* Ralfs		0,11	0,21
Amphora terroris Ehrenberg		0,05	0,06	*Navicula lanceolata* Kützing		2,12	1,33
Amphora turgida Gregory			0,11	*Navicula minuscula* Grunow			0,05
Amphora veneta Kützing		0,53	0,42	*Navicula protracta* Cleve			0,04
Amphora sp.	0,08	0,11	0,44	*Navicula ramosissima* Cleve			0,11
Asterionellopsis glacialis Round			0,37	*Navicula salinarum* Grunow			0,11
Bacillaria paradoxa Gmelin			0,11	*Navicula viridula* Ehrenberg			0,09
Bacteriastrum sp.			0,11	*Navicula* sp.	1,95	2,55	11,1
Chaetoceros affinis Lauder			0,32	*Nitzschia amphibia* Grunow			0,42
Chaetoceros anastomosans Grunow			1,22	*Nitzschia angularis* Smith	0,04		
Chaetoceros laciniosus Schutt			2,76	*Nitzschia conscricta* Ralfs		0,11	0,11
Chaetoceros muelleri Lemmermann	0,05			*Nitzschia compressa* Grunow			0,11
Chaetoceros rostratus Lauder	0,17			*Nitzschia cursoria* Grunow			0,11
Chaetoceros socialis Lauder		0,11	13,1	*Nitzschia dissipata* Smith			0,11
Chaetoceros sp.			2,66	*Nitzschia dissipata* var. *media* Grunow		0,11	0,16
Cocconeis costata Gregory			0,13	*Nitzschia frustulum* Grunow			0,11
Cocconeis dirupta Gregory		0,11		*Nitzschia lanceolata* Smith		1,48	0,53
Cocconeis molesta Kützing		0,32	0,64	*Nitzschia longissima* Grunow	0,42		2,02
Cocconeis quarnerensis Schmidt	2,04			*Nitzschia microcephala* Grunow		0,21	0,64
Cocconeis scutellum Ehrenberg	1,77	1,06	0,21	*Nitzschia palea* Smith	0,10		
Cocconeis sp.			0,21	*Nitzschia recta* Hantzsch			0,04

Table 3a cont'd

Coscinodiscus sp.		0,11		*Nitzschia sigma* Smith	0,05	0,63	0,04
Cyclotella sp.	4,41		1,17	*Nitzschia sigma* var. *rigida* Grunow		0,11	0,11
Cylindrotheca closterium Reimann & Lewin	95,14	28,3	205	*Nitzschia subtilis* Grunow			0,05
Cymbella sp.	0,22			*Nitzschia tryblionella* Hantzsch	0,05		
Dactyliosolen fragilissimus Hasle	0,08			*Nitzschia* sp.	8,24	1,69	3,72
Diploneis hyalina Cleve		0,05	0,02	*Paralia sulcata* Cleve		0,11	0,02
Diploneis sp.			0,11	*Phaeodactylum tricornutum* Bohlin	11,7		
Fragilaria hyalina Grunow			0,28	*Pleurosigma australe* Grunow		0,11	
Fragilaria sp.			3,82	*Pleurosigma naviculaceum* Brébisson			0,11
Gomphonema olivaceum Kützing			0,22	*Pleurosigma pulchrum* Grunow			0,02
Gomphonema parvulum Kützing	0,08			*Pleurosigma rigidum* Smith			0,02
Grammatophora oceanica Ehrenberg			0,11	*Pleurosigma* sp.			0,09
Guinardia striata Stol. Hasle			0,37	*Podosira* sp.			0,78
Gyrosigma balticum Rabenhorst			0,11	*Proboscia alata* Sundström			0,11
Gyrosigma distortum Griffith & Henfrey			0,22	*Psammodictyon panduriforme* Mann	0,22	0,42	0,11
Gyrosigma fasciola Griffith & Henfrey	0,10		0,78	*Skeletonema costatum* Cleve		0,42	15,7
Gyrosigma spenceri Griffith & Henfrey			0,11	*Surirella fluminensis* Grunow			0,02
Hantzschia amphioxys Grunow		1,91	0,11	*Surirella ovata* Kützing		0,63	0,42
Hantzschia hyalina Grunow			0,11	*Surirella* sp.		0,11	0,11
Hemiaulus hauckii Grunow		0,05		*Synedra crystallina* Kützing			0,05
Licmophora abbreviata Agardh		0,11		*Synedra investiens* Smith			0,22
Licmophora dalmatica Grunow			0,02	*Synedra tabulata* Kützing			0,11
Licmophora debilis Grunow			0,02	*Synedra* sp.			0,21
Licmophora gracilis Grunow		0,11	0,11	*Thalassionema nitzschioides* Van Heurck		0,74	0,21
Licmophora tenuis Grunow			0,05	*Thalassiosira* sp.	2,75	73,9	68,9
Licmophora sp.		0,11	0,11	*Tropidoneis lepidoptera* Cleve			0,05
Melosira nummuloides Agardh			0,02	Centricae not identified	57,4	0,21	1,27
Melosira sp.			0,21	Pennatae not identified	32,5	2,12	1,59
Navicula ammophila Grunow		0,21	0,27				

