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PHYTOPLANKTON AND BACTERIA ALKALINE PHOSPHATASE ACTIVITY IN THE NORTHERN ADRIATIC SEA

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ABSTRACT

The importance of bacterial, phytoplankton and dissolved alkaline phosphatase activity (APA) in the northern Adriatic was investigated during 2006. In upper waters total APA increased from early spring (0.05-0.08 μmol l⁻¹ h⁻¹) to late spring (up to 4.64 μmol l⁻¹ h⁻¹) and remained relatively high during the summer (0.46-0.71 μmol l⁻¹ h⁻¹), due to an increase in specific phytoplankton (up to 30 μmol μg C⁻¹ h⁻¹) and bacterial APA (up to 23 μmol μg C⁻¹ h⁻¹). Activity of free enzymes was not important. During late spring and summer both communities exploited dissolved organic phosphorus although, taking into account biomass, phytoplankton activity usually dominated over bacterial. In autumn an extra P supply from deeper waters drastically reduced phytoplankton APA, though not bacterial APA, in upper waters. Probably in these months bacteria that were degrading phytoplankton-produced organic matter were P limited. In deeper waters APA was low and mainly due to the activity of free enzymes.

1. INTRODUCTION

The northern Adriatic is characterised by significant freshwater input, mainly from the Po River. In Po River waters the average total phosphorus and total nitrogen concentrations in the 1999-2002 period (5.16 μmol l⁻¹ and 285.71 μmol l⁻¹, respectively; Milan et al., 2003), were more than an order of magnitude higher than in northern Adriatic waters (Giani, 2003). Consequently, riverine waters increase nutrient content in seawater leading to high microbial activity and eutrophication of the western area of the northern Adriatic (Gilmartin and Revelante, 1983; Gilmartin et al., 1990; Karner et al., 1992). However, in river waters inorganic nitrogen concentrations (DIN) were markedly higher than orthophosphate (PO₄) concentrations, resulting in a strongly unbalanced N/P atomic ratio (about 100/1; Milan et al., 2003) for microbial requirements (balanced N/P=16/1 for phytoplankton, 9/1 for bacteria; Redfield et al., 1963; Goldman et al., 1987). As a consequence P limitation is expected in productive northern Adriatic waters influenced by freshwater. It was observed that in these waters organic phosphorus concentrations markedly exceeded PO₄ concentrations, representing an important source of P for microbial communities (Ivančić and Degobbis, 1987). In the presence of low PO₄ concentrations microbes can induce extracellular alkaline phosphatase (AP), which enables them to use organic phosphorus esters as a source of this element (see Hoppe, 2003). A study carried out during 2004 showed that in the concerned area AP was important for providing P for microbial growth, particularly during phytoplankton blooms.
induced by freshwater imported nutrients (Ivančić et al., 2009). Alkaline phosphatase
activity (APA) studies in the marine environment have been focused mainly on algae and
have rarely dealt with bacterial activities even though bacteria are also known to have
significant APA (Martinez and Azam, 1993; Labry et al., 2005). Recently, Zaccone et al.
(2002) showed that most of the bacterial strains in the northern Adriatic are capable of
expressing APA.

The objectives of the present paper are to evaluate the importance of
phytoplankton and bacteria in expressing APA in one of the most productive areas of the
northern Adriatic. In this area where inorganic N supply greatly exceeds inorganic P
supply, productivity depends on the ability of microorganisms to obtain P from dissolved
organic phosphorus (DOP). For this purpose total APA and parameters characterising
microbial communities were measured seasonally at two stations mostly influenced by Po
River runoff. Phytoplankton and bacterial APA were determined during blooms induced by
freshwater imported nutrients, as well as during minimal external nutrient input in summer.
Even if size fractionation by filtration does not completely separate groups of
microorganisms (overlapping size) it does however give a useful indication as regards the
major microorganisms contributing to APA.

2. MATERIAL AND METHODS

2.1. Sampling strategy

Measurements were carried out at two stations (SJ101, SJ108) in the northern
Adriatic (Fig. 1) during 7 cruises performed from March to October 2006. These stations
were specifically chosen as they are in one area permanently under riverine nutrients
pressure, unlike other areas along the Rovinj-Po Delta profile which only intermittently
experience freshwater influence. Further, these stations represent two different regimes
where SJ108 is under direct freshwater nutrient influence while freshwater spreading
toward SJ101 is more impoverished with nutrients. During all cruises conventional
parameters (sea temperature, salinity, nutrients, DOP, chl a, bacteria and
picocyanobacteria counting and phytoplankton determination) and total APA were
measured at three depths within the water column (surface, 10 m, and 1 m from the
bottom: 30 m). In addition, APA fractions were determined during blooms in different
seasons (May, September and October), as well as during minimal phytoplankton biomass
in June.
2.2. Analytical protocol

Water samples were collected with 5 l PVC Niskin samplers. Temperature and salinity profiles were acquired during the downcasts of a Seabird SBE 25 CTD probe.

