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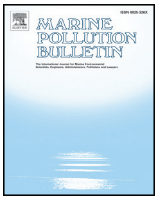

Artificial soft sediment resuspension and high density opportunistic macroalgal mat fragmentation as method for increasing sediment zoobenthic assemblage diversity in a eutrophic lagoon

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ABSTRACT

Superficial soft sediment resuspension and partial fragmentation of high density opportunistic macroalgal mats were investigated by boat to determine the impact on zoobenthic assemblages in a eutrophic Mediterranean lagoon. Sediment resuspension was used to oxidise superficial organic sediments as a method to counteract the effects of eutrophication. Likewise, artificial decay of macroalgal mat was calculated to reduce a permanent source of sediment organic matter. An area of 9 ha was disturbed (zone D) and two other areas of the same size were left undisturbed (zones U). We measured chemical–physical variables, estimated algal biomass and sedimentary organic matter, and conducted qualitative and quantitative determinations of the zoobenthic species detected in sediment and among algal mats. The results showed a constant major reduction in labile organic matter (LOM) and algal biomass in D, whereas values in U remained stable or increased. In the three zones, however, bare patches of lagoon bed increased in size, either by direct effect of the boats in D or by anaerobic decay of the algal mass in U. Zoobenthic assemblages in algal mats reduced the number of species in D, probably due to the sharp reduction in biomass, but remained stable in U, whereas in all three areas abundance increased. Sediment zoobenthic assemblages increased the number of species in D, as expected, due to drastic reduction in LOM, whereas values in U remained stable and again abundance increased in all three zones. In conclusion, we confirmed that reduction of sediment organic load enabled an increase in the number of species, while the algal mats proved to be an important substrate in the lagoon environment for zoobenthic assemblages, especially when mat alternated with bare intermat areas of lagoon bed. Sediment resuspension is confirmed as a management criterion for counteracting the effects of eutrophication and improving the biodiversity of zoobenthic assemblages in eutrophic lagoon environments.

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1. Introduction

Eutrophication of aquatic environments is a complex phenomenon arising from an increase in nutrient availability, especially nitrogen and phosphorus from the land. It leads to an increase in dissolved organic matter and particulate in the ecosystem (Nixon, 1995). In marine sediments, more than 50% of organic matter is degraded by bacterial sulphate-reduction processes (Jørgensen, 1983). A major build-up of organic matter in sediments increases sulphate-reduction that produces the acidifying gases carbon dioxide and hydrogen sulphide. The latter is toxic and may have considerable impact (Hijs et al., 2000), while sediments become enriched with reducing components. Low redox potential and pH lead to production of ammonium (Marty et al., 1990) and nitrite by ammonification of organic matter, and this too has a toxic effect on fauna (Torres-Beristain et al., 2006).

Transition waters which include estuaries, lagoons and coastal water bodies are often eutrophic. This may be due to direct human impact or the human impact in their hydrographic basin. In particular, the morphology and structure of coastal water bodies, such as non-tidal lagoons, make them susceptible to low water turnover, and they tend to retain all external inputs (Chapman, 2012). In general, transition waters are naturally stressed environments because of the high variability of their chemical–physical characteristics (Elliott and Quintino, 2007).

Such stressful conditions are a subsidy for marine or freshwater organisms well-adapted to these environments. In the absence of competition and with an abundance of food, some well-adapted species may develop large numerical abundance and biomass. In transitional waters, the characteristics of natural stress are similar to those of anthropogenic

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stress. Over-reliance of quality indicators on ecosystem structural features, such as diversity, therefore makes detection of anthropogenic stress more difficult (Elliott and Quintino, 2007).

A change in the quality/quantity of plant species has been postulated in relation to changes in dissolved nutrients (Duarte, 1995) and organic load of sediment (Lenzi et al., 2012). The stressor–response relationship predicts an impact of eutrophication and especially organic load of sediment on the macrozoobenthos, according to the model proposed by Pearson and Rosenberg (1978). The model describes a generalized pattern of benthic community response along a gradient of enrichment of organic matter and shows that the early stages of eutrophication are often characterized by increases in abundance, biomass and numbers of species, especially bacteria, filter-feeders and detritivores. If the phenomenon persists or increases, numbers of species decrease, followed by secondary maxima of biomass and abundance associated with a few small opportunistic species, mainly polychaetes. In the end all macrofauna disappears and sediments become azoic. According to Magni et al. (2009), abundance and diversity variations compared by TOC thresholds in eutrophic Mediterranean lagoon/coastal pond ecosystems were consistent with Pearson–Rosenberg model predictions.

Stahlberg et al. (2006) showed that frequent resuspension of sediment increased the mineralization rate with respect to undisturbed sediment by a factor between 2 and 5. On that basis, Lenzi et al. (2005, 2010) showed that repeated resuspension of soft surface sediment by boats in two Tyrrhenian lagoons increased the oxidative status of sediments, reducing the organic content, without any significant increase in nutrients or oxygen consumption in the water column. Resuspension of sediments therefore seemed a possible management tool for shallow eutrophic lagoons (Lenzi, 2010): a reduction of organic load limited the development of opportunistic macroalgae and the risk of dystrophic phenomena (Lenzi et al., 2012). Mechanical action by boats of appropriate size on surface sediment proved similar to that produced by *moderate breezes* or stronger winds (>5.5 m/s) (Rubegni et al., 2013).

