Available online at www.sciencedirect.com
SCIENCE DIRECT®
Oceanologica Acta 26 (2003) 3–13
OCEANOLOGICA ACTA International Journal of Oceanology
www.elsevier.com/locate/oceact

Original article

Role of macroalgal biomass and clam fishing on spatial and temporal changes in N and P sedimentary pools in the central part of the Venice lagoon

Rôle de la biomasse macroalgale et de la pêche de clams sur les changements spatiaux et temporels des réservoirs sédimentaires de N et de P dans la partie centrale de la lagune de Venise

Adriana Sfriso *, Chiara Facca, Sonia Ceoldo, Silvia Silvestri, Pier Francesco Ghetti

Department of Environmental Sciences, University of Venice, Calle Larga Santa Marta 2137, 30123 Venice, Italy

Received 21 July 2002; accepted 30 September 2002

Abstract

Nutrient concentrations have been investigated in the Venice lagoon for three scenarios: abnormal growth of nuisance macroalgae, decrease of macroalgal dominance and intense catching of the bivalve *Tapes philippinarum* Adams and Reeve by means of hydraulic and mechanical dredges. Total nitrogen and organic and total phosphorus monitored in June 1987, 1993 and 1998 showed significant changes both in concentrations and distribution. The disappearance of macroalgal blooms and the starting of intense clam fishing activities affected mainly organic phosphorus concentrations which, between 1987 and 1998, decreased from 104 ± 42 to 59 ± 31 µg cm^{-3}, accounting for 27% (1987) and 16% (1998) of total phosphorus, respectively. Peak values also decreased significantly: they changed from 246 to 124–146 µg cm^{-3}. Similar results were recorded both for the mean total nitrogen concentrations, which decreased from 1.21 ± 0.60 to 0.93 ± 0.48 mg cm^{-3}, and the highest total nitrogen values which collapsed from 2.98 to 1.37 mg cm^{-3}. It was also observed that spatial nutrient distribution was more homogeneous because of the high sediment re-suspension and spreading over the whole lagoon. The mean values of nutrient concentrations monitored one to three times per month per year in 1989–1990 (first scenario) and 1998–1999 (third scenario) at three stations located in the lagoon inlet (Alberoni, station A), in the central lagoon (Sacca Sessola, station B) and in proximity of the mainland (San Giuliano, station C) confirm the nutrient decrease recorded in the surface sediments of the whole central lagoon. At station B, an area characterised by a macroalgal biomass up to 20 kg m^{-2}, wet wt., in 1989, the mean total nitrogen concentration decreased from 1.43 ± 0.42 mg cm^{-3} in 1989–1990 to 0.75 ± 0.15 mg cm^{-3} in 1998–1999. Similarly, organic phosphorus decreased from 106 ± 39 to 62 ± 23 µg cm^{-3}. Station C showed similar changes, whereas at station A, recently colonised by seagrasses, the opposite results were found.

Résumé

Les teneurs en sels nutritifs ont été suivies dans la lagune de Venise durant trois scénarios : croissance anormale de macroalgues nuisibles, décroissance de la dominance de ces macroalgues et prélèvement intense du bivalve *Tapes philippinarum* Adams and Reeve par des bennes hydrauliques et mécaniques. L'azote total et l'azote organique ainsi que le phosphore total ont été suivis en juin 1987, 1993 et 1998 ; d'importants changements apparaissent tant dans les teneurs que dans la distribution. La disparition des floraisons macroalgales et le démarrage de l'exploitation intense des clams affectent principalement les concentrations en phosphore organique qui, entre 1987 et 1998, décroissent de 104 ± 42 à 59 ± 31 µg cm^{-3}, passant respectivement de 27 % (1987) à 16 % (1998) du phosphore total. Les valeurs maximales décroissent également : elles passent de 246 à 124–146 µg cm^{-3}. Des résultats similaires ont été trouvés aussi bien pour l'azote total moyen, qui décroît de 1,21 ± 0,60 à 0,93 ± 0,48 mg cm^{-3}, et les valeurs maximales d'azote total qui s'effondrent de 2,98 à 1,37 mg cm^{-3}. La distribution spatiale des sels nutritifs apparaît également plus homogène en raison de l'accentuation de la resuspension du sédiment sur toute la surface de

* Corresponding author.
E-mail address: sfrisoad@unive.it (A. Sfriso).

PII: S 0 3 9 9 - 1 7 8 4 (0 2) 0 0 0 0 8 - 7

la lagune. Les teneurs moyennes recueillies une à trois fois par mois chaque année en 1989–90 (premier scénario) et 1998–99 (troisième scénario) aux trois stations localisées à l'entrée de la lagune (Alberoni, station A), en son centre (Sacca Sessola, station B) et à proximité de la terre principale (San Giuliano, station C), confirment la diminution des sels nutritifs observée à la surface des sédiments de la partie centrale. À la station B, caractérisée par une biomasse macroalgale atteignant 20 kg m^{-2} (poids sec) en 1989, la concentration moyenne en azote total décroît de 1,43 ± 0,42 mg cm^{-3} en 1989–90 à 0,75 ± 0,15 mg cm^{-3} en 1998–99. Parallèlement, le phosphore organique s'abaisse de 106 ± 39 à 62 ± 23 µg cm^{-3}. La station C présente des changements similaires alors qu'à la station A, récemment colonisée par les herbiers, des résultats opposés sont trouvés.

Keywords: Nutrient concentrations; Surface sediments; Macroalgal biomass; Clam fishing; Venice lagoon

Mots clés : Sels nutritifs ; Sédiments superficiels ; Biomasse microalgale ; Lagune de Venise

1. Introduction

The general eutrophication increase recorded on a worldwide scale in the coastal areas during the second part of the 20th century has also been monitored along the Italian coastline and, in particular, in the shallow areas of the Northern Adriatic Sea such as the Venice lagoon. Since the 1960s this basin has suffered from high nutrient inputs, hydrological alterations and other anthropic activities, which have triggered changes both in the trophic conditions and the primary producer communities.

Nutrients concentrations in the lagoon have been monitored since 1948 and between 1948 and 1968 total nitrogen (TN) and total phosphorus (TP) increased 2.4 and 30 times, respectively (Giordani-Soika and Perin, 1974; Perin, 1975; Perin, 1983). The highest variations were recorded near the river mouths (Dese, Osellino and Taglio Novissimo of Brenta) and, on average, TP increased in 70% of lagoon bottoms (Orio and Donazzolo, 1987). Nutrient concentrations over the whole lagoon surface were also monitored by Consorzio Venezia Nuova (CNV, 1987), confirming the increased values previously recorded, although a slight decrease in the mean values was observed: TP concentrations particularly. This reduction was probably correlated to a gradual decrease of polyphosphate in detergents (from 8% in 1982, progressively, to 0% in 1989; CVN, 1989) and the closing of phospho-gypsum plants. However, an accurate comparison between the data sets is difficult due to the different sampling technologies used: sediment samples were collected by grabs or corers, but thickness varied between 5 and 20 cm, sampling sites were not located in the same positions and different analytical procedures were employed.

In 1987 the 5 cm sediment top layer of the central lagoon was monitored by Sfriso et al. (1995) during a campaign intended to record macroalgal distribution (Sfriso et al., 1989). At that time 34 sampling sites were monitored for the determination of both TN and the phosphorus compounds: total (TP), inorganic (IP) and organic (OP) fractions (Sfriso et al., 1995). The results showed mean values ranging between the data set recorded by Perin et al. (1983) and CVN (1989) for TP, whereas TN values did not show significant changes. However, peak values of both nutrients had almost halved in comparison with data from earlier studies. Later, in June 1993 and 1998, further campaigns were carried out at the same stations and in additional sampling sites in order to monitor biomass changes occurring in that period and sediment samples were also collected.

