Influence of macrophytes on sediment phosphorus accumulation in a eutrophic estuary (Palmones River, Southern Spain)

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Abstract

The estuary of the Palmones River is a small, shallow and eutrophic system, located in the South of Spain. Presently, it is dominated by the fast-growing macroalgae Ulva rotundata Bliding and Enteromorpha prol´ıfera J.G. Agardh, which respond efficiently to extreme nutrient input. The influence of macrophytes on phosphorus accumulation in sediment, over a long time-scale, was studied in this work. Different fractions of bound phosphorus were measured in four types of sediment: bare sediment (acting as control), sediment with Ulva, sediment with Enteromorpha, and sediment with Sarcocornia perennis perennis (L.) A.J. Scott, a chenopodiacean living on the border of the salt marsh. The results show that ulvaceans favour phosphorus storage in the sediment, throughout the settling of easily degradable organic matter and the subsequent retention of the phosphate being released from the sediment.

Keywords: Palmones estuary; Ulva; Enteromorpha; Sarcocornia; Phosphorus

1. Introduction

The Palmones River estuary (Southern Spain) is a well-studied example of a Spanish coastal system greatly affected by eutrophication during the last decade. Its location indicates the strong influence of drastic climatic changes and human activities. These facts lead to a continuous increase in nutrient load, reflected both in the sediment and in the water (Niell et al., 1996; Clavero et al., 1999a,b).

Several studies indicate that phosphorus is a key factor causing eutrophication (e.g. Sas, 1989), because it enhances production in an amplified positive feedback (Furrer et al., 1996). Its liberation from the sediment is essential to study the state of aquatic systems, mainly in shallow estuaries (Ingall and Jahnke, 1997). Also, the exchange of phosphorus between water and sediment is very complex, involving interrelated chemical, biological and physical processes (Bostrom et al., 1988; Baldwin et al., 1997; Clavero et al., 1997, 1999, 2000).

In the estuary of the Palmones River, phosphorus content at the upper part of the sediment has been studied for years (Clavero et al., 1999a,b) and is used as an index of progressive eutrophication. However, during this time the estuary has been subject to some changes. The acute eutrophication has generated a replacement in the composition of primary producers, in that the estuary is now dominated by ulvacean species, Ulva sp. and Enteromorpha sp. (Herna´ndez et al., 1997; Vergara et al., 1997). This is a common process in shallow coastal environments under eutrophication (e.g. Sand-Jensen and Borum, 1991; Viaroli et al., 1996; Clavero et al., 2000). Producers change from sea grass meadows to a dominance of phytoplankton and fast-growing macroalgae, which are able to survive because of their ability to rapidly take up and store nutrients.

In this study the importance of the actual vegetation on phosphorus retention is examined, focussing on the intertidal sediment, where nutrients interchange between water and sediment occurs through tidal movements. The study area is a depositional zone of the main tidal creek of the river, with extensive areas of mud that emerge daily. The mudflat is usually covered by both Ulva rotundata Bliding and Enteromorpha prolifera J.G.Agardh, which are set and removed continuously, although the areas of deposition for each of them are characteristic.

On the border with the salt marsh, but still in the intertidal mud, a rooted macrophyte of the Chenopodiacean genus, Sarcocornia perennis perennis (Miller) A.J. Scott is found. This is a plant of the low marshes, which grows as isolated tussocks that expand radially. Four areas of the mudflat were selected, with the aim of studying how macrophytes, settled over sediment, affect phosphorus accumulation, i.e. bare sediment (taken as control), sediment covered by Sarcocornia (just on the limit of the salt marsh), sediment with Ulva, and sediment with Enteromorpha.

2. Materials and methods

2.1. Description of the study area

The Palmones River estuary is located in Southern Spain, at the end of a small catchment area (302 km^2). Tidal movements are small, with maximal amplitude of 2 m (Niell et al., 1989), and the emersion period is usually long. The chosen site for this study is located in a well-studied area in the middle of the estuary (Pe´rez-Llorens and Niell, 1990; Clavero et al., 1992, 1994, 1999, 2000; Hernández et al., 1994, 1997).