Table 3b. Flagellate and Dinoflagellate taxa

Maximum cell abundance values are reported (x 105 cells dm-3)

Taxa	1993	1998	1998-99
CHLOROPHYCEAE			
Chlorophyceae not identified	21,2	6,69	2,97
CRYPTOPHYCEAE			
Cryptophyceae not identified	98,4	16,2	15,6
CHRYSOPHYCEAE			
Pseudokefrion sp.	0,43		
Chrysophyceae not identified		1,59	3,72
CYANOPHYCEAE			
Cyanophyceae not identified		1,27	0,11
DINOFLAGELLATE			
cfr. *Alexandrium* sp.	6,24		
Amphidinium carterae Hulburt	0,04		
Ceratium fusus Dujardin	0,08		
Gymnodinium sp.		0,05	
Gyrodinium estuariale Hulburt		1,01	
Gyrodinium sp.		0,11	
Prorocentrum balticum Loeblich	0,04		
Prorocentrum micans Ehrenberg	0,31		
Prorocentrum minimum Schiller	0,31	0,05	
Prorocentrum triestinum Schiller	0,16	0,11	
Prorocentrum sp.	0,08	0,21	
cfr. *Protoperidinium* sp.	0,04	1,06	
Protoperidinium diabolus Cleve	0,04		
Dinoflagellate tecate not identified	0,21		
EUGLENOPHYCEAE			
Eutreptiella marina da Cunha	2,38		
Eutreptiella pascheri Pascher	0,08		
Euglenophyceae not identified	0,10	0,32	0,32
FLAGELLATE			
Flagellate not identified	3,03		
NANOFLAGELLATAE			
Nanoflagellatae not identified	1496	31,2	13,4
PRASINOPHYCEAE			
Micromonas sp.	11,7		
Pseudoscourfieldia marina Manton	23,4		
Prasinophyceae not identified	0,87		
PRYMNESIOPHYCEAE			
Chrysochromulina sp.	72,5		
Prymnesiophyceae not identified		4,67	9,24

The Bacillariophyceae, centric diatoms typical of pelagic habitats such as *Chaetoceros muelleri*, *C. rostratus*, *Cyclotella* sp., and *Dactyliosolen fragilissimus*, were abundant in June 1993 before the beginning of the bivalve spread and collecting. In contrast, in June 1998 when clam fishing was intensive, there was a high number of pennate diatoms (*Amphora veneta*, *Cocconeis molesta, Navicula lanceolata*, *Nitzschia lanceolata*, *Pleurosigma australe* and *Surirella ovata*) typical to benthic communities (FACCA *et al.*, 2002b).

Nanoflagellates, small (≤5 μm) naked spherical cells that are difficult to identify under the light microscope, were often the most abundant fraction, reaching up to 58% of the total cell abundance. The abundance of diatom taxa increased from 10.5% in June 1993 to 39.7% in June 1998. Cryptophyceae accounted for a significant fraction of the phytoplankton communities in both years (21.2% in 1993 and 10.9% in 1998). Chlorophyceae, Dinophyceae, and Prymnesiophyceae did not change significantly and were 1.6 and 2.1%, 0.4 and 0.5%, and 2.5 and 4.5% of the total cell abundance during 1993 and 1998, respectively. Chrysophyceae and Euglenophyceae were steadily <1%.

The taxa most frequently recorded in the Venice lagoon (SOCAL *et al.*, 1985, 1999; FACCA *et al.*, 2002a) and observed in all the samples were *Cocconeis scutellum, Cylindrotheca closterium* and *Thalassiosira* sp. Other species belonged to genera *Navicula* and *Nitzschia*. The highest cell abundance was recorded near the mainland (Fig. 2).