In this paper we compare nutrient concentrations monitored in the surface sediment collected during three periods affected by different environmental scenarios. In 1987 the central lagoon was covered by ca. 0.6 × 10^6 tonnes of nuisance macroalgae (mainly *Ulva rigida* C. Ag.) with peaks up to 20 kg m^{-2} fwt extending over wide areas (Sfriso et al., 1989). The production and decomposition cycles of this huge biomass affected nutrient concentrations both in the water column and in the surface sediment (Sfriso et al., 1992; Sfriso and Marcomini, 1996a). Afterwards, in the early 1990s macroalgal biomass progressively declined mainly because of climatic changes and the synergetic influence of other cofactors (i.e. increase of sediment re-suspension and grazing pressure, biomass harvesting, reduction of nutrient inputs, especially phosphorus) which contributed significantly to accelerate biomass reduction in the whole lagoon (Sfriso, 1996; Sfriso and Marcomini, 1996b). The 1993 campaign, carried out in the same period (June) and stations, collecting the same sediment layer allows a direct comparison of changes occurred with relation to the biomass decrease. In 1998 a third sampling campaign allowed the monitoring of changes occurred after the spreading of the bivalve *T. philippinarum* Adams and Reeve over the areas free of macroalgae. The rapid sediment colonisation by that bivalve, introduced in the lagoon for economical purposes (Orel et al., 2000), induced an intense harvesting activity by means of hydraulic and mechanical dredges, which disrupt infaunal and epifaunal communities (Vaccarella et al., 1994; Pranovi and Giovanardi, 1994; Pranovi et al., 1998; Sorokin et al., 1999; Facca et al., 2002), dig deep (10–30 cm) furrows, disrupt the sediment texture, enhance sediment mixing and re-suspension and spread a large amount of fine material over the whole lagoon (Fontolan et al., 1995; Orel et al., 2000; Facca et al., 2002; Sfriso, 2000; Sfriso et al., 2002).

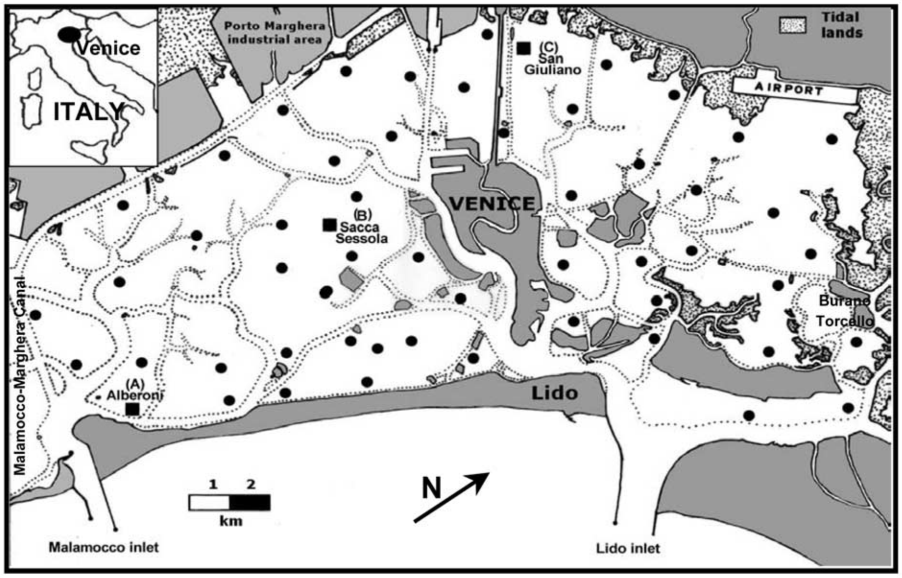

Fig. 1. Map of the central part of the Venice lagoon and sampling sites.

In order to monitor nutrient changes on a seasonal basis nutrient concentrations in surface sediment were recorded monthly over one whole year at three sampling sites (Alberoni, Sacca Sessola and San Giuliano) during the first and the third environmental scenarios characterised by the presence of significant macroalgal biomass and the impact of clam fishery, respectively.

2. Materials and methods

2.1. Sampling sites

The central lagoon extends as far as the Malamocco-Marghera canal in the south and Burano-Torcello tidal lands in the north (Fig. 1). It has a water surface of approximately 132 km^2 and a mean depth of approximately 1 m. The mean tidal amplitude is ±31 cm (Pirazzoli, 1974) but during syzygy periods the differences between flood and ebb tides range between 1.0 and 1.5 m. The basin receives effluents from the industrial area of Porto Marghera, the drainage waters from an intensely cultivated region and sewage from the main urban areas such as the city of Mestre, the hinterland and the Lido and Burano-Murano island complex. The central lagoon is also characterised by the presence of Venice historical centre where there are no sewage treating plants. In this basin ca. 180 sampling sites have been investigated to monitor macroalgal and phytoplankton changes (Sfriso et al., 1989). In 34 out of the 180 sampling sites, surface sediments were also collected. Sampling sites were chosen in shallow areas outside the lagoon canals taking into account the lagoon morphology and the presence/absence of macroalgal and phytoplankton biomass. The number of the investigated stations was increased up to 55 during the 1993 and 1998 campaigns.

Among these stations three sampling sites were selected. In the past two of them were covered with high macroalgal biomasses. The first one, Alberoni (station A), which is situated in proximity of the Malamocco inlet, is characterised by a high water exchange and a macroalgal biomass lower than 3–4 kg m^{-2} fwt. Nutrient concentrations, both in the water column and the surface sediment, are quite low. The second one, Sacca Sessola (station B), is located in the centre of the basin in the Lido watershed. This area in 1987 showed macroalgal peaks up to 20 kg m^{-2} fwt. In 1993 the biomass halved, whereas in 1998 it almost disappeared (Sfriso, 2000). Nutrient concentrations both in the water column and surface sediments were strongly affected by macrophyte growth and decomposition (Sfriso, 1987; Sfriso et al., 1992; Sfriso and Marcomini, 1996b). The third station, San Giuliano (station C) is located next to the mainland in an area affected both by macroalgal-phytoplankton blooms and the Osellino river, which drains the sewage coming from the city of Mestre and the hinterland.

2.2. Sediment samplings and analyses

Five to six sediment samples were collected at each station by means of a plexiglas corer (i.d. 10 cm). The upper 5 cm of all replicates were retained, homogenised and two subsamples taken: one was stored at 4 °C for density and grainsize analyses and the other was stored frozen at –20 °C till freeze-drying and nutrient determination.

Sample density (g cm^{-3} dwt) was determined by drying replicate samples at 110 °C taking into account both wet weight and sample volume. Sediment density was employed to estimate nutrient load on a volume basis. Other sediment aliquots were wet sieved at 63 µm in order to separate the fine fraction (clay and silt). Results are reported as percentage of fine material.

Total nitrogen concentration was determined on finely pulverised freeze-dried samples using a Carlo Erba CNS Autoanalyser, mod. NA 1500.

