Response of Summer Phytoplankton to Episodic Meteorological Events (Gulf of Trieste, Adriatic Sea)

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With 9 figures and 1 table

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Abstract. Despite increasing evidence that atmospheric deposition may contribute considerably to new production in coastal seas, the role of this nutrient source in the shallow northern Adriatic ecosystem has remained largely unassessed. This study demonstrates that locally collected rain water significantly stimulates primary production and phytoplankton biomass accumulation in microcosm experiments. The concentration of nutrients in rain water collected during summer storms (11.38–77.19 μmol·l⁻¹ nitrate, 4.45–36.38 μmol·l⁻¹ ammonium, 0.93–4.75 μmol·l⁻¹ phosphate) indicated that the precipitation is influenced by anthropogenic emissions from urbanised and industrialised regions of the European continent. Rainfall events delivered relatively large (127 tons nitrogen, 9.5 tons phosphorus in the period 10 June to 10 September, 1993), though episodic, nutrient input into the area. Field measurements showed that storm events were followed by an increase of phytoplankton standing crop and a shift of community structure.

Problem

The temporal and spatial distribution of phytoplankton production, standing stock and community structure in many temperate coastal waters is mainly controlled by nutrient inputs from freshwater inflow in conjunction with other environmental variables such as temperature, light availability, water column structure and circulation (cf. Harding, 1994). The annual dynamics of phytoplankton in such areas typically exhibit a seasonal sequence of events. During late winter–spring the low standing stock of phytoplankton receives a riverine nutrient input which triggers phytoplankton blooms dominated by chain-forming diatoms, which is succeeded by a mixture of nanoflagellates and small diatoms in a transient period from spring to summer. The thermally stratified, summer water column is characterized by the prevalence of nano- and picoplankton, with lower phytoplankton biomass above the pycnocline layer (Malone et al., 1991). Autumn overturn of the water column and floods may cause an increase of larger phytoplankton followed by a decline during the winter. Seasonal dynamics of phytoplankton such as these have been observed in the northern Adriatic (Revelante & Gilmartin, 1976; Fonda Umani et al.,

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1992) and also in the northernmost area, the Gulf of Trieste, as a response to its own freshwater input from the river Soča (Isonzo) (Malej et al., 1995, Turk, 1992).

Some recent evaluations of estuarine, coastal and ocean nutrient budgets have indicated that atmospheric deposition is potentially a significant source of plant nutrients (Paerl et al., 1990; Owens et al., 1992). The natural fluvial and atmospheric inputs of nitrogen to the oceans were estimated to be of similar magnitude, with both increasing due to human activity (Gallowey et al., 1995). The importance of atmospheric input as a source of new nutrients may increase in summer (Scudlark & Church, 1993) when river flows are low and water column stratification prevents replenishment of nutrients from below the pycnocline. Moreover, entrainment of the bottom mixed layer by the surface layer due to short-term wind mixing events associated with summer storms may bring nutrient-rich bottom waters to the upper layers. Field observations have shown that phytoplankton standing stock and productivity increase rapidly in response to short-term meteorological events occurring on a time scale of only days (Hitchcock & Smayda, 1987; Malone et al., 1993).

The purpose of this study was to assess the impact of short-term meteorological events on surface phytoplankton during the period of water column stratification, usually characterized by low phytoplankton biomass (Fonda Umani et al., 1992). We followed water column structure and sampled phytoplankton daily before and after summer storm events at an offshore location where freshwater input could only be attributed to rain. Regular monthly sampling covering the whole southeastern part of the Gulf of Trieste was also conducted. The study was complemented by bioassay enrichment experiments to examine possible stimulating effects of rainwater on production and biomass of surface phytoplankton.

**Material and Methods**

1. Area description and sampling

The Gulf of Trieste is the northernmost and shallowest part of the Adriatic Sea with maximum depths of ca. 25 m in the central region. The southeastern Gulf connects with the northern Adriatic, while the main freshwater input—the river Soča (Isonzo)—is from the northwestern coast. The study area is characterized by large annual temperature fluctuations (6–26°C in the surface layer and 6–20°C close to the bottom); typically, thermal stratification develops from mid-April through September in areas deeper than 16 m (Malačič, 1991). Surface salinity variability is also large, even in the central part of the Gulf (32–38.5). Salinities between 36.5–39 are generally observed in the bottom layer.

