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Macroalgal Population and Sustainability

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ABSTRACT

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Algal blooms, often associated with eutrophication, are common in temperate regions in coastal lagoons and estuarine areas as well as in open seas. However, because of recent changes in water flows and sediment and nutrient loads in most rivers, eutrophication phenomena are now occurring in areas previously non affected. One of its most widespread and easily recognized effects in a coastal marine ecosystem is the excessive growths and drifts of macroalgae, to such a degree that the biomass becomes a significant problem.

The nutrients, notably from anthropogenic origin, constitute a significant factor in the appearance of the blooms in coastal waters. Besides a background originating from natural areas and precipitations, nutrients come from agriculture, sewage, industry, and aquaculture, in very various proportions following the local conditions.

At first, the development of opportunist and tolerant seaweeds acts as a purifying system. Then, when the seaweed is stranded or the environmental conditions become unfavourable, the plants die and decompose. The degradation of the chemical equilibrium induces the break-down of the biological balance in the ecosystem. At this stage, a large biomass can become troublesome, resulting in an increase in the herbivore population, competition or toxicity towards flora and fauna, alteration of the sediment, recycling of nutrients and pollutants in the ecosystem, nuisance for local residents and reduction of tourism (beaches degradation, chironomids, odors). Sooner or later, the water deteriorates, which may have a toxic effect on fauna including the commercial fish stocks.

Eutrophication problems have thus become a matter of major concern. Its management is neither a simple nor a cheap task. But, environmental and sustainability concerns may, in a not too distant future, override the lack of financial benefit. At any rate, underlayed action is required because in estuarine and potamologic milieus, potential land disposal arrangements are becoming rarer and costlier.

Control of eutrophication can only be reached effectively by drastic reduction of the total nutrient load of an overloaded water system. In order to be successful, only an integrated approach, based on a water body's nutrient mass balance and taking into consideration specific geographical, climatological and ecological conditions, can be effective. Moreover, it may take many years before recovery of a eutrophicated ecosystem, because the sediments constitute a complementary source of nutrients for macroalgae. But, prevention will prevent the nutrients from being discharged in the lagoons or in the sea. It will concern the waste treatment, agricultural mode change and treatment of gaseous effluent from polluting human activities.

ADDITIONAL INDEX WORDS: *Black Sea, nutrients, eutrophication, macroalgae, green tides.*

INTRODUCTION

Obviously, transformations of ecosystems quicken. Until now, people could think that scientific progress would permit them to go beyond the limit that the planet imposes, such as resource limitations or pollution. Today, numerous examples show that, if drastic measures are not taken, and if inertia and interests are not put aside, changes which will occur inevitably will be irreversible or at best, not easily reversible. They will almost always be troublesome, principally because of their quick pace, which will not permit an adaptation without distress.

Such is the case for halieutic resources, in relation to which the European Union proposes a significant reduction of fishing, a proposal badly accepted locally and yet globally profitable. Such is also the case for the global climate change, for which predictive models shorten the projected periods of perturbations (temperature increase, expected water-level rise, extreme atmospheric events) as they take into account various feedback phenomena initially neglected (release of methane from methane hydrates, increase of microbial activity, . . .). Further, such is the case for the accumulation of wastes which multiply pollution and nuisances, managed as soon they are discovered, without global treatment of the problems at source point.

The lagoon or coastal ecosystems do not escape this fate. The phenomena of uncontrolled growths of marine flora increased during the twentieth century, both microalgae or macroalgae blooms and growths of toxic or invasive algae. If,

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locally different solutions could be found, for instance with hydraulic improvements, in order to diminish, even suppress, troublesome biomasses, the problem globally remains.

In this paper, we give an overview of the problem of the excessive growths of seaweed and of their consequences for the coastal areas. Having analysed their causes, we will try to see what can be, in the future, the evolution of the phenomenon, on the one hand through concrete examples, and on the other hand in the light of the evolution of the environmental context in which it develops. Finally, we will analyse the action possibilities to make our ecosystem "sustainable".

EXCESSIVE GROWTH OF MACROALGAE

Definition and Characteristics

A large concentration of macroalgal biomass which accumulates at some sites indicates an excessive growth of seaweeds. This biomass, either attached or free floating, decomposes *in situ* or accumulates high up on the beaches. Often confined to lagoons, bays and estuaries, these proliferations or accumulations are usually associated with industrial, urban, or agricultural areas. Excessive growth of macroalgae is a response, in a given biotope, to a supply, probably an oversupply, of nutrients of natural or anthropogenic origin; if anthropogenic, it results from an environmental disturbance (MORAND and BRIAND, 1996). In some locations, for example along the coast of Brittany in France, or in Puget Sound, Washington, U.S.A., the problem is characterized by the accumulation of the green alga *Ulva* in rows along the beaches (BRIAND, 1989; THOM and ALBRIGHT, 1990). In such cases, the term "Green Tide" has been applied to the phenomenon (Figure 1) observed since times immemorial. It was reported to have occured as early as 1905 in Belfast Lough (LETTS and RICHARD, 1911), but seems to have increased in extent only over the last four decades, involving both the geographical expansion of these proliferations, and an increased biomass at the various sites. The years spanning 1960–1970 marked the real start of this phenomenon, limited until then to a very small number of localities.

