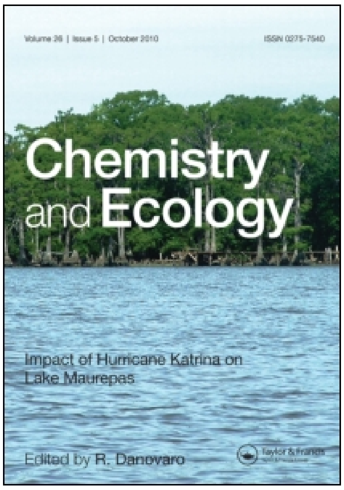


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# BENTHIC-PELAGIC COUPLING IN FRONTAL SYSTEM AREAS OF THE NORTHERN ADRIATIC SEA: ANALYSIS OF THE CARBON BUDGETS

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Sediment samples were collected between 1996 and 1998 during 4 cruises in the northern sector of the Adriatic Sea, facing the Po River outflow. In each sampling period, after identification of the front line, a grid of 6 sampling stations was selected in order to cover: the coastal area (largely affected by river waters), the inner and outer front areas, and the offshore waters. The biochemical composition of sedimentary organic matter (OM, lipids, proteins, carbohydrates and photosynthetic pigments) and enzymatic activity rates were studied to provide information on the potential organic matter turnover. Tentative estimates of the organic carbon budgets (input/production versus requirement by benthic consumers) are presented. Benthic carbon requirements, estimated from bacterial plus meiofaunal secondary production, was high ($897\,mg\,C\,m^{-2}\,d^{-1}$). OM concentrations in the Northern and Middle Adriatic Sea displayed high values, proteins being dominant, thus suggesting inputs of freshly produced material to the sea floor. OM turnover was generally rapid ($11–30\,d^{-1}$) and higher during summer. The uncoupled enzymatic rates (*i.e.* faster protein than carbohydrate mobilisation in February, 1997) determined a decrease of the OM quality that plays an important role in biogeochemical cycles and OM diagenesis, limiting bacterial secondary production and sedimentary organic carbon utilisation. These data suggest that the efficiency of the system in the transfer of energy through the food web is generally higher in summer, especially during mucilage production.

*Keywords*: Coupling; frontal system; analysis; carbon

## INTRODUCTION

The Northern Adriatic is the shallowest and most dynamic region of the Adriatic Sea. It is greatly influenced by river runoff on the western side, with the Po River being responsible for marked gradients in physical and chemical parameters. The eutrophication is usually most pronounced on the western side of the Northern Adriatic, especially off the Po Delta during summer (Franco *et al.*, 1982, Gilmartin *et al.*, 1990). A combination of strong seasonal stratification of the water column and high inputs of land derived nutrients contributes to exacerbate these effects. In these areas, the large amounts of

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organic matter reaching the sediment, are expected to induce a significant benthic response (Josenfson and Conley, 1997). Sediments, as a result of pelagic-benthic coupling processes, are sensitive to the inputs from the water column and may represent a record of the biological phenomena occurring in the overlying waters (Graf, 1992). Assessing changes in organic matter inputs and composition is crucial for a predictive understanding of the main bio-geochemical pathways and elemental cycling. This study was carried out within the framework of the programme PRISMA II to quantify the organic matter related processes, the OM input from the water column and its utilisation by benthic consumers.

## MATERIAL AND METHODS

### Sampling Strategy

Sediment sampling was carried out in the Adriatic Sea on board of the R/V "Urania", between 1996 and 1998, during 4 cruises (June–July, 1996, February–March, 1997, June–July, 1997 and February, 1998; Figure 1). Sampling strategy included two study areas with a different impact of the low salinity waters: the first close to the Po Delta (northern area) and the second located between Rimini and Ancona (southern area). Each sampling area included a grid of 6 stations selected after a preliminary hydrological survey to