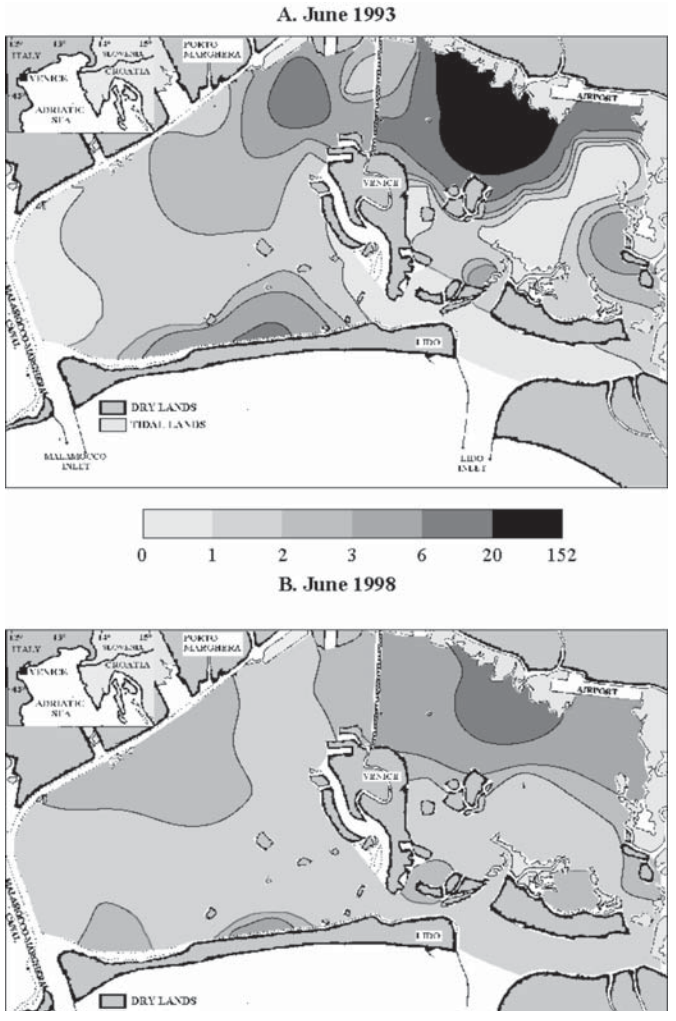

Fig. 2. Phytoplankton cell abundances in (A) June 1993 and (B) June 1998. Values are expressed as 10^6 cells dm^{-3}

In June 1993, cell abundance varied significantly from zone to zone and the highest values were recorded north of Venice where urban sewage concentrates. Significantly high cell abundances were also recorded near Lido Island and the industrial area of Porto Marghera. In June 1998, even though peak values in the central lagoon were just one order of magnitude lower than in June 1993, the phytoplankton communities appeared more homogeneously spread. About 80% of the samples were between 1 and 3 x 10^6 cells dm^{-3}.

In June 1993 the maximum cell bio-volume (9.6 mm^3 dm^{-3}) was recorded near the tidal lands of Burano and Torcello Islands, whereas in June 1998 the highest value (4.9 mm^3 dm^{-3}) was near the airport. Cryptophyceae accounted for 67% of the total cell bio-volume in the central part of the Venice lagoon in June 1993 and the highest value was near the Burano tidal lands. In June 1998 Cryptophyceae was significantly lower (less than 3% of the total cell volume) and the total cell bio-volume was dominated by the diatoms *Thalassiosira* sp. and *C. closterium*.

The SHANNON diversity index was rather low (H'<2; Table 4) in both June 1993 and June 1998 and spatial variations were slight. Nanoflagellates were the dominant taxa throughout the study area during both years, which could explain the diversity indices. *C. closterium* was observed in both periods, but in June 1998 it represented 11% of the phytoplankton community, while in June 1993 it reached only 3%.

Chlorophyll *a* distribution is described in SFRISO *et al.* (2003). Mean values were 4.3±5.8 and 3.5±4.9 µg dm^{-3} in June 1993 and June 1998, respectively. The highest chlorophyll *a* concentrations (10-33 µg dm^{-3}) were recorded northwest of Venice and the lowest near the lagoon inlets.

