Changes in the northern Adriatic ecosystem and the hypertrophic appearance of gelatinous aggregates

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Abstract

Biweekly to monthly measurements of a large number of physical, chemical, and biological parameters and visual observations (by scuba divers and underwater video cameras) were performed at 80 stations in the northern Adriatic in the framework of an ‘Alpe-Adria’ research of a phenomenon of gelatinous aggregate hypertrophy. This phenomenon was observed in the entire investigated region during the summers of 1988, 1989, and 1991 and only in the Kvarner gulf in 1990. Results for some parameters were compared with available historical data series collected since 1966. Some qualitative changes in the phytoplankton communities (increased diatom contribution, decreased diversity, different dominant species) were evident during the eighties compared with the seventies. However, chlorophyll a and nutrient concentrations remained approximately at the same level. The dynamics of the Po river discharge (and nutrient inputs) during the spring, which was the critical period for aggregate formation, was different during the eighties from that in the preceding decade. An hypothesis is developed which relates the appearance of large quantities of gelatinous material to modifications of the environmental conditions (climatic, hydrology, and oceanographic).

Keywords: Gelatinous aggregates; Environmental changes; Phytoplankton community; Northern Adriatic

1. Introduction

In the summers of 1988, 1989, and 1991, apparently after more than 50 years (Fonda-Umani et al., 1988), large quantities of gelatinous (muco-agglutinate) material appeared in the northern Adriatic (Degobbi, 1989; Rinaldi et al., 1990; Scharnowitsch et al., 1990; Malej, in press). Suspended and sinking aggregates (up to 3-4 m in dimension) created serious problems for fisheries. Sticky gelatinous masses, floating on sea surface, were

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driven by wind towards the coast, reducing the recreational suitability of beaches.

Initially, considerable controversy surrounded the origins and mechanisms of the aggregate development. Now there is a consensus that aggregates represent a buildup of suspended organic and inorganic material entrapped in a matrix, generated by gelling of phytoplankton (diatom) polysaccharide exudates (Degobbis, 1989; Marchetti et al., 1989; Mačej, in press). However, the causes and the 'triggering' mechanism(s) of the hypertrophic exudate production in the Adriatic have not yet been explained. No evidence, based on reliable data, was available to confirm some invoked relationships between anthropogenic eutrophication (and/or pollution) and the phenomenon.

To answer to these crucial questions, also essential for a selection of measures to eliminate or reduce the consequences of the aggregate hypertrophy events, a multidisciplinary research project was designed and started under the auspices of the Observatory for the northern Adriatic (Osservatorio per l'Alto Adriatico) of the Community 'Alpe-Adria', with the participation of the major marine research institutions located in the Italian regions Veneto and Friuli-Venezia Giulia, as well as in Slovenia and Croatia. A group of the University of Vienna, with a long research tradition in the northern Adriatic, also joined the project, which started in 1990 with the following aims.

(1) To identify the critical area and period in which the phenomenon starts and characterize different aggregate forms and their distribution (this information was also useful for a system of early warning).

(2) To identify the main species responsible for exudate production, determining the biological composition of the aggregates and surrounding water, as well as of the surface sediment. Laboratory experiments with these species were planned to establish the 'triggering' factor of the increased mucus excretion rate.

(3) To characterize the oceanographic, geochemical and biological conditions before and during the development of the phenomenon. To establish changes in the marine environment and plankton communities, which could be related to the causes of the phenomenon, actual data were compared with relevant historical data.

(4) To establish possible consequences of the phenomenon to the plankton and benthic communities.

In this paper preliminary results related to the first three aims are briefly summarized, and some hypotheses suggested which should be verified after a more comprehensive analysis and discussion of all collected data, and during future research.

2. Materials and methods

To fulfill the project aims several relevant oceanographic, chemical and biological parameters were measured in water, sediment and aggregates over an extended area of the northern Adriatic, with a frequency ranging from biweekly to monthly, particularly in spring and summer. The investigated region included the northernmost open Adriatic waters, the coastal belt from the Pi river delta to the western Istria coastal region (including the gulfs of Venice and Trieste), and some Kvarner (Quarnero) areas (Kvarner, Rijeka Bay, and the eastern Podvlebitski kanal; Fig. 1). CTD profiles and most of the parameters were measured on approximately 80 stations. Some of the biological analyses were performed on a reduced number of stations (at least 15). Most of the analyses, as well as the preservation of samples for laboratory determinations, were performed in the laboratory aboard the research vessels immediately after sample collection. Systematic visual observations of the water column and bottom were also performed by underwater video cameras or directly by scuba divers.