Among the green proliferating algae, *Ulva* is the most commonly encountered, as in Brittany, France (BRIAND, 1989), or in the Venice Lagoon, Italy (SFRISO *et al.,* 1993). *Cladophora* may be responsible for significant green tides, as in the southern Fyn archipelago, Denmark (THYBO-CHRISTESEN *et al.,* 1993), or in Peel Inlet, Western Australia (LAVERY *et al.,* 1991). *Monostroma* proliferates in Arcachon Bay (AUBY *et al.,* 1994). *Chaetomorpha* and *Enteromorpha* also are often reported, the five genera being found alone, together, or dominant in turn (as in Peel Inlet). *Gracilaria* is the red alga the most involved in the excessive growths, as in Florida, U.S.A. (VIRNSTEIN and CARBONARA, 1985). One brown alga, *Pilayella,* was mentioned, in Massachussets, U.S.A. (WILCE *et al.,* 1982), in Brittany (Dion, personal communication), in the Baltic Sea (LOTZE *et al.,* 1999) and in the Southern Fyn archipelago (THYBO-CHRISTESEN *et al.,* 1993).

The density of algae in drift mats or run aground piles varies between 0.2 and 600 kg w.w. m^{-2}, and their depth falls within the 1 cm to 1.2 m range (DIAZ PIFFEREZ and LOPEZ, 1959; BRIAND, 1989). The biomass can be very significant, as in the Venice Lagoon (600,000 t fresh weight), in Brittany (50,000–70,000 t), or in Peel Inlet (100,000–600,000 t). The annual production may be estimated to be 1.5 to 4.5 times higher than the maximum biomass present at the site, in respect of an algal density high or low, as in the Venice Lagoon (SFRISO *et al.,* 1993). CASABIANCA-CHASSANY (1992) indicates a ratio of 2.6 in the Prévost Lagoon (France), based upon measurements of particulate nitrogen, and NIENHUIS (1992) reports a ratio of 3 for the Veerse Meer lagoon (Netherlands).

Figure 1. Green tide in Lannion Bay (Brittany, France).

Table 1 provides some examples of recent macroalgae excessive growth occurrence in Europe.

Consequences to the Ecosystem

The effects of seaweed proliferation and accumulation on the biotope and the environment are both numerous and varied.

First, the seaweed biomass plays an important role in purifying the medium by absorbing excess nutrients and by accumulating some toxins (BRAULT, 1983). A primary function of excessive macroalgal development appears, therefore, to be the abatement of pollution in coastal ecosystems. Taking into consideration the entire cycle of growth and decay of the seaweed, the Venice Lagoon, for example, acts as an important denitrifying reactor (SFRISO and MARCOMINI, 1994).

Ulva concentrates several metals from water and is sometimes used to assess the level of this type of pollutants (MALEA and HARITONIDIS, 2000).

Associations between macrophytes and marine animals are

Table 1. *Some recent data about macroalgae excessive growths in Europe.*

Country	Location	Genus-Species	Density (kg w.w. or d.w.m^{-2})	Biomass (t w.w. or d.w.)	Annual harvesting or production (p)	Proliferation: Period	Proliferation: Date	References
France	Brittany coasts	*Ulva*		20,000 (w)*	43,000 m^3		1997	Merceron, 1998
				21,000 (w)*	51,000 m^3		1998	Merceron, 1999
	with:							
	• La Fresnaye Bay			1,800 (w)	3 m^3		1997	
	• St Brieuc Bay			11,000 (w)	11,000 m^3			
	• Lannion Bay			4,200 (w)	10,000 m^3			
	• Douarnenez Bay			120 (w)	4,500 m^3			
	• La Fresnaye Bay			2,800 (w)	4 m^3		1998	
	• St Brieuc Bay			8,400 (w)	6,600 m^3			
	• Lannion Bay			2,400 (w)	12,000 m^3			
	• Douarnenez Bay			3,400 (w)	9,800 m^3			
Germany	Baltic Sea	*Pilayella littoralis* + *Enteromorpha* spp.	0.01–0.8 (d)			March–August		Lotze, 1998
Italy	Venice Lagoon**				11,000 m^3		1993	Sfriso & Marcomini, 1996
	with:							
	• Central Venice Lagoon	*Ulva* principally	0.1–15 (w)	84,000 (w)	380,000 t.w.w.		1993	Sfriso & Marcomini, 1996
	• Palude della Rosa	*Ulva rigida*	3.5 (w)	7,500 (w)***	(p)	March–July	1992	Tagliapietra *et al.*, 1998
			0.4 (w)	900 (w)***		March–July	1993	
Spain	Tancada Lagoon (Ebro Delta)	*Chaetomorpha linum* +	0.3 (d)			April–August		Menéndez & Comin, 2000
		Cladophora spp. +	0.2 (d)			June–August		
		Gracilaria verrucosa	0.2 (d)			June–July		
	Palmones River Estuary	*Ulva*	0.2 (d)			March–July & October–December		Hernandez *et al.*, 1997
United Kingdom	Ythan Esutary (Scotland)	*Enteromorpha* spp. +	0.25 (d)	1,000 (w)***		May–October		Raffaelli *et al.*, 1998
		Chaetomorpa linum +	g0.05 (d)					
		Ulva lactuca	0.03 (d)					

* The decrease of the figures in relation to those of the preceding years is not due to a decrease of seaweed quantity, but to a change of observation mode (overview of one day by beach in June, July or August) and calculation (more precise on washed and dripped algae).
** Since the beginning of 1990s, *Ulva* production drastically declined.
*** Order of magnitude, according to calculations from the data given by the authors.

