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The impact of sewage discharge on nutrients and community production in a lagoon environment (Lagoon of Strunjan, Gulf of Trieste, northern Adriatic Sea) – a revisited experiment

Vpliv vnosa komunalnih odplak na hranila in produkcijo v lagunarnem okolju (Strunjanska laguna) – ponovni ogled poskusa

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Abstract: A specially constructed enclosure in the lagoon environment (Lagoon of Strunjan, Gulf of Trieste, northern Adriatic Sea) received sewage daily while another was kept clean and used as a reference. Nutrients and community production changes were monitored approximately bimonthly over a year. Nutrients introduced by the sewage discharges and diluted by tides were immobilized by enhanced community production, in particular benthic macroalgae. The dead organic matter afterwards settled and decomposed producing anoxic conditions and high levels of dissolved and suspended organic nutrients in the water and total nitrogen in the sediments. The daily mean gross community production showed no quantitative differences between the two enclosures during the study. Differences arose in the temporal succession of the studied events. An intensive nutrient recycling emerged from this study.

Keywords: carbon, lagoons, nutrients, northern Adriatic, oxygen, production

Izvleček: V posebej zgrajeni bazen v Strunjanski laguni smo dnevno uvajali komunalne odplake mesta Piran, medtem ko je drugi služil za primerjavo. V odbobju enega leta smo s približno dvomesečno frekvenco spremljali gibanja koncentracij hranil in produkcije. Vnešena hranila, redčena s plimovanjem, so povečala produkcijo predvsem bentoških makroalg. Odmrla organska snov se je nato posedla in razgrajevala ter povzročila nastanek anoksije in visokih koncentracij raztopljene in suspendirane organske snovi in celotnega dušika v sedimentu. Srednja dnevna bruto produkcija v celoletnem obdobju ni pokazala velikh razlik med bazenoma, medtem ko so bile le-te opazne v časovnem poteku študiranih procesov. Iz poskusa je razvidno intenzivno kroženje vnešenih hranil.

Ključne besede: hranila, kisik, lagune, ogljik, produkcija, severni Jadran

Introduction

Pollution problems are particularly evident in coastal, estuarine and lagoon environments although the long-term effects extending over wider marine areas and oceans now deserve great attention (Clark 2001). However, most studies have dealt with the pollution of stressed coastal and estuarine environments (Kennish 1997, Prepas and Charette 2005). The application of mesoscale seawater enclosures (mesocosmos) allows for the testing of the responses of the isolated communities to various pollutants and provides a possibility for experimental manipulation and control. The requirements, advantages and disadvantages of this approach, an intermediate between microcosmos and field observations, were extensively reviewed in the past by Grice and Reeve (1982).

Due to their shallowness and penetration of sunlight to the bottom, lagoons, areas of great economic importance and influenced by pollution, are characterised by intense benthic primary production and respiration and are places of intense accumulation and recycling of organic carbon and nutrients (Nixon et al. 1976; Nowicki and Nixon 1985, McGlathery et al. 2001, Cloern 2001). Sediments with benthic communities are the most sensitive compartments of the lagoon system affected by eutrophication and oxygenation (Sfriso et al. 1992, Boynton et al. 1996). Due to the large storage capacity of organic matter and nutrients, their sediments have an important regulatory function. They influence the oxygen budget of bottom waters and releasing nutrients to the overlying water and affect the benthic and pelagic primary production (Jorgensen 1996). Due to the high rate of microbial processes, lagoon sediments are anoxic except for a thin surface layer and around the infauna burrows containing oxygen. The depth of the oxic-anoxic interface changes seasonally, mostly dependent on organic matter accumulation and oxygen levels in the overlying water. At present, our knowledge of the carbon and nutrient fluxes in these environments, which is the key factor to understand the functioning of lagoon and coastal systems, is still limited (Boynton et al. 1996).

In the present experiment, designed by the late professor J. *Štirn*, conducted in the period 1975-78 in the Lagoon of Strunjan (Gulf of Trieste, northern Adriatic Sea), the ecological (Malej et al. 1979) and pollution (Salihoglu et al. 1980, Stegnar et al. 1980) consequences of domestic sewage on the lagoon environment were studied. In this article, the results of an approximately year-long study on nutrients and community production changes are presented and discussed in the new perspective.

Materials and methods

Study area and design of the controlled pollution experiment

The Lagoon of Strunjan (<1 km^2) is located in the southeastern part of the Gulf of Trieste (Slovenia), the northernmost part of the Adriatic Sea (Fig. 1). The lagoon is very shallow (0.6 m, on average) and at lower low tide some portions of the bottom are exposed to the air. The lagoon is characterised by semi-diurnal tidal fluxes (65 cm mean). Freshwater inflows are scarce and limited mostly to the northwestern part. Salinity varies between 33 and 38. Water temperature ranges from maximum values (28 °C) in summer to minimum values in winter (4 °C).

Sediment from the Lagoon of Strunjan is composed mainly of calcite (31%) and quartz (29%) and consists of >90% of silt-clay sized material (Ogorelec et al. 1991). A well-defined colour stratigraphy determined by the relative abundance of Fe-oxides and sulphides is present. The top centimetre was brown, followed by a black layer which coincides with reduced redox conditions in sediment.