In the intertidal system, different areas can be distinguished in the mudflat (Fig. 1). In the upper part, still subject to tidal fluctuations and bordering on the salt marsh, there are zones of sediment occupied by the Chenopodiaceae *S. perennis perennis*. In the deepest part, there are zones of bare sediment. In the middle, there are found settling zones for the ulvaceans, *Ulva* at lower levels than *Enteromorpha*, which is more resistant to emersion. Data on biomass and composition of algae are abundant in the area (Niell et al., 1996; Hernández et al., 1997). The cover value is usually around 75%, although it can change over time by the annual growth dynamics of the algae, the high rates of decomposition in summer, or the export of biomass as a consequence of eventual increase in river flow.

Moreover, significant movements of free-floating thalli are observed at high tide, which accentuate the continuous redistribution of biomass within the estuary.

On the other hand, *S. perennis perennis* is a little shrub, a pioneer in the development of the salt marsh, able to tolerate high salinity and daily periods of immersion. Because of its radial growth, its biomass per area remains quite homogeneous during the year (unpublished data).

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2.2. Sampling

Sediment cores were taken in triplicate, bimonthly, from August 1996 to June 1997, to be analysed for phosphorus, using PVC core tubes (10 cm i.d., 25 cm long) inserted at low tide into the sediment. Cores were immediately covered at both ends and frozen for transportation to the laboratory, where they were sliced into sections of 2 cm, from the surface to 10 cm depth. Each section was dried at 60 8C and divided into two subsamples that were used to determine, in duplicate, the different phosphorus fractions.

2.3. Analytical methods

Two fractions of inorganic phosphorus were analytically discriminated (Williams et al., 1976): non-calcium bound phosphorus (NAIP) and calcium bound phosphorus (AIP). NAIP was considered as the sum of CDB (citrate-dithionite-bicarbonate) and NaOH extractable phosphorus; AIP was extracted with HCl on the residue after the NAIP treatment. The total inorganic phosphorus (IP) was considered as the sum of both fractions (NAIP + AIP). The organic phosphorus (OP) was determined by extraction with HCl + NaOH (Sommers and Nelson, 1972). Total phosphorus (TP) was assumed to be the sum of all the fractions (NAIP + AIP + OP).

The analysis of phosphate was carried out by means of the malachite green method (Fernández et al., 1985) using a Technicon AAII.

2.4. Statistical analysis

Two-way analysis of variance (a = 0.05) was used to compare the profiles in depth and time of different fractions of phosphorus and TP. Previously the data were tested for normality using the G-test.

Significant differences were not found in depth. Therefore, results from the 10 cm of depth were integrated and expressed in g m^{-2}, assuming a constant density of the sediment of 2.3 g cm^{-3}.

Ulva and Enteromorpha were not present in the estuary in certain months, so differences in phosphorus concentrations in the four types of sediment were evaluated separately in each one of the samplings, applying the Student's t-test (a = 0.05).

3. Results

Variations in the different phosphorus fractions over time, for the four types of sediment, are shown in Fig. 2 a–d. Maximum values were found, in all the cases, in October 1996, for the organic fraction. They ranged between 49.4 g m-2, in the sediment covered by Ulva, and 25.5 g m-2, in the sediment with *Enteromorpha*. In the rest of the data, the NAIP and AIP fractions, as a whole, were more abundant than the organic. Maximum concentrations of NAIP and AIP were detected in October: 20 g m^{-2} of NAIP in the sediment under the canopy of *Enteromorpha* and 12.39 g m^{-2} of AIP, in the control sediment. Minimum values for the three fractions appeared in April 1997 in the control: 0.89 g m^{-2} for the NAIP, 1.59 g m^{-2} for the AIP, and 1.19 g m^{-2} for the organic fraction.