Figure 2. *Ulva* collect in Hillion Bay (Brittany, France). Harvesting is made with loaders, resulting in the collection of a heterogeneous mixture of seaweed and sand.

often considered to be positive. In some cases, seaweed proliferations provide a supplementary food source which can have a favourable effect on the development of herbivores. Another significant ecological role of excessive growths of algae is the provision of habitats and refuges against predators. For instance, LENANTON *et al.* (1985) noted that an increase in fish catches followed an increase in the biomass of *Cladophora* and *Chaetomorpha,* while VIRNSTEIN and CARBONARA (1985) reported high densities of small animals (peracarid crustaceans, gastropod molluscs, *etc.*) in *Gracilaria* drift beds. These proliferations do, however, pose significant fouling problems in aquacultural areas.

Moreover, the seaweeds involved in the proliferations appear not to be very numerous in terms of species, but represent a stronger proportion of the algal community, with the growth being selective according to their degree of tolerance of pollution and to their affinity for the nutrients. The most sensitive species regress in quantity or disappear in favour of more tolerant species. In Norwegian fjords, the competition for substrata and the screen effect caused by algal deposits strongly reduce thus the chance of development for the original populations of *Ascophyllum nodosum* (LOBBAN *et al.,* 1985).

When seaweed is washed ashore or when degradation begins, the problem of proliferation is stated in terms of pollution. The significant quantities of N and P coming from the decomposition of deposits maintain a state of eutrophication.

The decomposition of algae leads to the production of toxins, and the oxidation of the organic matter creates anoxic conditions, which, favoured by the low rate of renewal and the stratification of water, can result in the death of benthic animals (JOHNSON and WELSH, 1985). In aquaculture areas, the decomposition of the algae leads to the death of shellfish; in some fishing grounds, a reduction in catches is observed. For example, in the south-east Kattegat (Sweden), the mass occurrence of macroalgae in nearshore areas in 1980 was followed by the death of fish and, in shallow waters, by mass mortality of bivalves (ROSENBERG *et al.,* 1990).

The accumulation of rubbish alters the actual nature of the sediment, sometimes transforming a sandy sediment into organic mud. The removal of the cast seaweed also causes considerable exports of sediment, the equipment employed (such as public loaders) not being very selective (BRAULT and GOLVEN, 1983) (Figure 2). For Lannion Bay alone, exports of sand are estimated at approximately 500 tonnes per season. The impact of such traffic (2000 truck arrivals and departures) and such removals, in hydrological and ecological terms, has not yet been determined. In Peel Inlet, Western Australia, it was noted that the loaders compacted the sediment, beach sand was picked up with the algae, and rushes, which stabilise the foreshore, were destroyed, resulting in erosion and receding of certain beaches by approximately 10–12 m based on observations spanning over seventeen years of beach cleaning (ATKINS *et al.,* 1993).

Another pollution comes from the fermentation of sulphured polysaccharides, which liberates significant quantities of hydrogen sulphide into the atmosphere, and thus bothers the inhabitants and tourists in the regions affected (BRIAND, 1989). Hydrogen sulphide production was estimated at 95,000 m^3 in the city of Tunis (Tunisia), when significant excessive growths occurred in the lagoon, the average concentration in the atmosphere reaching 3 ml H_2S m^{-3} (STIRN, 1968). Moreover, chironomids form clouds and are favoured by their tolerance of anoxic conditions and a temporary disappearance of zoobenthos and fish (CERETTI *et al.,* 1985). BOURGUÈS (1992), referring to Arcachon Bay, mentioned that the chironomids strongly appear during the algae decay and take part in the fragmentation of plant material.

Causes

Among the different elements of the biotope which can be involved in the excessive growth of algae (light, temperature, substratum, depth, salinity, turbidity, water motion, . . .), the presence of nutrients in excess is essential: a minimum quantity is required for algal proliferation, sensibly 0.1–0.2 mg l^{-1} of inorganic nitrogen and 0.02–0.03 mg l^{-1} of inorganic phosphorus (HODGKIN *et al.,* 1980). Generally, unlike freshwater systems which are, principally, phosphorus limited, marine waters are mostly nitrogen and, sometimes, iron limited (MÉNESGUEN and PIRIOU, 1995; SEQUI *et al.,* 1992). The unusual P limitation in most cases of eutrophication in bodies of marine water of Western Australia is explained by the nature and use of the soils, as well as meteorological conditions (HODGKIN and YEATES, 1993).