Table 1
Sediment properties and nutrient concentration in the surface sediment sampled during June campaigns and in the three stations sampled on yearly basis

	Central lagoon			Station A (Alberoni)		Station B (Sacca Sessola)		Station C (San Giuliano)	
Year	1987	1993	1998	1998–1999	1989–1999	1989–1990	1998–1999	1989–1990	1998–1999
N	34	34	34	12	12	12	12	12	12
Sediment density									
Mean	1.01	–	1.05	1.29	1.15	1.11	1.08	0.57	0.81
S.D.	0.26	–	0.21	0.02	0.03	0.03	0.07	0.03	0.05
Max	1.42	–	1.37	1.34	1.19	1.15	1.19	0.60	0.87
Min	0.47	–	0.72	1.25	1.09	1.05	0.97	0.52	0.71
Fraction < 63 µm									
Mean	71.0	–	59.2	20	42	80	78	99	89
S.D.	26.7	–	28.9	3	4	3	2	1	3
Max	98.7	–	95.8	25	50	85	81	100	92
Min	12.6	–	11.1	16	37	75	74	97	82
TN (mg cm^{-3})									
Mean	1.21	1.14	0.93	0.34	0.77	1.43	0.75	1.59	1.19
S.D.	0.60	0.48	0.48	0.11	0.12	0.42	0.15	0.13	0.13
Max	2.98	2.62	1.37	0.53	0.97	2.59	1.04	1.77	0.69
Min	0.22	0.33	0.10	0.16	0.58	1.01	0.57	1.29	0.99
TP (µg cm^{-3})									
Mean	386	361	375	519	402	445	389	357	441
S.D.	96	80	65	28	35	70	30	24	36
Max	720	511	541	565	474	657	438	409	501
Min	227	184	257	475	353	408	349	320	399
IP (µg cm^{-3})									
Mean	282	294	316	471	338	339	327	254	334
S.D.	71	72	61	31	30	35	30	19	20
Max	473	423	477	513	393	446	376	295	368
Min	146	140	218	414	293	314	273	229	308
OP (µg cm^{-3})									
Mean	104	67	59	48	64	106	62	102	107
S.D.	42	28	31	38	28	39	23	13	21
Max	246	124	146	146	107	211	104	131	144
Min	49	27	16	9	29	69	29	82	70

Inorganic phosphorus (IP) was determined by sediment sonication (ca. 0.4 g) in 1 N HCl according to the procedure by Aspila et al. (1976). The resulting solutions were analysed spectrophotometrically according to Strickland and Parsons (1972). Total phosphorus was obtained using the same procedure after 2 h sample combustion at 550 °C. The organic phosphorus (OP) fraction was calculated by difference. All measurements were replicated at least three times.

2.3. Statistical analyses and data plotting

The data sets collected during the different campaigns were tested using one-way Anova in order to detect significant changes between the different environmental scenarios.

Sediment density, sediment grain-size and nutrient concentrations in samples collected during the June campaigns were plotted in maps by using the Surfer mapping system (Golden software Inc., 1993–2000). Map arrangements, which take into account the lagoon morphology were drawn by Corel Photo-Paint 8 by considering the whole sampling sites (34 in 1987 and 55 in 1993 and 1998). The comparison between June campaigns was performed by considering the 34 sampling sites monitored in 1987, only.

3. Results

Data on grain-size distribution and sediment density determined in 1987 in the presence of abnormal macroalgal coverage and in 1998 during the intense clam fishing activities are summarised in Table 1 and plotted in Fig. 2.

The percentage of the fine sediment (fraction < 63 µm = silt + clay) shows mean values, which decrease from 71.0 ± 26.7 to 59.2 ± 128.9. Although this difference is not significant (Table 2) it shows a general decrease of the percent of fine sediment near the mainland and an increase near Malamocco inlet (Fig. 2). This result was also obtained by analysing significant changes monitored at Sts. A and C (Table 2). The percentage of fine fraction had doubled at station A, whereas at station C it had decreased to 10% (Table 1).

Grain-size variations were coupled with sediment density changes. Although mean values were similar (Table 1) sediment density ranged from 0.47 to 1.42 in 1987 and from 0.72 to 1.37 in 1998 with increasing values near the mainland due to the loss of fine material and decreasing values near the lagoon inlet due to sedimentation processes (Fig. 2). In particular, the increase of sediment density and the loss of fine material was highly significant (one-way Anova, Table 2) at

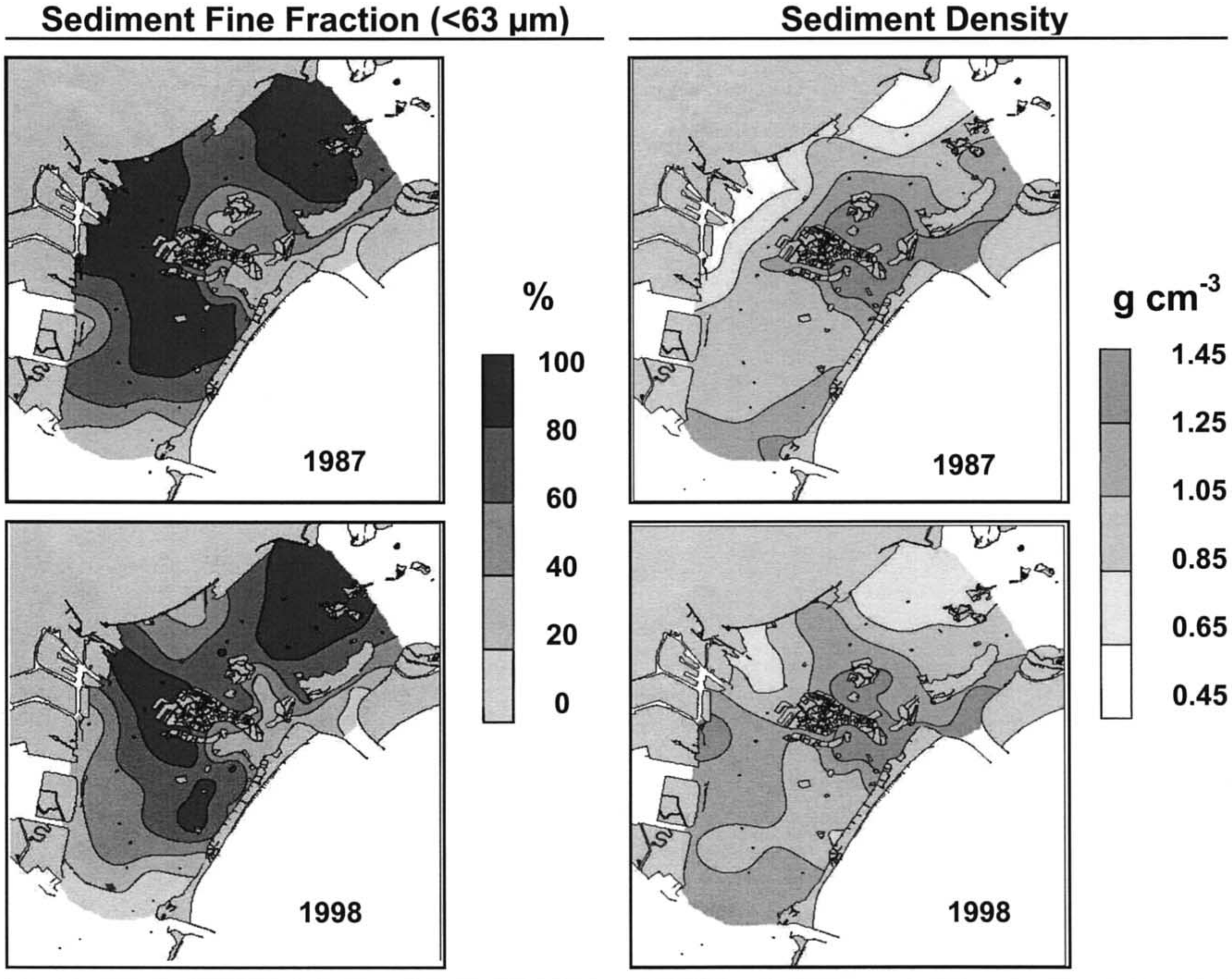

Fig. 2. Maps of the sediment density and percentage of the fine fraction (< 63 µm) recorded in June 1987 and 1998.

station C (San Giuliano) near the mainland. Vice versa at station A (Alberoni) near Malamocco inlet sediment density decreased due to the colonisation of seagrass beds (*Zostera marina* L.) which favoured the sedimentation of fine material which had been re-suspended in the innermost lagoon areas. No significant changes were recorded at station B (Sacca Sessola) placed in the Lido watershed.