Water samples were collected by Niskin samplers at least at five depths. Sediment and aggregate samples were collected by scuba divers. Flocks of approximately the same dimension were collected with 20-cm² syringes, cut in front. San-
samples for plankton counts were preserved with 2–4% formalin or, in some cases, with Lugol.

CTD probes were used with additional sensors for fluorescence, PAR, beam transmittance, dissolved oxygen, and pH. Temperature was also measured by reversing thermometers, salinity by high precision laboratory salinometers, and transparency with a 30-cm Secchi disk. The other parameters (dissolved oxygen, pH, alkalinity, ammonia, nitrite, nitrate, orthophosphate, orthosilicate) were measured by methods widely used in oceanography (Strickland and Parsons, 1972). Chlorophyll a concentration was measured both with spectrophotometric and fluorometric techniques. Total phosphorus and nitrogen were measured after UV decomposition of organic matter (Armstrong and Tibbitts, 1968). Phytoplankton counts were performed with inverted microscopes (Ultermöhl, 1958). Scanning electronic microscopes were also used for a more precise determination of some species. Autotrophic and heterotrophic pico- and nano-plankton, including cyanobacteria, was counted by epifluorescence microscopes (Hobbs et al., 1977; Caron, 1983; Takahashi et al., 1985).

Data were stored in the Paradox 3.5 Database Management System (Borland International), and statistical analyses were performed with commercial software packages on a PC. An average year model of the chlorophyll a concentration was calculated from data collected in the period 1969–1991 distributed in 11.4-day intervals (32 periods/year). A filter based on Fourier analysis (Bloomfield, 1976) was applied as a running smoother. To obtain the smoothed curve values a Fourier transform of 39 values was computed and
then its inverse transform was calculated, retaining only the first five harmonics. The daily Po river discharge rate data were smoothed with the same Fourier analysis procedure, retaining an optimal number of harmonics.

3. Results and discussion

3.1. Critical areas and period of gelatious aggregate formation

Research on ‘marine snow’ (including flocks, strings, and small clouds) in the northern Adriatic started only in 1986 (Herndl and Peduzzi, 1988), but the presence of marine snow was noticed regularly each year by scuba divers of various research institutions operating in the region. The highest concentrations were observed during the phytoplankton blooms, and particularly in spring and summer. The formation of these aggregates probably occurs everywhere in the oceans, due to various mechanisms (Aldredge and Silver, 1988). In contrast, the observations suggested that the gelatinous aggregates in the Adriatic, besides its larger dimensions, had different properties in respect to ‘marine snow’, maybe due to an unusually high concentration of gelizing substances. As an example, filtration of water samples, which contained gelatious material, was much more difficult than in the cases when only ‘marine snow’ was present, even in high concentrations.

Scientific observations in the northern Adriatic (Fonda-Umani et al., 1989; Fanuko and Turk, 1990; Degobbis et al., 1991a; Cabrini et al., 1992), and information from mass media, suggested that in 1989 the phenomenon started earlier (second part of June) than it had in 1988 (probably in middle July). More detailed information available for 1989 indicated that gelatinous layers were formed earlier in the eastern transitional areas between less and more saline waters than in the western parts. In 1991 larger aggregates were first noticed in the water column of the northeastern Adriatic, including the Kvarner areas, in the last week of June. Approximately 2 weeks later, suspended gelatious aggregates and surface layers were present in the most part of the investigated region, except the Kvarner area. In contrast, aggregates in the water column and floating gelatious fronts (covering about 10% of the sea surface) were observed only in the Kvarner areas during the cruise of 26 June 1990. However, on 14 July only small flocks and stringers were present (‘marine snow’). The first part of July 1990, in contrast to 1988, 1989, and 1991, was characterized by windy weather (Meteorological Bulletins of the Hydrometeorological Institute, Split), which may have affected the hydrodynamics of these areas, reducing significantly the concentration of the larger aggregates. These meteorological conditions may also have prevented aggregation and accumulation of the gelatious matter in the northern Adriatic proper.