Phytoplankton: seasonal variations

Seasonal variations of phytoplankton were monitored monthly from November 1998 to October 1999 at stations A, B, C, and D (SFRISO, 2000; FACCA *et al.*, 2002a) in very different areas of the central lagoon. On the whole, 108 taxa were recorded. No Dinophyceae were identified, whereas 101 diatoms (Bacillariophyceae) were counted. Diatoms represented 46%, 63%, 88%, and 80% of the total phytoplankton community at stations A, B, C, and D, respectively. However, the percentage varied depending on the month and station. Diatoms were very abundant (>80%) at all the stations in February

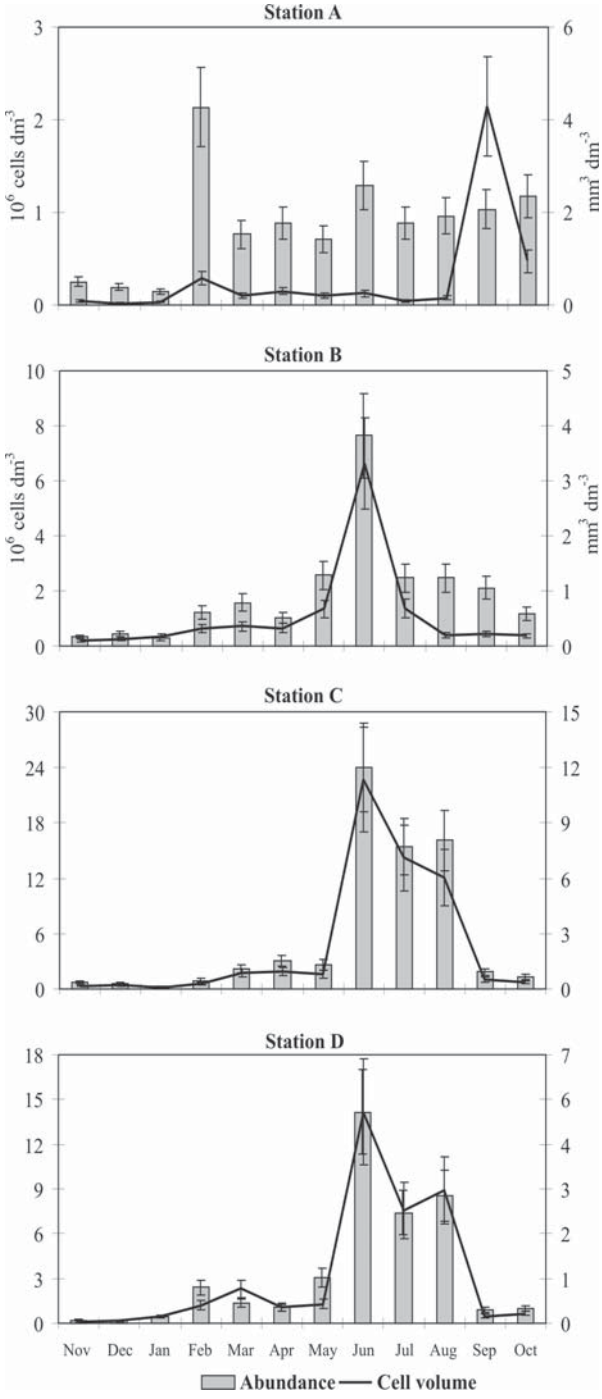

Fig. 3. Seasonal phytoplankton cell abundance and cell bio-volume from November 1998 to October 1999

because of the *Skeletonema costatum* bloom, and at stations B, C, and D in June because of the *C. closterium* bloom. Nanoflagellates and small flagellates (especially Cryptophyceae and Chlorophyceae) were abundant at station A but rare at station B in August and September. The highest cell abundance occurred at stations C and D. Peak values were observed in February at station A (especially *S. costatum*) and in June at stations B, C, and D (*C. closterium* represented 62%, 85%, and 58% of the total cell abundance, respectively). The lowest values were recorded in January at stations A, B, and C and in December at station D (Fig. 3).

The seasonal variations of cell bio-volume were the same as those of cell abundance. A significant difference was recorded only at station A, in September, when large diatoms appeared. The SHANNON diversity index varied significantly among months, although the means (3.0-3.4) and peaks (4.0-4.4) of the stations were quite similar (Table 4).

Table 4. Main phytoplankton characteristics in Venice central lagoon

	Cell abundance 10^6 cells dm^{-3}	Cell volume $mm^3\ dm^{-3}$	Diversity H'	Total cell volume m^3
		June 1993		
Mean	6,97	1,54	1,58	244
Std. Dev.	22,6	1,99	0,70	315
Max.	151,3	9,62	3,64	-
Min.	0,07	0,05	0,00	-
		June 1998		
Mean	2,55	0,54	1,62	86
Std. Dev.	2,41	0,76	0,66	120
Max.	16,1	4,91	3,03	-
Min.	0,58	0,08	0,55	-
		Station A (1998-99)		
Mean	0,87	0,60	3,21	
Std. Dev.	0,55	1,19	0,69	
Max.	2,13	4,28	4,20	
Min.	0,15	0,04	1,39	
		Station B (1998-99)		
Mean	1,94	0,56	2,93	
Std. Dev.	1,98	0,89	0,87	
Max.	7,65	3,33	4,28	
Min.	0,27	0,09	1,40	
		Station C (1998-99)		
Mean	5,75	2,40	2,91	
Std. Dev.	8,02	3,70	1,01	
Max.	24,1	11,38	4,21	
Min.	0,24	0,07	0,73	
		Station D (1998-99)		
Mean	3,39	1,17	2,76	
Std. Dev.	4,38	1,66	0,73	
Max.	14,2	5,19	3,53	
Min.	0,19	0,04	1,32	