The main anthropogenic source of nitrogen is primarily agricultural, as on the coasts of Brittany (BRIAND, 1989), in the Venice Lagoon (SFRISO *et al.,* 1992), or in Peel Inlet (HODGKIN *et al.,* 1980). Conversely, the influence of agriculture on the marine environment is generally due to nitrogen and not to phosphorus: the N/P ratio in waters coming from soil drainage usually ranges from 10 to 1000 (SEQUI *et al.,* 1992). Nitrogen inputs from rivers and of atmospheric origin may be of the same order of magnitude (THYBO-CHRISTESEN *et al.,* 1993). Phosphorus, on the other hand, is trapped in the sediment from year to year. In the Venice Lagoon, the P and N concentrations in the top 5–10 cm of sediment have increased by a factor up to 30 and 2.4 respectively from 1948 to 1968 (SFRISO *et al.,* 1992). Finally, recycled nutrients are a major source for primary production, the recycling reaching values on the order of 60–65% for N and 50–65% for P (GABRIELSON *et al.,* 1983; THYBO-CHRISTESEN *et al.,* 1993). In countries with intensive marine fish farms, such as Norway, Japan, or Philippines, aquaculture also contributes a significant quantity of nutrients by way of residual feed and excrements from fish, which, moreover, form nutrients-rich sediments in confined areas.

Nevertheless, the phenomenon is all the more remarkable when concomitance exists between the problem of eutrophication and the particular environmental conditions (winds, currents, weak rate of water renewal, *etc.*). Thus, the actual lagoon configuration facilitates the trapping of nutritional salts and chemical wastes. Lagoons, generally shallow, also allow rapid water warming and significant photosynthetic activity. In an open sea, an extensive intertidal sandy area with gentle slope, a supply of fresh water with sufficient nutrient flows, and very slight residual tide water circulation resulting in a sea water trapping situation encountered in the lagoons, are necessary for the occurrence of "green tides" (PIRIOU *et al.,* 1991).

A reduction in photosynthesis may be a cause of limitation of the seaweed proliferations. It can occur when light is too low. It also occurs, for instance, when there is light attenuation by shading by other algae (macro or micro) or cyanobacteria, as described in the Peel-Harvey system (LAVERY *et al.,* 1991). In the Venice Lagoon, SFRISO and PAVONI (1994) showed that when macroalgae were absent, it was mainly due to the particulate matter content, which, in forming a deposit on the bottom algae, prevented their growth. Conversely, LEVAVASSEUR (1986) has shown that strong and long periods of light result in the destruction of the chlorophyll pigments of *Ulva.* In Brittany, a comparison between 'green tides' in the Bays of Saint-Brieuc and Lannion provided some evidence of a limitation in the photosynthetic rate (LE BOZEC, 1993). The growth halts each year at the beginning of Summer. It seems to be due, essentially, to a loss of the photosynthetic capacity of the alga, the *Ulva* of 'green tides' being particular sensitive to light (PIRIOU and DUVAL, 1990).

Impact on the Local Economy

The decrease in phytoplankton in shellfish cultivation areas, the increase of nutrients linked with dystrophic crises resulting in 'red tides', the difficulty of access to beaches, the presence of seaweed in water, as well as the production of nauseating hydrogen sulphide stemming from the accumulation and decomposition of green seaweed, are particularly troublesome with sometimes ensuing significant financial effects.

Some communities, therefore, undertake systematic collection of the algae, a very costly undertaking. In France, at the end of the 1980s, it cost, from FFR 50 to 800 (1 FFR = 0.15 €) per tonne collected, depending on the type of machine used and the area affected (BRIAND, 1991). In Peel Inlet, the cost was estimated at 230,000 AUD annually (1 AUD = 0.55 USD) for 13,000 m^3 of algae, 90% of which was removed from the beaches (ATKINS *et al.,* 1993). In Brittany, harvesting was undertaken in the Bays of Saint-Brieuc and Lannion (department of the Côtes du Nord, now Côtes d'Armor). This was considered to be too expensive (it had cost 670,000 FFR in 1972—KOPP, 1977), and harvesting was reduced until the 1980s when it was resumed. In 1986, the cost exceeded one million French francs for this department alone (BRIAND, 1989). It increases regularly: 1.6 million francs for the whole of Brittany, for 46,000 m^3 harvested, in 1987; 3.2 for 98,000 m^3 in 1991; 3.6 for 90,000 m^3 in 1992 (CEVA, 1993). Forty five percent of the districts along the Brittany coast are obliged to remove mechanically the green algae from their beaches (DION, 1994). The cast seaweed is then spread in fields as a fertilising agent, or piled in dumps. In the Orbetello Lagoon (Italy), because of the economical importance of fishing in the lagoon, *Chaetomorpha linum* is harvested to prevent anoxia, such as that reported in the Venice Lagoon, and to promote the life of the fauna, fish and crustaceans. In 1988, 1480 t w.w. were collected at a cost of 36.5 million lire (1000 ITL = 1 €), representing 15% of the seaweed in an area of 290 ha, covered by an average of 3.4 kg m^{-2} (ORLANDINI, 1988).

As the systematic collection of the algae is often insufficient, restoration measures are usually necessary. Some concern change in agricultural practices and waste water management. Others are directly related to the eutrophicated water body and their costs may be clearly attributed to the fight against seaweed proliferation. Thus, the construction of the Damesville Channel from the Harvey Estuary to the sea, designed to reduce the phosphorus concentration in Peel Inlet, is estimated at 60.10^6 AUD, which gives an idea of the social concern for the welfare of the estuary (HODGKIN and HAMILTON, 1993).