Generally, in a successive phase of the phenomenon evolution during early summer, the gelatious material was observed over the entire investigated area, but appeared to be more concentrated along frontal systems, particularly developed in the western regions, off the Po delta. More specific research is needed to evaluate the relative importance of physical processes versus an increased biological activity (resulting in mucous formation), which influenced the aggregate distribution.

During the rest of summer, the distribution of the gelatious masses depended on both the advective transport by an eddy circulation pattern, which generally prevails in summer (Franco, 1970; Franco and Michalato, 1993), and local winds. For instance, winds blowing from the sea to the land (e.g. ‘maestral’) prevailed in 1988, and gelatious material was deposited along the northern and eastern coasts of the northern Adriatic. In contrast, during 1989, northerly to eastern winds accumulated the material along the Emilia-Romagna coastal region (Rinaldi et al., 1990). In 1991, although the quantities in the open sea were similar, if not higher than in 1988 and 1989, winds and local storms prevented a significant impact of the aggregates along the coasts.

In conclusion, the observations suggested that gelatious material was formed in the entire northern Adriatic, but the process generally started earlier in the Kvarner areas. Aggregate formation and accumulation was favoured by the
increased stability of the water column and a reduced water exchange with the central Adriatic. In this respect it is noteworthy that in the Kvarner areas the water exchange is at a minimum in May/June (Legović, 1982), i.e. at least 1 month earlier than in the northern Adriatic proper. For the same reason, there is probably only a limited exchange of gelatinous material between the Kvarner and the other northern Adriatic areas.

The research has also shown that gelling substances were mainly produced in the upper parts of the water column, and that accumulation occurred in the pycnocline layers. In 1991 turbid layers of gel-like dispersed material, approximately 0.5 m thick, were observed in the open northern Adriatic, in correspondence to various pycnoclines formed in the upper part of the water column. These observations support the assumption that larger aggregates (clouds) and a creamy layer (see description by Stachowitsch et al., 1990) may be formed directly by coagulation of this substance, entraping plankton cells, particulate matter and 'marine snow' particles. This would be in contrast to an hypothesized gradual marine snow aggregation process in the pycnocline layer (Herndl et al., 1992). Later during the summer, aggregate sedimentation became significant, particularly after mixing of the surface layer by storms.

3.2. Causative organisms and long-term changes in the phytoplankton community

Particular attention was dedicated to the phytoplankton composition in the aggregates and surrounding water of all investigated areas of the northern Adriatic to attempt the identification of the species, which might be responsible for exudate production.

The results have shown a variable phytoplankton composition in different areas and years, particularly concerning diversity and dominant species in the critical late spring blooms (examples in Fig. 2). Some Nitzschia species, particularly N. delicatissima complex, were observed throughout the investigated period at all stations. N. delicatissima complex was often dominant in the area off the Po delta, where the most intense blooms occurred. In other areas some Chaetoceros (eastern regions, including the Kvarner areas) and Cylindroelasma species (northern coastal areas and Gulf of Trieste) also significantly contributed to late spring and early summer blooms. Blooms of Skeletonema costatum occurred generally during late winter in the northwestern Adriatic.

The abundance of nanoplanктон, mostly nanoflagellates, was also at a maximum during late spring. Nanoflagellates contributed less significantly or even negligible to the phytoplankton total abundance in the period 1988–1992, except in June 1991, when a bloom dominated by Procentrum minus var. triangulatum occurred in the northwestern areas, and was particularly marked off the Po delta. This bloom was preceded by a concomitant bloom of N. delicatissima and C. socialis (or radius). Recurrent blooms of the latter two species represent a major change in the spring phytoplankton bloom composition during recent years (Degobbi, 1989; Filipić, 1990; Degobbi et al., 1991a). Before 1988 the presence of C. socialis was not documented in the northern Adriatic (Revelante and Gilmartin, 1992). Moreover, N. delicatissima has been a major bloom constituent only during the last decade (CMR, unpublished data). These species substituted some diatom and dinoflagellate species (e.g. Nitzschia seriata and Procentrum micans), which were prominent bloom constituents in the northern Adriatic under the influence of the Po river discharge during the sixties and seventies (Vollolina, 1971; Revelante and Gilmartin, 1977, 1985; Montresor et al., 1982; Socal et al., 1982). In the last decade, the diatoms Rhizosolenia stelleri, Chaetoceros curvisetus, and C. diversus, which had occurred most frequently in the eastern parts of the northern Adriatic during summer of the seventies, have been replaced by N. delicatissima, R. fragilissima, C. insignis, C. affinis, and others. In addition, a significant decrease of the microphytoplankton diversity (Shannon index) was observed since 1987 (examples for the Gulf of Trieste in Fig. 3).