Statistical analyses

According to the PEARSON matrices, the abundance of phytoplankton in June 1993 significantly and negatively correlated with the SECCHI disk reading (water turbidity) and chlorinity, and significantly and positively correlated with dissolved oxygen, pH, and redox potential (Table 1). Similar correlations were observed in June 1998 when nutrients were determined, but no correlations were found with phosphorous and nitrogen compounds (Table 2). In 1998, only turbidity and the reactive phosphorus concentration (RP) significantly correlated with the SHANNON diversity index.

Principal Component Analysis (PCA) shows that three components explained 63.5% (June 1993) and 65.3% (June 1998) of the total variance. In June 1993, all the variables except dissolved oxygen, showed significant loading in one of the three components (Table 1). In June 1998, chlorinity, dissolved oxygen, chlorophyll *a*, nitrate, and nitrite showed significant loading (Table 2). The loading of phytoplankton, like cell abundance and diversity, was insignificant in both 1993 and 1998.

Figs. 4 and 5 show the results of the Canonical Correspondence Analysis (CCA) as biplots: arrows represent the environmental parameters and circles the phytoplankton species. All species were well ranked along each variable gradient and it is possible to observe how each variable affected taxa distribution

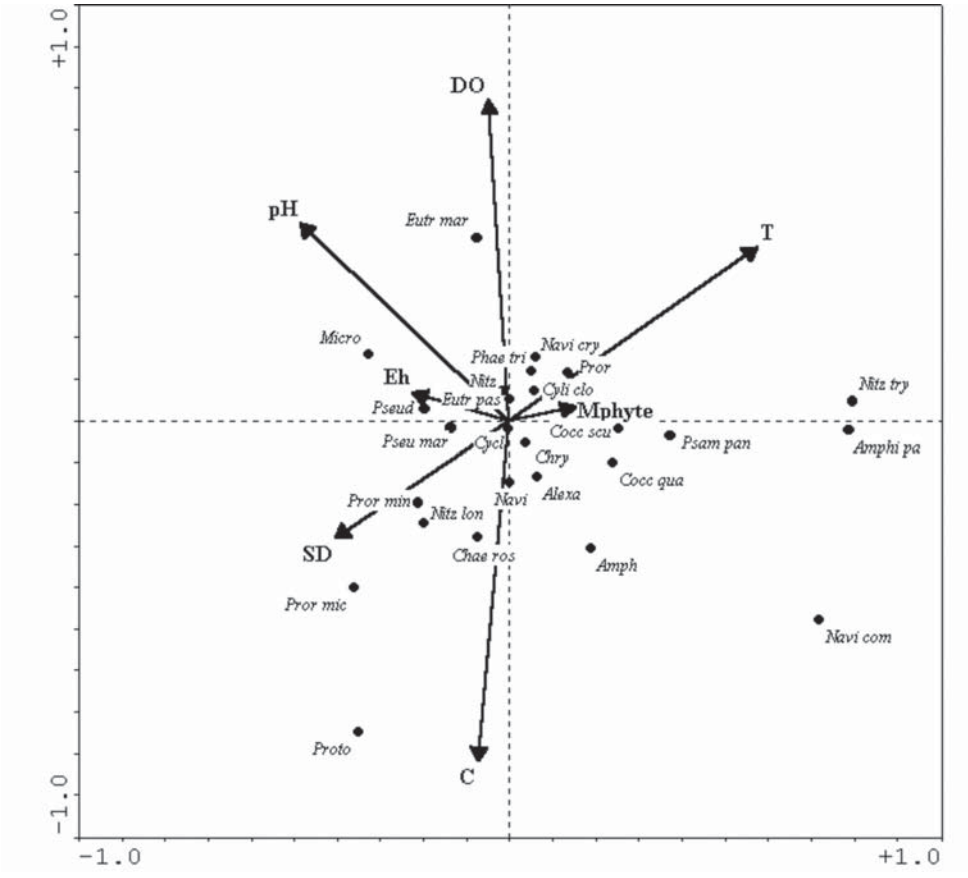

Fig. 4. Biplot of Canonical Correspondence Analysis (CCA) in June 1993. C = chlorinity, DO = dissolved oxygen (percent saturation), Eh = redox potential, Mphyte = Macrophyte biomass, SD = SECCHI disk (turbidity), T = temperature; Alexa = Alexandrium sp., Amph = Amphora sp., Amphi pa = Amphiprora paludosa, Chae ros = Chaetoceros rostratus, Chry = Chrysocromulina sp., Cocc qua = Cocconeis quarnerensis, Cocc scu = Cocconeis scutellum, Cycl = Cyclotella sp., Cyli clo = Cylindrotheca closterium, Eutr mar = Eutreptiella marina, Eutr pas = Eutriptiella pascheri, Micro = Micromonas sp., Navi = Navicula sp., Navi com = Navicula complanatae, Navi cry = Navicula cryptocephala, Nitz = Nitzschia sp., Nitz lon = Nitzschia longissima, Nitz try = Nitzschia tryblionella, Phae tri = Phaeodactylum tricornutum, Pror = Prorocentrum sp., Pror mic = Prorocentrum micans, Pror min = Prorocentrum minimum, Proto = Protoperidinium sp., Psam pan = Psammodictyon panduriforme, Pseud = Pseudokefrion sp., Pseu mar = Pseudoscourfieldia marina.

