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Preliminary paper

Preliminary results on eelgrass regression and red seaweed dominance under increasing eutrophication (Thau Lagoon, France)

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This study measures the biomass, composition and species diversity of macrophyte communities in three sites with different levels of eutrophication in the Thau Lagoon where shellfish are intensively farmed and the percent of silt and shell fragments in the sediment increases at the expense of sand. Measurements were taken during three periods in one year at a depth of 1.50 m. As eutrophication increased, the dominant communities were: (I) mixed eelgrass (Zostera noltii)*; (II) mixed eelgrass* (Z. marina) *invaded by seaweeds* (Rhodophyceae *and* Chlorophyceae)*; and (III) a red seaweed community dominated by three* Gracilaria *species. Algae diversity was highest in the second site, where the maximum shell debris favored the settlement of algae. In the third and most eutrophicated site, the sea grass disappeared due to the large quantity of mud, the red algae increased and the light intensity decreased. The observed effects of the increasing eutrophication most likely reflect the historical steps in long-term eelgrass degradation and, therefore, the data are important for the management of eutrophicated marine areas.*

Key words: Mediterranean lagoon, eutrophication, algal diversity, eelgrass, red algae communities, shellfish farming

INTRODUCTION

A great number of works deal with how environmental characteristics affect the species that constitute simple or mixed eelgrass beds (DEN HARTOG, 1970; ORTH, 1977; PHILLIPS *et al.*, 1983; WETZEL & PENHALE, 1983; ORTH, 1986; SHORT, 1987; ORTH & MOORE, 1988; STEVENSON, 1988; DUARTE, 1989; HARRISON, 1993; OLESEN & SAND-JENSEN, 1994; SHORT *et al.*, 1995; ZIMMERMANN *et al.*, 1995) Some works deal specifically with the autecology of the *Zostera* species (RIGOLLET *et al.*, 1998; LAUGIER *et al.*, 1999) in the Thau Lagoon, in which our study was conducted.

The degradation, elimination and replacement of eelgrass is induced by eutrophication. The first works on the communities of the complex marine Thau Lagoon (GERBAL & VERLAQUE, 1995; DE CASABIANCA *et al.*, 1997b) led us to hypothesize that we could reconstruct the successive steps of sea grass degradation and their substitution by seaweeds from the beginning of the shellfish farming activity in the last century, and draw an inference from our analysis for management purposes.

The initial results of increased human activity on coasts and lagoons are an increase of nutrients and turbidity in the water and an increase of organic mud in the sediment (LUNDIN & LINDEN, 1993). These consequences generally affect macrophyte communities by inducing blooms of green seaweed (SFRISO *et al.*, 1987; FLETCHER, 1996) and decreasing the specific diversity of the macrophyte community (TEWARI & TOSHI, 1988; MUNDA, 1993). We present here a different way of studying the impact of eutrophication on macrophyte communities by analyzing the effects of the shellfish farming activity at Thau Lagoon. To understand the effects of shellfish farming on macrophyte communities, we studied the seasonal evolution of a sediment parameter - granulometric composition, one of the most simple and representative indicators of eutrophication (DE CASABIANCA *et al.*, 1997a) - at three sites in the Thau Lagoon, each with a different level of eutrophication.

MATERIAL AND METHODS

Study area

The Thau Lagoon (43°24'N, 3°36'E; south of France), with a surface area of 75 km^2 and an average depth of 4.5 m (40% of the bottom is between 8 and 10 m deep), is parallel to the coast and has access to the Mediterranean Sea at both ends (Fig.1).

The primary water exchange in the lagoon is through the Sète Channel. The dominant marine influx and limited input of fresh water result in a predominantly marine environment (salinity ranges from 35.9 to 40.5 ppt). The lagoon is undergoing heavy eutrophication due to shellfish farming, with fixed shellfish farming structures covering 20% of the lagoon area. Some 35,000 tones of oysters and mussels are yielded annually, producing 500 kg ha^{-1} yr^{-1} of nitrogen and 3000 kg ha^{-1} yr^{-1} of carbon in the form of the feces which continually enrich the water and sediment with organic matter. The inputs of