Monthly measurements were conducted in the southern part of the Gulf of Trieste (Fig. 1), while short-term sampling before and after summer storms was limited to one location (station F). This location was chosen because it was far enough from local rivers that episodic pulses of high flow following summer storms did not affect surface waters. Therefore, surface salinity decreases could be attributed only to rain water inputs. Three such events were followed in 1993; 5–12 June, 5–14 July, and 25 August–8 September. The first was characterized by predominant southerly winds ("jugo"), the second by strong northeast winds ("burja") and the last by weaker, intermittent winds of different directions. All three events were accompanied by rainshowers; no precipitation occurred at any other time during the summer of 1993, coinciding with weak breezes through mid-October.

During each rain event, rainwater was collected in acid-washed polycarbonate buckets at a coastal location approx. 50 m from shore. Samples for nutrient analysis were immediately frozen and analysed within one month. Meteorological data (wind direction and speed, and precipitation) from the two
meteorological stations on the Slovenian coast (near Piran—SE and near Koper—KP, see Fig. 1) were supplied by Hydrometeorological Survey of R Slovenia.

2. Field measurements and analyses

Temperature, salinity, density and fluorescence profiles were recorded using a CTD fine-scale probe (University of Western Australia, a Sea Tech Inc. Fluorometer). Discrete samples for chemical and biological analyses were collected with a 5-l Niskin bottle at five depths (0.5, 5, 10, 15, 20 m). Concentrations of nutrients (nitrate, nitrite, ammonium, total nitrogen, phosphate, total phosphorus, silicate) were measured on unfiltered samples using standard colorimetric procedures (Grasshoff, 1983). The same methods were also used to determine nutrient concentrations in the rain water.

Chlorophyll a (Chl a) concentrations were determined fluorometrically (Holm-Hansen et al., 1965). 25 ml subsamples were filtered onto 0.22 μm Millipore filters, extracted in 90% acetone and the fluorescence of extracts measured on a Turner 112 Fluorometer. The Chl a concentrations from the discrete depth were integrated over the surface mixed layer.

Samples for enumerating phytoplankton were preserved with neutralized formaldehyde (3.0% final concentration). Micro- and nanophytoplankton were identified and counted on an inverted microscope using the technique of Utermöhl (1958): 100 or 50 fields of the bottom chamber were examined at 200 × and, if necessary, at 400 × magnification.

3. Enrichment experiments

Subsurface (2 m) seawater samples were collected at station F and screened through a 200 μm mesh to remove most of the zooplankton. Bioassays to assess the impact of rain water (15% v/v rainwater)
enrichment on natural plankton were carried out in 8-l polycarbonate containers that were incubated *in situ* at 2 m depth for periods up to 6 days. Control containers did not receive any addition. Subsamples for nutrients, Chl *a*, phytoplankton community structure and size-fractionated primary production were withdrawn daily. We used changes in Chl *a* and ^14^CO₂ fixation relative to controls as indicators of stimulation by rainwater. All responses were expressed as percentage of control. Enrichment experiments using river water and artificial nutrient additions were also carried out within the framework of the EU Environment project PALOMA and are described in detail elsewhere (Malej et al., in press).

Methods used for the determination of nutrients, Chl *a* and phytoplankton counts were the same as described above. Size-fractionated primary production was determined using the ^14^C technique (Steeman Nielsen, 1952). Subsamples were incubated in 75 ml polycarbonate bottles after addition of 6 μCi of NaH^14^CO₃. Bottles were kept suspended *in situ* close to experimental containers in dark and light for 4 h. At the end of incubations, cells were collected on 10 μm, 2 μm, 0.6 μm and 0.2 μm polycarbonate filters; 0.2 μm filtrate (5 ml exudate) and unfiltered subsamples were also obtained. The samples were acidified with 5 M HCl to remove residual (^14^C) bicarbonate; 5 and 10 ml of scintillation cocktail was added to filter samples and filtrates, respectively. The activity was measured on a Canberra TriCarb 2500 scintillation counter; assimilation of carbon was calculated as described by Gargas (1975).

**Results**

1. **Meteorological conditions, physical structure of the water column and fluorescence profiles**

Generally, the summer of 1993 was rather dry and calm with a weak seasonal diurnal breeze. A period with heavy rain during mid-October continued for several days, while during summer, storm rain events lasted 1–5 h at most.