The controlled lagoon ecosystem consisted of two stony enclosures each of 63 m^2 with an average depth of 0.6 m. The enclosures were connected to the main lagoon to allow for tidal oscillations. Each enclosure contained 38 m^3 of seawater at the mean tidal level. One enclosure (PB) was treated daily with 300 l of primary settled sewage (Tab. 1) during the lowest level of seawater. The sewage was transported from the Piran sewerage system monthly and stored in a 5 m^3 plastic tank. The addition of the sewage to the polluted enclosure was done via a single discharge outlet. The other enclosure (CB) was kept clean as a control.

Naturally, the lagoon sediment was mainly inhabited by sea grasses (*Cymodocea nodosa* and *Zoosterella noltii*) with some branches of *Laurentia obtusa* and *Cystoseira barbata*, while the central part of the PB was occupied by some islands of *Ulva rigida* and *Enteromorpha compressa*. In the CB, *Ulva riqida* reached its normal spring peak and coexisted with *Laurentia obtusa, Cystoseira barbata* and *Giqartina acicularis*, whereas the PB became literally filled up with *Ulva*. At the end of

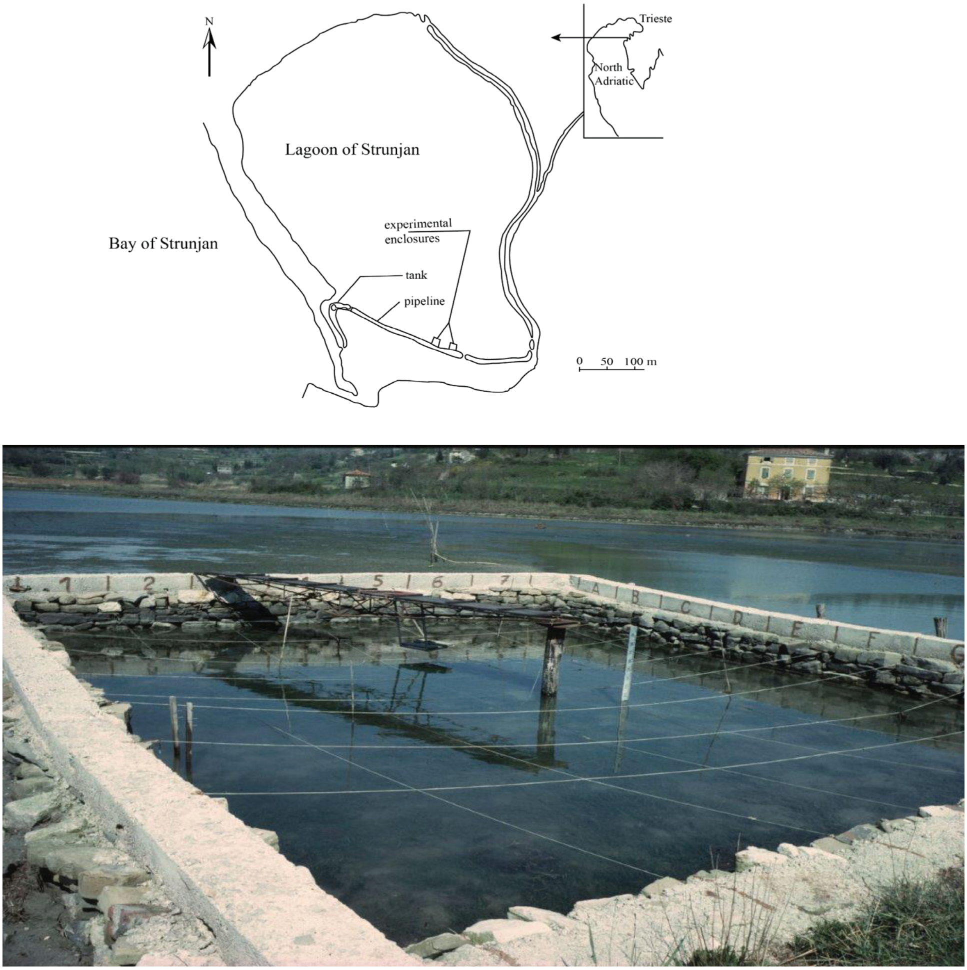

Figure 1: Location and design of the controlled ecosystem pollution experiment at Strunjan, Gulf of Trieste, northern Adriatic Sea

Slika 1: Lokacija in shema poskusa v Strunjanski laguni v Tržaškem zalivu, Severni Jadran.

spring all the vegetation decayed and bare sediment covered by Cyanophycea and Bacteria was left behined. In the CB, after the decay of *Ulva*, sea grasses and some macroalgae (*Cladophora battersi, Laurentia obtusa, Cladophora echinus, Cystoseira barbata, Polysiphonia tenerrirna*) developed according their normal seasonal dynamics (Malej et al. 1979). Natural lagoon macrofauna typically associated with sea grass modified under the stress of experimental pollution, and a few supertolerant organisms, increased in biomass and abundance: *Neantes succinea, Scolelepis fuliginosa and Capitella capitata,* a shrimp *Upogebia litoralis* and some Amphipodes which were the most abundant (Malej et al. 1979). The main groups of meiofauna in both experimental enclosures were Nematoda, Harpacticoidea, Polychaeta, Olygochaeta and Ostracoda, while Kinorhyncha, Turbellaria, Cumacea and some others were only accidental, these being found in the PB only at the beginning of the experiment (Vrišer 1982). The main phytoplankton genera in both enclosures

Table 1: Average daily discharged nutrients to the polluted enclosure by primary settled sewage from the town of Piran (in grams per 300 L of sewage) (N = 7).