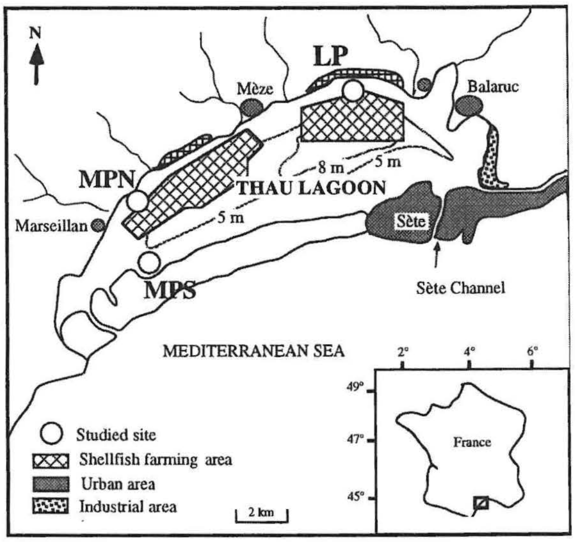

Fig. 1. Study site (Thau lagoon, France) and sampling areas

nitrogen and phosphorus coming from urban sewage and agricultural activity represent only about 1% of those coming from the shellfish farming activity (DE CASABIANCA, 1996; DE CASABIANCA *et al.*, 1997a). The three study sites in the Thau Lagoon were: MPS, in the southern area of the lagoon, which is free of shellfish farming; MPN, in the northern part of the lagoon, in which the shellfish farming influence is just beginning; and LP, in the northeast zone of the lagoon, which has fixed shellfish farming structures.

Sampling techniques

Samplings were conducted by free diving at a depth of 1.5 m in 1995 during three months: February (water temperature 7 ± 1°C), March (water temperature 12 ± 2°C) and July (water temperature from 24 ± 3°C).

Benthic macrophytes were sampled (three replicates) using a metal frame (0.25 x 0.25 m) according to the permanent quadrates method (NIENHUIS, 1978). The biomass of the species was measured after drying at 60°C for 24 h. Only species that constituted at least 1% of the total biomass were reported. Species diversity was estimated by the SHANNON index ($\log_2$ base; SHANNON & WEAVER, 1948).

Surface sediments (0-5 cm) were sampled with a corer and stored in a cold box. Granulometric fractions of the surface sediments were determined by passing an aliquot of wet surface sediments through two sieves (1.5 mm and 400 µm mesh) to determine the percentage (dry weight) of shell fragments, sand and silt after drying. The organic matter in the sediments (percent dry weight) was calculated as the difference between the weight of the sediment after 24 h at 60°C and the weight of the sediment after 24 h at 400°C, after removal of the carbonates. For each site, the monthly differences in sediment composition were tested with ANOVA.

RESULTS

There were large differences in the seasonal development of the macrophyte taxa among the three sites (Table 1). The composition of the community correlated with the composition of the sediment (Fig. 2).

As the sites became more eutrophicated, the amount of sand in the sediment decreased and the amounts of silt and shell fragments and percent of organic matter increased (Fig.2).

The macrophyte composition at MPS, the least eutrophic area, consisted of only eelgrass (*Zostera noltii* dominant). At MPN, the intermediate site, the eelgrass was invaded by red

Table 1. Seasonal changes (February, March and July 1995) in sediments (granulometric composition and organic matter percentage), and in macrophytes communities (species composition, biomass, and SHANNON index) at three sites (increasing eutrophic gradient from MPS to LP, Thau Lagoon, France)