Inorganic nutrient analyses were performed onboard, on unfiltered water immediately after sample collection, using methods widely used in oceanography (Strickland and Parsons, 1972; Ivančić and Degobbis, 1984). Samples for total dissolved phosphorus were filtered (Whatmann GF/C, precombusted at 500 °C) and stored in polyethylene tubes at -30 °C. In the laboratory ashore analyses were performed using a chemical combustion method with persulphate (Menzel and Corwin, 1965). DOP was calculated by subtracting PO₄ from the total dissolved phosphorus. DIN was calculated as the sum of nitrate, nitrite and ammonia. The N/P ratio was calculated by linear regression between PO₄ and DIN.

Determination of APA was performed aboard the research vessel immediately after sample collection. Measurements were carried out in unfiltered water (total APA) and two pre-filtered fractions: <0.22 μm and <3 μm. Picocyanobacteria and heterotrophic bacteria overlap in size ranges, and for this reason filters of 3 μm were preferred (retaining bacteria and picocyanobacteria) instead of 1 μm, which do not retain all bacteria, or 2 μm at which an unknown part of picocyanobacteria is retained. The abundance of picoeukaryotes which are not retained on the 3 μm filters was three orders of magnitude lower than picocyanobacteria abundance (Fuks, unpublished data). The nanophytoplankton fraction was retained on the 3 μm filter, as confirmed by microscopic measurements. The 0.2-3 μm fraction contained heterotrophic bacteria and picocyanobacteria, mainly *Synechococcus* (Fuks, unpublished data), and is subsequently referenced in the text as the bacterial fraction. The >3 μm fraction contained nano- and microphytoplankton and is subsequently referenced as the phytoplankton fraction.

All APA measurements were performed in duplicate with a fluorogenic substrate analogue using methyllumbelliferyl-phosphate (MUF-P) dissolved in methylcelllosolve and diluted with water immediately before addition following the procedure of Hoppe (1983). The final concentration of substrate in sample was 50 μmol l⁻¹. This concentration was chosen since it was observed that in seawater with various microbial activities saturation
with substrate was always achieved (Ivančić et al., 2009). In addition, kinetic parameters
(half saturation constant \(K_m\), maximum activity \(V_{max}\)) were determined at the surface at
SJ108 in May, June and September using various MUF-P concentrations (0.5, 5, 10, 50,
100, 150, 200, 250 \(\mu\)mol l\(^{-1}\)). Incubation was performed in the dark in an insulated water
bath using water collected from the same depth as the sample to maintain the \textit{in situ}
temperature and pH. Fluorescence was measured immediately after substrate addition
and after \(\sim 1\) h of incubation using a Turner TD-700 fluorometer with excitation at 365 nm
and emission at 460 nm. APA was calculated as the difference between these two
measurements divided by the incubation time after calibration of the fluorometer with
methylumbelliferone. Results are presented as the mean value of duplicates. \(K_m\) and \(V_{max}\)
were calculated using Woolf-Hanes linearization. Although several methods are available,
P turnover time \((T_n)\) was estimated by the \(K_m/V_{max}\) ratio as, for example, in Labry et al.
(2005). An alternative method for determining turnover time as described by Xu et al.
(2008) gave nearly identical results when DOP concentration was used as the natural
substrate concentration (organic phosphorus esters). However, results using the latter
method are not reported here since DOP concentration is not always a good
approximation of the natural substrate concentration which is not measured.

The samples for chl \(a\) determination (Strickland and Parsons, 1972) were filtered
onboard through Whatmann GF/C filters and stored at \(-30\) °C. Extractions with 90%
acetone and fluorometric analyses were performed in the onshore laboratory within a few
days.

Samples for microphytoplankton determination (200 ml) were filtered through a 300 \(\mu\)m
mesh plankton net to remove zooplankton, and filtrates were preserved with Lugol solution
(2% final concentration) and buffered with sodium acetate. Microphytoplankton abundance
and composition were determined in the filtrate at 200x magnification by a Zeiss inverted
microscope after 40 hours of sedimentation of a 50 ml subsample using the Utermöhl (1958)
settling technique.

Samples for bacteria abundance (BA) and picocyanobacteria abundance (CBA)
were preserved with formaldehyde (2% final concentration) and stored at 4 °C. BA was
determined by cell counting using an epifluorescence microscope after staining with 4’,6-
diamido-2-phenylindole (Porter and Feig, 1980). CBA was also determined by
epifluorescence microscopy and distinguished by orange autofluorescence under green
excitation (Takahashi et al., 1985).
Specific APA in different fractions was calculated as the ratio between APA and the carbon content in each respective fraction. BA was converted to carbon content by a conversion factor of 20 fg C/cell (Lee and Fuhrman, 1987) and CBA by a factor of 250 fg C/cell (Kana and Gilbert, 1987). Phytoplankton C content was obtained by converting chl a using a factor of 50 µg C/µg chl a (Antia et al., 1963) followed by the subtraction of C content in picocyanobacteria. The bacterial and phytoplankton C content calculated from the abovementioned factors are commonly used to calculate their respective specific APA (Sala et al., 2001, Nausch et al., 2004; Labry et al., 2004) and data presented here are comparable with literature data.