Tabela 1: Povprečni dnevni vnos hranil v onesnaženi bazen s primarno čiščeno piransko komunalno odplako (v gramih na 300 L odplake) (N = 7).

Nutrient	Quantity
NO_3^-	0.03
NO_2^-	0.03
NH_4^+	2.50
DON	1.61
PN	2.82
PO_4^{3-}	3.75
DOP	0.09
PP	3.40
SiO_4^{4-}	4.26
POC	6.89
Total suspended matter	**25.60**

Abbreviations:
DON, dissolved organic nitrogen, raztopljeni organski dušik; DOP, dissolved organic phosphorus, raztopljeni organski fosfor; PN, particulate nitrogen, suspendirani dušik; PP, particulate phosphorus, suspendirani fosfor; POC, particulate organic carbon, suspendirani organski ogljik.

were *Navicula*, *Nitzschia*, *Amphora*, *Amphiprora* and *Gymnodinium* as well as microflagellates which were more numerous in the PB, while diatoms were more abundant in the CB (Fanuko 1984). Conversely the phytoplankton biomass and abundance were lower in the PB (Fanuko 1984). During the experiment the zooplankton community in the PB showed some regressive modifications since some organisms found in the CB were not detected in the PB: *Sarsia qemmifera*, *Muggiacea kochi*, *Ctenocalanus vanus*, *Clytemnestra sp.*, *Sapphirina sp.*, *Corycaeus sp.*, *Oikoplura lonqicauda*, *Oikopleura fusiformis*. In the first phase of the experiment the biomass and abundance of zooplankton organisms increased, the inhibitory effects of pollution later prevailed (Malej 1979).

Sampling

Seven diurnal samplings were conducted in both enclosures: September 16-17, 1976, November 15-16, 1976, February 28 – March 1, 1977, April 19-20, 1977, June 22-23, 1977, August 3-4, 1977, and October 4-5, 1977. Seawater samples were taken every 5-6 hours just below the surface and at a depth of 0.5 m using a Van Dorn sampler in a horizontal position. Undisturbed sediment cores were taken by pushing a plexiglass tube (6 cm i.d., 20 cm length) into the sediment. The top 2 cm was used for analyses.

Analyses

Dissolved O_2 in seawater was analysed via the Winkler method (Grasshoff 1976) using an automated titration system (Mettler Toledo, DL 21). The reproducibility of the method was 5 %. H_2S was determined spectrophotometrically after trapping with Zn acetate (Grasshoff 1976). The reproducibility of the method was 10 %. Dissolved inorganic carbon (DIC) was determined using a Van Slyke gas apparatus (Strickland and Parsons 1968). The reproducibility of the method was between 1.5–3 %. Nutrients analyses in unfiltered seawater and filtered sewage samples, through preignited glass fibre filters Whatman GF/C, were performed photometrically for ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-). phosphate (PO_4^{3-}) and silicate (SiO_4^{4-}), using standard methods (Strickland and Parsons 1968; Grasshoff 1976). Total dissolved nitrogen (TDN) and phosphorus (TDP) in the samples filtered through preignited glass fibre filters Whatman GF/C were analysed by irradiation for 3.5-4 hours using short wavelength UV radiation (1200 W, Hanovia, USA) in the presence of a few drops of 30 % H_2O_2 (Armstrong et al. 1966). Dissolved organic nitrogen (DON) and phosphorus (DOP) were calculated as the difference between TDN and dissolved inorganic nitrogen and between TDP and PO_4^{3-}, respectively. The precision of nutrient and DON and DOP analyses was 3%.

Analyses of organic C (C_{org}) and total N (N_{tot}) in freeze-dried particulate matter (particulate organic carbon - POC and particulate nitrogen - PN), collected on preignited Whatman GF/C glass fibre filters, and freeze-dried and homogenized sediment samples were performed using a Coleman C, H (Konrad et al. 1970) and N (Keeney and Bremner 1967) elemental analysers at combustion temperatures of 650 and 900 °C, respectively. Total P in freeze-dried particulate matter (PP), collected on preignited Whatman GF/C glass fibre filters, and sediments was determined by digestion of the sample with a mixture of perchloric and nitric acid followed by colorimetric detection of the phosphate produced (Strickland and Parsons 1968). The precision for C_{org},, N_{tot} and $P_{tot.}$ was about 3%.

Gross production was calculated from diurnal cycles of dissolved O_2 and DIC, examining the differences between extremes and estimating system parameters directly from ΔO_2 and ΔDIC (Odum 1956).