SITES	MPS			MPN			LP		
Months	Feb.	Mar.	July	Feb.	Mar.	July	Feb.	Mar.	July
Rytiphloea tinctoria (Clemente) C. Agardh	–	–	–	6	–	–	–	–	–
Laurencia pinnatifida (Hudson) Lamouroux	–	–	–	10	37		56	–	–
Halopitys incurvus (Hudson) Batters	–	–	–	48	128	42	–	–	–
Gracilaria gracilis Stackhouse	–	–	–	–	–	–	62	126	41
Gracilaria dura (C. Agardh) J. Agardh	–	–	–	5	–	–	–	102	–
Gracilaria bursa-pastoris (S. G. Gmelin) Silva	–	–	–	–	14	–	–	252	132
Dasya hutchinsiae Harvey in Hooker	–	–	–	–	–	–	7	–	–
Chylocladia verticillata (Lightfoot) Bliding	–	–	–	–	–	–	47	–	–
Alsidium corallinum C. Agardh	–	–	–	22	6	37	11	–	–
Dictyota dichotoma (Hudson) Lamouroux	–	–	–	–	–	–	58	31	–
Monostroma grevillei (Thuret) Wittrock	–	–	–	–	–	–	3	12	–
Codium fragile (Suringar) Hariot	–	–	–	–	–	–	–	63	29
Chaetomorpha linum (O. F. Müller) Kützing	–	–	–	3	54	83	–	10	–
Zostera noltii Hornemann	20	19	100.9	3	56	95	–	–	–
Zostera marina Linnaeus	40	86	25	60	79	75	–	–	–
Other species	–	–	–	3	6	5	4	14	2
Total biomass (g. dry weight. m^{-2})	60	105	125.9	160	380	337	248	610	204
Shannon-Weaver diversity index	0.9	0.7	0.7	2.3	2.5	2.3	2.5	2.3	1.4

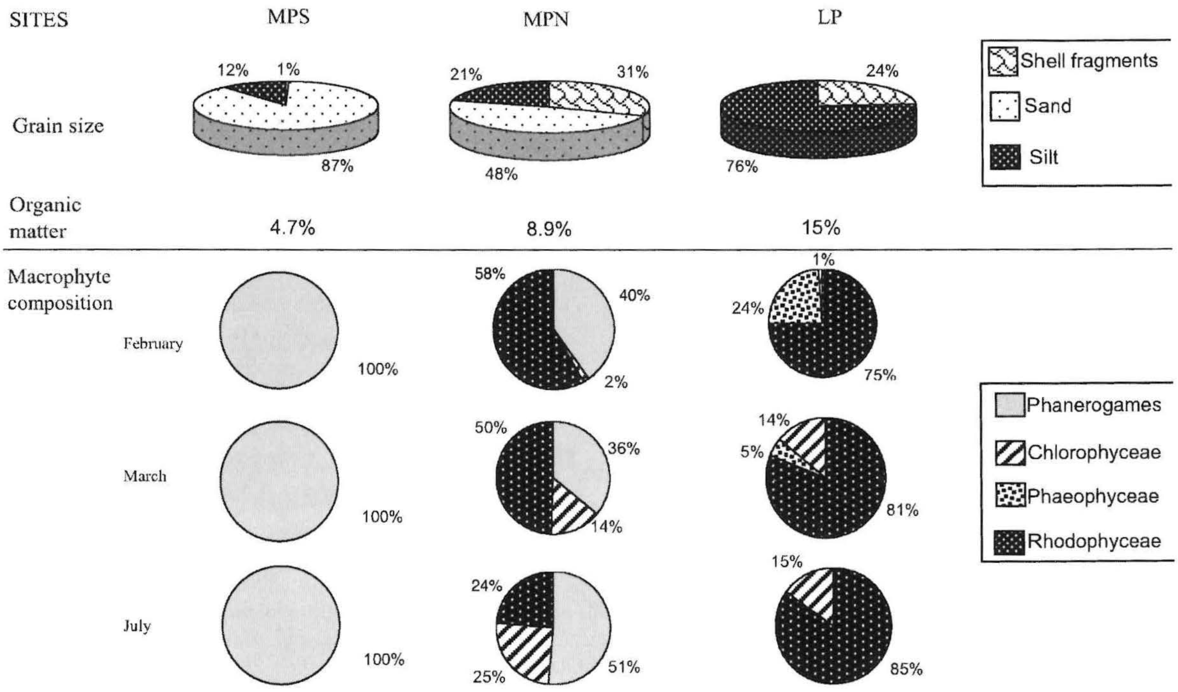

Fig. 2. Granulometric composition of sediments and seasonal changes (February, March and July, 1995) in macrophyte taxa, at three sites along increasing eutrophic gradient (Thau lagoon, France)

seaweed. The biomass of the mixed eelgrass (*Z. marina* dominant) represented only half of the total biomass in July while Rhodophyceae dominated the community in February and March with *Halopitis incurvus* representing 30.0% to 33.5% of the total biomass. In this site, the Chlorophyceae (*Chaetomorpha linum* dominant) reached a quarter of the total biomass in July. At LP, with the most eutrophication, the eelgrass disappeared and the red seaweed prevailed in all periods reaching a maximum in July of 85% of the total biomass. The highest biomass was measured at LP in March, with three *Gracilaria* species (*G. bursa pastoris, G. gracilis* and *G. dura*) representing 79% of the total biomass. The SHANNON index varied 0.7-0.9 at MPS, 2.3-2.5 at MPN and 1.4-2.5 at LP.