Nutrient distributions in the sediment of central lagoon can be plotted on dry weight (mg or µg g^{-1}) or volume basis (mg or µg cm^{-3}). Fig. 3 shows that data on 1987 TP distribution differ depending on the way they are plotted. On a dry weight basis the trend shows that the highest concentrations occurred near the mainland and the anthropic areas such has historical centre of Venice and progressively decreased on approaching the lagoon inlets. On a volumetric basis, the results are significantly different and allow possible different data interpretations. However, since only volume processed data allow an estimation of nutrient loads in the surface sediments, all nutrient concentrations are showed according to that model.

Concentrations and distribution of TN recorded during the three scenarios in the central lagoon are presented in Table 1

Table 2
Analysis of variance (one-way Anova)

	1987–1993	1993–1998	1987–1998	Station A	Station B	Station C
Significant values $P < 0.05$						
Sediment density	–	–	n.s.	5.4E-11	n.s.	4.4E-13
Fraction < 63 µm	–	–	n.s.	5.6E-13	n.s.	9.4E-10
TN	n.s.	n.s.	0.040	6.7E-09	2.4E-05	1.2E-07
TP	n.s.	n.s.	n.s.	4.3E-12	0.04	7.9E-07
IP	n.s.	n.s.	0.036	7.0E-13	n.s.	1.6E-09
OP	4.3E-05	n.s.	4.6E-06	n.s.	0.003	n.s.

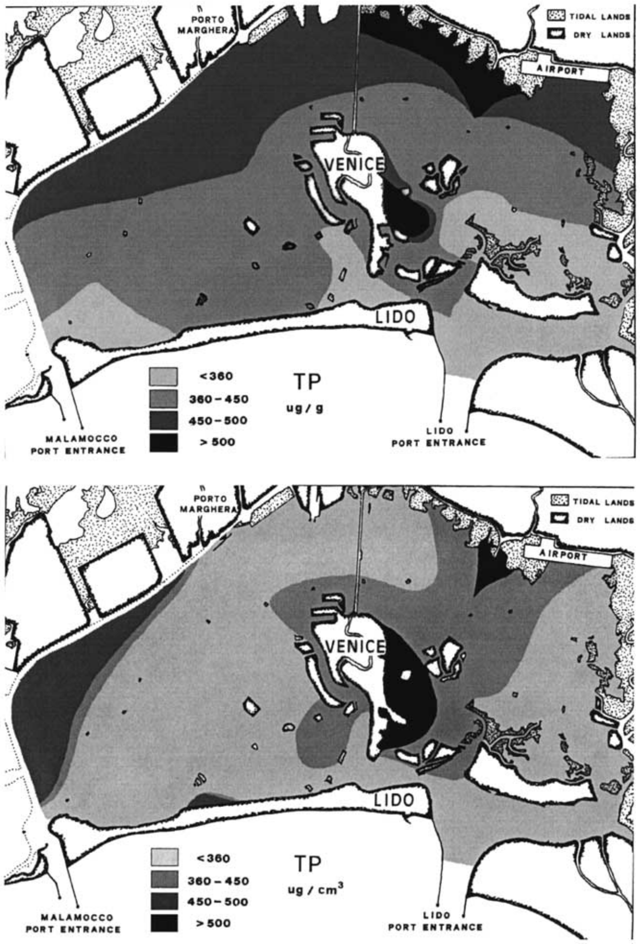

Fig. 3. Comparison of TP concentrations plotted on dry weight (µg g^{-1}) or volume (µg cm^{-3}) basis.

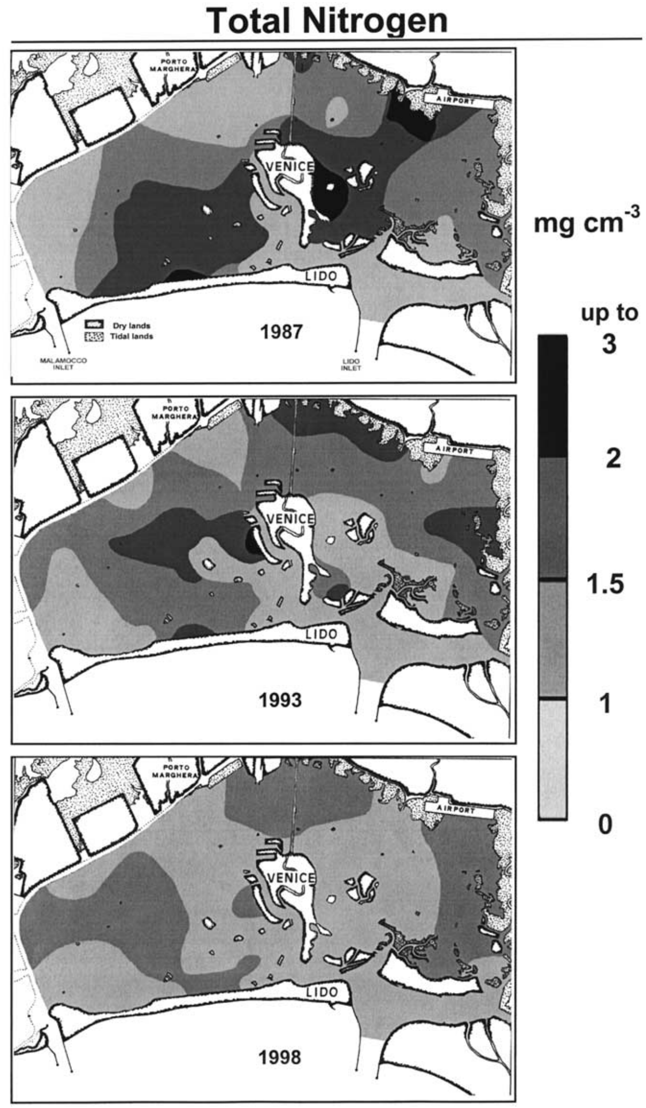

Fig. 4. Maps of TN concentrations recorded in 1987 (34 sampling sites), 1993 and 1998 (55 sampling sites).

and plotted in Fig. 4. Mean and peak values show a significant progressive decrease over the whole study period (1987–1998), although more relevant changes were recorded in the second period, between 1993 and 1998, during clam fishing activities. In June 1987 the highest concentrations (> 2 mg cm^{-3}) were recorded near the airport, in northern Venice and in proximity of Malamocco landfill area. In June 1993 these "hot spots" had disappeared and the highest concentrations were recorded south of Venice. The general TN decrease was evident in June 1998 when concentrations never exceeded 1.37 mg cm^{-3} and were substantially low in all areas of the lagoon.

By considering only the three stations monitored on a monthly basis, TN changes were highly significant (Table 1, Fig. 5). Concentrations decreased in the areas (station B and C), which were previously affected by macroalgal blooms whereas at station A, which was progressively colonised by *Z. marina* L., the concentration of TN doubled.