Production

Substantial diurnal O_2 and DIC changes were observed in both enclosures during the series of measurements. Inverse correlation appeared between diurnal O_2 and DIC changes in the experimental enclosures daily (Fig. 2). Differences in O_2 concentrations between the two enclosures started in spring 1977 and higher O_2 concentrations were observed in PB. In June 1977 (Fig. 2) in PB anoxic conditions prevailed during the night and H_2S was observed (up to 160 μM). Later (in autumn) the O_2 concentrations became uniform in both basins. The production (Tab. 2) measured from O_2 concentrations showed the highest values in CB in June and August 1977, while this occurred in PB in February 1977. Similar situation was found for the metabolism dynamics based on DIC measurements, considering that DIC concentrations in the northern Adriatic are largely attributed to the production and decomposition of

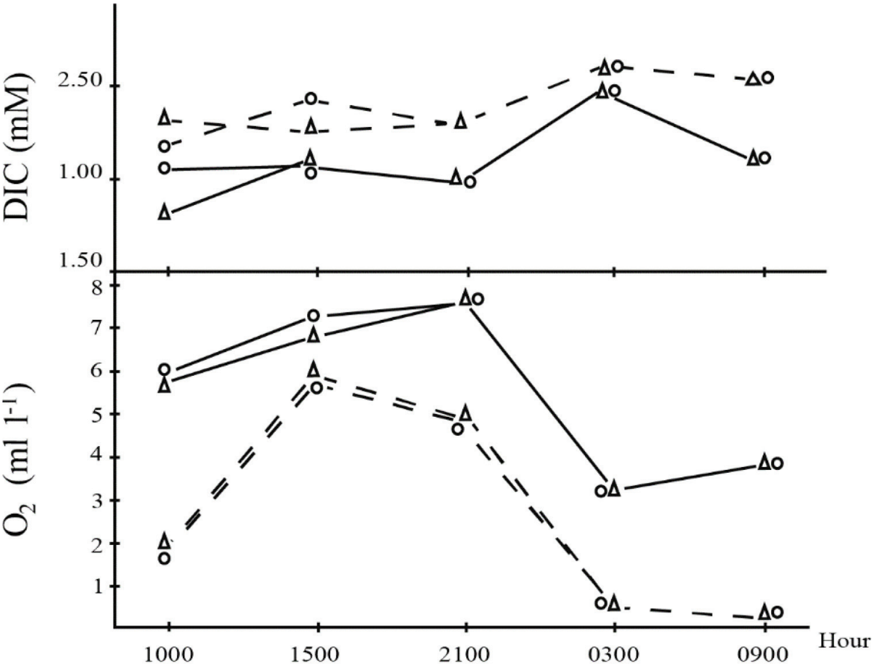

Figure 2: Diurnal variations of dissolved inorganic carbon (DIC) and oxygen (O_2) in clean enclosure (solid line) and polluted enclosure (dotted line) in surface (○) and bottom (Δ) layer in June 1977.

Slika 2: Dnevne variacije raztopljenega anorganskega ogljika (DIC) in kisika (O_2) v čistem bazenu (polna črta) in onesnaženem bazenu (črtkano) na površini **(○)** in pri dnu **(**Δ**)** junija 1977.

Table 2: Daytime community gross production in clean (CB) and polluted (PB) enclosure in the Lagoon of Strunjan (g m^{-2} day^{-1})
Tabela 2: Dnevna bruto produkcija v čistem (CB) in onesnaženem (PB) bazenu v Strunjanski laguni (g m^{-2} dan^{-1})

		O_2 production		DIC production	
Date	**Temperature (°C)**	**CB**	**PB**	**CB**	**PB**
9/28-29/1976	19.0-22.5	2.19	1.73	2.20	1.80
11/16-17/1976	12.3-18.7	2.00	2.18	3.02	2.04
2/28-3/1/1977	4.2-11.3	3.59	6.22	2.00	4.57
4/19-20/1977	10.9-16.6	2.28	5.46	2.02	3.27
6/22-23/1977	22.3-25.0	6.47	3.11	4.12	1.71
8/3-4/1977	22.0-26.7	5.44	3.62	-	-

Abbreviations: DIC, dissolved inorganic carbon; - , no data.
Okrajšavi: DIC, raztopljeni anorganski ogljik; -, ni podatka.

organic matter and less to carbonate dissolution and precipitation (Ogrinc et al. 2003). The highest values in CB and PB were found in February and June 1977, respectively. The production in PB in spring (March-April 1977) exceeded that of CB. Photosynthetic quotients (PQ, $\Delta O_2/\Delta DIC$) were mostly less than 1.0, except during high production in February 1977 in CB and in June 1977 in PB, probably as the consequence of the precipitation of carbonates (Cermelj et al. 2001) and the nonalgal incorporation of CO_2 (Johnson et al. 1981). Annual daily mean gross production from O_2 concentration variations was 3.7 g O_2 m^2 day^{-1} in both enclosures, those from DIC concentrations was 2.7 g C m^2 day^{-1}.

Nutrients

Nitrogen

Diurnal fluctuations of NH_4^+ concentrations were the most pronounced of all inorganic nitrogen compounds. The lowest NH_4^+ concentrations were observed in general during the photoperiodin both enclosures, while the highest concentrations were observed in PB just after the sewage input (Fig. 3). Great differences of NO_3^- and NO_2^- concentrations between the two enclosures were not observed during the diel cycles. The levels of inorganic nitrogen were higher during the winter (February 1977). In general, somewhat higher inorganic nitrogen, DON and PN concentrations were observed in PB (Fig. 4). The dissolved organic forms of nitrogen were lower than inorganic during the experiment except during the period of anoxia in June 1977 (Fig.4). The $N_{tot.}$ content in sediments averaged approximately 0.15 % in both enclosures, except in spring and summer 1977, when much higher levels (0.4-0.5 %) were found in PB (Fig. 4).