**June event.** Successive synoptic charts showed that western Europe was covered by a shallow cyclonic field on 10 June and the surface cold front extended meridionally from Palma de Mallorca towards Geneva. The cold front then moved eastward and passed the northern Adriatic in the early morning of 12 June. The southerly wind (Fig. 2, top) due to passage of this front, with short-term gusts up to 18.5 m·s⁻¹ (not shown in Fig. 2), was followed by a rainshowers that at its peak delivered 22.1 mm rainwater in about 2 h (Fig. 2, bottom). The southerly wind deepened the surface mixed layer and caused the advection of warmer southern water into the area (Fig. 3). The vertical distribution of Chl *a* fluorescence was only slightly altered in response to this meteorological event (Fig. 3, bottom, thick dashed line) and fluorescence was essentially uniform with depth.

**July event.** This was linked to movement of another cold front that passed the Adriatic overnight from 6 to 7 July. The surface synoptic charts indicated the presence of a large anticyclonic field over western Europe. The cold front moved in a SE direction; while passing the northern Adriatic the front induced a strong ENE wind (‘burja’, Fig. 4), with gusts of 22–25 m·s⁻¹ (not shown in Fig. 4). The event was accompanied by a four-hour rainshowers delivering 19.5 mm precipitation. As a result of this meteorological forcing, the water column was mixed down to about 16 m (Fig. 5 thick solid line); the upper layer was cooled from over 25°C before the event to 22°C (Fig. 5, top); the rain-diluted surface water was redistributed throughout the upper mixed layer; and in the upper 4 m the Chl *a* fluorescence decreased, while in the deeper layers it increased (Fig. 5, bottom, dashed line).

**August–September event.** The period from 23 to 26 August was characterized by
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Fig. 2. The time series of the southerly wind speed (top) and precipitation (bottom) on 12 June 1993 (midnight to 06:00 local solar time) recorded at the weather station in Piran. Wind speed is given as the mean within 10 minute intervals (solid line) and as hourly means (dashed line).

A marked decrease of air temperature (from daily maximum of nearly 34°C on 23 August to less than 23°C on 26 August, and night minimum from about 24°C to less than 17°C). Prior to 25 August there was no rain; afterward, during that day a modest rainfall precipitated 3 mm. Overnight on 25–26 August this reached 6.6 mm and subsequently increased further to 10.1 mm on 26 August. Moderate SE to SW winds were blowing before 25 August, with stronger NE to ENE wind pulses (up to 10 m·s⁻¹) on 25–26 August and moderate (<7 m·s⁻¹) NE winds
Fig. 3. Temperature, density ($\sigma_T$), in situ fluorescence (CTD/fluorescence probe) and $\Sigma N_m$ ($\mu$mol $\cdot$ l$^{-1}$) depth profiles on 11 June (thin lines) and 12 June (thick lines). Top: the profiles of temperature (right) and $\Sigma N_m$ from discrete samples (left); bottom: the profiles of $\sigma_T$ (right) and fluorescence (left).

during first 10 days in September. Early September was also quite dry with only a few short-lived rain episodes on 5, 6 and 7 September with a cumulative rainfall of 5.5 mm. These meteorological conditions caused a marked surface cooling and a gradual deepening of the mixed layer which led to a nearly homogeneous water column in early September (Fig. 6, left). Chl $a$ fluorescence showed slightly higher levels near and below the thermocline on 25 August. The introduction of nutrient-
rich rainwater following mixing of the upper water column coincided with an increase of Chl a fluorescence in the thick layer below 5 m that was evident on 31 August. In the upper layer, fluorescence continued to increase until 8 September (Fig. 6, middle).

2. Rainwater nutrient concentrations

Nutrient concentrations in rainwater collected during summer 1993 are shown in Table I. The concentrations were quite variable even when samples were collected at the beginning and at the end of each rain event. Southerly winds were generally associated with lower nutrient concentrations. Variability was greater for nitrogen nutrient species than for phosphorus. The mean molar ratio between $\Sigma N_n$ and phosphate was $29.7 \pm 21.7$ and between $\Sigma N_n$ and silicate $34.8 \pm 28.3$. A considerable fraction of both nitrogen and phosphorus seems to have been bound in the organic form.

