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"The Anoxic Crises in Distrophic Processes of Coastal Lagoons: An Energetic Explanation"

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THE ANOXIC CRISES IN DISTROPHIC PROCESSES OF COASTAL LAGOONS: AN ENERGETIC EXPLANATION

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SUMMARY

In a thermodynamic view, lagoons can be considered as systems reproducing, on a reduced scale and within a short time, the disequilibrium between energy resources and human activity.

A dynamic equilibrium can be reached in these environments if the energy transfer into biomass is accompanied by an adequate dissipation, able to ensure a consistent increase in the entropy of the ecosystem when considered together with the surrounding environment.

External energies, such as wind and hydrodynamics, enable ecosystems to communicate with the surrounding environment.

Under hypertrophic conditions, external energies are often unable to allow adequate dispersion of the energy surplus; under these circumstances an anoxic crisis may occur and the environment, after a catastrophic event (death of aerobic populations), sets out for a lower organization and biomass level.

There is evidence that bacterial sulphate reduction (BSR) activity, which normally represents a terminal step in the mineralization processes of organic matter, increases exponentially at the increasing temperature and in absence of water circulation, leads at the very least to the anoxy of the water column.

1. INTRODUCTION

In the summer months, and particularly during the early morning, anoxic crises occur in many Mediterranean lagoons, initially on a local scale and then in entire lagoons. The most obvious consequence of this phenomenon is the death of aerobic fauna such as fish. This leads to serious economic damage to the fishing industry, and often has negative indirect consequences on the tourist industry. An understanding of this phenomenon is required to enable the development of monitoring methodology and processes for the recovery of the ecosystem which should be in accordance with the type of activities and common practices in the areas involved.

This is the goal of ENEA and the Central Laboratory for Hydrobiology, which since 1987 have been promoting interdisciplinary research on a number of lagoons in North-Central Italy (the lagoons of Orbetello, Venice, Valli di Comacchio, and those of the Pontine area; Fig. 1) showing evidence of this phenomenon. This report provides a brief summary of the results achieved with a proposed general theory of interpretation of the dystrophy and anoxic process and its dynamic evolution.

