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A new approach to macroalgal bloom control in eutrophic, shallow-water, coastal areas

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A B S T R A C T

In summer 2012, an experiment was conducted in a shallow eutrophic lagoon with poor water exchange to determine the consequences of harvesting algae on the algal mat itself, which was traversed and repeatedly disturbed by large harvester boats. Four areas with high macroalgal density, measuring half a hectare each, were selected. Two were subjected to frequent disturbance of the algal mat and sediment (12 two-hour operations over a 38-day period) and the other two were left undisturbed as control. The following variables were determined: 1) water column physical chemistry and nutrients; 2) redox potential, nutrients and organic load in sediments; 3) C, N and P content of algal thalli; 4) macroalgal biomass.

In 2013, a further experiment was conducted on a larger scale. Biomass was estimated in a high-density mat measuring 235 ha, where macroalgae were harvested and stirred up by four harvesting boats, and in two high-density mats measuring 150 and 120 ha, left undisturbed as control (9.15, 9.92 and 3.68 kg/m^2, respectively).

In the first experiment, no significant changes were observed in the water column. In sediment the main variation was a significant reduction in labile organic matter in the disturbed areas and a significant increase mainly in refractory organic matter in the undisturbed areas. Biomass showed a significant drastic reduction in disturbed areas and substantial stability in undisturbed areas. In the large-scale experiment, the biomass of the disturbed mat declined by about 63%, only 6.5% of which was due to harvesting. On the other hand, the undisturbed mat with higher density underwent a natural decline in biomass of about 23% and the other increased by about 50%. These results demonstrate that disturbance of high-density mat in shallow water by boats can cause decay of the mat.

1. Introduction

In the last 30 years, coastal areas have been subject to increasing eutrophication (Hauxwell and Valiela, 2004; Kroeze et al., 2013), the consequences of which are accentuated by geomorphological conformation and low water turnover in the case of non-tidal lagoons. The development of large dense mats of opportunistic macroalgae is a *facies* of eurihaline, eurithermal lagoon biocoenoses in response to eutrophication and complex ecological constraints (Pérès and Picard, 1964; Lotze and Schramm, 2000). Major blooms especially involve the chlorophyceae genera *Ulva*, *Chaetomorpha* and *Cladophora*, and the rhodophyceae genera *Gracilaria*, *Gracilariopsis* and *Spyridia*. These taxa are widely recognised to resist stress, grow rapidly and reproduce aggressively, being classified as "r-strategist" opportunistic species (Littler and Littler, 1980). Reported from coastal areas all over the world (Fletcher, 1996; Morand and Briand, 1996; Hiraoka et al., 2004; Morand and Merceron, 2005; Gubelit and Berezina, 2010; Ye et al., 2011), macroalgal blooms are not, however, simply the result of an increase in nutrients but of complex interactions between many variables, such as light, temperature, flow conditions and so forth (Schramm, 1999; Kennison and Fong, 2014).

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In eutrophic non-tidal lagoons, dense algal mats may form, occupying the whole water column in shallow basins (1–1.5 m) (Pavoni et al., 1999; Lenzi et al., 2011). Competition for substrate and light-exclusion by macroalgal mats impede the growth of other less tolerant species, reducing phytobenthic biodiversity (Lobban et al., 1985), as well as being a major cause of the disappearance of marine phanerogams (Hauxwell et al., 2001). In high-density mats, the upper layer prevents light from reaching the lower layers (self-shading) (Gordon and McComb, 1989; Lavery et al., 1991; Peckol and Rivers, 1996). This may lead to stratification of physical and chemical parameters and nutrients in the water column (Krause-Jensen et al., 1996; McGlathery et al., 1997; Lenzi et al., 2013a). Due to prolonged low light conditions, biomass near the bottom begins to die and decompose, becoming itself a source of nutrients (Sfriso, 1987; Hanisak, 1993). Organic matter from algal decay forms layers on the bottom and alters the nature of sediment, transforming sandy/silty sediment into very fine organic mud, with consequent impact on infaunal communities and species richness, the intensity of which also depends on the habitat where these communities occur (Raffaelli et al., 1998; Lyons et al., 2014). During decay, dissolved oxygen is impoverished in the lower layers and a transition to anoxygenic decomposition of organic matter occurs. Sediment anoxygenic processes release ammonium (Marty et al., 1990) and orthophosphates (Golterman, 2001), which become available for new blooms of vegetation (Rozan et al., 2002), and finally hydrogen sulphide, which can cause die-off of fauna (Giordani et al., 1996). This phenomenon, known as dystrophy, occurring especially in warmer seasons, though disastrous for fauna and flora, is a dissipative process: the ecosystem gets rid of the excess energy accumulated (Lenzi et al., 2011, 2012).