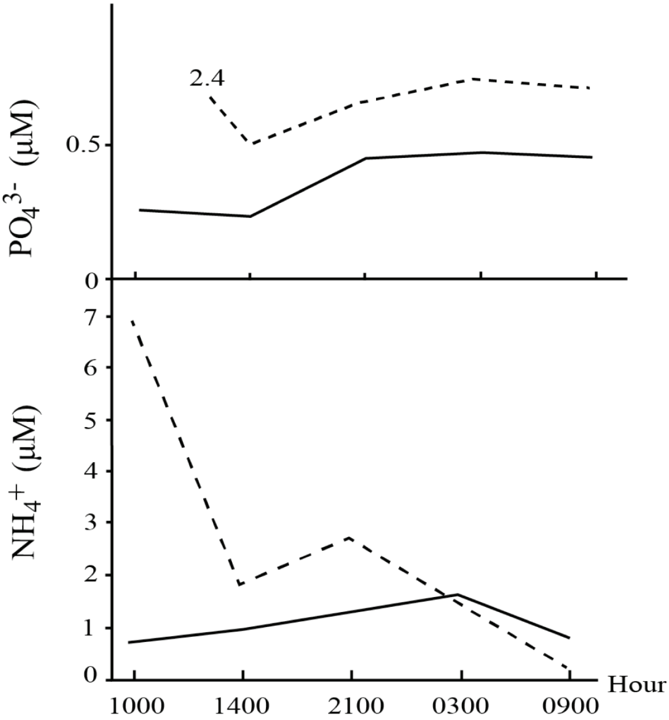

Figure 3: Diurnal variations of PO_4^{3-} and NH_4^+ in clean enclosure (solid line) and polluted enclosure (dotted line) in June 1977.

Slika 3: Dnevne variacije PO_4^{3-} and NH_4^+ v čistem bazenu (polna črta) in onesnaženem bazenu (črtkano) junija 1977.

Phosphorus

Diurnal fluctuations of PO_4^{3-} concentrations again showed lowest values during the photoperiod (Fig. 3). Somewhat higher PO_4^{3-} was detected in PB, especially just after sewage input, but the PO_4^{3-} concentrations dropped relatively fast to a level approximately equal to that in CB (Fig. 3). The lowest PO_4^{3-} concentrations in both enclosures during the experiment were observed in autumn (November 1977). The levels of DOP and PP were up to 100-times higher than that of PO_4^{3-} with the highest concentrations in PB during anoxia in June 1977 (Fig. 5). The DOP and PP concentrations in PB as well as the $P_{tot.}$ content in sediments of PB were in general slightly higher than in CB (Fig. 5). The $P_{tot.}$ contents in sediments of both enclosures nearly doubled (0.10-0.15 %) in spring 1977.

Silica

Diurnal fluctuations of SiO_4^{4-} concentrations (not presented) were similar to those of inorganic nitrogen and phosphorus, usually with lower concentrations during the photoperiod. The lowest concentrations in both enclosures were observed in February 1977 and the differences between the two enclosures were negligible (Fig. 6).

Organic carbon

Seasonal variations of POC concentrations showed the highest values in PB during anoxia (June 1977) and starting from 1977 higher levels were observed in PB (Fig. 6). Conversely, seasonal fluctuations of the $C_{org.}$ content in sediments in both enclosures were similar averaging approximately 2 % except in April 1977 when higher levels (3-4 %) were found (Fig. 6).