Statistical analyses were performed using ANOVA and t-test for groups (differences between seasons) and for pairs (differences between stations) on log transformed data.

3. RESULTS

3.1. Hydrological conditions and nutrient status

In March the entire water column at both stations was cold (7.6-8.1 °C) and homogenous (Fig. 2a). In the April-July period temperatures increased (16.9-27.8 °C at the surface and 8.7-13.4 °C at the bottom) with the establishment of thermal stratification. During September cooling of the surface started mixing in the water column and in October a nearly homogenous layer extended down to 20 m (18.1-21.6 °C) with increased values in the bottom waters (16.2-18.4 °C; Fig. 2a). Haline stratification started from April and persisted during the entire investigated period, except at SJ101 in June (Fig. 2b). At SJ108 the Po River plume (salinity <36) was detected in April, May and September to a depth of about 2-6 m. At this station freshwater influence was weak in June, July and October (surface salinity 36.6-37.1; Fig. 2b). At SJ101 the Po River plume was detected in May, September and October to a depth of about 1-6 m, while in April, June and July freshwater influence was weak (surface salinity 36.4-37.9; Fig. 2b). It should be noted that salinity was usually lower at SJ108 than at SJ101 though differences were not significant at a probability level p<0.05. At a depth of 10 m and below the contribution of riverine water at both stations was always low and salinity was >37.

Fig. 2

PO₄ concentrations were always low (0.00-0.07 µmol l⁻¹) in the entire water column at both stations, even in the Po River plume, except for higher values (0.23 µmol l⁻¹) at the
bottom in October (Fig. 3a). DOP concentrations were always several times higher than PO₄ concentrations. In March and October DOP (generally 0.3-0.5 μmol l⁻¹) was considerably higher than from April to July (generally 0.05-0.25 μmol l⁻¹) when somewhat higher values (up to 0.3 μmol l⁻¹) were periodically found at the bottom (Fig. 3b). Periods with low DOP coincided with high APA, and vice versa (See next section). At the surface and 10 m depth DIN was present in surplus with respect to PO₄, resulting in a high N/P ratio (28/1; data not shown). At the surface high DIN concentrations (3.5-14.0 μmol l⁻¹) were found during freshets (April, May, September, October), while minimal values (0.58-1.18 μmol l⁻¹) were found during minimal freshwater influence (June and July; Fig. 3c). At 10 m depth values were lower than at the surface, but showed basically the same trend (Fig. 3c). At the bottom minimal DIN concentrations were found during June and July (generally about 1 μmol l⁻¹), and maximal during October (up to 8.68 μmol l⁻¹). In these waters DIN and PO₄ were generally balanced for microbial requirements (N/P 9/1; data not shown).

Fig. 3

It should be noted that nutrients’ concentrations at the surface were generally higher at SJ108 than at SJ101 due to better nutrient supply by freshwater though differences were not significant at a probability level p<0.05.

3.2. Microbial biomass evolution and total APA

The Po River plume was observed in April, May and September at SJ108, and in May, September and October at SJ101. In these waters freshwater imported nutrients increased phytoplankton biomass (102-667 μg C l⁻¹) while during the period of low freshwater influence phytoplankton biomass in the surface layer was markedly lower (about 1-24 μg C l⁻¹; Fig. 4a). Bacterial and picocyanobacterial biomass in the surface layer was not affected by freshwater, being generally higher in the July-October period (29-60 μg C l⁻¹) than in the first part of the year (typically 14-18 μg C l⁻¹; Fig. 4a). During blooms, phytoplankton biomass markedly exceeded bacterial and picocyanobacterial biomass, while in other situations they were either similar or bacterial and picocyanobacterial biomass exceeded that of phytoplankton. The highest total APA (2.59-4.64 μmol l⁻¹ h⁻¹) was observed during phytoplankton blooms, except at SJ101 in September and October when the increase in surface phytoplankton biomass did not result in increased total APA (Fig 4a). During June and July, as well as in October at
SJ108, periods characterised by low phytoplankton biomass, surface total APA (0.28-0.71 μmol l⁻¹ h⁻¹) was markedly lower. Minimal surface total APA (0.05-0.08 μmol l⁻¹ h⁻¹) was found in March when the water column was mixed, even though the microbial biomass was not lower than during the summer months (Fig. 4a).

Fig. 4

The phytoplankton blooms did not extend to intermediate waters (10 m depth) where phytoplankton biomass was generally low (6-34 μg C l⁻¹) and seasonal changes much less pronounced (Fig. 4b). In these waters bacterial and picocyanobacterial biomass was also generally lower (8-38 μg C l⁻¹) than at the surface, though usually higher than that of phytoplankton (Fig. 4b). In these waters total APA was lower than in upper waters (Fig. 4b). The lowest APA was found in March and at SJ101 also in October (down to 0.02 μmol l⁻¹ h⁻¹). In other months APA was generally 0.2-0.5 μmol l⁻¹ h⁻¹.