Total phosphorus in the four sediments (Fig. 3) showed a parallel seasonal variation, with maximum values in October 1996 and minimum in April 1997. Values ranged from 3.67 to 50.85 g m^{-2} in the control; between 4.34 and 50.38 g m^{-2} in the sediment with *Sarcocornia*; with Ulva between 9.09 and 64.4 g m^{-2}, and between 8.93 and 51.44 g m^{-2} in the sediment with *Enteromorpha*.

Seasonal variations were analysed using ANOVA (a = 0.05) separately for each type of sediment (data are not shown). The results showed that TP concentrations, as well as NAIP, AIP and OP, decreased significantly during the study period. Indeed, they are two different periods, which can be related to rainfall in the estuary (Table 1 and Fig. 3). The first one, corresponding to the last months of 1996, and the second one, from January to June of 1997, after the greatest rainfall.

Moreover, vegetation added one more important source of variation, leading to significant differences in most of the cases (Student's t-test). These differences did not stay constant with time, but there were several repetitive trends. Sediments with *Ulva* and *Enteromorpha* showed higher concentrations of TP than the control sediment, in contrast to the sediment with *Sarcocornia* that remained constant. Organic fraction followed the same trend as TP, increasing in the sediment with ulvaceans. In the inorganic fractions, AIP often appeared in the control with concentrations significantly higher than the rest of sediments, while the NAIP followed the opposite trend.

The effect of vegetation upon phosphorus accumulation is more evident if the variation of concentrations with time is compared among the four types of sediment. With this purpose, mass balances were calculated (Table 2) as a way of reflecting the net result over a year of the processes happening in the upper layers of sediment. They were obtained by plotting depth-integrated phosphorus concentrations against time and calculating the first derivative (dP/dt) of the resulting function. Results show that the four kinds of sediments had a net loss of phosphorus during the study, ranging from -0.31 g m^{-2} $month^{-1}$ in the sediment with *Ulva* to -12.56 g m^{-2} $month^{-1}$ in the control. The greatest losses happened in the inorganic fractions, mainly in the NAIP, with a maximum value of -7.55 g m^{-2} $month^{-1}$ in the sediment with *Sarcocornia*. Losses of OP increased to only -3.76 g m^{-2} $month^{-1}$ in the control, and reverted to a net accumulation in the sediment with Ulva (5.49 g m^{-2} $month^{-1}$).

4. Discussion

Several studies have dealt with the influence of macrophytes on phosphorus processes in sediment, mainly focussing on dissolved phosphorus dynamics over a short time-scale, displaying their importance when fluxes between water and sediment are evaluated (e.g. Viaroli et al., 1996; Flindt et al., 1999). These processes also have repercussions on the most stable fraction, sediment-bound phosphorus, and it should be taken into account as an index of eutrophication of aquatic systems.

Moreover, in the intertidal mudflat, nutrient interchanges play a key role in the sustenance and development of the low salt marsh, as well as in water productivity, so macrophytes become even more important.

In the estuary of the Palmones River, the dominant trend in recent years has been a net input of phosphorus to sediment from water, as a consequence of the diminution of river flow, coupled with the enhancement of tidal fertilization (Clavero et al., 1999a,b, 2000). Nonetheless, climatic events, characterized by acute rainfall, are able to disturb the usual state of the system, reversing this input to a release of phosphorus from sediment. In this study, this process is recorded in the four types of sediment: the high initial values of phosphorus content in sediment are a consequence of drought during the earlier months of the study and the previous ones. The subsequent reduction originates from basin flushing, in terms of nutrients, caused by winter rainfall in 1996–1997 (see Table 1). Mass balances of the whole year, in which dry and wet seasons are included, show a net loss of total phosphorus content, but a clear difference exists between the bare sediment and the one covered by *S. perennis* with respect to the sediments with ulvaceans (Table 2). The net loss of phosphorus during the year is reduced by two and a half times with *Enteropmorpha* and more than 40 times when Ulva covers the sediment. It means that these algae enhance phosphorus storage in sediment in an important way, removing it from water in the estuary. They do it by means of avoiding inorganic phosphorus release from sediment and increasing the organic fraction, mainly in the case of *Ulva*.