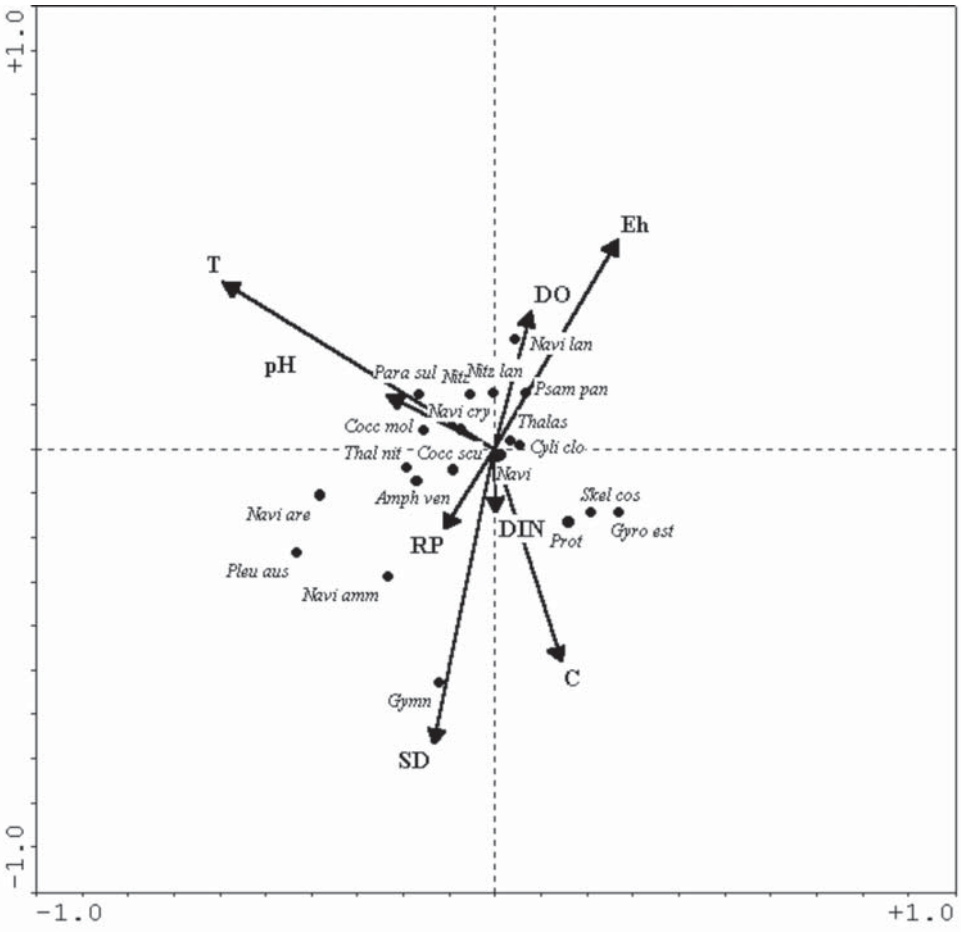

Fig. 5. Biplot of Canonical Correspondence Analysis (CCA) in June 1998. C = chlorinity, DIN = dissolved inorganic nitrogen (sum of nitrogen compounds), DO = dissolved oxygen (percent saturation), Eh = redox potential, RP = reactive phosphorus, SD = SECCHI disk (turbidity), T = temperature; Amph ven = Amphora veneta; Cocc mol = Cocconeis molesta, Cocc scu = Cocconeis scutellum, Cyli clo = Cylindrotheca closterium, Gymn = Gymnodinium sp., Gyro est = Gyrodinium estuariale, Navi = Navicula sp., Navi amm = Navicula ammophila, Navi are = Navicula arenicola, Navi cry = Navicula cryptocephala, Navi lan = Navicula lanceolata, Nitz = Nitzschia sp., Nitz lan = Nitzschia lanceolata, Para sul = Paralia sulcata, Pleu aus = Pleurosigma australe, Prot = Protoperidinium sp., Psam pan = Psammodictyon panduriforme, Skel cos = Skeletonema costatum, Thalas = Thalassiosira sp., Thal nit = Thalassionema nitzschioides.

by projecting circles on arrows. For example, in June 1993, the variation of chlorinity (C) which, together with dissolved oxygen (DO) had the highest loading (≥0.70), was strongly related to the distribution of *Protoperidinium* sp., whereas *Eutreptiella marina* seemed the most euryhaline (Fig. 4). The low variation of SECCHI disk (SD) appeared well related to the presence of Dinophyceae such as *Prorocentrum micans* and *P. minimum* while other parameters had little relation to these species. In June 1998, all the environmental parameters had loadings of ≤0.70, but the highest was SECCHI disk (Fig. 5). Nutrient variations were negligible and only temperature (T) and chlorinity had important relationships to the species distribution.

DISCUSSION AND CONCLUSIONS

The Venice lagoon has always been the subject of morphological, hydraulic, and environmental studies since the development, history, and human activity of the city are strictly connected to conditions in the lagoon. The aim of

most scientific papers has been to understand the relationship between environmental dynamics and economic interests. Therefore, much literature is available, especially on fishing resources and activities. Macroalgae have also been widely studied, as they regulated the lagoon ecosystem between the 1970s and early 1990s. As primary production in the lagoon mainly depended on macrophyte cycles, little attention was paid to phytoplankton, whose contribution was negligible except during macroalgae decomposition (MARCOMINI *et al.