We have no information on the areal extent of precipitation and had to estimate the quantity of nutrients delivered to the Gulf of Trieste. All three major meteorological events we have described were accompanied by precipitation both along the eastern coast of the Gulf and also along the western coast. According to data of the Hydrometeorological Survey of R Slovenia, total precipitation in the eastern coastal area of the Gulf of Trieste amounted to slightly less than 100 mm during the period from 10 June to 10 September 1993. During the same period in Trieste (western coast of the Gulf), precipitation was nearly 150 mm. Using an average value of 120 mm for the whole Gulf during the study period, and average nutrient concentrations measured in rainwater (Table I) we estimated mean wet atmo-
spheric ΣNₘ deposition of 98 μmol·m⁻²·d⁻¹ and average phosphate input of 3.6 μmol·m⁻²·d⁻¹. Inclusion of organic fractions into these calculations would increase the values to 156 μmol·m⁻²·d⁻¹ for total N and 5 μmol·m⁻²·d⁻¹ for total P depositions. A mean rainfall of 120 mm with average total nitrogen (116.8 μmol·l⁻¹) and phosphorus (3.82 μmol·l⁻¹) concentrations (Table 1) was considered to have fallen over the whole Gulf of Trieste (surface of 600 km²), yielding
Fig. 6. Temperature (left), in situ fluorescence (middle) and $\Sigma N_a$ ($\mu$mol·l$^{-1}$, discrete samples, right) on 25 August (solid lines), 31 August (dashed lines) and 8 September (dotted lines).

Table 1. Results of the analyses of rainwater samples collected during summer 1993 (concentrations in $\mu$mol·l$^{-1}$, standard deviation expressed as % of mean).

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<td>185.00</td>
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a total depositional input of 127 metric tons nitrogen and 9.5 metric tons phosphorus for the period 10 June to 10 September, an average 1.4 tons N and 0.1 tons P per day.

3. Nutrients in the seawater and phytoplankton

Nutrient concentrations in the surface mixed layer were low from June through September 1993, with nitrate and ammonium concentrations both around
1 μmol·l⁻¹, phosphate below 0.2 μmol·l⁻¹ and most silicate concentrations below 2 μmol·l⁻¹. The ΣNₘᵦ concentrations before and after the storm events of summer 1993 are shown in Figs 3 and 6 with CTD/fluorescence data. In early June, ΣNₘᵦ was fairly uniform throughout the water column, ranging between 2.46 and 2.85 μmol·l⁻¹, and was similar to the distribution of phosphate (values from 0.12 and 0.19 μmol·l⁻¹). After the storm ΣNₘᵦ increased and reached the highest concentrations in the bottom layer (Fig. 3, top left), presumably due to resuspension. Throughout July, nutrient concentrations were low (ΣNₘᵦ 1.09–2.85 μmol·l⁻¹), with a maximum just above the sea bed. On 25 August, before the storm, the ΣNₘᵦ in the upper 10 m was 1.2–1.58 μmol·l⁻¹, while the concentration just above the sea floor was 6.21 μmol·l⁻¹. On 26 August, the surface concentration increased to 3.53 μmol·l⁻¹ (Fig. 6) and decreased to 2.28 μmol·l⁻¹ on 31 August. Surface concentrations further decreased until 8 September, concomitant with increased phytoplankton biomass indicated by fluorescence (Fig. 6, right). Chl a was generally low in the surface mixed layer throughout the summer (concentrations: 0.11–0.93 mg·m⁻³), and variations of phytoplankton biomass appeared to be linked to the meteorological forcing. Following the June storm, integrated Chl a in the upper 10 m increased from 3.38 mg·m⁻² on 11 June to 4.88 mg·m⁻² after the event. Concentrations returned to pre-storm levels (3.1 mg·m⁻²) on 21 June and decreased to 1.38 mg·m⁻² by early July. Chl a biomass increased again to 4.45 on 7 July and to 6.28 mg·m⁻² a week after the storm (14 July). Chl a was 3.5 mg·m⁻² in early August and slightly higher on the day before a storm (25 August). After this storm we measured both the highest summer phytoplankton Chl a (7.23 mg·m⁻²) and the lowest nutrient concentrations.