INVASION OF ECOSYSTEM BY SEAWEED

The phenomenon of proliferating algae is fundamentally different from that of invasive algae, such as *Sargassum muticum* (Yendo) Fensholt (BELSHER and BOYEN, 1983; CRITCHLEY *et al.,* 1990) or *Caulerpa taxifolia* (Vahl) C. Agardh (MEINESZ *et al.,* 1993), the excessive growth of the latter resulting from the introduction of the alga into waters where it has no predator. In the case of *Caulerpa taxifolia,* for the most part, the sites colonized are typical of unpolluted environments (BELSHER *et al.,* 1994).

Nevertheless, it is sometimes difficult to say to what extent each of the phenomena is involved. The introduction of foreign species, capable of taking advantage of coastal water pollution, may result in changes to the local vegetation. For instance, in Japan, *Ulva fasciata,* stimulated by chemical factors, and supported by vigorous propagation, has supplanted the indigenous dominant species *Ulva pertusa* Kjellman (ARAZAKI, 1984). BACH and JOSSELYN (1979) envisaged two alternative hypotheses for excessive growths of *Cladophora prolifera,* which occured in Bermuda. It could be either an invasive or opportunist alga, the increase in the concentration of nutrients due to human activity being the cause of the proliferation. Finally, LAPOINTE and O'CONNELL (1989) showed that the spread of the alga through Bermuda's inshore waters was clearly related to the enrichment in nutrients over the past 20 years. The opportunistic seaweed *Gracilaria tikvahiae,* which now proliferates in Waquoit Bay (Massachussets) or in Rhode Island, was not noted as being present in earlier studies concerning these zones (PECKOL *et al.,* 1994).

PROLIFERATING SEAWEED AND CORAL REEFS

WILKINSON (1996) estimates that 30% of coral reefs are doomed, and 30% are seriously threatened, with only 40% being safe.

It seems obvious that the main factor responsible for this state is human pressure on a local scale, rather than global change, although global warming and depletion of ozone may be involved (DUBINSKY and STAMBLER, 1996). Coral is adversely affected by elevated nutrient levels, but the effect could be indirect. The zooxanthellae, photosynthetic dinoflagellate symbionts of the corals, are less efficient than seaweed for catching the nutrients. In all cases when corals were overgrown by algae, their eventual death results from the combination of shading, night-time depletion of oxygen due to impeded circulation, and toxins, notably H_2S, from the decaying algae and anoxic sediments.

MARSZALEK (1981), in a review of the effects of sewage effluents on the coral reefs, concluded that the most serious damage resulted from competition with high-nutrient stimulated algae, rather than from effluent toxicity. Recent examples of these phenomena have been described for the Red Sea reefs at the Eastern Sinai Peninsula (RIEGL and VELIMIROV, 1991), or in the Gulf of Aqaba, where the green seaweed *Enteromorpha* sp. smothered the corals during cold winters (GENIN *et al.,* 1995), and for Mauritius (Indian Ocean), with the development of an important belt of the free floating alga *Ulva reticulata* (beds up to 30–50 cm in thickness) in all the outer zone of the reef in the vicinity of the sewage outfall (THOMASSIN *et al.,* 1998).

LAPOINTE (1997) mentioned the unusual growth of macroalgae in Florida and in Jamaica as a serious danger for the coral reefs. HUGUES *et al.* (1999) argued that macroalgal blooms on reefs in these places were controlled by the decrease in fishes (overfishing) and sea urchins (die off). During the past decade, however, macroalgal blooms (*Chaetomorpha linum* notably) have become increasingly common on Jamaican reefs adjacent to nutrient input from seawage or agricultural runoff (LAPOINTE, 1999). The term 'macroalgal bloom' is used here only to indicate an increase in abundance. So, even if the mechanism is probably similar to this one leading to the excessive growth, and reported for this reason, the scale of the phenomenon is not the same.

THE BLACK SEA CASE

In the Black Sea, the exchange rate with the ocean is very low, the communication with the Mediterranean Sea being restricted. A great part of the polluting load comes from agriculture (CADDY and GRIFFITHS, 1996). The retention of the water masses near the coast could then have significant consequences on the macro-algal population. In actual fact, attention is rather focused on phytoplankton and its relationship with the invasion of the comb jelly *Mnemiopsis leidyi* and the decrease of the fish stocks (FAO, 1996; LANCELOT *et al.,* 2002). No excessive growth of seaweed were reported until recently, even if such phenomena were mentioned in harbor sites, but at a low extent (CELAN and BAVARU, 1977), and observed, it seems, more recently at a more significant scale (VERSHININ and KAMNEV, 2001; Frangopol, personal communication). Moreover, the disappearance of *Cystoseira barbata* was reported for the Vama Veche site (Romania), substrata being now colonized by opportunistic algae such as *Enteromorpha, Ulva, Cladophora, etc.* (PETRANU *et al.,* 1999).

Nevertheless, some conditions seem to be favorable to the proliferations: numerous authors consider the Black Sea as an eutrophicated sea (KONOVALOV and MURRAY, 2001). The low salinity of the water gives generally an advantage to opportunistic green algae. The presence of slight slopes and lagoons, combined with lack of tide, is another element. Similarly, the metal concentrations inside *Ulva rigida* encountered along the Turkish coasts and *Ulva* spp., which develop in Brittany, are very similar (BRIAND, 1989; TOPCUOGLU *et al.,* 2002). Conversely, the existence of an anoxic area in depth, which traps the nutrients and is the place of biochemical transformations, the occurrence of contrasted temperatures, the presence of sediments are unfavourable conditions.