*, 1995). Some papers describe phytoplankton dynamics in fishponds where shrimp (ANDREOLI & TOLOMIO, 1988a) and dory fry (ANDREOLI & TOLOMIO, 1988b) were cultivated. Others deal with phytoplankton distribution in the lagoon inlets (SOCAL *et al.*, 1985, 1987; TOLOMIO *et al.*, 1999) and the wetlands north of the lagoon (Palude della Rosa; SOCAL, 1981; BARILLARI *et al.*, 1984; BIANCHI *et al.*, 2000). The present paper focuses on phytoplankton in the shallow waters (approximately 1 m deep) of the central part of the lagoon. Therefore, data cannot easily be compared with earlier reports.

A comparison between June 1993 and June 1998 data does not provide exhaustive information on changes in microalgae but confirm some changes in phytoplankton as chlorophyll *a* concentrations decrease (FACCA *et al.*, 2001, 2002a; SFRISO *et al.*, 2003). The spatial sampling campaigns furnish interesting information on community composition and species distribution more than on cell abundance. Since phytoplankton can bloom in different periods, cell abundance was examined by comparing monthly data. The results confirmed both the June blooming period and the cell abundance, which did not exceed 25 x 10^6 cells dm^{-3}.

A marked change in lagoon environmental conditions was observed in the 1990s. Macroalgae, which had regulated the lagoon biogeochemical cycles for some twenty years, had almost disappeared allowing the colonization of bivalves. This greatly influenced clam fishing, which was most intense in the late 1990s. As a consequence, the amount of re-suspended sediment increased approximately one order of magnitude and water transparency as well as phytoplankton abundance drastically decreased. In 1999, phytoplankton in the central lagoon accounted for an average 1-2% of the total suspended matter, peaking at 24% (FACCA *et al.*, 2002a). The annual Settling of Particulate Matter in sediment traps placed on the bottom at stations A, B, and C in 1998-99 was 7, 11, and 5 times higher than in 1989-90 (SFRISO *et al.*, 1992; SFRISO, 2000). During the 1990s, the sediment layer was continuously disrupted and re-suspended by hydraulic and mechanical devices used to catch bivalves, and microalgae typical of sea bottoms spread into the water column, affecting the composition of the phytoplankton communities. The reduction of light transmission in the water column seems to be the main cause for the general phytoplankton decrease, since nutrient availability did not appear to be a significant limiting factor as the CCA and PEARSON's correlation highlighted.