DISCUSSION

With the increasing eutrophication (indicated by the increasing silt to sand fraction from MPS to LP), seaweed invaded eelgrass and finally replaced it completely in accordance with our previous summer results in the lagoon (DE CASABIANCA *et al.*, 1997b), in spite of the large variations in temperature that effect seasonal changes in seaweed populations of different communities (DE CASABIANCA *et al.*, 1997c,d). Further, the seasonal changes in the macrophyte community show that the red algae community is the final step in the eutrophication succession.

There are several aspects relating to the changes in the composition of the community that should be considered. (I) One is the change in the prevailing species from *Z. noltii* (in the first site) to *Z. marina* (in the second site), according to ecological preferences (DEN HARTOG, 1970) and strategies (PHILLIPS *et al.*, 1983; DUARTRE, 1989; OLESEN & SAN JENSEN, 1994). The most fundamental explanation for the change is the enrichment of organic matter in the sediment (ORTH, 1977; SHORT, 1987; ORTH & MOORE, 1988; SHORT *et al.*, 1995). (II) Another is the invasion of the sea grass by macroalgae due to the increase of the shell fraction in the sediment which is conducive to the settlement of algae. (III) In the most eutrophicated site, the sea grass was eliminated due to competition with the seaweeds for light (DENNISON & ALBERTE, 1982; PHILLIPS *et al.*, 1983; WETZEL & PENHALE, 1983; ORTH & MOORE, 1986, 1988; HARRISON, 1993; DEN HARTOG, 1994; ZIMMERMAN, 1995) and space and due to the increased organic fraction in the sediment, which correlates with a decreased light intensity in the water column. (IV) Another aspect is the replacing of the sea grass by red macroalgae and, finally, (V) the evolution of the specific biodiversity. The last two aspects are particularly important at Thau Lagoon: first, because the red macroalgae were dominant in the eutrophic conditions, instead of the green macroalgae or green tides generally observed (SFRISO *et al.*, 1987; DEN HARTOG, 1994; FLETCHER, 1996) and, second, because the algal diversity increased with the increasing eutrophication, instead of the usual decrease (TEWARI & TOSHI, 1988; MUNDA, 1993).

Concerning the dominance of red macroalgae, two other main variables characterizing eutrophication in macrophyte populations must be considered: the nutrients of the water column and the incidental light at the depth where the community grows. At Thau, there were no significant seasonal differences between the concentration in nutrients at the *Gracilaria* site (LP) and other *Ulva* sites previously analyzed (DE CASABIANCA *et al.*, 1997a), i.e., 20-130 µmol l^{-1} of total inorganic nitrogen (N-NH_4 + N-NO_3 + N-NO_2) at LP was similar to 25-100 µmol l^{-1} at the *Ulva* sites, 0.1-17.5 µmol l^{-1} of dissolved reactive phosphorus (P-PO_4) at LP was similar to 0.2-20 µmol l^{-1} at the *Ulva* sites. But, there were significant differences in incidental light (DE CASABIANCA *et al.*, 1997a, d; BARTHELEMY *et al.*, 2001). The red seaweed dominated the most turbid conditions (LP) because of the silt and organic fractions of the sediment. The light intensity at the benthos was 250-290 µE m^{-2} s^{-1} at MPN (eelgrasses on sandy sediments) and 50-110 µE m^{-2} s^{-1} at LP (red algae on silty sediments) - adequate for Rhodophyceae growth (ROSENBERG & RAMUS, 1982; LAPOINTE, *et al.*, 1984; DE CASABIANCA *et al.*, 1997c). We noted that the light intensity during the growth period of the Chlorophycea *Ulva rigida* C. Agard (usually responsible for green tides) was 80-280 µE m^{-2} s^{-1} at Thau and 800-1200 µE m^{-2} s^{-1} at the Lido station of the Venice lagoon (DE CASABIANCA *et al.*, 1997d, 2002; BARTHELEMY *et al.*, 2001). So, for the same depth, with an overabundance in nutrients, light intensity at the water bottom is one of the factors that determines whether Chlorophyceae or Rhodophyceae will settle. In fact, the weak light intensity was the factor that determined the presence of red macroalgae at the LP site.