Another question is the ratio between the different elements (N/P/Si). As significant phytoplankton biomass was reported (MONCHEVA *et al.*, 2001; GARNIER *et al.,* 2002), it seems that this ratio is such that micro-algae develop rather than macro-algae when an anthropogenic supply of nutrients is excessive. The question of the changes brought by the Danube damming can be evolutive, the first effect having been to decrease the diatom population, by retaining silicates (TURKEY, 1999). At Constantza station (Romania), the N/P ratio was larger in 1997 (molar ratio = 17) than during all the preceding years since 1980, from when it was measured, and it followed a rising curve (COCIASU *et al.,* 1998). Phosphorus would become a limiting factor for phytoplankton, and macroalgal "blooms" could occur.

EVOLUTION OF PERTURBED ECOSYSTEMS

Ecosystems touched by excessive growth of seaweeds were followed for decades. Each one is a special case, because all differ in their natural environment, but also in the human activities and the interventions to which they were subjected. Four examples give an idea of the possible evolutions.

Brittany

In Brittany, as the nutrient supply to the sea is still increasing, the number of locations where green tides develop is also increasing from year to year, even if the biomass was not increased inside well-installed locations. The duration of the presence of *Ulva* mass on beaches becomes longer and longer; in some places like the Bay of La Fresnaye, it tends now to stay year-round instead of only during spring and summer. Another way of development of green tides is seawards. In some sites where the algal proliferation appeared for several decades (bays of Douarnenez, Concarneau, Lannion, Saint-Brieuc), drifting *Ulva* deposited on the bay's bottom can be observed seawards up to 20 meter depth. Its density range is from nil to several kg.m^{-2} wet weight; the latter case displays an endless green carpet put on sand. Globally this "offshore" biomass frequently exceeds that of the "nearshore" one which is the only one, till now, that has been quantified.

A program to remove phosphorus from the waste waters of the towns was enforced, yet had no effect on the excessive growths of seaweed, the limiting factor being nitrogen in Brittany coastal waters.

Without reduction of the nitrogen supply to the sea and/or nitrogen outputs from agriculture, the situation will worsen, with annual variations caused by temperature, irradiance, and river flow conditions.

Tunis Lagoon

In contrast, a decrease in the macroalgal biomass and a change in its composition were observed following a reduction in the concentration of nutrients as a result of environmental restoration measures. In the Lagoon of Tunis, total N and P concentrations decreased, on average, from about 4000 μg L^{-1} to 1000, then to 400, and 600 μg L^{-1} to 100, then to 20 respectively. Waste water discharge into the lagoon was suppressed in 1981. In 1987, water circulation in the lagoon was improved by building a sea wall separating the lagoon into two parts, the macroalgae being restrained to the shallow (1 m) southern part. Following this change, the *Ulva* biomass decreased from about 12,000 t w.w. annually to 3600 in 1989 and proliferation stopped in 1990, whereas *Chaetomorpha* became the dominant species (4200 t in 1989, 5600 in 1990) and *Gracilaria* appeared (BEN CHARRADA, 1992).

Venice Lagoon

The Venice Lagoon may be considered as an unstable system. Nutrients come from agriculture and numerous industrial plants. Harvesting of *Gracilaria* and fishing were traditional. Collecting of *Ulva* was introduced, when this alga began to be really troublesome. Boat circulation inside the lagoon is significant. Hydraulic changes and nutrient inputs led, from the '60s, to an abnormal growth of *Ulva rigida,* whose biomass degradation caused frequent anoxic crises, the decrease of the biomass of seagrasses, and the disappearance of many seaweeds unable to tolerate dystrophic conditions. Starting from the '90s, a strong reduction of *Ulva* was observed, leading to a partial repopulation of the marine phanerogams, phenomenon limited by the harvesting of *Tapes philippinarum,* a bivalve introduced in the lagoon for economic purposes, with dredges which resuspended the sediments. Moreover, non-indigenous species, such as *Sargassum muticum, Undaria pinnatifida,* or *Grateloupia doryphora,* spread all over the lagoon (CALICETI *et al.,* 2002). SFRISO and PAVONI (1994) had stressed the recent and unusual phytoplankton blooms, due to the sedimentation of particulate matter re-suspended from the bottom sediments, which then covered the macroalgal fronds.

Peel-Harvey Estuarine System

In most cases in Western Australia the sandy soils are unable to retain phosphorus and the applied dose (18 kg ha^{-1} y^{-1}) is adapted to newly clean land and not to developed land; the rains at the end of the dry season leach the mineralised nutrients, and the fertilisers added by farmers before the rains make the soils unworkable (HODGKIN and HAMILTON, 1993). Thus N and P both come, in solution, in the drainage waters from the coastal plain catchment and N is limited in marine embayments only when there is little drainage from the land.