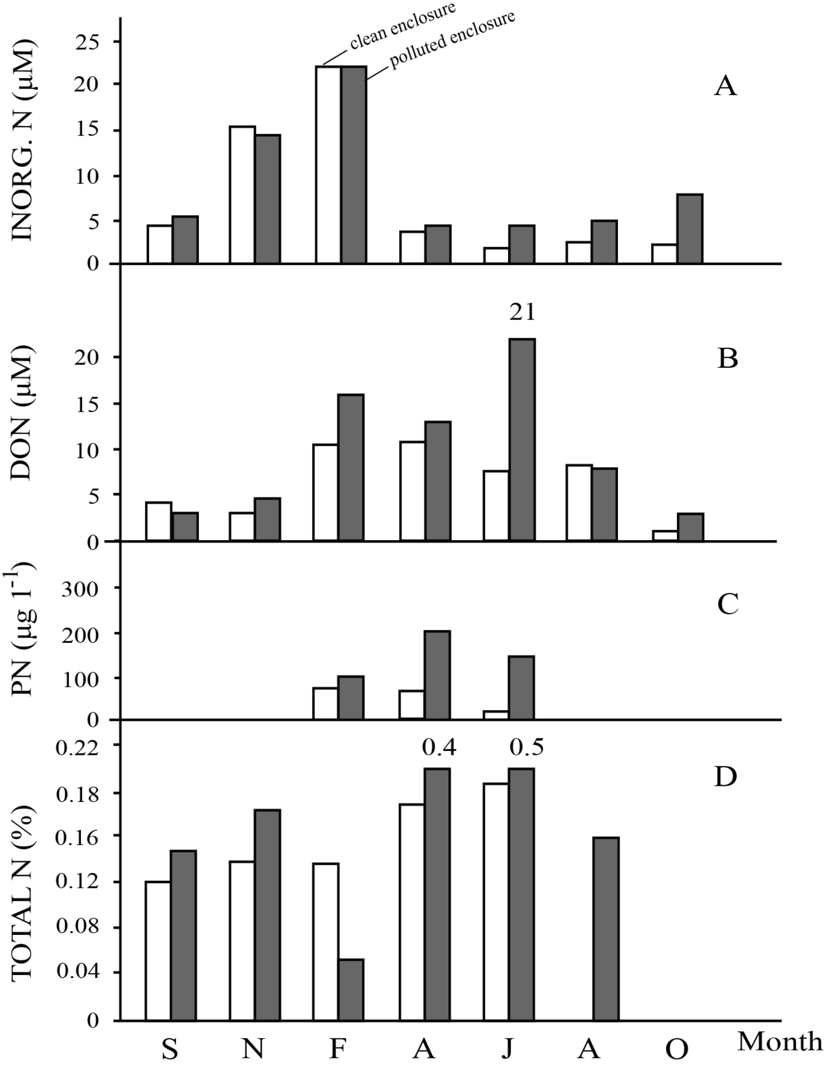

Figure 4: Variations of daily mean total inorganic nitrogen (NO_2^-+NO_3^-+NH_4^+) (A), dissolved organic nitrogen DON (B) and particulate nitrogen PN (C) concentrations in seawater, and total nitrogen content (D) in sediment in the experimental enclosures during the period September 1976 - October 1977.

Slika 4: Variacije povprečnih dnevnih koncentracij celotnega anorganskega dušika (NO_2^-+NO_3^-+NH_4^+) (A), raztopljenega organskega dušika DON (B) in suspendiranega dušika PN (C) v vodi ter koncentracij celotnega dušika v sedimentu (D) v poskusnih bazenih med septembrom 1976 in oktobrom 1977.

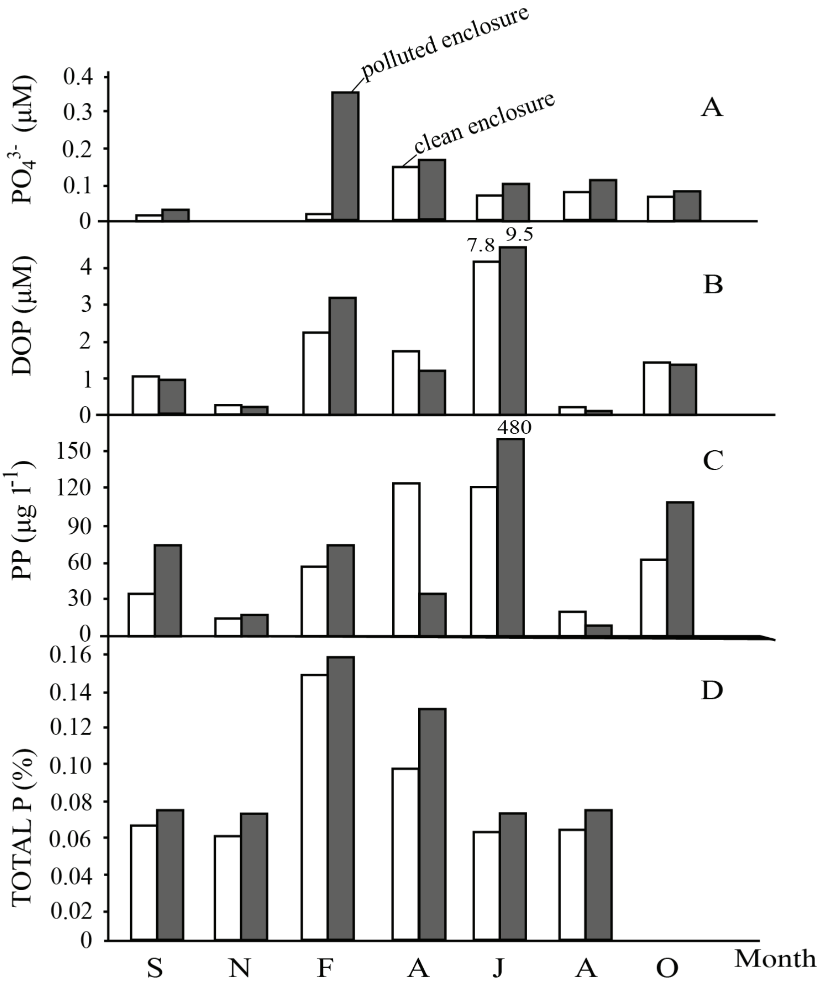

Figure 5: Variations of daily mean phosphate (A), dissolved organic phosphorus DOP (B) and particulate phosphorus PP (C) concentrations in seawater, and total phosphorus content in sediment (D) in the experimental enclosures during the period September 1976 – October 1977.

Slika 5: Variacije povprečnih dnevnih koncentracij fosfata (A), raztopljenega organskega fosforja DOP (B) in suspendiranega fosforja PP (C) v vodi ter koncentracij celotnega fosforja v sedimentu (D) v poskusnih bazenih med septembrom 1976 in oktobrom 1977.