Both macroalgae are opportunistic and fast-growing producers, which are known to play a key role in the regulation of the entire benthic metabolism (Sand-Jensen and Borum, 1991). They usually exhibit high rates of nutrient uptake, leading to storage of N and P in excess, related to their physiological requirements (e.g. Markager and Sand-Jensen, 1994). Consequently, they present high N/C and P/C ratios (Table 3), which favour microbial degradation (e.g. Enríquez et al., 1993). In the Palmones River estuary, 1.9–5% dry wt of N and 0.11–0.29% dry wt of P in the case of the ulvaceans have been measured, which are above the mean values given for macroalgae in other studies (Niell et al., 1996; Hernández et al., 1997). Their high productivity leads to the settling of great amounts of organic matter when these algae reach their seasonal decay, which, coupled with the rapid bacterial degradation, generates an increase in OP concentration. However, if the internal composition of the algae allows a rapid degradation by bacteria, an accumulation of phosphorus as hard-degradable organic compounds would not be expected. So, it is very possible that a significant percentage of the organic phosphorus measured in the sediment was located in the bacteria itself (Clavero, 1992). This hypothesis is supported by data of bacterial density in the sediment (Izquierdo, 2001): the number of bacteria per gram of sediment with Ulva is almost double the value of bare sediment.

As algae mineralization increases the organic fraction, it also enhances the phosphate pool, which becomes available to bind to inorganic particles: being adsorbed on solid particles (Krom and Berner, 1981) or precipitating as non-soluble labile phosphorus compounds (NAIP fraction), and forming calcium-bound compounds (AIP fraction) (Jahnke et al., 1983). In this way, these algae counteract the loss of sediment-bound phosphorus: they respond quickly to nutrients input in the estuary, by accumulating phosphorus that subsequently ends up in the sediment. Moreover, these algae form thick mats, which act as natural physical barriers, reducing phosphate fluxes from the sediment to the overlying water, e.g. Nowicki and Nixon (1985) while at the same time preventing oxygenation and behaving as a continuous source of organic matter. In the case of Ulva, the thallus area index reaches values of nearly 17 m^2 m^{-2} (Hernández et al., 1997). Therefore, these mats prevent the phosphate being released by degradation of the deepest algal layers, enhancing the formation of non-soluble P compounds, mainly as calcium-bound phosphorus, since great amounts of calcium are available in the pore-water (Clavero et al., 1992). Ulva canopies can be said to act in a more efficient way than *Enteromorpha*, which despite the formation of dense mats, allow fluxes of phosphate because of its filamentous, ramified and tubular morphology, generating watery compartments between sediment and water.

The role of *Sarcocornia perennis* in phosphorus dynamics in the mudflat is quite different from the ulvaceans. This is a plant of the lowest salt marsh, which participates in the first stages of marsh soil development from sediment accretion. It grows in the upper part of the intertidal mudflat, generating isolated patches in which the mean biomass is around 76 ± 18 g dry wt m-2, of which roots accounted only for the 6% of the dry wt (unpublished data). Vegetated sediments with rooted macrophytes often show a reduction of the phosphate pool in the sediment, because of plant uptake and an increase in P sorption caused by the release of oxygen (Flindt et al., 1999). Therefore, differences in the non-calcium-bound phosphorus could be expected, since it is the fraction most sensitive to physical and chemical changes (Jahnke et al., 1983; Gerke and Hermann, 1992), directly in equilibrium with the pool of phosphate. Despite this, in most cases, the sediment with *Sarcocornia* does not show significant differences of P concentrations of both inorganic fractions; indeed it behaves as the bare sediment. Probably, it could be explained by the small rhyzosphere of the plant, and the little requirements because of its growth rate. Moreover, it has a completely different morphology than the studied algae, forming little shrubs that allow daily water–sediment nutrient interchanges and the continuous renovation of sediment. The organic fraction also shows the same trend as the bare sediment, which reveals the unimportance of the organic material falling from this plant in comparison with the algae. It occurs not only in terms of quantity, but also in terms of quality: coefficients of 23 C:N and 649 C:P were measured for the photosynthetic part of the plant, which means a less degradable material for bacterial activity than with algae (Table 3).