The relationship between sediment disturbance and organic matter enrichment in relation to the diversity and community structure of macrozoobenthic assemblages was examined by Widdicombe and Austen (2001) in a mesocosm. In line with the model proposed by Huston (1979), which assumed that diversity is a balance between growth rates (productivity/organic enrichment) and disturbance, with maximum diversity for assemblages with intermediate levels of productivity and disturbance, these authors confirmed that community structure was significantly affected by physical disturbance, organic enrichment, and interactions between the two.

Since artificial resuspension of soft superficial sediment was applied in Orbetello Lagoon in an attempt to counteract the undesirable effects of eutrophication, the present study is concerned with zoobenthic assemblages and is one of a series of studies conducted to determine the impact of this method of management on the lagoon environment. Specifically, we considered zoobenthic assemblages in sediments and in free-floating bentho-pleustophytic macroalgal mats. The working hypothesis was that reduction of sediment organic load by oxidative mineralisation, induced by resuspension of sediment in the water column and interaction with physical disturbance, enabled more zoobenthic species to obtain benefit from the sediment, increasing population diversity, than in a naturally stressed ecosystem such as a coastal water body.

2. Materials and methods

2.1. Study area and experimental design

This experiment was conducted in Orbetello Lagoon (Fig. 1), a shallow, eutrophic coastal water body with an area of 25.25 km^2 in southern Tuscany (Italian west coast 42°25′–42°29′N, 11°10′–11°17′E). The environment is eutrophic due to fish-farm wastewater, intermittent streams containing agricultural run-off and civil effluent, and historical input stored in sediment (Lenzi et al., 2003). Due to high nutrient availability, morphology and low-water-turnover, Orbetello Lagoon is subject to severe macroalgal proliferation, which can cause dystrophic crises with die-offs. Macroalgal harvesting was initially used as a remediation measure (Lenzi et al., 2003) but proved expensive and failed to decrease the algal mat, despite the thousands of tonnes removed (Lenzi et al., 2011). In 2014 it was therefore decided to apply the method of resuspension of soft superficial sediment (Lenzi, 2010) to counteract the processes of eutrophication.

For the purposes of the present study, we identified three study "zones" of 90,000 m^2 (300 × 300 m) (Fig. 1), homogeneous for substrate grain size (16–18% coarse sand, >1000 mm; 52–56% fine sand, 250–125 mm; 14–18% silt and clay, <63 mm) (Renzi et al., 2007), depth (0.9–1.2 m) and macroalgal density (6.5–9.3 kg m^{-2}), consisting of the Chlorophyceae *Chaetomorpha linum* (Müll.) Kütz. and *Valonia aegagropila* C. Agardh, the first of which was dominant. The areas were marked out with bamboo canes at ten-metre intervals. Two zones (U1 and U2) were used as control and left undisturbed, the third (zone D) underwent disturbance between June 2014 and March 2015, with 60 interventions lasting about 30 min each (Table 1). The disturbance was conducted by boats 13 m long, 4.5 m wide, capacity 13 t and draught 0.4 m. The boats stir up soft surface sediment (3–5 cm) as they move, and this has the direct effect of resuspending sediment in the water column and the indirect effect of fall-out of resuspended sediment on the surrounding bottom (Lenzi et al., 2013). The boats also stir up the algae and chop them to some extent (Lenzi et al., 2015). The three zones were chosen at a distance from each other so that resuspended matter would not affect the undisturbed zones. Resuspended matter was found to settle within a minimum distance of 100 m (Lenzi et al., 2013). Two independent sampling "areas" (A1, A2; Fig. 1) of about 10,000 m^2, approximately 140 m from each other, were marked out in each of the three zones. Sampling trials were conducted in each at four times: T0 before disturbance (May 2014), T1 and T2 during disturbance (July and September 2014) and T3 (May 2015), three months after the last disturbance, conducted in February 2015.

2.2. Chemical–physical variables

For each sampling trial, three in situ measures of pH (pH scale; DELTA OHM HD8705 electronic digital pH meter), salinity (S, practical salinity scale; ATAGO S/Mill refractometer), temperature (T, °C) and dissolved oxygen (DO, % saturation; OxyGuard Handy Mk III oxymeter) were made between 10 and 11 am in areas A1 and A2.

2.3. Estimates of macroalgal biomass

In order to measure macroalgal density, three samples of algal biomass were collected at random in areas A1 and A2, excluding bare bottom. Sampling plots of 3600 cm^2 were delineated by a 60 × 60 cm square metal frame. Samples were washed in sea-water, exposed to air in the shade for 3 h, and weighed (kg wet weight, kg$_{\mathrm{WW}}$). Biomass was expressed per square metre (kg$_{\mathrm{WW}}$ m^{-2}), using the following conversion factors:

$$\mathrm{kg_{WW}}\ \ 3600\ \ \mathrm{cm}^{-2} \times 10^{-4} \times 2.778 = \mathrm{kg_{WW}}\ \ \mathrm{m}^{-2}.$$

Standing crop (SC), i.e. mass of algae in an area at a given sampling time, was calculated with the following equation using the biomass values:

$$\mathrm{SC} = \mathrm{b} \times \mathrm{Su} \times \mathrm{CT} \times 10^{-3}$$

where b is the macroalgal biomass in kg$_{\mathrm{WW}}$ m^{-2}, obtained by averaging six normalized samples, Su is the surface area in m^2 of the zone in question, CT is total cover of the substrate by mat in the sampling area, and

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