Sediment re-suspension not only reduced phytoplankton, it also affected species distribution. In both June 1993 and 1998, phytoplankton was more abundant near the mainland than elsewhere, but the abundance gradient was more marked in 1993 than in 1998. The homogenization of cell abundance and species distribution is related to the increased sediment re-suspension. Formerly, free-floating *Ulva* thalli hampered re-suspension induced by tides and winds. In the 1990s, reduction of macroalgae beds and the use of hydraulic and mechanical dredges to collect bivalves triggered the spread of fine sediments (particles <63 μm), nutrients, and pollutants (SFRISO, 2000; FACCA *et al.*, 2002a). Pennate diatoms, typical to bottom habitats, normally use extracellular polysaccharide to aggregate on sediment particles. The surface micro-layer of extracellular polysaccharide helps reduce re-suspension (AUSTEN *et al.*, 1999; DE BROUWER *et al.*, 2000). But in cases of particularly intense perturbation, as occurs in the Venice lagoon, destruction of the micro-layer favors re-suspension of the sediment. During June 1998, there were a high number of cells of *Amphora veneta* (an epiphytic, epilithic, or epipelic pennate diatom, ROUND *et al.*, 1990), *Cocconeis scutellum* (a pennate diatom that lives on plants, rocks, etc.;

ROUND *et al.*, 1990), and *Navicula* sp., as also described in FACCA *et al.* (2002a).

All these considerations could explain the different structure of the phytoplankton community recorded in June 1998 when numerous pennate diatoms were re-suspended in the water column and Bacillariophyceae (four times higher in 1998 than in 1993) represented the most important microalgae group (BARRANGUET, 1997; WULFF *et al*., 1997; BROTAS and PLANTE-CUNY, 1998). Nanoflagellates were the dominant taxon in both years, even though their abundance and spatial distribution differed. In June 1993 nanoflagellates were abundant near the mainland, especially near the airport, but rare or absent elsewhere. In June 1998 they were everywhere in the central lagoon, confirming the key role played by fishing activities in spreading microalgae, particularly small cells. We can conclude that, although phytoplankton distribution was regulated mainly by chlorinity and temperature in the past (Fig. 4), it is now affected mainly by water transparency (Fig. 5).

Finally, by considering the mean cell biovolume, it is possible to estimate the total phytoplankton standing crop in the central lagoon as 244±315 m^3 in June 1993 and 86±120 m^3 in June 1998. This biomass estimation could be a first step towards calculating the contribution of phytoplankton to the primary production of the lagoon, taking into account that primary production is now measured in many areas of the lagoon.

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Received: 14 January 2003
Accepted: 26 April 2004

Sastav i raspodjela fitoplanktonske zajednice u eutrofnom obalnom području (Venecijanska laguna, Italija)

Chiara FACCA, Adriano SFRISO i Pier Francesco GHETTI

Odjel za znanosti okoliša, Sveučilište u Veneciji, Calle Larga Santa Marta 2137, 30123 Venecija, Italija
E-mail: sfrisoad@unive.it

SAŽETAK

Istraživanja fitoplanktona središnjeg dijela Venecijanske lagune su izvršena devedesetih godina. Uzorci mora sakupljani su na 46 postaja u lipnju 1993. i u lipnju 1998. godine, a na 4 postaje jedanput mjesečno od studenog 1998. do listopada 1999. godine. Sakupljeni podaci uključuju sastav zajednice, numeričku abundanciju i stanične volumene, određene obrnutim svjetlosnim mikroskopom. Raspodjela abundancije stanica bila je u prosjeku 6,9 x 10^6 i 2,5 x 10^6 dm^{-3} u lipnju 1993. godine, odnosno lipnju 1998., a maksimalne vrijednosti od 151 i 16 x 10^6 dm^{-3} u lipnju 1993., odnosno lipnju 1998. Razlozi za razlike vrsta u cvatnji proučavani su u odnosu na faktore sredine ("Canonical Correspondence Analysis"). Najjači utjecaj na prostornu raspodjelu vrsta imali su slanost i temperatura mora u lipnju 1993. te slanost i prozirnost mora u lipnju 1998. S time se podudara i prostorna raspodjela fitoplanktona. Vrijeme cvatnje nastupalo je u lipnju, s najvišim vrijednostima neopsredno uz obalu.

Ključne riječi: raspodjela fitoplanktona, abundancija, biomasa, zajednica mikroalga, Venecijanska laguna