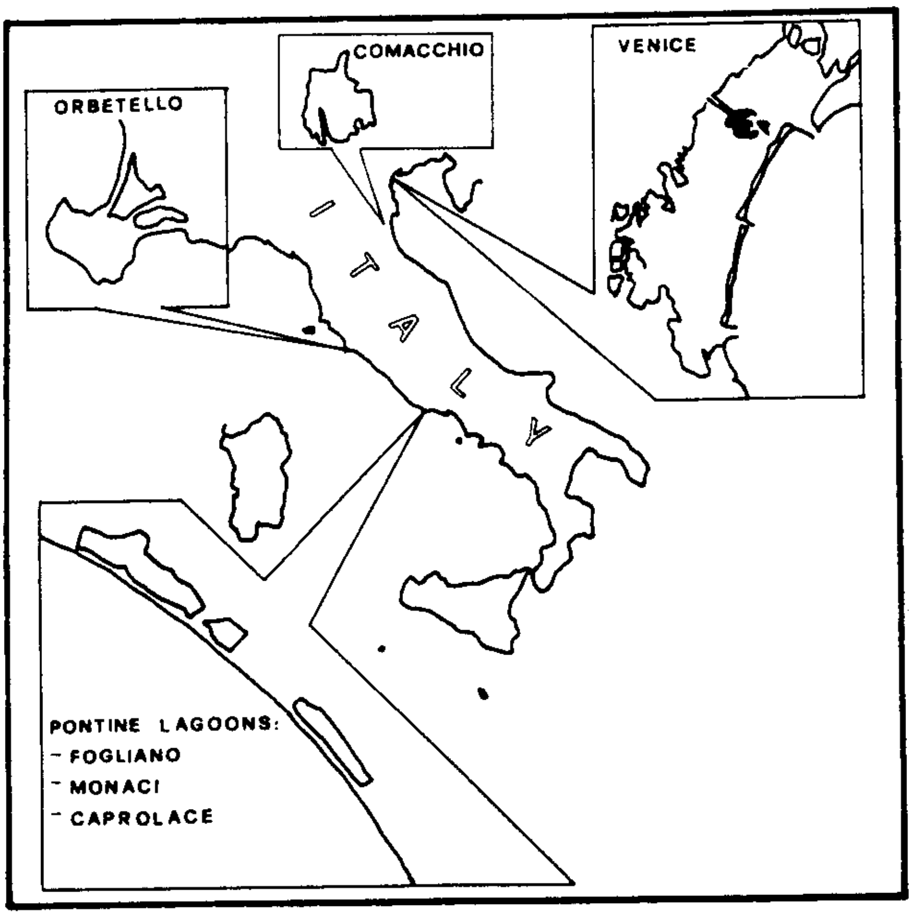

Fig. 1 - The lagoons where the experimental studies have been carried out.

For a detailed description of the areas studied and the experimental and field methodologies used, see the ENEA technical reports (1) and Hull and others(2).

The hydrological studies characterised the circulation between the lagoons and the near seas under various climatic conditions. Basically, water exchange was efficient only when there was a steady wind or during heavy rainfall, while flow efficiency due to tidal action only was rare. As a result, especially in the summer during locally calm conditions, special situations often arose when the areas studied were shown to be thermally insulated from both the adjacent sea water and the atmosphere.

The space and time distribution of the plant biomass highlighted the fact that the microalgae component is always considerably smaller in quantity than the macroalgae component, and that the latter is represented mainly by populations which are "nitrophilic and pleustophytes"(3) (i.e.Chaetomorpha sp. and/or Ulva sp.) with density levels of up to and over 10 Kg/m^2(of fresh weight).

Geochemical research has confirmed the importance of sediments in recycling nutrients in order to make them available for plant growth; the amount of nitrogen and phosphorus released have also been estimated.

Microbiological research focused the role of bacterial anaerobic activity in sediments, highlighting a significant correlation between sulphate reduction activity, the temperature and the substrate (4,5).

During the experiments, automatic stations equipped for full-time monitoring of hydrological parameters (temperature, conductivity, dissolved oxygen and pH) and weather parameters (air temperature, solar radiation, , wind direction and speed and atmospheric pressure) were used.

Most of the experimental results reported in this paper refer to the Lagoon of Orbetello, but similar indications have been pointed out in all the investigated environments.

2. CHARACTERISTICS OF THE ANOXIC PROCESS

The correct interpretation of the anoxic process requires a detailed analysis of the conditions arising in extreme climatic situations - i.e. in summer - when the abnormal growth of the plant biomass tends to saturate the biological carrying capacity of the ecosystem, making it extremely unstable.

In the spring and summer period the algae biomass, favoured by the considerable release of the nutrients from the sediments and by favourable levels of temperature and light, reaches maximum productivity levels. However, this process also gives rise to the formation of proportional amounts of organic detritus.

The organic detritus is mineralized in the water column and on the sediment surface either by aerobic microorganisms, when the physical and photosynthetic re-aeration rates are steady, or by anaerobic microorganisms when there is a shortage of oxygen.

In shallow acquatic environments the two processes -aerobic and anaerobic - coexist as a pooling of bacterial activity, although the percentage proportion varies according to the space (vertically) and time (the day/night cycle). The change in this ratio is regulated by daytime photosynthesis and hydrodynamic circulation in the water column, in which the amount of dissolved oxygen is increased because the solubilization process has been made easier. Furthermore, the velocity of re-aeration of the water is in inverse proportion to the depth; if the vertical circulation process is inhibited, the percentage ratio of the two mineralization patterns varies significantly with the depth.

This is why the organic matter will undergo anaerobic or aerobic breakdown according to its position in the water column, as well as being affected by the changes in the amount of oxygen available due to the day/night cycle.

If the matter undergoes anaerobic breakdown, the result is fermentation leading sulphate reduction.