In conclusion, the results of this work show the contribution of macroalgae to phosphorus load in sediment. Although the process on a wider scale controls the nutrient state of the estuary of the

Palmones River, algae contribute to the removal of phosphorus into sediment, where it is buried in a less available form.

Acknowledgements

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Table 1. Temperature (8C) and rainfall (mm) in the catchment area over the period study.

Months	Temperature (8C)	Rainfall (mm)
August/96	22.9	2.8
October/96	19.5	81.2
December/96	16.2	828.7
February/97	15.8	0.0
April/97	17.8	36.8
June/97	20.5	34.2

Data from the Spanish Ministry of Environment.

Table 2. Mass balance calculations (g P m-2 month-1) of different P fractions over the four types of sediments studied. Arrows illustrate the direction and intensity of the fluxes.

	Control	*Sarcocornia*	*Ulva*	*Enteromorpha*
NAIP	-6.14	-7.55	-6.01	-2.94
AIP	-2.66	-2.40	-0.21	-0.74
OP	-3.76	-2.13	5.49	-1.25
TP	-12.56 ⇧	-12.08 ⇧	-0.31 ↑	-4.93 ⇧

Table 3. Mean values of biomass (g dry wt m^{-2}) and elemental composition (C:N and C:P ratios) for the different macrophytes in the estuary.

	Biomass (g dry wt m^{-2})	C:N ratio	C:P ratio
S. perennis perennis	76	23	649
Ulvaceans			
Ulva	0–200	10	420
Enteromorpha	0–100	10	420

Figure caption

Fig. 1. Schematic representation of the distribution of macrophytes living in the mudflat, (a) bare sediment, (b) sediment with *E. prolífera*, (c) sediment covered by *U. rotundata*, and (d) sediment with *S. perennis*.

Fig. 2. Seasonal changes of mean (±S.D.) of phosphorus fractions using the depth-integrated phosphorus concentrations (units are g m^{-2}) and the ratio of inorganic (IP) vs. organic phosphorus (OP) in the same time. NAIP, non-calcium bound phosphorus; AIP, calcium bound phosphorus; OP, organic phosphorus (a, control; b, *S. perennis*; c, *U. rotundata* and d, *E. prolifera*).

Fig. 3. Seasonal changes of mean (±S.D.) of total phosphorus (TP) using the depth-integrated phosphorus concentrations in the four sediment types studied and the rainfall (black line) in the catchment area. Units are g m^{-2} and l m^{-2}, respectively.