At the bottom phytoplankton biomass (14-40 μg C l⁻¹) was somewhat higher, while bacterial and picocyanobacterial biomass had similar ranges as in intermediate waters (Fig. 4c). In these waters phytoplankton biomass was generally similar to those of bacteria and picocyanobacteria. Total APA was lower than in upper waters and generally <0.15 μmol l⁻¹ h⁻¹ (Fig. 4c).

3.3. APA fractions

The overlap of the size spectra of bacteria, picocyanobacteria and phytoplankton could affect their APA estimation. However, in surface and intermediate waters the ratios APA in 0.2-3 μm fraction/total APA and APA>3 μm fraction/total APA were significantly correlated (r²=0.579, p<0.001) with the ratios bacterial biomass/total biomass and phytoplankton biomass/total biomass, respectively. This suggests that APA in the 0.2-3 μm fraction represented the bulk of bacterial and picocyanobacterial, while APA in the >3 μm fraction the bulk of phytoplankton, activity. Calculations were not made for the bottom layer where APA was not related to microbial biomass, but mostly due to free enzymes.

At the surface enzymatic activity was usually due to microbes, while activity of free enzymes was negligible (generally 0.0-4.2% of total activity; Fig. 5a). During the phytoplankton bloom in May practically all surface activity at both stations was due to the phytoplankton fraction (93.0-94.3%). In other months activity of the bacterial fraction also
became important (30.8-47.9%), and in September (at SJ101) and October (at SJ108) most of the enzymatic activity was due to this fraction (64.8-79.1%; Fig. 5a). At 10 m depth the contribution of free enzymes (7-20%) was higher than at the surface, though still much less important than that of the microbial fraction (Fig. 5b). In this layer the contribution of phytoplankton to total APA was generally lower than at the surface, while the bacterial contribution increased (Fig. 5b). At both stations in May and at SJ101 in June, most of the activity was due to the phytoplankton fraction (about 49-66%), while in September and October, and also in June at SJ108, the contribution of the bacterial fraction was more important (52.8-91.0%, Fig. 5b). At the bottom APA was mostly due to free enzymes (54-100%, Fig. 5c), except at SJ101 in June when the low activity was mostly due to bacteria.

Fig. 5

3.4 Specific APA and composition of the microbial communities

Statistical analysis (ANOVA) showed that at the surface and in intermediate waters specific phytoplankton and specific bacterial APA were significantly higher than at the bottom (p<0.02 and p<0.001, respectively), while differences between surface and intermediate waters were not significant. At the surface and in intermediate waters both phytoplankton and bacterial specific APA were high in May and June (7.64->30 nmol µg C\(^{-1}\) h\(^{-1}\) and 5.83-23.76 nmol µg C\(^{-1}\) h\(^{-1}\), respectively; Fig. 6a,b). It should be noted that due to the very low phytoplankton biomass in June there was greater uncertainty in the calculation of specific phytoplankton APA, hence these data were simply denoted as >30 nmol µg C\(^{-1}\) h\(^{-1}\) (in statistical analyses a value of 30 was used). In September and October specific phytoplankton APA dropped to low values (1.11-4.52 nmol µg C\(^{-1}\) h\(^{-1}\)), while specific bacterial APA did not show such a drastic decrease in these months. Statistical analyses (t-test for groups) confirmed that in surface and intermediate waters specific phytoplankton APA during May and June (stratification period; mean value 17.11 nmol µg C\(^{-1}\) h\(^{-1}\)) was significantly higher than during September and October (period when mixing in the water column started; mean value 2.03 nmol µg C\(^{-1}\) h\(^{-1}\); Table 1), while differences in specific bacterial APA for those two periods were much smaller (mean values 9.91 and 7.27 nmol µg C\(^{-1}\) h\(^{-1}\), respectively) and were not significant (Table 1). At the surface specific bacterial APA in October was lower (3.78-6.07 nmol µg C\(^{-1}\) h\(^{-1}\)) than in other months, while in intermediate waters a decrease in October was observed only at SJ101 (Fig. 6b).
In surface and intermediate waters specific bacterial APA was always higher at SJ108 than at SJ101 (Fig. 6b; Table 1) while, to the contrary, specific phytoplankton APA was higher at SJ101, though only during the stratification period (Fig 6a; Table 1). Differences between stations for specific bacterial APA were statistically significant while those for specific phytoplankton APA were not significant.

Table 1

At the bottom the specific APA of both fractions was always low (generally <2 nmol μg C⁻¹ h⁻¹; Fig 6a,b) and no statistical differences between stations and periods were found (data not shown).

Since observed seasonal and spatial variation in specific phytoplankton and bacterial APA in the surface and intermediate waters could be due to changes in the respective communities’ composition, data characterising communities composition were analysed and compared with changes in their respective specific APA. At both stations the micro- and nanophytoplankton contributions alternated in importance irrespective of high or low specific phytoplankton APA (Table 2). At both stations and in all months diatoms predominated in the microphytoplankton fraction, except in June at the surface at SJ101.