Total phytoplankton density and community structure also showed patterns related to meteorological forcing in the upper water column (Fig. 7). Increased phytoplankton abundance after the July and August storm events are clear, but unfortunately we have no data on phytoplankton composition and density after the June storm. In late June, total phytoplankton abundance was low in the upper 10 m (0.36–0.44×10⁶ cells·l⁻¹), and the community was dominated by microflagellates (62–75%), diatoms (11–24%), dinoflagellates (8–9%) and coco-
lithophorids (3–3.5%). A week after the storm event in July, the number of cells in the upper 10 m varied between 0.52–2.15 × 10^6 cells·l^{-1} and diatoms were the most important component (43–88%), followed by microflagellates (33–48%). Dinoflagellates decreased substantially after the storm (to 2–4%), while the contribution of coccolithophorids was relatively unchanged (2–3%). Before the storm on 25 August, phytoplankton abundance was very low (< 0.3 × 10^6 cells·l^{-1}), but increased to 0.43–0.61 × 10^6 cells·l^{-1} in the following two weeks (31 August–8 September). These changes in phytoplankton community structure were also reflected in accessory pigment composition as a change in the fucoxanthin/19′hexanoyloxyfucoxanthin ratio from 0.5 to 1.2 before storm events to 1.2 to 1.8 afterwards (Švagelsj et al., 1996; Terzić, 1996), suggesting a rapid response of diatoms to storms.

Storm events were generally followed by a higher phytoplankton standing crop (biomass and abundance) and a shift of community structure in favour of diatoms, although microflagellates also increased. The most abundant diatom species were Rhizosolenia delicatula, Lauderia annulata and Chaetoceros spp. Typical summer conditions were re-established within two weeks of a storm event, with a shift from diatom-dominated phytoplankton towards nanophytoplankton.

4. Enrichment experiments

The response of the coastal phytoplankton to natural rainfall in terms of production and Chl a biomass was followed in early summer (27 June–2 July) and early autumn (5–9 October). During both experiments the stimulating effect of rainwater was evident (Figs 8 and 9). The Chl a biomass in rainwater-treated containers increased
by 200% and 300% relative to controls during 5–6 days in early summer and early autumn, respectively (Fig. 8). Primary production also showed a clear response to rain water addition (Fig. 9). During the early summer experiment (Fig. 9, left), the largest response of the >10 μm fraction was observed on the second day after addition, while the greatest response of 2–10 μm phytoplankton was measured on day 5. In the >10 μm phytoplankton the most abundant diatom was the genus *Chaetoceros*, while in the 2–10 μm fraction small flagellates (2–3 μm) became predominant. Picoplankton was stimulated initially but seemed to have been out-competed by the larger, especially 2–10 μm, fraction later during the experiment. In the October experiment, rainwater additions stimulated all phytoplankton size fractions, most notably picoplankton, on the first day of the experiment (Fig. 9, right top). Total primary production in the rain-treated samples and the controls increased after four days incubation (Fig. 9, right bottom), the 2–10 μm and >10 μm phytoplankton reaching nearly 200% relative to control, while the picoplankton response was lower.

**Discussion**

Observations of phytoplankton blooms, oxygen depletion and benthic mortalities in the northern Adriatic have been mainly linked to the river inputs of nutrients (DEGOBBI, 1989; JUSTIĆ et al., 1993). Despite the fact that data have been collected on rainwater nutrient concentrations along the eastern (ALEBIC-JURETIC, 1994) and western (MANTOVAN et al., 1995) coasts of the northern Adriatic, the importance of this input has not been sufficiently evaluated, but has been suspected to be a significant source of nutrients (DEGOBBI, 1988; MALONE et al., 1996).

Our results demonstrate that locally collected rainwater significantly stimulated total primary production (160 and 240% relative to control in early summer
and early autumn, respectively; enhanced biomass accumulation (200 and 300% increase of the Chl a within less than 1 week); and affected phytoplankton community structure (favouring diatoms and small flagellates) during enrichment experiments. Furthermore, field data confirmed results from enrichment experiments, showing increased phytoplankton biomass, abundance and community changes in the surface waters after summer storms events.

The atmospheric input of nitrogen and its stimulating effects on marine phytoplankton are well documented (PAERL, 1993; OWENS et al., 1992), although some authors consider the deposition of atmospheric nitrogen insignificant to impact primary production of oligotrophic oceans (KNAP et al., 1986). Recent studies have indicated that present estimates of atmospheric deposition to the oceans may need to be doubled to account for dissolved organic nitrogen content (CORNELL et al., 1995). Therefore, nitrogen inputs from atmosphere may be more important than previously thought.

Despite increasing evidence that atmospheric deposition may contribute considerably to biomass accumulation and new production, hence exacerbating eutrophication, there are very few data concerning this nutrient source in the Mediterranean, and, particularly in some areas susceptible to eutrophication such as the northern Adriatic.