Moreover, a significant increase of the diatom abundance was observed in the surface layer during the eighties in respect to the seventies, partic-
Fig. 2. Concentration (C) of dominant phytoplankton species in the period (r) 1990–1991 at stations CZ, SJ107, and SJ108.
ularly evident in the eastern, more oligotrophic region (Fig. 4a). Probably as a consequence of this change in the phytoplankton community structure, orthosilicate concentrations decreased in the last decade (Fig. 4b). In contrast, during these two periods chlorophyll a concentrations at stations have not deviated significantly from the mean model for the same region (Fig. 5), i.e. most probably no substantial changes of the phytoplankton standing crop have occurred. Extreme deviations were observed in June 1977 at station SJ107 (chlorophyll a concentrations up to 13 μg/dm³) and May 1989 at station SJ305 (up to 15 μg/dm³), when blooms were due to unusual freshwater intrusions. Concurrently, the episodes of high dinoflagellate abundance have been reduced, which might partly have compensated the diatom increase. Besides, a shift towards smaller diatom species also contributed to maintain the average total phytoplankton standing crop at the same level, despite the increased diatom abundance.

Unusually intense cyanobacteria blooms occurred in June and July 1991 in the western and in July and August in the eastern parts of the investigated region, with abundances up to 10⁷ cells/dm³, an order of magnitude higher than those observed in 1990 and 1992 ('Alpe-Adria' Project, unpublished data). Despite this, cyanobacteria may have not played a significant role in the mucus aggregation, since their maximal abundances were generally measured after

Fig. 3. Monthly C' values of the phytoplankton Shannon diversity index (E') at stations C in the Gulf of Trieste in the period 1986–1991.

Fig. 4. (A) Dissolved concentrations (C) for the period (c) 1972–1992 at stations SJ105 and SJ107 in the northeastern Adriatic in May–June. (B) Orthosilicic acid concentrations (c) for the period (c) 1969–1992 at station SJ107 in May–June.

Fig. 5. Chlorophyll a concentration (c) deviations from the year average model for the period (c) 1969–1991 at station SJ107 in May–June.
In marine snow and gelatinous aggregate samples mainly pelagic, and some ichthyoplagic phytoplankton species were observed with electron or inverted light microscopes (see also Degobbis, 1989; Fanuko et al., 1989; Schadowitsch et al., 1990). Diatoms highly dominated the microplankton community. The same species prevailed in the aggregate samples, as well as in the water column during spring (examples in Table 1). In contrast, during summer the composition of aggregates and surrounding waters differed substantially. This indicated that independent biological transformations and processes might occur in the aggregates in respect to the water column.

Aggregates markedly enriched with the diatom *Nitzschia closterium* were collected during summer, more often in the northern and eastern coastal areas, including the Podvelbeci kanal. In the same period, this species was not observed in the surrounding water or it occurred at a low abundance.

Phytoplankton counts in water and aggregate samples were not sufficient to distinguish species which produced exudates from those which were simply entrapped during coagulation and aggregation processes, or successively colonized the aggregates. Additional laboratory experiments were thus necessary. Experiments were performed with some of the dominant species in the investigated area (*Skeletomema coronum*, *Nitzschia delicatissima* and two Chamaecyclus species) to determine extracellular carbohydrate release (low and high molecular weight fractions, LMW and HMW, respectively). The results indicated an increased significance of HMW release in the stationary phase of culture growth, and also during exponential growth in Phaeudium medium (Malej and Harris, 1993). It was also found that copepod feeding was inhibited by HMW diatom exudate, i.e. it acted as a grazer deterrent. Reduction of copepod feeding rates in transitional and stationary growth phase allow diatom stock to persist and continue to produce exudates. Other experiments have shown a significant reproduction of *N. closterium* in gelatinous materials (Monti et al., in press).

In conclusion, the obtained results indicated that several diatom species were involved in the exudate hyperproduction. Different species can have higher exudate production rates and/or survive and reproduce more effectively in the gelatinous material. More combined in situ and laboratory investigations are needed to explain in more detail the mechanism of phytoplankton exudate production.