Bacterial sulphate reduction in marine environments is a process which has been the object of considerable research (6,7,8), and is responsible for about 50% of the mineralization of organic matter. In the context of this research, it is also vital to consider that the organic substrate of these bacteria consists of small molecules (9,10,11) which are produced in syntropism by the fermentation bacteria. This process always occurs under microaerophilic conditions due to the aerobic microbial population which has the capacity to ferment the organic substrate when the amount of dissolved oxygen is insufficient for complete mineralization. As soon as aeration conditions in the water column change, the organic matter may undergo two completely different forms of breakdown, with differing environmental implications.

It should be stressed that bacterial sulphate reduction (BSR) indirectly consumes the oxygen available in the water column, since the hydrogen sulfide produced as a reaction to anaerobic respiration is re-oxidised chemically (9) using a double amount of oxygen compared to the requirements of the aerobic process, thus exacerbating the oxygen shortage.

The most plausible model (Fig. 2) for the persistence of weather conditions causing serious stagnation is that the vertical separation of the deepest area, with a mainly anaerobic metabolism, tends to spread to areas closer to the surface during the night, with further increases during the daylight hours.

4

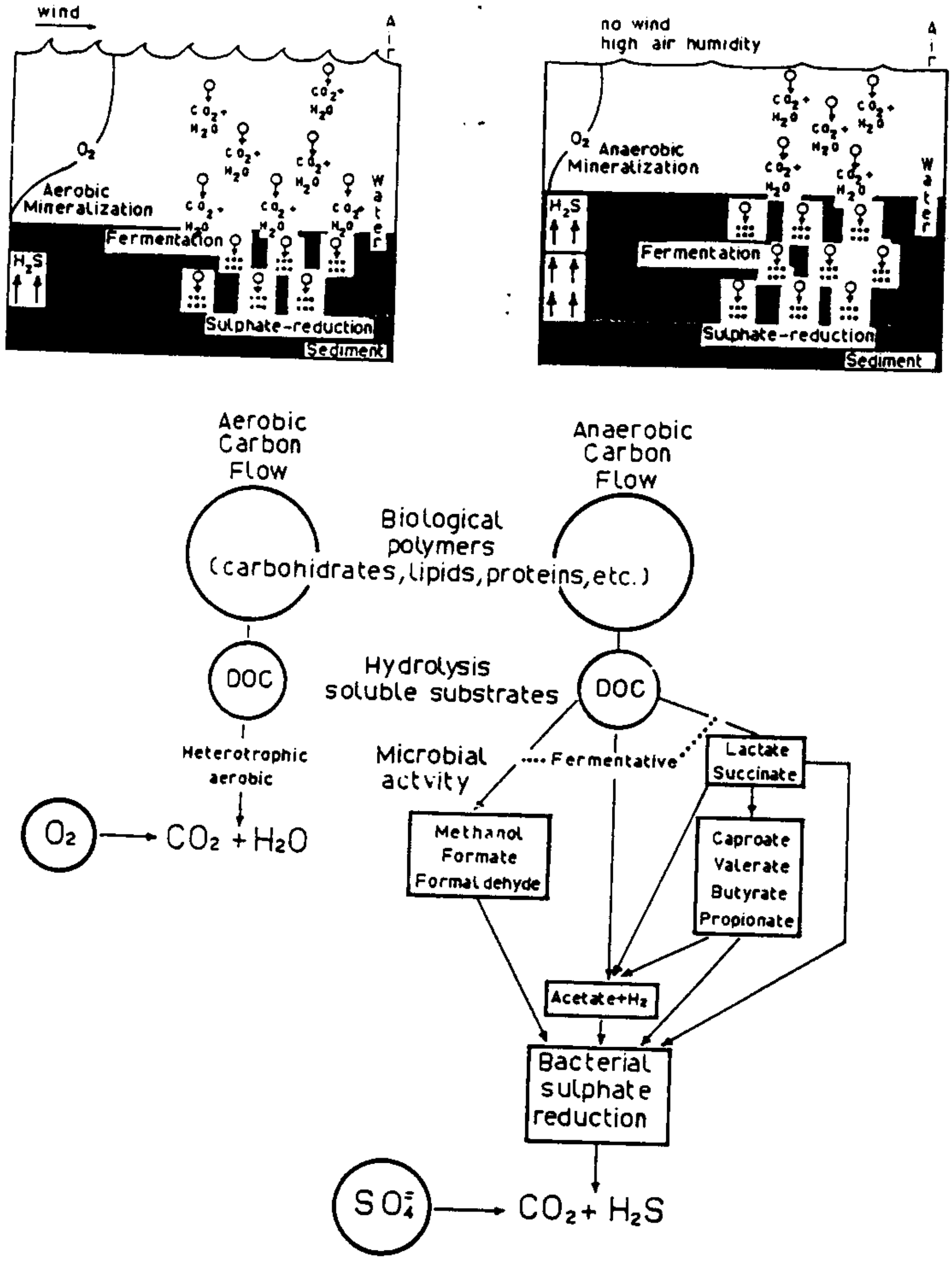