On the basis of data collected in the northwestern Mediterranean, MARTIN et al. (1989) suggested that inputs of inorganic nitrogen supplied by rivers and rain were approximately equivalent, while the atmospheric deposition of inorganic phosphorus appeared to be significantly lower than the riverine flux. BERGAMETTI et al. (1991) suggested that the atmospheric input of phosphorus could be significant to oligotrophic areas of the Mediterranean during summer. MIGNON et al. (1988) estimated annual wet atmospheric deposition of 30000 mol·km⁻² total nitrogen and 500 mol·km⁻² phosphate off the French Mediterranean coast.

Rainfall events delivered relatively large, though episodic, nutrient input into the Gulf of Trieste. During a storm event in June, precipitation delivered 22.1 mm rain on the eastern coast and 39.6 on the western coast, with an overall mean of 30 mm for the whole Gulf (surface area approx. 600 km²). Taking into account the nutrient concentration determined in rainwater from the eastern coast (14.15 μmol·l⁻¹ nitrate, 12.56 μmol·l⁻¹ ammonium and 2.78 μmol·l⁻¹ phosphate), we estimate 6.7 tons nitrogen and 1.6 tons phosphorus were delivered to the Gulf of Trieste during the June storm event. Despite higher nutrient concentrations in rainwater in July and August, the total rainfall was lower and consequently the amount of nutrients delivered was less. The period covered by our study was the driest period of the year (OGRIN, 1995); therefore, on a yearly basis, inputs from rainwater would be significantly higher than these estimates.

Reported rainwater concentrations (11.38–77.19 μmol·l⁻¹ nitrate, 4.45–36.38 μmol·l⁻¹ ammonium, 0.93–4.75 μmol·l⁻¹ phosphate, Table 1) are the upper range for wet deposition as they are based on bulk samples. On the basis of analyses in the northwestern Mediterranean, LOYE-PILOT et al. (1991) present ΣN₃ concentrations of 15–25 μmol·l⁻¹ as representative of open waters, while average concentrations of 50 μmol·l⁻¹, and up to 200 μmol·l⁻¹, suggest precipitation that is influenced by anthropogenic emissions. Even higher nitrogen concentrations associated with southerly air mass transport (up to 111 μmol·l⁻¹ for nitrate and 517 μmol·l⁻¹ for ammonium) were measured in rain over the North Sea (SPAKES
et al., 1993), although it was concluded that atmospheric inputs probably were not a major source of nutrients to support primary production in that region.

High atmospheric nutrient deposition appears to be very episodic, and estimating total atmospheric input on a seasonal and annual basis requires extensive spatial and temporal coverage. Estimates of nitrogen loading from atmospheric sources range from 10% in waters adjacent to undeveloped regions, to 50% in waters impacted by air masses from industrialized and urbanized regions. There is an increased evidence that enhanced N loading may exacerbate eutrophication in N-limited estuarine and coastal waters. Atmospheric inputs seem to be the least known among all anthropogenically generated sources of nutrients and, moreover, they remain largely uncontrolled (PAERL, 1993).

Atmospheric inputs of nutrients are probably not a major source of eutrophication in areas such as the northern Adriatic. Nevertheless, episodic high nutrient deposition may have a significant impact on phytoplankton. In contrast to other terrigenuous nutrient sources (rivers, wastewater, runoff) that tend to be confined to a narrow coastal belt, precipitations may affect the whole northern Adriatic basin. A better quantification of this nutrient source on a regional scale is therefore needed.

Summary

Nutrient concentrations in rainwater collected in the Gulf of Trieste during summer 1993 (mean values: 49.88 μmol·l⁻¹ nitrate, 23.33 μmol·l⁻¹ ammonium, 2.97 μmol·l⁻¹ silicate, 2.98 μmol·l⁻¹ phosphate) reflect the influence of European anthropogenic emissions. Rainfall events delivered considerable nutrient input into the study area; we estimated that 127 tons nitrogen and 9.5 tons phosphorus were deposited during the period 10 June to 10 September 1993. The response of the coastal phytoplankton to natural rainfall dilutions in microcosm experiments was significant, showing enhanced primary production and phytoplankton biomass accumulation. Field measurements showed that storm events were generally followed by an increase of phytoplankton biomass and modified community structure. Our study was limited to summer and covered only the eastern part of the Gulf of Trieste, but it would be important to re-evaluate different nutrient sources, including atmospheric deposition, on a seasonal and annual basis.

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References

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