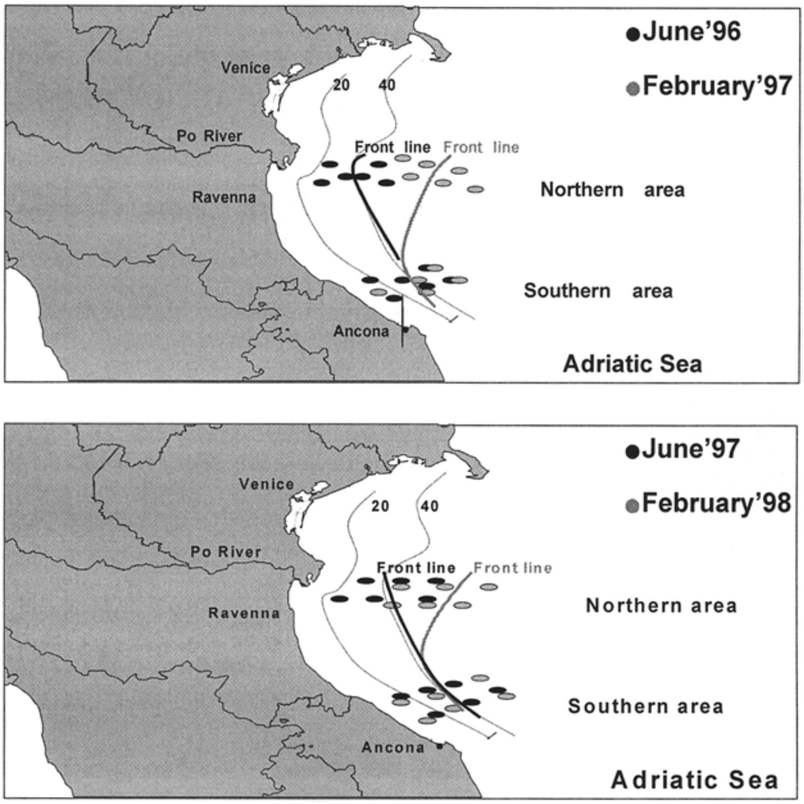


FIGURE 1 Sampling areas and stations location in the Northern Adriatic Sea.

identify the presence of frontal systems. The grids were selected to cross the front line. In each grid 6 stations were sampled: 2 coastal stations, 2 stations across the front and 2 stations outside the front. Coastal and offshore stations were both about 10–12 miles far from the frontal stations. Undisturbed sediment cores were collected using a multiple corer (Mod. Midi, $n = 4$ with 5.7 and 9.5 cm inner diameter). For microbial analyses, 3 sampling replicates were collected using sterile syringes. For the analysis of the biochemical composition of the sedimentary organic matter, 2–3 cores were collected at each station, vertically sectioned, and frozen at $-20°C$.

### Chemical and Biological Analyses

Carbohydrate, lipid and protein contents of the sediments were analysed according to Fabiano *et al.* (1995). Biopolymeric organic carbon (BPC) is expressed as the sum of carbohydrates, proteins and lipids converted to carbon content using 0.4, 0.49 and 0.75 $\mu g\,C\,\mu g^{-1}$ as conversion factors. The BPC typically account for about 5–15% of the total sedimentary OC.

Microphytobenthic biomass was determined as chlorophyll-a content. Chlorophyll-a analyses were carried out according to Lorenzen and Jeffrey (1980). Micro-phytobenthic production was roughly estimated from chlorophyll-a concentrations according to Danovaro and Fabiano (1994).

Bacterial analyses were carried out as described by Montagna (1982) and previously reported in Danovaro *et al.* (1994). Bacteria biomass was determined counting bacteria after a division into different size classes. Their biovolume was then converted to carbon content assuming $310 \times 10^{-15}$ g C per $\mu m^{-3}$ (Fry, 1990). Analyses of extracellular enzymatic activities: $\beta$-D-glucosidase (MFU-$\beta$-glucopyranoside, MUF-glu) and aminopeptidase (L-leucine-4-methylcoumarinyl-7-amide, Leu-MCA) were carried out following Fabiano and Danovaro (1998). Exo-enzymatic activities were converted to carbohydrate and protein mobilised using the conversion factor $72\,\mu g\,C\,\mu M^{-1}\,h^{-1}$. Bacterial production was measured using the $^{3}H$-leucine incorporation method (Kirchman *et al.*, 1986; Simon and Azam, 1989) following the procedure for sediments described by Van Duyl and Kop (1994) with a few adaptations. Organic carbon consumption by bacteria was estimated assuming a carbon conversion efficiency (CCE) of 50%.