Fig. 2 - The scheme shows the model of the organic carbon brake-down in hypertrophic lagoons. The spring and summer microclimate conditions can regulate the biochemical by-pass from the aerobic to anaerobic carbon flow. In a windless condition with high air humidity the fermentative microbial activity produces more suitable molecules for sulphate-reducers bacteria. DOC= Dissolved Organic Carbon.

Under these climatic conditions, the dynamic equilibrium between aerobiosis and anaerobiosis changes over to higher sulphate reducing activity, which uses up the remaining oxygen still available in the water column.

The most effective way to block this chain reaction is the circulation of the water column, since this favours re-aeration, thus slowing down the buildup of substrate for sulphate reducers. This action is brought about either by turbulence or by simple convection motions caused by active evaporation produced by surface wind.

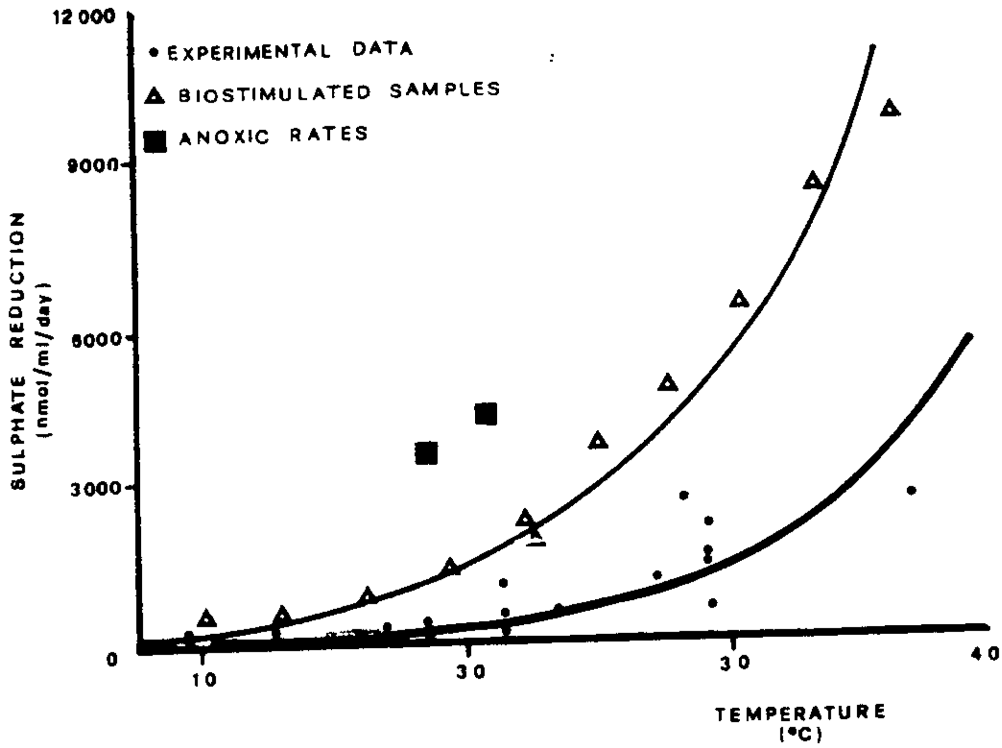

Fig.3 - In the graph, one curve shows (dots) sulphate-reduction rates measured in situ (twice a month for three years in two station points of the Orbetello Lagoon). The second curve (triangles) shows the rates measured in a laboratory experiment stimulating the sediment sample with sodium-lactate added in excess. The two square dots are the rates that have been marked out during a localized anoxic crisis. The laboratory experiment suggests that the bacterial activity, in normal conditions, is carbon limited , but is not during anoxic crisis.