The consequences of vegetation blooms have in some cases been opposed by harvesting (Lenzi, 1992; King and Hodgson, 1995; Runca et al., 1996; Lavery et al., 1999; De Leo et al., 2002; Cotroneo et al., 2010). Harvesting algae is a burden on the public purse, involves problems of logistics, disposal and legislation, and is often insufficient as sole management criterion, unless undertaken on a massive scale. The material cannot be used easily and competitively recycled in industrial countries (Bastianoni et al., 2008; Migliore et al., 2012) and in Italy it is classified in the same category as solid urban waste.

It may seem evident that by harvesting and disposing of the algal biomass, the impact of bacterial degradation processes on this organic matter is reduced and a quantity of nutrients is removed from nutrient-rich areas. However, very few studies have evaluated the efficacy of harvesting macroalgal masses in managing eutrophic environments or the impact that harvesting can have on the ecosystems involved. For example, De Leo et al. (2002) used a mathematical model to evaluate the costs and benefits of harvesting algae in relation to the damage that macroalgal blooms had on small clam production in the Sacca di Goro. Lavery et al. (1999) estimated the time taken for the original zoobenthic population to be restored in a lagoon subject to harvesting of algae. More recently, we evaluated the impact of harvesting in terms of quantity of resuspended sediment and redistribution of macronutrients in the sediment layer (Lenzi et al., 2013b). Nevertheless, there are still many aspects to clarify, such as the minimum quantity of plant biomass to remove to obtain an improvement in environmental quality, the most effective and economic harvesting methods and the best timing during the year to optimise results. The possibility of other solutions has not been investigated and whether these are cost-effective.

On this topic, it is estimated that in Orbetello lagoon, 6000 tons of macroalgae (wet weight) harvested in about 6 months of activity caused resuspension of about 16,500 tons of sediment (Lenzi et al., 2013b). The mere passage of the harvesting vessel over the algae disturbs and stirs up the mat and superficial sediment, as an effect of boat propulsion and propeller rotation (Lenzi et al., 2005). This raised the question of whether sediment resuspension could have more effect than algal removal, considering the quantities involved. Another aspect worth clarifying is what happens to the plant mass stirred up by passage of the boat. Two scenarios and intermediate situations are possible. Stirring up of the algal mat by the boat could expose the lower-layer vegetation to light, reactivating photosynthesis and uptake of nutrients, as suggested by Peckol and Rivers (1995) for *Cladophora vagabunda*, and stimulating growth by fragmentation. In this way the macroalgal mass may not collapse, causing dystrophy, but may grow to the maximum sterically possible. At the other extreme, resuspension of anoxic sediment under the algal layer and the processes triggered by disturbance could have negative effects on the algae, increasing turbidity of the water column, incrementing the pool of aggressive bacteria and redepositing sediment on algal thalli. The resuspension of superficial anoxic sediment could also modify physical and chemical variables of the water column and alter biogeochemical nutrient cycles, creating nutrient limitation that could promote collapse of the algal mass.

The aim of the present study was to determine the effects of boat movements in lagoon areas with high density macroalgal mats (without removal of plant mass) by assessing mat growth and major chemical and physical variables of the water column. A manipulative field experiment was conducted to answer the following questions: Does frequent passage of boats induce an increase or decrease in macroalgal biomass? Does disturbance by boats exacerbate or mitigate environmental conditions, or has it no appreciable effect?

2. Materials and methods

2.1. Study area

The study was conducted in Orbetello lagoon (mean depth about 1 m) on the Tyrrhenian coast of Tuscany, Italy (42°41′–42°48′N, 11°17′–11°28′E; Fig. 1). The lagoon is 25.25 Km^2 wide and separated from the sea by two sand bars. It is divided into two basins, western and eastern, by Orbetello isthmus and a dam. Three canals link the lagoon to the sea, two in the west basin and one in the east basin (Fig. 1). Eutrophication of this lagoon ecosystem is mainly anthropogenic, due to past discharge of municipal wastewater (now discharged into the sea), treated and otherwise, which has accumulated in sediments, discharge of fish-farm wastewater, and nutrient input from agriculture in the catchment of the river Albegna, into the estuary of which one of the western canals opens (Lenzi et al., 2003). Vast dense macroalgal mats can cover hundreds of hectares without interruption, in a thick layer that reaches the surface, affecting the entire water column (100–150 cm). In the warm season, these mats can degenerate partially or totally, depending on meteorological conditions, and produce dystrophies, with variably extensive die-offs of benthic and vagile fauna (Lenzi et al., 2003, 2011).

Mitigation of the effects of eutrophication is conducted by pumping sea-water through the two western canals in summer, and by harvesting macroalgae (Lenzi, 1992; Lenzi et al., 2003). Macroalgae are harvested systematically for 5–6 months of the year by four boats that stow up to 2 tons.

2.2. Experimental design

2.2.1. Small-scale experiment

The study was conducted in the west basin of Orbetello lagoon, close to Monte Argentario, in an area between the two underwater