### 3.3 Changes in the environment

Physical and/or chemical composition changes (nutrients, pollutants), which can occur in the environment, may influence phytoplankton polysaccharide excretion rate (e.g. Myklestad, 1974; Myklestad et al., 1989; Sandbank, 1990).

Data relevant for pelagic ecosystem studies were collected with a fixed sampling and analytical protocol (Gilmartin et al., 1972) at three (since 1566) to six (since 1972) stations, distributed from the Rovinj coastal waters to the open northern Adriatic up to the border of Italian national waters, off the Po delta, with a frequency ranging from biweekly to seasonal. Furthermore, a series of more than a hundred cruises on numerous stations were performed in the northern Adriatic since 1965 (Franco, 1970, 1972, 1982; Franco and Michelato, 1992). These data are hardly comparable with earlier oceanographic and nutrient data obtained during cruises in 1911-1914 (*Najade* and *Cleopatra* cruises; temperature, salinity and dissolved oxygen only), 1953 (*Picotti*, 1963) and 1969 (*Jovanelli*, 1961), due to different analytical methods and sampling station locations.

Temporal series for several parameters were analysed and compared to establish possible modifications in the marine ecosystem, related to the gelatinous aggregate hyperrophy events.

Although average temperature and salinity did not change significantly during the last two decades, an increased variability of these two parameters was observed since 1988, indicating an enhanced instability of the oceanographic conditions (Degobbis et al., 1991b; *Alpe-Adria* Project, unpublished data). As an example, in 1989 water column stratification was established earlier; during a warmer than usual winter. In summer, high surface temperature (in 1988) and bottom
Table 1
Examples of dominant microphytoplankton species in aggregates and surrounding water

<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>Aggregate</th>
<th>Dominant species</th>
<th>Water column</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 April 1990</td>
<td>CR001</td>
<td>Th. pseudoflava</td>
<td>N. delicatissima</td>
<td>N. delicatissima</td>
</tr>
<tr>
<td>8 May 1990</td>
<td>SJ107</td>
<td>R. fragilis</td>
<td>N. delicatissima</td>
<td>N. delicatissima</td>
</tr>
<tr>
<td>10 May 1990</td>
<td>CR001</td>
<td>Ch. affinis</td>
<td>N. delicatissima</td>
<td>Ch. affinis</td>
</tr>
<tr>
<td>21 May 1991</td>
<td>F</td>
<td>Cyclotella sp.</td>
<td>N. delicatissima</td>
<td>Ch. affinis</td>
</tr>
<tr>
<td>23 May 1990</td>
<td>ZB012</td>
<td>N. delicatissima</td>
<td>N. delicatissima</td>
<td>R. alatus f. gracilissma</td>
</tr>
<tr>
<td>30 May 1990</td>
<td>ZB052</td>
<td>Ch. affinis</td>
<td></td>
<td>Ch. affinis</td>
</tr>
<tr>
<td>31 May 1990</td>
<td>SJ107</td>
<td>N. closterum</td>
<td>N. closterum</td>
<td>N. closterum</td>
</tr>
<tr>
<td>17 June 1991</td>
<td>F</td>
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<td>R. alatus f. gracilissma</td>
<td>R. alatus f. gracilissma</td>
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<td>SJ107</td>
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<td>Ch. affinis</td>
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<tr>
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<td>25 June 1990</td>
<td>VV034</td>
<td>Ch. affinis</td>
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<tr>
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<tr>
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<td>N. tetraonitis</td>
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<tr>
<td>8 August 1991</td>
<td>CR001</td>
<td>N. tetraonitis</td>
<td>N. tetraonitis</td>
<td>N. tetraonitis</td>
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<tr>
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<td>SJ101</td>
<td>Ch. compressus</td>
<td>S. conicum</td>
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Table 1 (continued)

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<th>Date</th>
<th>Station/</th>
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<th>Water column</th>
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<td>CR001</td>
<td>Ch. socialis</td>
<td>Ch. insignis</td>
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<tr>
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<td>SI007</td>
<td>N. clausum</td>
<td>N. delicatissima</td>
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<td>SI001</td>
<td>N. clausum</td>
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<td>Ch. insignis</td>
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<tr>
<td>5 September 1991</td>
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<td>Ch. insignis</td>
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<td>SI006</td>
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<td>N. temnoeasree</td>
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<td>Ch. socialis</td>
<td>N. temnoeasree</td>
<td></td>
</tr>
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*Gens abbreviations: Ch. Chaetoceros; D. Detonula; L. Leptocylindrus; N. Nitzschia; P. Procentrum; R. Rhizosolenia; S. Stramenopila; T. Thalassiosira.