Meiofauna was extracted by silicagel centrifugation (Danovaro, 1996). All organisms were sorted and counted under a stereomicroscope and converted into biomass assuming standard conversion factors (Feller and Warwick, 1988). Meiofauna production was determined assuming an annual production to biomass ratio (P/B) of 9. Organic carbon consumption was estimated assuming a CCE of 37.5%.

All values were expressed in terms of organic carbon and referred to one $m^2$. Primary and secondary production and organic fluxes were referred as $mg\,C\,m^{-2}\,d^{-1}$.

## RESULTS AND DISCUSSION

Organic carbon vertical flux was 49.1 $mg\,C\,m^{-2}\,d^{-1}$ (on average of the four sampling periods) and displayed wide seasonal changes ranging from 25.5 to 81 $mg\,C\,m^{-2}\,d^{-1}$

(Rabitti, personal communication and this volume). Large differences were also observed between the two areas, the southern showing on average OC fluxes about double that in the other. No significant differences were observed among stations so that average values for sampling period were utilised. Chlorophyll-a concentrations were generally high and corresponded to a mean microphytobenthic production of $54.3\,mg\,C\,m^{-2}\,d^{-1}$, ranging from 37.8 to $63.5\,mg\,C\,m^{-2}\,d^{-1}$ in June, 1996 and June, 1997, (the latter value during mucilage production). Micro-phytobenthic production was generally 1.5 fold higher in the northern area. Sedimentary biopolymeric carbon (BPC, as the sum of the lipid, protein and carbohydrate carbon equivalents) was on average $13{,}500\,mg\,C\,m^{-2}$ and ranged from 7,281 to $17{,}300\,mg\,C\,m^{-2}$ in February, 1997 and February, 1998. OM composition was dominated by proteins that, together with carbohydrates, accounted for 70% of the BPC on average, with a mean protein (PRT) to carbohydrate (CHO) ratio of 3.2. High PRT:CHO ratios were observed in June, 1996 (5.9) and the lowest in February, 1997 (1.9). Organic carbon mobilisation, based on exo-enzymatic activity rates, indicated high turnover rates of sedimentary organic carbon pools: on average protein and carbohydrate pool were mobilised in 10.5 and 24 h respectively. Bacterial secondary production was, on average, $425\,mg\,C\,m^{-2}\,d^{-1}$, with a corresponding organic carbon consumption (as food requirement, FR) of $850\,mg\,C\,m^{-2}\,d^{-1}$. Bacterial secondary production varied widely among seasons and between areas: high values were reported in June, 1996 and 1997 (609 and $560\,mg\,C\,m^{-2}\,d^{-1}$, respectively) and low values in February, 1997 and 1998 (272 and $258\,mg\,C\,m^{-2}\,d^{-1}$). Meiofaunal production estimates were low if compared to bacterial production and did not display wide seasonal variations ranging from 16.4 to $18.7\,mg\,C\,m^{-2}\,d^{-1}$. These values correspond to a mean OC consumption (as FR) of $46.75\,mg\,C\,m^{-2}\,d^{-1}$.

A conceptual scheme of the relative significance and role of different components is illustrated in Figure 2. The reported budget highlights that both investigated areas are characterised by very high secondary production levels that indeed correspond to a very rapid turnover of the sedimentary organic carbon pool, $15\,d^{-1}$, on average. The remarkable and striking result is the very limited significance of OC vertical fluxes, that