Table 2

Dominant species during the period of high specific phytoplankton APA (Pseudo-nitzschia delicatissima, Nitzschiella sp., Skeletonema sp.) were also abundant during the period of low specific phytoplankton APA (Table 3). During the period of high specific phytoplankton APA species composition at the surface (Table 3) and in intermediate waters (data not shown) in June differed at the studied stations. However, in May at both stations Pseudo-nitzschia delicatissima strongly dominated in the microphytoplankton fraction. Further, in May the abundance of Nitzschiella sp was similar at the surface at both stations. Moreover, while in June at SJ101 Prorocentrum triestinum was the dominant species at the surface (Table 3) and Pseudo-nitzschia delicatissima in intermediate waters (data not shown), both of these species were however present in much higher abundance during the bloom in May at SJ108.

Table 3
The bacterial and picocyanobacterial contributions to the bacterial fraction biomass alternated in importance at both stations and no relation with the level of specific bacterial APA was observed (Table 4).

Table 4

3.5. Kinetic parameters of APA

Total APA as a function of substrate concentration measured in May, June and September at the surface of SJ108 fitted the Michaelis-Menten model (Fig. 7). Activity increased up to a substrate concentration of 50 μmol l⁻¹, where V_max was reached, and then remained constant or slightly decreased. In May and September V_max (3.89 and 3.83 μmol l⁻¹ h⁻¹, respectively) was similar and markedly higher than in June (0.54 μmol l⁻¹ h⁻¹). The highest K_m was calculated for June (7.97 μmol l⁻¹), while in May and September (1.22 and 0.62 μmol l⁻¹, respectively) was significantly lower. Turnover time of phosphorus estimated from V_max and K_m was very short in May and September (0.31 and 0.16 h, respectively) and longer in June (14.79 h; Fig. 7).

Fig. 7

DISCUSSION

The seasonal evolution of total APA during 2006 was similar to that found in 2004 (Ivančić et al., 2009) and 2005 (Ivančić, unpublished data). Furthermore a decrease of DOP concentrations as a result of high APA was again observed. This indicates that the same seasonal pattern of APA occurs year by year and that DOP is an important source of P in the region. In March 2006 the investigated area was not influenced by freshwater, and hence the freshwater import of nutrients was minimal. At the time a modest phytoplankton and bacterial biomass developed on nutrient reserves regenerated in the water column during winter. Very low total APA, as well as specific APA (total APA/ total microbial carbon content, 1.46-1.89 nmol μg C⁻¹ h⁻¹; data not shown), showed that microbes were not P limited. As a consequence of the microbial activity during early spring, regenerated nutrients in the surface layer were consumed. The phytoplankton blooms that developed in April and May in the low saline waters were stimulated with freshwater imported nutrients. Since freshwater P supply is markedly lower when compared to N supply (see Introduction), significant DIN remained in the water while PO₄ was exhausted and DOP became the largest reservoir of dissolved P available to
microbes. Consequently, a large increase of total APA (up to 40 times) occurred. As
temperature differences of about 10 °C were noted, APA would be expected to only
double (Petersson and Jansson, 1978). Therefore, temperature was considered to be a
less important factor, and the increased APA was the response of the microbial
communities to P limitation. APA was practically all due to microbial expression, and
activity of free enzymes was not important. A major part of the surface activity was due to
the phytoplankton fraction, mainly due to a markedly greater algal than bacterial biomass.
The dominance of algal APA during the blooms was also observed in the Bay of Biscay
(Labry et al., 2005). In the present study specific APA was high in both the phytoplankton
and bacterial fractions, indicating that both communities were P limited. At SJ108 P
turnover time in surface waters, estimated from AP kinetic parameters, was very short
(about 20 min). Such a calculated P turnover time could be used to compare the rate of P
recycling in different situations since it agrees with $^{33}$P turnover times (Nausch et al., 2004;
Xu et al., 2008). Short AP mediated P turnover times (3-16 h) in P depleted conditions
were also found in many other areas, compared to much longer (<30-4585 h) in P
repleted conditions (Nausch et al., 2004; Labry et al., 2005; Xu et al., 2008).

In June and July the freshwater influence was weak and persistent stratification
hindered the replenishment of nutrients from deeper waters. Due to low external nutrient
input, phytoplankton biomass dropped to low values, while the decrease in bacterial and
picocyanobacterial biomass (smaller cells more efficiently use low nutrient concentrations)
was markedly less pronounced. In these conditions a marked decrease of surface total
APA was observed, mainly due to the decrease of phytoplankton APA, as shown by
fractionation in June. Surface APA was again practically all due to microbial expression,
although in contrast to May, in conditions of low phytoplankton biomass, bacteria
significantly contributed to total APA (30-44%). In June specific APA of both the
phytoplankton and bacterial fractions was even higher than in May, suggesting strong P
limitation. However, in conditions of low N supply this element could also limit microbial
growth and this is probably the reason for markedly longer P turnover times in surface
waters of SJ108 in June (about 15 h) compared to those during the bloom in May (about
20 min).