Salinity (in 1988 and 1989) contributed to an additional stability of the water column. Current velocity during late spring was reduced in 1988 and 1989 compared with earlier years, at least in the eastern northern Adriatic, off the western Istria. In 1990 the freshwater input was at an historical minimum and surface salinity in the area off the Po delta were higher than the maximum value measured in the period 1970-1989 (Degobbis et al., 1991a). During late winter and in spring 1991 the freshwater influence was significant, although not unusually high, but the water temperature was below the average (‘Alpe-Adria’ Project, unpublished data). In late June, the weather was stabilized and the sea surface was warmed very fast up to usual temperature values. These events coincided with the appearance of large aggregates in the water column.

No significant trends were observed for total inorganic nitrogen (TIN) and total phosphorus (TP) concentrations in the northern Adriatic surface layer in May/June during the last two decades (Fig. 6). Analyses of data collected in other seasonal periods led to a similar conclusion. Relationships between salinity and TP or TIN concentrations for the 1970s and 1980s for stations 29 km off the Po delta did not differ significantly (CMR; unpublished data). This suggests that the nutrient concentrations in the diluted waters, which have been transferred from the coastal zone off the Po delta to the open area, did not change significantly in the last two decades.

Fig. 6. Total inorganic nitrogen (TIN) and total phosphorus (TP) concentrations (μ mol/l) for the period (t) 1969–1992 at station SI007 in May/June.
Unusually long periods of high barometric pressure occurred since 1988 (Rinaldi et al., 1990; Crisciani et al., 1991), characterized by a calm and sunny weather. During these periods, surface nutrient concentrations, particularly orthophosphates, were often at a minimum (Degobbis et al., 1991b; ‘Alpe-Adria’ Project, unpublished data). In 1990 this can be ascribed to the strongly reduced river inputs. However, in 1988, 1989, and 1991, when freshwater discharge rates were within usual ranges, an increased nutrient utilization efficiency may also be hypothesized. Phyttoplankton photosynthesis might have been stimulated in conditions of extremely reduced vertical and horizontal water mixing and increased irradiance, while its growth was limited by reduced nutrient availability. This is also supported by some analyses of relationships between nutrient concentrations and apparent oxygen utilization (AOU), which indicated that organic matter, which have been decomposed in the bottom layer during summer, might contain less nitrogen and phosphorus (but not silicon) during the late eighties than during the seventies (Degobbis et al., 1991c).

In favourable light conditions and calm sea, but under significant nutrient limitation, phyttoplankton organic production can be dosed towards an excessive polysaccharide excretion. Mucus material aggregation and accumulation was favoured by a marked stability of the water column.

Heavy metals and organic pollutants have been measured in water, plankton, benthic organisms and sediments of the open northern Adriatic at least 1–2 times per year since 1979 (Bregant and Catalano, 1989; Campesan et al., 1989; Fossato et al., 1989; Giordani et al., 1989; Hieke Merlin et al., 1989; Serriassetti and Viviani, 1989; CMR, Rovinj, technical reports) in the framework of an international monitoring project (ASCOP), involving Italian and Croatian research institutions (Degobbis et al., 1986). Available data did not show any significant changes in pollutant levels during the eighties. Thus they may be excluded as a significant trigger factor of a phytoplankton hypertrophic excretion.

In contrast, it is well known (e.g., Franco and Michelato, 1992) that the Po river waters significantly influence the northern Adriatic ecosystem in several ways:

1. Freshwater inflows significantly enhance water column stratification and modify the general circulation and water exchange rate between the northern and central Adriatic.
2. The Po discharges greatly affect the chemical composition of the northern Adriatic water, including nutrient concentrations.
3. The physical and chemical influence of the Po river, combined with favourable meteorological conditions (e.g., increased nutrient input in highly stratified water column and calm weather), can cause significant biological changes in the marine ecosystem, like marked phytoplankton blooms followed by an increase of heterotrophic activity, oxygen consumption, organic matter sedimentation, etc. Thus, the Po discharges may also influence selection and succession of plankton species.