The Peel-Harvey estuarine system, 80 km south of Perth, has been particularly well studied because of the trouble caused by eutrophication in this residential and recreative area (HODGKIN *et al.,* 1980). The Harvey Estuary and Peel Inlet are two basins subjected to cyanobacterial blooms and macroalgae proliferations respectively. The problem is recent, and results from a large increase in nutrients input into the estuary. In Peel Inlet, seaweed growth and drifting onto the beaches has necessitated harvesting (MCCOMB *et al.,* 1981). The biomass almost exclusively comprises four genera of green algae, *viz. Cladophora, Chaetomorpha, Enteromorpha,* and *Ulva,* each one having been dominant in turn with 50,000 t d.w. in 1979 of *Cladophora,* 18,000 t in 1981 of *Chaetomorpha,* 15,000 t in 1984 of *Enteromorpha,* and 14,000 t in 1985 of *Ulva* (LAVERY *et al.,* 1991). Events which caused the changes vary in nature and include a storm, a cyanobacteria bloom in Harvey Estuary leading to a light attenuation in Peel Inlet, temperatures, irradiance levels, flow of the rivers, and change in the nutrient rates.

Comparing two similar beaches in the Peel-Harvey estuarine system, where accumulations of macroalgae occur, LAVERY *et al.* (1999) noticed that, in the long-term, the beach, where harvesting was performed for 1974, had a macro-in-

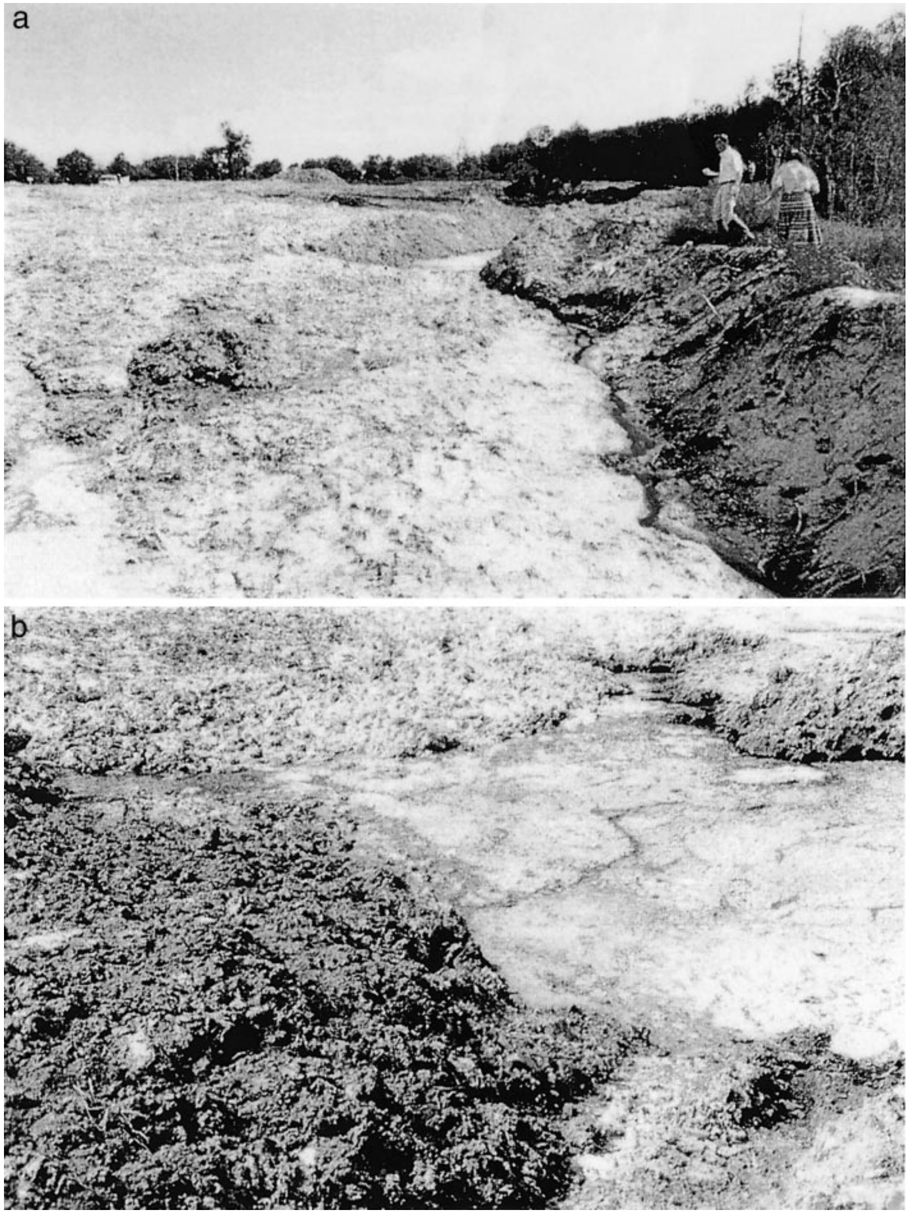

Figure 3. (a) Stranded *Ulva* dump near Hillion (Brittany, France): General view showing the scale of the dump and, in the back, a composting pile of a mixture of seaweed and straw, the pile keeping its initial height, contrary to the seaweed which liquefies and spread out. (b) Stranded *Ulva* dump near Hillion (Brittany, France): Close view showing the release of juice by the liquefying seaweed.

vertebrate assemblage similar to that of another similar beach in which macroalgae did not accumulate. The beach where stranded seaweeds were not removed had a different faunal assemblage. Moreover, the short-term effects of the harvesting were only temporary.