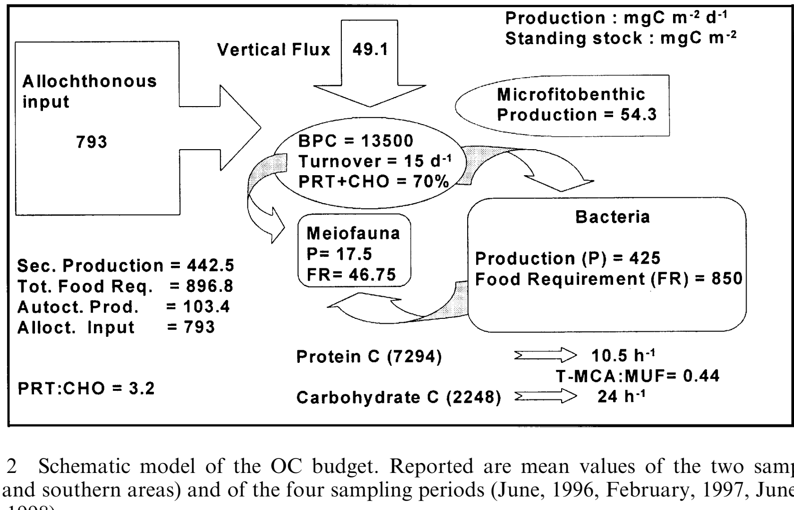


FIGURE 2 Schematic model of the OC budget. Reported are mean values of the two sampling areas (northern and southern areas) and of the four sampling periods (June, 1996, February, 1997, June, 1997 and February, 1998).

on the basis of our estimates, contribute only for about 5.5% to the total food requirement of benthic consumers. In addition, benthic food requirements might be largely underestimated because the highest carbon conversion coefficients were utilized for both bacteria and meiofauna. Moreover, macrofauna contribution to organic carbon consumption was assumed to be negligible when compared to bacteria and meiofauna. Vertical OC fluxes reported here clearly underestimate the actual OC input to the sediments. It is interesting to note that micro-phytobenthic primary production itself provided about 11.5% of the OC requirement of benthic consumers, a contribution about double than that due to OC vertical fluxes. As a consequence, our budget clearly points out that OC consumption is higher than OC inputs and that such deficiency must be balanced by important allochthonous input (*i.e.* material brought from the river or by lateral advection), equivalent to about 83% of the total food requirement (793 mg C $m^{-2}$ $d^{-1}$). These values are similar to total organic carbon fluxes (about 1 g C $m^{-2}$ $d^{-1}$) estimated for different areas close to the Po River estuary (Alvisi *et al.*, this volume). Despite seasonal changes of most studied parameters, the general picture of the carbon budget of the system remains rather constant. This applies also to June, 1997 during mucilage production, even though in this case the increased bacterial production and low vertical fluxes indicate the presence of stronger allochthonous OC inputs. The high exo-enzymatic activity rates encountered in this study might have important implications in OM diagenesis and its utilisation by benthic consumers. Large differences were observed between sampling periods. In fact, the turnover of aminopeptidase and $\beta$-D-glucosidase ratio (MCA : MUF) varied from 3.2 in June, 1996 to 0.57 in February, 1997. Ratios lower than 1 mean that proteins are mobilised faster than carbohydrates. This implies that in February, 1997 the benthic system, despite the protein dominance (*i.e.* large production of fresh organic matter) tends to accumulate carbohydrates that reduce the quality and the availability of sedimentary OM.

This, in turn, might reduce the bacterial efficiency, as bacteria are involved more in enzyme synthesis than in growth. By contrast, in June, 1996 the faster carbohydrate mobilisation suggests protein accumulation (as indicated by higher protein to carbohydrate ratios: 5.6 against 5.9 in February, 1997 and June, 1996). This might have important implications in terms of organic matter turnover which, despite the presence of higher OM concentrations, is faster in June, 1996 (11.2 $d^{-1}$) than in February, 1997 (12.4 $d^{-1}$).

The analysis of seasonal *vs* spatial (*i.e.* northern *vs* southern) variability of the system clearly indicates that the described model follows the same seasonal processes in both areas. In fact, no significant differences were observed in terms of bacterial or meiofaunal production, and the lower micro-phytobenthic production of the southern area is balanced by higher vertical fluxes.

## CONCLUSIONS

Vertical fluxes provide very low OC inputs that can not explain the high values of benthic production observed. The micro-phytobenthic production is a potentially important alternative OC source for benthic consumers. The overall autochthonous production, in both study areas, accounted only for 6–25% of the total carbon requirement, therefore important allochthonous inputs must be present. Bacterial parameters peaked in summer during dystrophic phenomena, and proteins were rapidly mobilised, particularly during mucilage production. However, the inverse relation between OM mobilisation and bacterial production suggests an uncoupled enzyme-production system that might reduce the system efficiency in the transfer of energy and material to higher trophic levels.

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