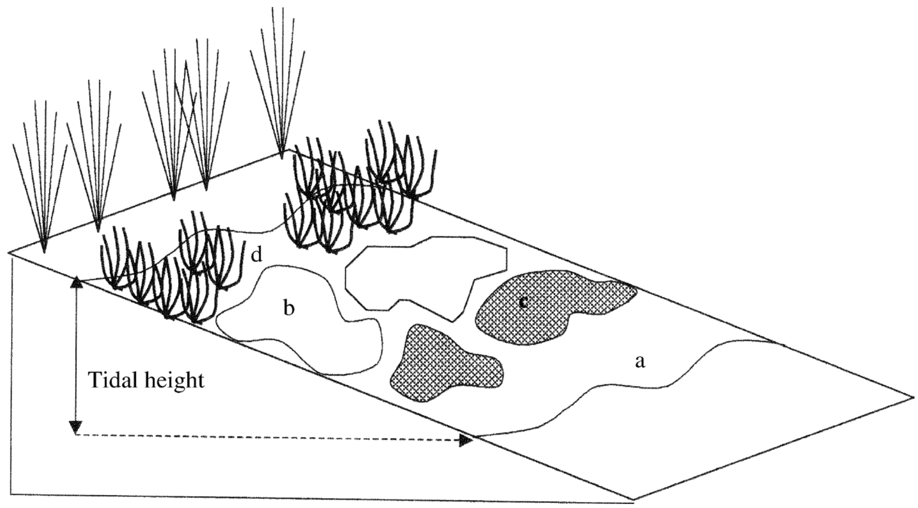


Fig. 1

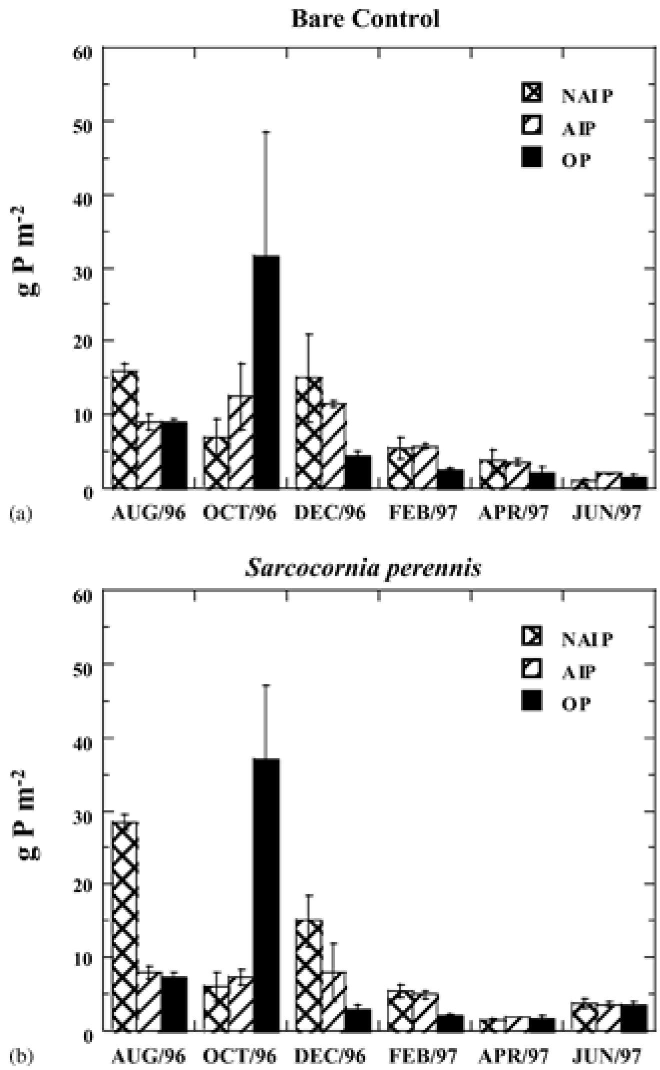
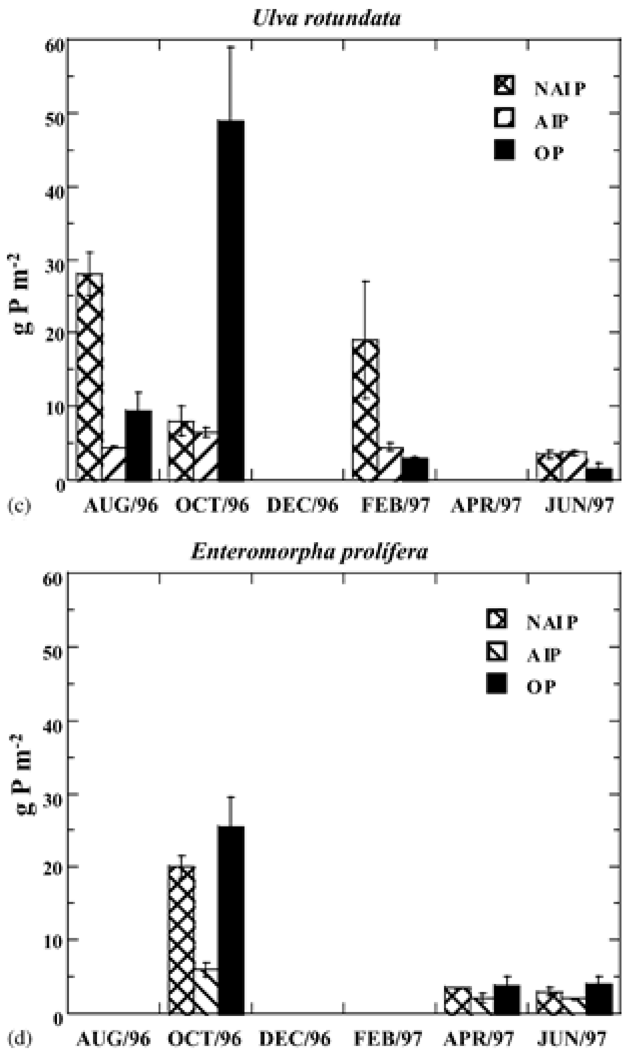
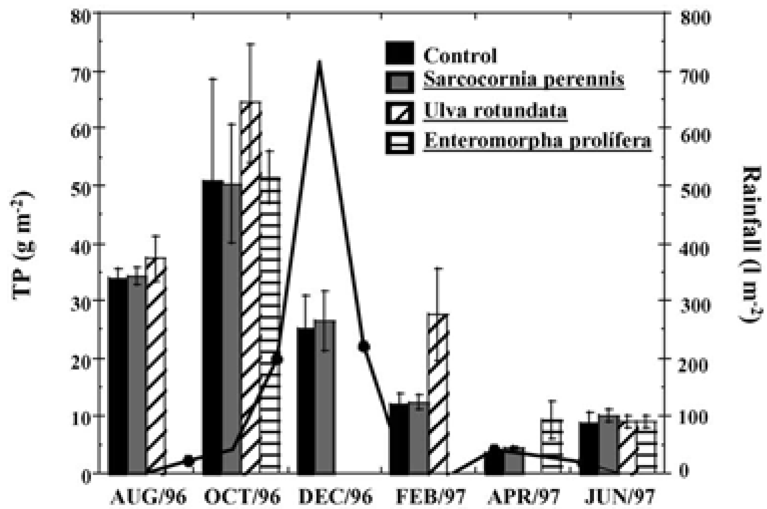

Bare Control
60
50
40
30
20
10
0
g P m-2
NAI P
AIP
OP
(a)
AUG/96 OCT/96 DEC/96 FEB/97 APR/97 JUN/97
Sarcocornia perennis
60
50
40
30
20
10
0
g P m-2
NAI P
AIP
OP
(b)
AUG/96 OCT/96 DEC/96 FEB/97 APR/97 JUN/97

Fig. 2 (a)



Ulva rotundata
NAI P
AI P
OP
g P m-2
0
10
20
30
40
50
60
(c)
AUG/96
OCT/96
DEC/96
FEB/97
APR/97
JUN/97
Enteromorpha prolifera
NAI P
AI P
OP
g P m-2
0
10
20
30
40
50
60
(d)
AUG/96
OCT/96
DEC/96
FEB/97
APR/97
JUN/97

Fig. 2 (b)



80
70
60
50
40
30
20
10
0
TP (g m-2)
800
700
600
500
400
300
200
100
0
Rainfall (l m-2)
Control
Sarcocornia perennis
Ulva rotundata
Enteromorpha prolifera
AUG/96
OCT/96
DEC/96
FEB/97
APR/97
JUN/97

Fig. 3