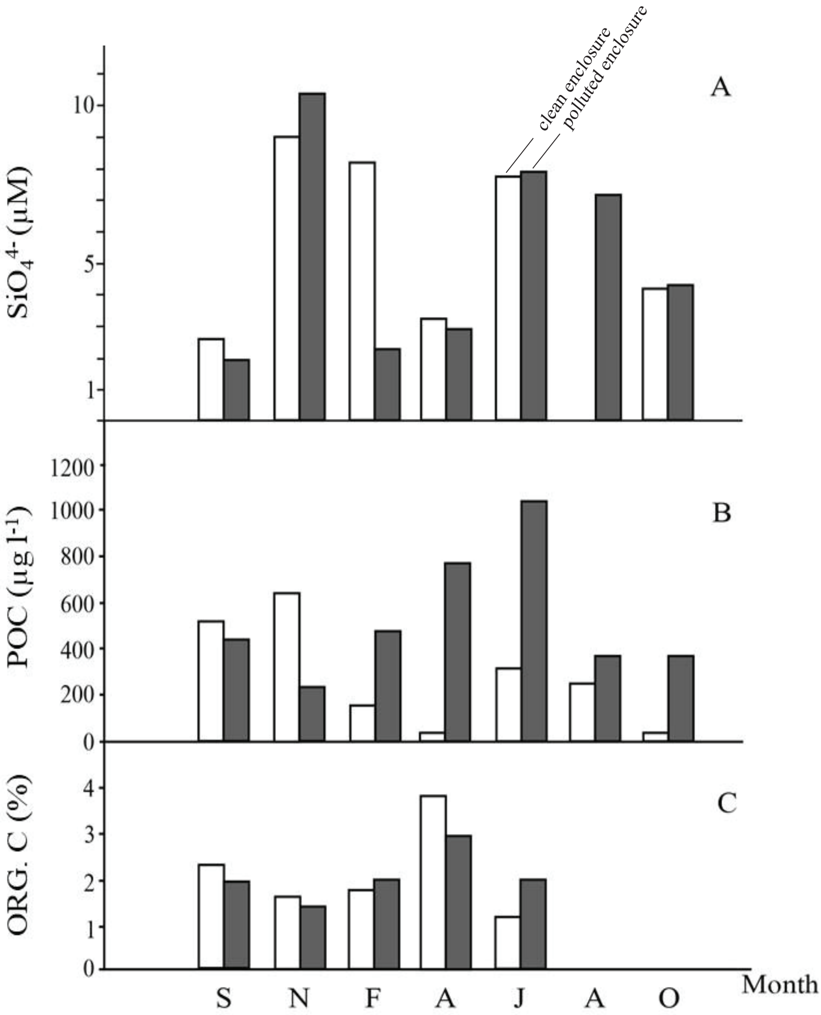

Figure 6: Variations of daily mean silicate (A) and particulate organic carbon POC concentrations (B) in seawater, and organic carbon content in sediment (C) in the experimental enclosures during the period September 1976 - October 1977.

Slika 6: Variacije povprečnih dnevnih koncentracij silikata (A) in suspendiranega organskega ogljika POC (B) v vodi ter koncentracij organskega ogljika v sedimentu (C) v poskusnih bazenih med septembrom 1976 in oktobrom 1977.

Discussion

From the results it is evident that the community in PB assimilated high nutrient input from the sewage discharges quite quickly. In addition, the dilution present due to the tidal exchange of water, particularly in spring and late summer, between the enclosures and the surrounding lagoon led to uniform nutrient concentrations after some hours in the two basins. Nutrients introduced in PB were also adsorbed onto suspended and sedimented particles, such as the adsorption of NH_4^+ on aluminosilicates (Faganeli et al. 1991), and PO_4^{3-} on Fe-oxides and the precipitation of authigenic P minerals (Ogrinc and Faganeli 2006) which was reflected in higher $P_{tot.}$ content in the PB sediments compared to CB. Rather low SiO_4^{4-} concentrations (2-3 μM) detected in September 1976 and April 1977 in both enclosures were likely due to the assimilation of Si by benthic diatoms (Welker et al. 2002) while high levels found in other periods may indicate dissolution of biogenic Si accumulating in sediments over time (Faganeli and Ogrinc 2009, Škrinjar et al. 2012). A significant decrease of NH_4^+ concentrations in PB after the sewage input, which prevails over NO_3^- in both enclosures, suggested NH_4^+ as an active inorganic nitrogen nutrient in assimilation processes. The high NH_4^+ concentrations could be also attributed to decomposition and mineralization of DON and bacterial reduction of NO_3^- during night anoxia in PB in June 1977 (Canfield et al. 2005). Levels of N, P and Si nutrients in CB, around those described for the Gulf of Trieste in the same period (Faganeli and Tušnik 1983, Faganeli 1983), supported rather high biomass in the lagoon. This indicated an efficient recycling of biogenic elements within the lagoon community (Mee 1978). High inorganic N/P ratios (>15, molar) observed in both enclosures suggest that an excess of nitrogen was present and that the whole lagoon ecosystem should be phosphorus limited in accordance with phosphorus limitation of the Sečovlje saltern (Škrinjar et al. 2012), Grado and Marano Lagoon (De Vittor et al. 2012, Petranich et al. 2018) and of pelagic primary production in the waters of the Gulf of Trieste (Faganeli and Tušnik 1983) postulated by high inorganic N/P ratios. Nutrient regeneration and fluxes at the sediment-water interface, significantly impacted by the infauna bioturbation activity (Cermelj et al. 1997; Thouzeau et al. 2007) and redox conditions (Faganeli and Ogrinc 2009; Rigaud et al. 2013), is likely the primary natural source of nutrients available for assimilation processes (De Vittor et al. 2012, Petranich et al. 2018, Testa et al. 2021) in CB, especially in the warmer period of the year, since the natural nutrient input by freshwater inflows into the lagoon is limited. High benthic effluxes of NH_4^+ and in lesser extent of PO_4^{3-} were measured during the summer period in the shallow Grado and Marano Lagoon (De Vittor et al. 2012) as well in the Gulf of Trieste (Bertuzzi et al. 1997). The lowest inorganic N/P ratios observed in April 1977 in both enclosures, and in June 1977 in CB, in correlation with high community production, were due to decreasing inorganic nitrogen content in sea water probably as a result of enhanced assimilation by primary producers influencing the limitation conditions. The highest concentrations of DON, DOP, POC, PN, and PP in seawater and $N_{tot..}$ in sediment observed in June 1977 in PB was mostly the consequence of macrophyte decomposition after an intense growth illustrated by the high community production measured in April 1977. The high oxygen consumption of decomposing organic matter caused the night anoxia and the proliferation of sulphate reducing bacteria producing H_2S and pyrite in sediments (Hines et al. 1997).