Data concerning phosphorus pools are displayed in Table 1 and plotted in Figs. 6 and 7. Although some stations during the three scenarios showed consistent fluctuations in all the phosphorus fractions, on average, TP exhibited quite similar concentrations, IP increased weakly and OP decreased significantly. In particular, both mean and peak OP values halved and minimum OP values in 1998 were three times lower than those in 1987 (Table 1). Changes were highly significant between 1987 and 1993, during the macroalgal biomass disappearance. During the same period the impact of clam fishing activities showed a lower effect. Map plots (Figs. 6 and 7) show a significant decrease of both TP and OP north of Venice. In that area concentrations dropped from values higher than 500 and 180 µg cm^{-3}, respectively, in 1987 to concentrations lower than 450 and 80 µg cm^{-3}, in 1993 and 1998. Surely, polyphosphate banning from detergent formulations since 1989 could have played a key role in those changes. In 1998 high TP concentrations were recorded in front of Porto Marghera where clam fishing activities and sediment erosion processes were more intense (Fig. 6). In that area the progressive loss of surface sediment (ca. 10–15 cm since 1994, Sfriso, 2000) may have exposed deep and polluted sediments enriched with phosphorus during the

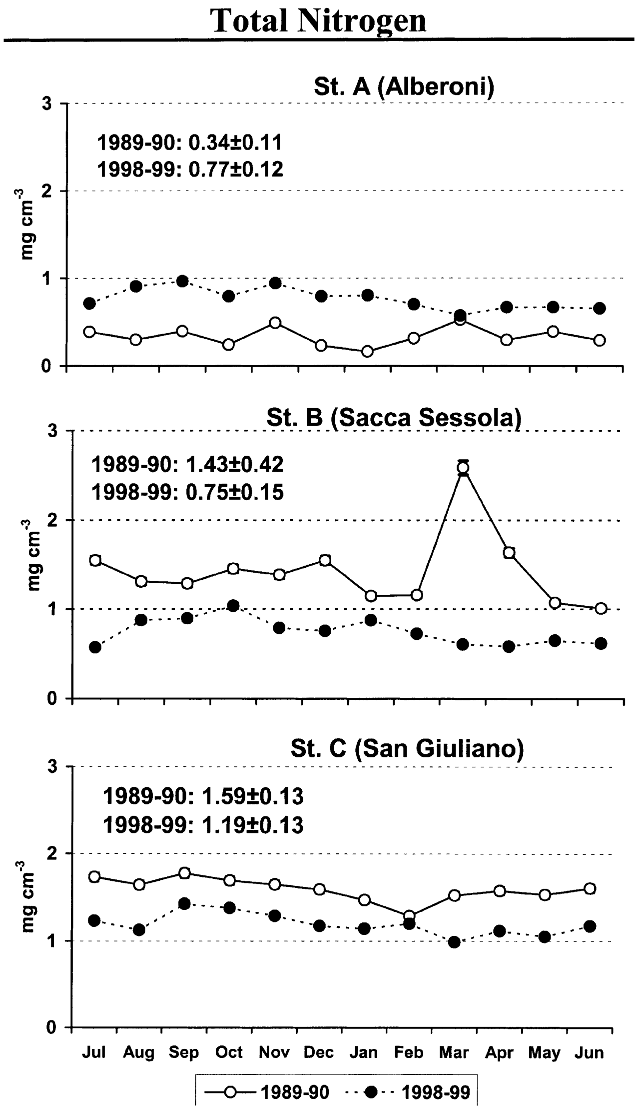

Fig. 5. Seasonal trends of TN in the three steering stations in 1989–1990 and 1998–1999. Bars represent standard deviation (S.D.) of replicated analyses.

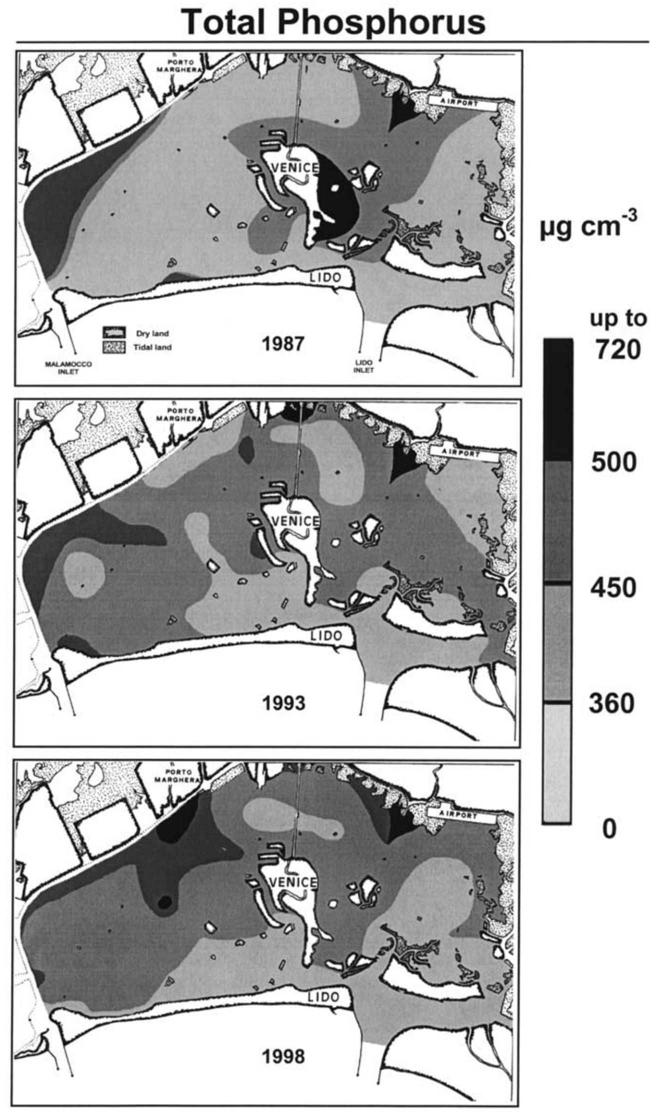

Fig. 6. Maps of TP concentrations recorded in 1987 (34 sampling sites), 1993 and 1998 (55 sampling sites).

1960s and 1970s when the activity in Porto Marghera industrial area was at its maximum. In contrast the concentrations of OP were significantly reduced and displayed values never exceeding 146 µg cm^{-3} (Fig. 7). During the three sampling campaigns high TP values were also found near Venice airport where the Osellino freshwaters, which collect treated and untreated sewage from Mestre and the hinterland, enter the lagoon.

Seasonal trends in the three selected stations sampled in 1989–1990 and 1998–1999 showed contrasting results. Total phosphorus changes were significant in all the three areas: values decreased at Sts. A and B and increased at station C. Changes were particularly high at station A progressively colonised by seagrasses which in the absence of phosphorus in the water column can take up this nutrient from surface sediment by the root-rhizome system, and at station C where sediment erosion was estimated to be ca. 1.5 cm per year (Sfriso, 2000). Organic phosphorus changes were significant only at station B, which in the past was covered by huge macroalgal biomasses. In that area, but also at station C, the most evident change, as observed for TN, was the disappearance of spring peaks with annual trends substantially flattened (Fig. 8). However the difference between the minimum concentrations was not so evident as it was for maximum values, which at station B decreased from 657 (1989–1990) to 438 (1989–1990) µg cm^{-3}. Nevertheless the highest concentrations were always recorded in spring (March-April) whereas the lowest ones occurred between autumn and winter.