During autumn months total APA at the surface was low, irrespective of high or low
microbial biomass, except for a high value in September in an area where a large
microbial bloom was observed. Activity of free enzymes at the surface was not important.
While bacteria significantly contributed to total APA during phytoplankton blooms (31-
48%), their contribution was dominant in the absence of phytoplankton blooms (65-78%). The low specific phytoplankton APA found in autumn may be caused by a different percentage of phytoplankton actively expressing the enzyme due to less severe P limitation and/or by different phytoplankton species composition. However, inter-seasonal changes of size structure and composition of phytoplankton were not consistent with changes in specific phytoplankton APA. It is more probable that in autumn P limited phytoplankton growth less than during late spring and summer. In these months mixing of the water column started enriching upper waters with nutrients from deeper waters where they were regenerated in a close to balanced ratio for microbial requirements, as already observed during a previous study (Degobbis, 1990). Thus phytoplankton growth was stimulated not only by freshwater nutrients, but also by the nutrient flux from bottom waters. As a result PO₄ imported into the surface layer might be at higher concentrations and less deficient with respect to DIN than during spring and summer. Nausch (1998) found that PO₄ concentrations <0.2 µmol l⁻¹ stimulated production of enzymes leading to very high specific APA, while at PO₄ concentrations between 0.2-1 µmol l⁻¹ APA was a linear function of biomass and specific APA remained at the same level. Furthermore, a threshold for the regulatory function of PO₄ on APA was found at concentrations of 0.05-0.1 µmol l⁻¹ (Labry et al., 2005; Sebastian et al., 2004). In the present study it was difficult to compare PO₄ concentrations and enzyme production since imported PO₄ uptake was very fast and its concentrations in water were usually below the detection limit. However, specific phytoplankton APA indicated highly stimulated enzyme production during late spring and summer, while during autumn APA was simply a function of biomass, and specific APA remained at the same low level. In contrast, specific APA of the bacterial fraction did not show a significant decrease during autumn. While it may be noted that bacterial AP has a more complex function than that of phytoplankton, i.e. AP could also serve to provide C (see Hoppe, 2003), it is unlikely that bacteria were C limited. It is important to note that changes in specific bacterial APA were not related to the contribution of picocyanobacterial biomass to the total biomass of this fraction. It seems more probable that phytoplankton exhausted imported PO₄ and picocyanobacteria and bacteria were P limited. At the surface the highest specific APA in this fraction was observed at SJ108 during a large phytoplankton bloom in September. The high quantity of organic matter produced supported a large increase of bacteria. Most likely bacteria degrading the produced organic matter were P limited. During this bloom P turnover was fast (about 10 min) not only due to high bacterial activity, but also due to a high level of phytoplankton enzymes since phytoplankton biomass was very high.
In intermediate waters (10 m depth) total APA was markedly lower than in surface waters, in contrast to 2004 when activity at this depth did not differ noticeably from the surface (Ivančić et al., 2009). In 2006 Po River flow during spring and summer was considerably lower than in 2004 (unpublished data provided by Ministero dei Lavori Pubblici, Servizio Idrografico, Parma, Italy) and did not notably influence intermediate waters. As a consequence microbial biomass in these waters, especially phytoplankton, was low resulting in low total APA. In these waters the importance of free enzymes increased (9-30%), although the major part of APA was still due to microbes. In conditions where bacterial biomass was similar or somewhat higher than phytoplankton biomass, there was an increase of the bacterial contribution to enzyme production (up to 91%). Specific APA of both fractions followed the same pattern as in surface waters suggesting a similar seasonal evolution of P limitation in both communities.

A disproportion between specific phytoplankton APA and specific bacterial APA observed in surface and intermediate waters at the two stations was not related to differences in phytoplankton size and species composition or to the contribution of picocyanobacteria to the bacterial fraction, and was probably due to different nutrient content in those waters. Station SJ108 was generally better supplied with freshwater nutrients than SJ101. Phytoplankton superiority in PO₄ uptake was observed at high and bacterial superiority at low PO₄ concentrations (Thingstad et al., 1993; Xu et al., 2008). Therefore, at SJ108 phytoplankton probably took up most of the imported PO₄ and bacteria, degrading the phytoplankton produced matter, were even more P limited than phytoplankton. On the contrary, at SJ101 bacteria used low concentrations of PO₄ more efficiently and were less P limited than phytoplankton.

At the bottom total APA was low (generally <0.1 μmol l⁻¹ h⁻¹). In these waters low enzymatic activity was due mainly to free enzymes (up to 100%), while particulate activity was low. As a consequence phytoplankton and bacterial enzymatic activity was usually lower than expected from their biomass and thus specific APA was always low (generally <2 μg C⁻¹ h⁻¹) confirming that, in these waters where regeneration predominates over assimilation, microbes were not significantly P limited.

CONCLUSIONS

Both phytoplankton and bacteria use APA to obtain P, though with different seasonal patterns. During late spring phytoplankton blooms the major part of APA was
due to the phytoplankton fraction, mainly as a result of markedly greater algal biomass
than bacterial biomass. In summer, when phytoplankton and bacterial biomass were
similar, both communities significantly contributed to total APA. Strong P limitation of both
communities was observed during the stratification period when the phosphorus supply in
upper waters depended on phosphorus recycling in these waters or freshwater input. A
more balanced P supply during the period when mixing in the water column started
drastically reduced phytoplankton, though not bacterial, AP production in upper waters. In
this period the strongest P limitation of bacteria was observed during the massive
phytoplankton bloom in September when they were degrading a high quantity of
phytoplankton produced organic matter. In upper waters activity of free enzymes was not
important, while in bottom waters enzymatic activity was due mainly to free enzymes.