SUSTAINABILITY

General Principles

Eutrophication is certainly a risk for numerous coastal ecosystems, due to agricultural and industrial human activities, and to domestic waste waters. To this risk, add the foreseeable climate changes. Under such conditions, it is necessary to define criterions in order that an ecosystem may be considered sustainable.

Sustainability does not involve a return to the initial state, but rather a maintenance in an equilibrium state, where a sufficient biodiversity is compatible with the durability of the ecosystem, and where the human functions which are assigned to it (production, recreation, environment) may be assumed. The economics also intervene, because the cost/benefit ratio should be favourable or neutral. Subjective criteria are inescapable: what are we ready to accept? The first thing to define then is a sustainable acceptable ecosystem.

The second thing to be taken into account is the probability of evolution towards something which is or is not an acceptable ecosystem. Therefore it is necessary to anticipate. The climate changes should be considered, especially when invasive species, opportunistic or not, vegetal or animal, are involved.

The means at our disposal are preventive or curative. In the field of prevention, it is sometimes difficult to be understood, because the fight against some causes of eutrophication involves many people. A program should be very exhaustive, and the approach integrated. For instance, it is known that the atmospheric fallouts of nitrogen in an ammoniacal or oxidized form in a closed water body may be of the same order of magnitude than the nitrogenous loadings coming from the streams (CORPEN, 2001). This consideration has to be translated into a reduction of nitrogen compounds release at the source.

In the field of remediation, things are sometimes easier, but often costly. Solutions include hydrology, bioremediation, harvesting, and treatment of waste. Storage in a dump is unacceptable because it leads to a recycling of nutrients (Figure 3).

Proposals

The most avanced plan concerns Western Australia (HODGKIN and YEATES, 1993). Emphasis has been placed here on phosphorus (but a number of measures concern the reduction of both N and P), although the lowering of P load alone may result, for a time, in an increase of seaweed proliferation by clearing the water and favouring some species. Siliceous, acidic, sandy-surfaced soils, with an extremely low clay and colloidal content have a very low P retention capacity: 20 to 200 $\mu g\ g^{-1}$ for 70% of the soils of the basin areas. Considerable research has been carried out (i) on enrichments suitable for their improvement, leading to a push for the use of bauxite processing residues, (ii) to develop "slow release sources" of phosphorus, agronomically and economically effective, in order to replace superphosphate. The programme includes many other measures in the framework of a long term strategy: —using rational fertilisation and alternative farming systems, which would be beneficial to both farmers and the general community, —replacing shallow-rooted annual plants with deep-rooted agricultural or forestry species, —protecting the remaining indigenous vegetation, —planting trees, notably *Eucalyptus globulus,* in strategic blocks, —modifying the coastal plain drainage system and the river banks, building flood detention reservoirs, —preserving and improving natural wetlands, —and, finally, processing the point sources (pigsties, sheep farms, intensive poultry farms, slaughterhouses, sewage treatment works, domestic gardens and public open spaces).

In Brittany, a better knowledge of the conditions of their development has led to measures proposed according to the sites concerned (PIRIOU *et al.,* 1993). As the nitrogen input residence time is two to five days on the sensitive coastal sites, principal flows of late spring and early summer are to be reduced. Inland, granite soils are characterised by relatively regular water and nitrogen fluxes, due to the buffer role of the groundwater loaded by the nutrient surplus; schistose soils are non-permeable. In the first case, rigorous fertiliser management is recommended; in the second, an improvement of the streams (afforestation, *etc.*) in order to cut back the spring rises in the water level. The development of the wetlands is also proposed to improve the actual purification of the streams.

Because it is fragile due to supplies of fresh water that may be loaded with nutrients, pesticides, chemicals, and metals, the Black Sea is the object of programs such as the NATO TU-Black Sea Project (BARBOUR, 1997), an environmental program on the Danube River Basin (BOTTERWEG and RODDA, 1999), and EROS 21 (LANCELOT *et al.,* 2002). Each of the programs recommends the decrease of nutrient discharge, but no one can be sure of the real impact of the advocated measures. The question of excessive growth of opportunistic seaweed is not envisaged in those programs, but they can be avoided, unless climate warming and change in the nutrient range act contrary to that.

CONCLUSION

Algae seem thus to be simultaneously a scourge and a resource. Eutrophication problems have become a matter of major concern even if the phenomenon is far from being a new development. It has been necessary to cope with it for more than a quarter of the last century. Its management is neither a simple nor a cheap task. Doubtlessly a good deal of the problem is due to anthropic causes and constitutes an important part of the efforts to reach efficient integrated coastal zone management (CHARLIER and LONHIENNE, 1996).

Removal of algae requires manpower and equipment, neither of which comes cheaply. The idea of utilization of the algal biomass, and of avoiding its discharge on dumps, also costly, has been courted for some time: uses in food, fodder, medicine, pharmacy, cosmetology, agriculture, and others have been brought forth, tested but often stumble against pre-conceived positions, even myths, customer resistance, and economics.

Succesful implementation of management programmes concerning the decrease of the nutrients at the source will be long and difficult, with scientific, social and political implications. It is however the necessary condition for a really sustainable development.

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