4. Discussion

After World War II, the Venice lagoon was affected by a fast development which increased industrial activities, agricultural practices and the tourist vocation of the city. The industrial area of Porto Marghera, which dates back to

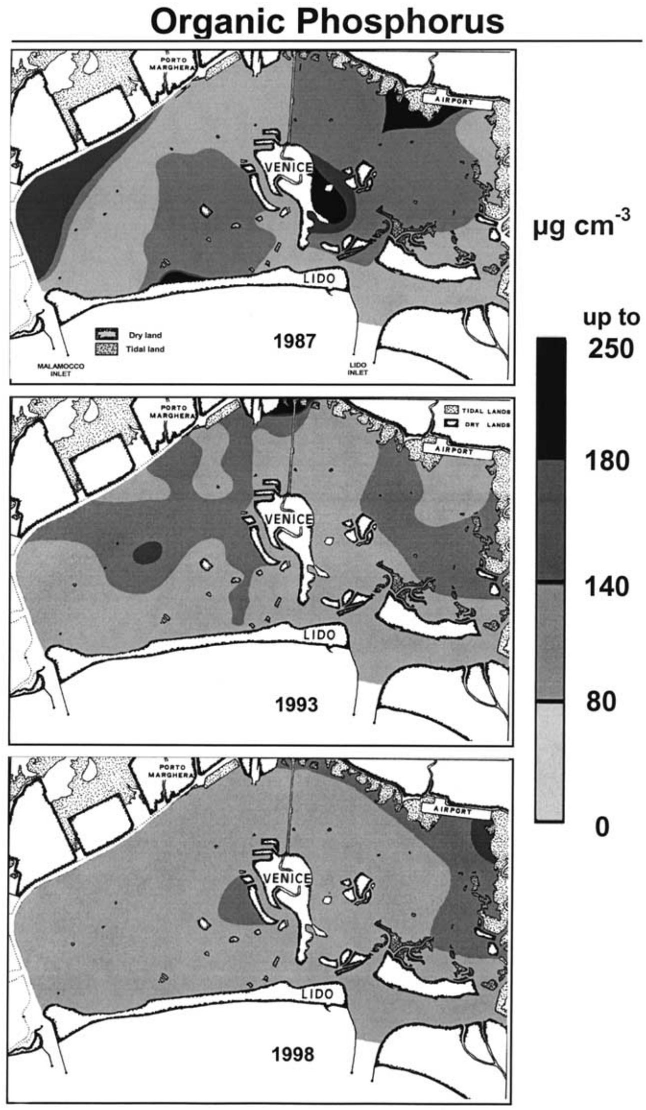

Fig. 7. Maps of OP concentrations recorded in 1987 (34 sampling sites), 1993 and 1998 (55 sampling sites).

1920s–1930s, was characterised by a fast expansion which reached the highest development during the 1960s when approximately 30 000 workers were employed. The main activities were related to petroleum and its derivates, oil refining, coal distillation and the production of sulphuric acid, phosphate and ammonium fertilisers, pesticides and many chemical products. In the same area mechanical and ship building production developed favouring the digging of large and deep canals for ship transit from the lagoon inlets towards the mainland. In the hinterland intensive monocultural productions replaced the traditional agricultural activities. Large amounts of fertilisers and pesticides were used and massively conveyed into the lagoon through a draining basin approximately 1839 km^2 (Appi et al., 1989; Bendoricchio et al., 1985; Vazzoler et al., 1987; CVN, 1989; Andreottola et al., 1990). The development of tourism, especially in Venice historical centre, increased significantly the direct discharge of untreated wastewater into the lagoon since the city was not provided with a sewage system (APTV, 1987; Pavoni et al., 1990). As a consequence the lagoon received huge amounts of pollutants, nutrient included (Cossu et al., 1984; Cossu et al., 1985; Bernardi et al., 1986; Orio and Donazzolo, 1987; Pavoni et al., 1990; Vazzoler et al., 1987) and its hydrodynamic changed markedly (Rabagliati, 1987). Macroalgal blooms rapidly replaced seagrasses and hypertrophic-dystrophic conditions were favoured.

During the late 1980s the total direct (domestic, agricultural, industrial) and indirect (rivers and canals) nutrient loads in the lagoon had been estimated to be approximately 8437 tonnes per year TN and 1148 tonnes per year TP (Andreottola, 1990). Out of them approximately 4262 tonnes per year TN and 652 tonnes per year TP (Table 3) were washed into the lagoon through approximately 24 rivers and canals (Bernardi et al., 1986). Recently, in the framework of Drain Project (CNR, 2001), indirect nutrient inputs from freshwaters have been estimated. Nutrient sources were 4005 tonnes per year TN and 230 tonnes per year TP. Unfortunately no updated data on direct loads are available. However, atmospheric deposition contributed 870 tonnes per year TN and 66 tonnes per year TP to the total loads reported by Andreottola (1990). The updating of atmospheric deposition was approximately 1250 tonnes per year TN and 60 tonnes per year TP (CNR, 2001). By the comparison of these data we infer that, during the considered period, TN inputs in the lagoon remained almost unchanged whereas the amounts of TP entering the lagoon, at present, are approximately 40% of the total estimated in the 1980s. Therefore, the observed TN decrease in surface sediments did not depend on changes in the lagoon inputs but, presumably, on the disappearance of the macroalgal biomass which took up nitrogen from the water column storing it temporarily in the surface sediments during decomposition (Sfriso et al., 1992). Most of TN trapped by the macroalgal standing crop and temporarily stored in the surface sediment during the macroalgal blooms (ca. 2.4 times the TN annually entering the central lagoon) or lost in the atmosphere as N_2 and N_2O during denitrifying processes (ca. 4.3 times the TN annually entering the central lagoon) came from tidal exchanges (Sfriso et al., 1994; Sfriso and Marcomini, 1996b). Conversely, whereas TP, on average, did not change significantly in the sediment of the central lagoon, OP showed a marked decrease, especially in the period of the macroalgal biomass disappearance (1987–1993). As for clam fishing activities their effect appears to have been negligible.

By considering the stations separately OP, IP, TP and TN, showed significant changes during the whole study period. Such changes depended on the composition of the biomass (Ulvaceae, other species, seagrasses), the amount of biomass blooms involved and the different impact of clam fishing activities and nutrient sources. Particularly, changes in nutrient concentrations of the three stations studied monthly in 1989–1990 and 1998–1999 show some of those differences. In fact, OP and TN decreased significantly in the area (station B: Sacca Sessola) in the past affected by abnormal macroal-