Discharge rate data (daily averages for the period 1917–1990) were reported for the Po river in the Annali Idrologici (Hydrological Annals) of the Ministero dei Lavori Pubblici, Servizio Idrografico del Po, Rome, Italy, and Annual Reports of the Emilia-Romagna Region ‘Environment and water’ (in Italian), Bologna, Italy. Some of these data (up to 1975) were elaborated by Casi (1981).

The analysis of the Po river discharge rates was focused on spring (May/June), when a major exudate production might occur. Two essentially different types of interannual variability of spring discharge rates were observed (Fig. 7). During the thirties and in the period from the fifties up to the end of seventies discharge maxima and minima were alternating each 1–2 years. In contrast, the twenties, forties and eighties were characterized by a longer period of decreased freshwater input (1921–1924, 1942–1946, and 1979–1982, respectively) followed by a period of higher discharge (1926, 1948–1949, and 1983–1986, respectively), with pulses of daily discharge rate exceeding 5000 m³/s (up to 9000 m³/s, examples in Fig. 8).

Then,
a year of lower and another (1928, 1931, 1988) of higher discharge occurred, but more distributed during spring, with lower pulses (daily discharge rates up to 5000 m³/s). In 1928 and 1988 the phenomenon of gelatinous aggregate hyper trophy was well documented (Fonda-Umani et al., 1980). No scientific reports were available regarding a possible 1951 event, although some fishermen’s reminiscences (Stachowisch et al., 1990) and a note on the phenomenon in general (Canadija, 1951) dated back to that year. This is not surprising that such an event (if it occurred) was not described in more detail, because no significant research and fishing activities were performed during the late forties and early fifties, i.e. in a period of high political tension in the area. In 1920 the phenomenon also occurred after a period of high pulses (1917–1918) and a next year of minimum discharge (Fig. 7). Unfortunately, Po discharge rates were not measured in the preceding years.

3.4. An hypothesis

The results suggest that a particular ten years pattern of the Po river discharge (water and nutrients) might have a significant influence on the plankton communities, selecting species and/or modifying relationships in the food webs, which resulted in a significant exudate production and accumulation. Moreover, a short but marked freshwater pulse in conditions of low turbulence can induce an intense surface bloom, i.e. which the added nutrients are quickly depleted. Thus, during the decay phase of the bloom high molecular weight exudates still be produced in larger quantities (Lewin, 1955; Ittekkot et al., 1981; Sandengaard and Schierup, 1982; Möller Jensen, 1983; MaAsløstad et al., 1989), and accumulated in the absence of a significant grazing and microheterotrophic activity. In fact, since 1988 marked phytoplankton blooms, although limited to the northwestern Adriatic, were observed during calm weather, often dominated by only one or two species, with high exudate rates (Malej and Harris, 1993). This may also explain why to gelatinous aggregates occurred in 1990, when

![Graph](image)

Fig. 7. May–June Po river mean discharge rate (Q) for the period (t) 1917–1990. Gelatinous aggregate events are indicated with small arrows.)
Fig. 8. Daily Po River discharge rate ($Q_t$) for a 1-year period ($t$) and selected years.
spring Po daily discharge peaks were lower than 2000 m³/s.

The assumption that a particular pulsing mechanism of freshwater input, rather than total water quantities, may be essential for the development of the phenomenon is supported by the fact that large quantities of gelatinous aggregates were not observed in periods of extremely low (during the sixties), nor extremely high (1977 and 1978), nor moderate (the 1930s, 1950s, and the first half of the 1970s) Po discharge rates.

4. Conclusions

From the data analyses it can be hypothesized that climatic changes during the eighties, modifying oceanographic conditions and hydrological regimes, might have influenced the dynamic of nutrient inputs and recycling mechanisms, resulting in a selection of plankton communities, in which phytoplankton exudates can accumulate, as a response to the environmental changes. Even if the gelatinous aggregate hypertrophy phenomenon has certainly a natural origin, its intensity and duration were particularly marked in the northern Adriatic compared with other Adriatic regions or the Tyrrenhian Sea. This may be due to the eddy circulation, which develops in the northern Adriatic in summer, and to an higher phytoplankton abundance.

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