Concerning algal diversity, the increase of the Shannon index value from the least eutrophic area (MPS, 0.7-0.9) to the intermediate eutrophic area (MPN, 2.3-2.5) and the subsequent decrease in most eutrophic site (LP, 1.35-2.46) could be explained by the percentage of shell fragments, which reached the maximum at MPN and were covered by silt at LP. Shell fragments, characteristic of shellfish farming eutrophication, provide available surfaces for the attachment of algae.

Shellfish-farming-derived eutrophication is unusual in that, in addition to nutrients, it comprises a large fraction of undiluted solid matter in the form of feces of mussels and oysters. This material has a large impact on the sediment, as it increases the proportion of mud. The increase of small particles in the sediment increases turbidity in the water column. On the other hand, the fraction comprised by shell debris increases the surfaces available for the settlement of algae and therefore increases the diversity of the community. Eutrophication increased from station MPS to station MPN and, again, from station MPN to station LP. At station MPS, the pure sea grass bed was present on a sandy substrate. At station MPN, mud and shell debris settled on the bottom, contributing to regression of the sea grass bed that became smothered by new algae. At station LP, the numerous shells were covered by large quantities of mud and the sea grass bed disappeared. Red algae were dominant, as the luminosity was weak. There was insufficient light for Chlorophycea *Ulva* that is found in lagoon areas that are not directly influenced by shellfish culture. These genera are found on sandy-rocky substrates in waters with similar nutrient levels (DE CASABIANCA, 1997a,d).

Each set of parameters relative to the sediment and light intensity characterizes a step in the process of eelgrass degradation or replacement. The degradation observed in this study under increasing eutrophication possibly reflects the historic evolution of the Thau Lagoon, where eelgrass was originally the dominant benthic macrophyte (CALVET, 1908). Our results show that the eelgrass community presents the lowest macrophyte diversity. The red algae community does not represent an ultimate step of degradation, because it is still characterized by a high degree of biodiversity. We conclude that these defined eutrophic levels may be useful for long-term control of degradation or reversible community evolution of these areas, and for forecasting and planning management or remediation of other marine areas subject to intensive shellfish eutrophication.

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Preliminarna istraživanja uzmicanja morskih cvjetnica i prevlasti crvenih algi uslijed pojaćane eutrofikacije (Thau Lagoon, Francuska)

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SAŽETAK

U ovom se radu iznose podaci o biomasi, sastavu i različitosti vrsta makrofitskih zajednica na tri postaje smještene uzduž eutrofikacijslog gradijenta u sredozemnoj laguni Thau u kojoj se intenzivno uzgajaju školjkaši (povećano zamuljavanje i porast postotka dijelova ljušturica u pjeskovitom sedimentu). Istraživalo se godinu dana na dubini od 1,50 m u tri različita razdoblja. Duž eutrofikacijskog gradijenta prevladavale su slijedeće zajednice: (I) mješovita zajednica morskih cvjetnica *Zostera noltii*; (II) mješovita zajednica *Zostera marina* s ubačenim algama (III) mješana zajednica morske cvjetnice *Zostera marina* koju su napale svojte alga iz razreda Rhodophyceae i Chlorophyceae; (III) zajednica crvenih algi iz roda *Gracilaria*. Stupanj različitosti vrsta u zajednici bio je najveći na drugoj postaji pošto krhotine ljušturica školjaka omogućuju algama dobru podlogu za naseljavanje. Na trećoj postaji su morske cvjetnice nestale uslijed velike količine mulja, a crvene su alge počele prevladavati uslijed smanjenog intenziteta svjetla. Postojeći porast eutrofikacijskog gradijenta u skladu je sa stupnjem dugogodišnjeg propadanja morskih cvjetnica. Rezultati ovih istraživanja važni su za gospodarenje u morskim eutrofiziranim područjima.

Ključne riječi: sredozemna laguna, stupnjevi eutrofikacije, različitost algi, zajednice morskih cvjetnica, zajednice crvenih algi, eutrofikacija uzgajališta školjkaša