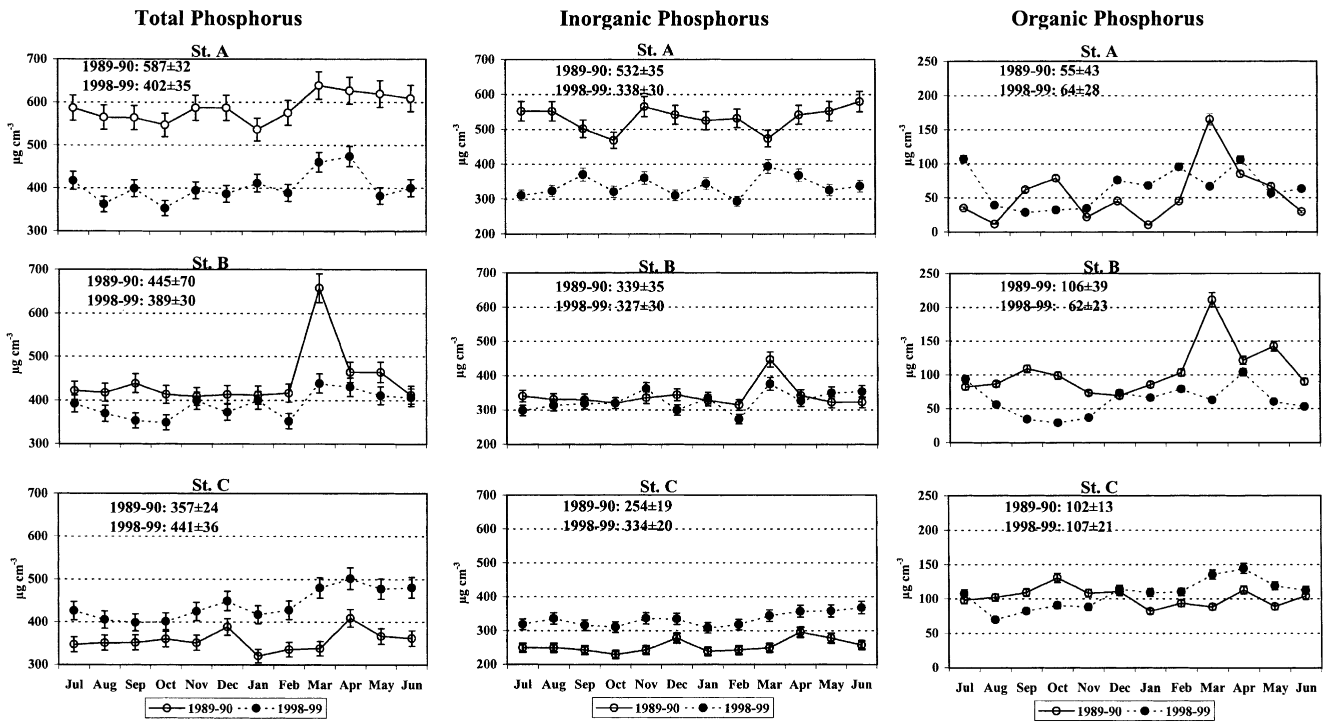

Fig. 8. Seasonal trends of phosphorus compounds in the three stations in 1989–1990 and 1998–1999. Bars represent S.D. of replicated analyses.

gal blooms, whereas they increased remarkably at station A (Alberoni) which has been progressively colonised by *Z. marina* L. However, at station A IP decreased significantly, as in most of the central lagoon. Whereas in that area a direct IP uptake by the root-rhizome system of *Zostera* can not be excluded (Sfriso and Marcomini, 1999), in other stations the IP increase, observed during the three scenarios, seems to depend mainly on both OP mineralisation and the re-suspension and settlement of deep sediment. The settled particulate matter collected with traps placed on the bottoms showed phosphorus concentrations approximately 50% higher than those in surface sediments, most of which was IP (Sfriso, 2000).

The changes of nutrient concentrations recorded in the surface sediment of the central part of Venice lagoon in the second part of the 20th century are summarised in Table 4. Although the only data directly comparable with those quoted in this paper (1993 and 1998 June maps) are the values referred to 1987 June map reported by Sfriso et al. (1995), nutrient mean and range values can supply interesting information on concentration trends. On average, TP increased from 24 ± 16 µg g^{-1} in 1948–1949 (Giordani-Soika and Perin, 1974) to 454 ± 126 µg g^{-1} in 1983 (Perin et al., 1983). Then, the mean TP concentrations started to decrease slightly without showing significant changes. However peak values up to 1102 µg g^{-1}, were never found after 1987–1988. Conversely, TN showed lower changes. It increased from 1.00 ± 086 mg g^{-1} in 1948–1949 (Giordani-Soika and Perin, 1974) up to 1.33 ± 0.89 mg g^{-1} in 1987–1988 (CVN, 1989) and dropped to 1.02 ± 0.66 mg g^{-1} in 1998. This value is about the same monitored before the expansion of Porto Marghera industrial area.

The differences account for the different bio-geo-chemical cycles of those nutrients. Phosphorus, which is characterised by a sedimentary cycle, after it enriched, remained stored in the sediment acting as an indelible environmental marker of the trophic changes occurring in the environment. Conversely, nitrogen whose pool is in the atmosphere, after a significant increase went back to the values monitored before eutrophication developed.

Table 3
Nutrient inputs in the lagoon

	Andreattola (1990) (tonnes per year)		Drain (2001) (tonnes per year)	
	TN	TP	TN	TP
Indirect loads (rivers and canals)	4262	657	4005	230
Direct loads (domestic, agricultural, industrial, atmospheric sources)	4175	491	–	–
Atmospheric loads	870	66	1250	60
Total loads (indirect + direct)	8437	1148	–	–
Indirect + atmospheric loads	5132	723	5255	290

Table 4
Time changes of nutrient concentrations in surface sediments of the central part of the Venice lagoon

	Years	Sediment thickness (cm)	TP (µg g^{-1})			TN (mg g^{-1})		
			Range	Mean	S.D.	Range	Mean	S.D.
Giordani-Soika and Perin (1974)	1948–1949	30	10–50	24	16	0.73–1.96	1.00	0.86
	1968–1973	30	50–250	164	79	1.06–3.56	1.86	2.20
Perin et al. (1983)	1983	20	327–682	454	126	0.90–2.74	1.33	0.59
CVN (1989)	1987–1988	20	36–1102	339	215	0.26–4.80	1.33	0.89
Sfriso et al. (1995)	1987	5	240–577	397	82	0.16–2.72	1.25	0.60
This work	1993	5	236–597	372	86	0.25–2.85	1.26	0.71
	1998	5	221–560	370	79	0.07–2.50	1.02	0.66

5. Conclusions

The Venice lagoon in the past 15 years has affected marked changes. The main causes were both the disappearance of *Ulva* blooms and the establishment of intense clam fishing activities due to the introduction and spread of *T. philippinarum* which has colonised the areas free of macrophytes. The biomass reduction (ca. 97–98% of the biomass monitored in 1987, Sfriso et al., 2002) and the re-suspension and spread of large amounts of fine sediment (ca. one order of magnitude higher than in 1989–1990, Sfriso, 2000) have caused changes in the sediment grain-size composition and density. At present sediment appears more homogenised due to the loss of fine material in the areas close to the mainland and deposition in areas near to the lagoon inlets. Nutrient concentrations in surface sediments have also changed. On average, TN decreased significantly in the whole central lagoon showing the concentrations monitored before expansion of Porto Marghera Industrial area, even though nitrogen inputs in the lagoon have not changed. Total phosphorus changes were not significant whereas OP, on average, halved its concentrations in areas free of seagrasses, especially between 1987 and 1993 when the macroalgal biomass disappeared, although the banning of polyphosphates in the commercial detergent formulations (1978) could have contributed as a key cofactor. Hot spots, monitored in 1987 in the presence of abnormal macroalgal coverage, disappeared as peak values during annual trends. At present the clam fishing impact on the surface sediment is dramatic and only the proper management of that activity could change the situation. In the last 3–4 years approximately 500 ha of lagoon surface have been licensed to fisherman's cooperatives in order to promote a change from uncontrolled clam fishing over the whole lagoon to clam farming in particular areas. Additional 2500 ha have been allocated and will be licensed within the year. As a result sediment re-suspension is expected to reduce and new environmental changes, especially in the benthic communities, to be detected in the lagoon during the next few years.

Acknowledgements

Part of the environmental data used in this work were collected in the framework of the project "Cofin 1999: Production, change and vulnerability of Adriatic transitional aquatic environments" co-financed by the Ministry of University and Scientific and Technological Research and coordinated by Professor Ireneo Ferrari from the Parma University. Other data were collected in the framework of the project "New Interventions for Venice safety", sub-project D: "Eutrofication and pollution of waters and sediments in the central part of the Venice lagoon", which was funded by the Italian Ministry of Works and carried out in collaboration with Magistrato alle Acque (Venice Water Authorities) and its concessionary agent: Consorzio Venezia Nuova. The authors are grateful to the referees for their useful comments and suggestions and to Dr. Orietta Zucchetta for reviewing the English text.

References

Andreottola, G., Cossu, R., Ragazzi, M., 1990. Nutrient loads from the Venice lagoon catchment area: comparison between direct and indirect assessment methods (in Italian). Ingegneria Sanitaria 19, 176–185.