The gross production estimations based on O_2 and DIC measurements indicated the stimulation effect of nutrients added by the sewage discharges in PB in spring 1977. No attempt was made to discriminate between the production of phytoplankton and benthic macroalgae, but phytoplankton biomass measurements in PB clearly indicated the reduction of phytoplankton biomass in parallel with the increased biomass of benthic macroalgae (Fanuko 1984). In the production experiments in an open lagoon in Florida (USA) it was found that in shallow water (<1 m deep) the benthic macrophytes and microalgae dominated the primary production of the lagoon community (Mee 1978). This was likely also the case of the Lagoon of Strunjan. The estimated yearly production in both enclosures were similar, despite the higher production in PB during spring 1977. Decomposition of dead macroalgae and the anoxic conditions stopped the vigorous primary production in PB. The production in CB reached the highest values only in summer. A comparison with the Marano and Grado Lagoon (De Vittor et al. 2012) where the waters are deeper shows higher (gross) production values in our study area.

The lagoon environment at Strunjan accumulated nutrients introduced via sewage discharges, in particular through benthic macroalgae assimilation and subsequent deposition and intense decomposition of dead plant material on the bottom. The tentative mas balance, assuming the Redfield ratio (Redfield et al. 1963) for N and P, and 50 % of those of C for Si assimilation (Brezezinski et al. 2003) and estimated from the carbon net production (assumed as ½ of the gross production), showed that <2, 0.2 and 10% of inorganic N, P and Si introduced by sewage, respectively, were assimilated in PB. The great majority of introduced chemical species were, therefore, exported by tides in the surrounding lagoon and deposited in PB especially PN and PP, which are composed of both organic (especially N) and inorganic (especially P) fractions, reflected in the low $C_{org.}/P_{tot.}$ ratios (4-16, molar) in surface sediments. The low $C_{org.}/P_{tot.}$ ratios could also be attributerd to formation of phosphate minerals, e.g. apatite (Ogrinc and Faganeli 2006). The high $C_{org.}/N_{tot.}$ ratios (>14, molar) in surface sediments indicated the prevalent degradation of N over C in the sedimentary organic matter in both enclosures (Ogrinc et al. 2005). Lower values (<14) found in November 1976 and June 1977 were more the direct consequence of the presence of microalgae, with a typical $C_{org.}/N_{tot.}$ ratio <10 (Faganeli et al. 2009), and *Ulva*, with typical $C_{org.}/N_{tot.}$ ratio of 11 (Faganeli et al. 1986), respectively.

Conclusions

The present study indicates that nutrients introduced by sewage into a partially closed lagoon environment and diluted by tides were immobilized by enhanced production, especially by benthic macroalgae. Afterwards, the dead organic matter settled and decomposed producing anoxic conditions in late spring. Decomposition led to high levels of dissolved and suspended organic nutrients in the water and $N_{tot.}$. in sediments bearing in mind that the nutrients introduced with sewage were also to some extent adsorbed on suspended and sedimented particles. The daily mean gross production estimated on an annual basis showed no quantitative differences between the two enclosures. Differences arose in the temporal succession of the studied events. This lagoon environment provides an example of quite intensive nutrient recycling.

Povzetek

Med poskusom v Strunjanski laguni v obdobju 1976-77 smo dnevno uvajali 300l primarno čiščenih komunalnih odplak mesta Piran v posebej zgrajeni bazen. Drugi bazen je služil za primerjavo. V odbobju enega leta smo s približno dvomesečno frekvenco spremljali nihanja koncentracij hranil N, P in Si ter bruto produkcije na osnovi dnevnih variacij koncentracije O_2 in DIC. Na osnovi visokega anorganskega razmerja N/P sklepamo na limitativnost P. Vnešena hranila, redčena s plimovanjem, so povečala produkcijo predvsem bentoških makroalg, ki so odmrle pozno pomladi. Odmrla organska snov se je nato posedla in razgrajevala ter povzročila nastanek anoksije ponoči in visokih koncentracij raztopljene in suspendirane organske snovi in celotnega dušika v sedimentu. Srednja dnevna bruto produkcija v celoletnem obdobju ni pokazala velikh razlik med bazenoma, medtem ko so bile le-te opazne v časovnem poteku študiranih procesov. Iz poskusa je razvidno dokaj intenzivno kroženje vnešenih hranil.

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