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of microbial communities in northern Adriatic fronts” (098-0982705-2729), „Mechanism of long-
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funded by the Ministry of Science, Education and Sport of the Republic of Croatia.

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controlling plant nutrient concentrations in the northern Adriatic Sea. Internationale


CAPTIONS

Fig. 1. Research area and sampling stations in the northern Adriatic Sea.

Fig. 2. (a) Temperature and (b) salinity profiles in March (○●), April (△▲), May (◇◆), June (▽▼), July (▷◆), September (◁▲) and October (□■) at SJ101 (open symbols and thin line) and SJ108 (filled symbols and thick line) in 2006.

Fig. 3. (a) PO₄, (b) DOP and (c) DIN profiles in March (○●), April (△▲), May (◇◆), June (▽▼), July (▷◆), September (◁▲) and October (□■) at SJ101 (open symbols and thin line) and SJ108 (filled symbols and thick line) in 2006.

Fig. 4. Seasonal evolution of phytoplankton (○, thin line) and bacterial and picocyanobacterial (△, dashed line) biomass and total APA (◇, thick line) at (a) the surface, (b) 10 m depth and (c) the bottom at sampling stations in 2006.

Fig. 5. Contribution of phytoplankton (grey), bacteria and picocyanobacteria (white) and free enzymes (black) to total APA at (a) the surface, (b) 10 m depth and (c) the bottom at sampling stations in 2006.

Fig. 6. (a) Specific phytoplankton and (b) bacterial APA at the surface (●), 10 m depth (◇, dashed line) and the bottom (△, dash dot line) at sampling stations in 2006.

Fig. 7. Michaelis-Menten kinetics of total APA in May (●, thick line), June (△, dashed line) and September (◇, thin line) at the surface at station SJ108. Values of $V_{\text{max}}$ (μmol l⁻¹ h⁻¹), $K_m$ (μmol l⁻¹) and $T_n$ (h) are also reported.
Table 1. Mean values (\(\bar{x}\)), standard error (SE) and number of data (N) for specific phytoplankton APA (sAPA\textsubscript{phyto}) and specific bacterial APA (sAPA\textsubscript{bact}). (a) Probability level (p) for differences between stratification and beginning of mixing periods at the surface and 10 m depth and (b) probability level for differences between stations at the surface and 10 m depths.

<table>
<thead>
<tr>
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<th>A</th>
<th></th>
<th>B</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Stratification</td>
<td>Beg. of mix.</td>
<td>SJ108</td>
<td>SJ101</td>
</tr>
<tr>
<td></td>
<td>(\bar{x}) (SE)</td>
<td>N</td>
<td>(\bar{x}) (SE)</td>
<td>N</td>
</tr>
<tr>
<td>sAPA\textsubscript{phyto}</td>
<td>17.10 (3.07)</td>
<td>8</td>
<td>2.03 (0.66)</td>
<td>8</td>
</tr>
<tr>
<td>sAPA\textsubscript{bact}</td>
<td>9.91 (2.60)</td>
<td>8</td>
<td>7.27 (2.00)</td>
<td>8</td>
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</table>

*data for the stratification period only
Table 2. Size composition of phytoplankton expressed as the % of micro fraction (Micro) in total chlorophyll a (chl a) and % of Diatoms in micro fraction during the period of high and low specific phytoplankton APA at the surface and 10 m depth.

<table>
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<th>Date</th>
<th>Micro %</th>
<th>Diatoms %</th>
<th>Date</th>
<th>Micro %</th>
<th>Diatoms %</th>
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<td>64</td>
<td>60</td>
<td>21.09.06</td>
<td>48</td>
<td>98</td>
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<td></td>
<td>10</td>
<td></td>
<td>41</td>
<td>95</td>
<td></td>
<td>13</td>
<td>98</td>
</tr>
<tr>
<td>SJ101</td>
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<td>18.05.06</td>
<td>85</td>
<td>98</td>
<td>21.09.06</td>
<td>15</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>62</td>
<td>96</td>
<td></td>
<td>18</td>
<td>100</td>
</tr>
<tr>
<td>SJ108</td>
<td>0</td>
<td>12.06.06</td>
<td>53</td>
<td>99</td>
<td>17.10.06</td>
<td>24</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>28</td>
<td>96</td>
<td></td>
<td>19</td>
<td>100</td>
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<td>33</td>
<td>25</td>
<td>17.10.06</td>
<td>54</td>
<td>100</td>
</tr>
<tr>
<td></td>
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<td>30</td>
<td>79</td>
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<td>27</td>
<td>97</td>
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</table>
Table 3. List of the most abundant species of microphytoplankton at the surface during periods of high and low specific phytoplankton APA.