Aspila, K.I., Agemian, H., Chau, A.S.J., 1976. A semi-automated method for the determination of inorganic, organic and total phosphate in sediments. Analyst. 101, 187–197.

Appi, A., Basili, M., Bendoricchio, G., Berbenni, P., Bortolussi, R., Fontanile, A., Franco, M., Marchesi, R., Perruccio, L., Prokopowicz, J., 1989. Agriculture Run-off Pollution in the Venice Lagoon (in Italian). In: Consorzio Venezia Nuova (Ed.). Soc.Coop. Tipogr., Padova.

APTV – Azienda di Promozione Turistica di Venezia, 1987. Statistics Office, Touristic fluxes in the Venice Municipality in 1986 (in Italian).

Bendoricchio, G., Agostinello, L., Alessandrini, S., 1985. Nutrients of non-point sources from the catchments of the rivers inflowing into the lagoon (in Italian). Acqua Aria 2, 177–183.

Bernardi, S., Cecchi, R., Costa, F., Ghermardi, G., Vazzoler, S., 1986. Fresh water and pollutant transfer in the lagoon of Venice (in Italian). Inquinamento 28, 46–64.

CNR, 2001. Determination of the pollutant load discharged into the Venice lagoon by the drainage basin. Drain Project Workshop. Arti Grafiche Venete, Venice 111 pp.

Cossu, R., De Fraja Frangipane, E., Donazzolo, R., Orio, A.A., 1984. An outline to balance nutrients in the Venice lagoon (in Italian). Ingegneria Ambientale 13, 80–90.

Cossu, A., De Fraja Frangipane, E., 1985. Pollution in the Venice lagoon: State of art. Italian Ministry of Works, Venice Water Authority, Consorzio Venezia Nuova. Venice Project., vol. 4. Consorzio Venezia Nuova, Venice.

CVN-Consorzio Venezia Nuova, 1989. The agricultural pollution in the Venice Lagoon (in Italian). In: Consorzio Venezia Nuova (Ed.). Società Cooperativa Tipografica, Padova, pp. 144.

Facca, C., Sfriso, A., Socal, G., 2002. Temporal and spatial distribution of diatoms in the surface sediment of the central part of the Venice Lagoon. Bot. Mar. 45 (2), 170–183.

Fontolan, G., Orel, G., Pessa, G., Zentilin, A., 1995. Environmental changes caused by clam farming on the sediment texture and macrofaunal communities in the Marano lagoon. In: Berletti, M., Rossi, R., Spreafico, E. (Eds.), Ricerche e sperimentazioni 1988-1994.

Giordani-Soika, A., Perin, G., 1974. The pollution of the Venice lagoon: study of chemical and macrofaunal changes in the lagoon sediments in the last 20 years (in Italian). Boll. Mus. Civ. St. Nat. Venezia 26 (1), 25–68.

Orel, G., Boatto, V., Sfriso, A., Pellizzato, M., 2000. Management project for the alieutic sources of the lagoons in the Venice Province (in Italian). Sannioprint, Benevento, pp. 102.

Orio, A.A., Donazzolo, R., 1987. Toxic and eutrophicating substances in the lagoon and the gulf of Venice (in Italian). Atti Ist. Ven. Lett. Sci. Arti. 11, 149–215.

Pavoni, B., Donazzolo, R., Sfriso, A., Orio, A.A., 1990. The influence of waste waters from the city of Venice and the hinterland on the eutrophication of the lagoon. Sci. Total Environ. 96, 235–252.

Perin, G., 1975. The pollution of the Venice lagoon. Summary of 7 research years. Atti Tavola Rotonda C.D.A., 47–90.

Perin, G., Orio, A.A., Pavoni, B., Donazzolo, R., Pastres, A., Carniel, A., Gabelli, A., Pasquetto, A., 1983. Nutrients and heavy metals in the sediments. Acqua Aria. 6, 623–632.

Pirazzoli, P., 1974. Historical data on the mean tidal level in Venice (in Italian). Atti Accademia Scienze Istituto di Bologna 18, 124–148.

Pranovi, F., Giovanardi, O., 1994. The impact of hydraulic dredging for short-necked clams, *Tapes* spp., on an infaunal community in the lagoon of Venice. Sci. Mar. 58, 345–353.

Pranovi, F., Giovanardi, O., Franceschini, G., 1998. Recolonization dynamics in areas disturbed by bottom fishing gears. Hydrobiologia, 125–135.

Rabagliati, R., 1987. Hydrodynamic characteristics and evolution trends of the Venice lagoon (in Italian). The Lagoon of Venice: Conservation of an Ecosystem. Arsenale Editrice, Venice.

Sfriso, A., 1987. Flora and vertical distribution of macroalgae in the lagoon of Venice: a comparison with previous studies. G. Bot. Ital. 121, 69–85.

Sfriso, A., 1996. Production decrease and macroalgal vegetation changes in the Venice lagoon (in Italian). Inquinamento 5, 80–88.

Sfriso, A., 2000. Eutrophication and pollution in the water column and surface sediments in the central part of the Venice lagoon. MAV, CVN, Final Report, vol. 3.

Sfriso, A., Pavoni, B., Marcomini, A., 1989. Macroalgae and phytoplankton standing crops in the central Venice lagoon: primary production and nutrient balance. Sci. Total Environ. 80, 139–159.

Sfriso, A., Pavoni, B., Marcomini, A., Orio, A.A., 1992. Macroalgae, nutrient cycles and pollutants in the lagoon of Venice. Estuaries. 15, 517–528.

Sfriso, A., Marcomini, A., Pavoni, A.A., 1994. Annual nutrient exchanges between the central lagoon of Venice and the northern Adriatic sea. Sci. Total Environ. 156, 77–92.

Sfriso, A., Pavoni, B., Marcomini, A., 1995. Nutrient distributions in the surface sediments of the central lagoon of Venice. Sci. Total Environ. 172, 21–35.

Sfriso, A., Marcomini, A., 1996a. Italy-the lagoon of Venice. In: Schramm, W., Nienhuis, P.N. (Eds.), Marine Benthic Vegetation, Ecological Studies, vol. 123. Springer Verlag, Berlin Heidelberg, pp. 339–368 (Chap.15).

Sfriso, A., Marcomini, A., 1996b. Decline of *Ulva* growth in the lagoon of Venice. Bioresource Technol. 58, 299–307.

Sfriso, A., Marcomini, A., 1999. Macrophyte production in a shallow coastal lagoon. Part II. Coupling with sediment, SPM and tissue nutrient concentrations. Mar. Environ. Res. 47, 285–309.

Sfriso, A., Facca, C., Ghetti, P.F., 2002. Temporal and spatial changes of macroalgae and phytoplankton in shallow coastal areas: the Venice lagoon as a study case. Submitted for publication. Mar. Environ. Res.

Sorokin, I.I., Giovanardi, O., Pranovi, F., Sorokin, P.I., 1999. Need for restricting bivalve culture in the southern basin of the Lagoon of Venice. Hydrobiologia 400, 141–148.

Strickland, J.D.H., Parsons, T.R., 1972. A practical handbook of seawater analyses. Fish. Res. Board Can. Bull. Ottawa.

Vaccarella, R., Pastorelli, A.M., Marano, G., 1994. Study on yield efficiency of hydraulical dredges and effects on the benthic communities (in Italian). Boll. Malacol. 5, 30.

Vazzoler, S., Costa, F., Bernardi, S., 1987. Lagoon of Venice and transfer of freshwaters and pollutants (in Italian). Ist. Veneto Sci. Lett. Arti. 11, 81–124.