<table>
<thead>
<tr>
<th>Station</th>
<th>Date</th>
<th>High specific APA</th>
<th>Cell l⁻¹</th>
<th>Date</th>
<th>Low specific APA</th>
<th>Cell l⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ108</td>
<td>15.05.06</td>
<td><em>Pseudo-nitzschia delicatissima</em> 205860</td>
<td>21.09.06</td>
<td><em>Chaetoceros sp.</em> 306900</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Prorocentrum balticum</em></td>
<td>102930</td>
<td><em>Thalassiosira sp.</em> 244200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Diplolopsis lenticula</em></td>
<td>18980</td>
<td><em>Nitzschiella sp.</em> 244200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Nitzschiella sp.</em></td>
<td>14600</td>
<td><em>Asterionellopsis glacialis</em> 86900</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Prorocentrum triestinum</em></td>
<td>9460</td>
<td><em>Pseudo-nitzschia delicatissima</em> 55000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Chaetoceros sp.</em></td>
<td>8760</td>
<td><em>Thalassiosira sp.</em> 244200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Prorocentrum micans</em></td>
<td>8760</td>
<td><em>Nitzschiella sp.</em> 244200</td>
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<td></td>
<td><em>Glenodinium sp.</em></td>
<td>5110</td>
<td><em>Asterionellopsis glacialis</em> 86900</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td><em>Ceratium furca</em></td>
<td>5110</td>
<td><em>Pseudo-nitzschia delicatissima</em> 55000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SJ101</td>
<td></td>
<td><strong>Pseudo-nitzschia delicatissima</strong> 273750</td>
<td></td>
<td><strong>Chaetoceros affinis</strong> 7700</td>
<td>52800</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td><em>Nitzschiella sp.</em></td>
<td>13140</td>
<td><em>Asterionellopsis glacialis</em> 34600</td>
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<tr>
<td></td>
<td></td>
<td><em>Bacteriastrium delicatum</em></td>
<td>6570</td>
<td><em>Leptocylindrus danicus</em> 15900</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td><em>Prorocentrum triestinum</em></td>
<td>9460</td>
<td><em>Pseudo-nitzschia delicatissima</em> 15400</td>
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<td>8760</td>
<td><em>Chaetoceros sp.</em> 64900</td>
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<td>SJ108</td>
<td>12.06.06</td>
<td><em>Skeletonema sp.</em></td>
<td>8140</td>
<td>17.10.06</td>
<td><em>Chaetoceros affinis</em> 13200</td>
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<td><em>Cerataulina pelagica</em></td>
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<td><em>Prorocentrum micans</em></td>
<td>2220</td>
<td><em>Cyclotella sp.</em></td>
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<td></td>
<td></td>
<td><em>Nitzschiella sp.</em></td>
<td>2220</td>
<td><em>Chlorella sp.</em></td>
<td>9900</td>
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<tr>
<td>SJ101</td>
<td></td>
<td><strong>Pseudo-nitzschia delicatissima</strong> 11100</td>
<td></td>
<td>*<em>Nitzschiella sp.</em> 244200</td>
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<tr>
<td></td>
<td></td>
<td><em>Hemiaulus hauckii</em></td>
<td>1110</td>
<td><em>Leptocylindrus danicus</em> 7700</td>
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<td></td>
<td></td>
<td><em>Glenodinium sp.</em></td>
<td>1110</td>
<td><em>Cerataulina pelagica</em></td>
<td>7700</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><em>Guinardia striata</em></td>
<td>6050</td>
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Table 4. Specific bacterial APA (bAPA) and % of picocyanobacteria (CB) in the bacterial fraction at the surface and 10 m depth.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>Depth</th>
<th>bAPA</th>
<th>CB</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>m</td>
<td>nmol µg C⁻¹ h⁻¹</td>
<td>%</td>
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<tr>
<td>15.05.06</td>
<td>SJ108</td>
<td>0</td>
<td>9.55</td>
<td>26</td>
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<td></td>
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<td>6.77</td>
<td>53</td>
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<td></td>
<td>SJ108</td>
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<td>5.83</td>
<td>12</td>
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<td></td>
<td>SJ108</td>
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<td>0.10</td>
<td>58</td>
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<td>12.06.06</td>
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<td>17.11</td>
<td>51</td>
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<td>27</td>
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<td>SJ108</td>
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<td>68</td>
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</table>
Figure 2

Fig. 2
Figure 3
Figure 4
Figure 5

Fig. 5
Figure 6

SJ108

Specific phytoplankton APA
nmol µg C\(^{-1}\)

Specific bacterial APA
nmol µg C\(^{-1}\)

15-May, 12-Jun, 21-Sep, 17-Oct

SJ101

>30

15-May, 12-Jun, 21-Sep, 17-Oct

Fig. 6
Figure 7

**May:** $V_{\text{max}} = 3.89; K_m = 1.22; T = 0.31$

**June:** $V_{\text{max}} = 0.54; K_m = 7.97; T = 14.79$

**September:** $V_{\text{max}} = 3.83; K_m = 0.62; T = 0.16$

**Fig. 7**