The graph in figure 3 illustrates the activity of sulphate reducing bacteria as measured over 15-day periods for two years in the Orbetello Lagoon, in relation to sediment temperature. Although there is a significant exponential correlation between BSR and temperature, the data also highlights the crucial role of the supply of the substrate for reaching the anaerobic activity rates leading to total anoxia in a water column (5). Since the supply of the substrate depends heavily on microclimatic conditions, it can be supposed that these

6

conditions give rise to the instability leading to catastrophic effects such as the death of aerobic organisms.

It should therefore be stressed that it is not the sudden death of the plant biomass that triggers the anoxic phenomenon, but rather local microclimatic conditions (stagnation for a period of about a week) which accelerate the supply of the organic substrate to the anaerobic bacterial pool under conditions of poor aeration; this then favours the acceleration of the biological production of hydrogen sulphide.

3. THEORETICAL ENERGETIC MODEL

The biochemical process described above can supply a satisfactory explanation of the mechanisms leading up to a dystrophic and anoxic crisis. However, in order to grasp the implications for the environment further clarifications must be made.

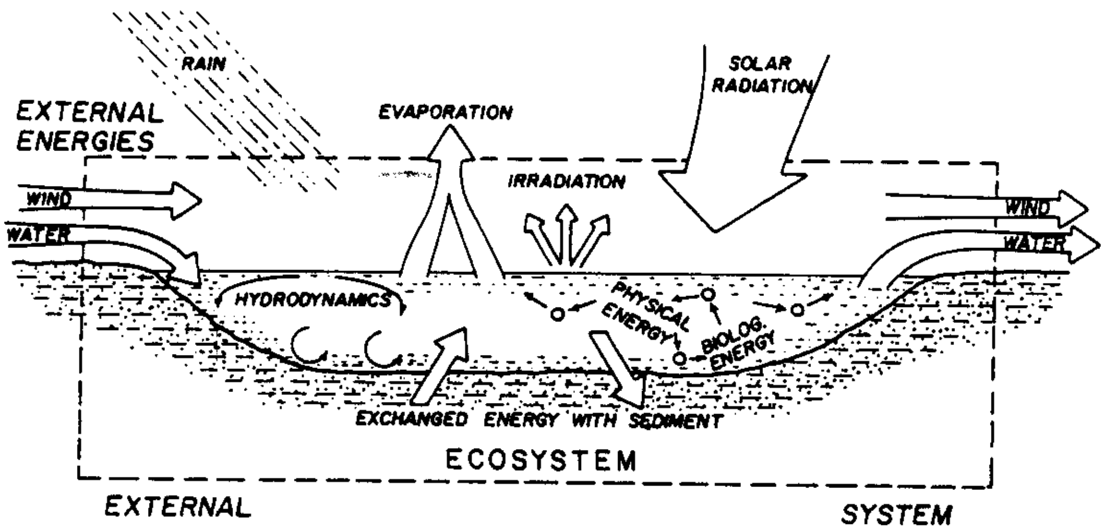

Fig.4 - Energetic model of a lagoon.

Figure 4 shows an energetic model based on observations in the lagoons covered in the studies. The diagram can easily be reduced to the following literal equation:

Light Energy = Fixed Energy + Dispersed Energy where Fixed Energy refers to that part of radiating energy accumulated in the form of biomass (Chemical Energy - from photosysthesis); Dispersed Energy refers to forms of energy dispersion given off to the surrounding environment e.g. low level heat.

According to an estimate made by Gates (12), the amount of light energy from the sun reaching the surface of the atmosphere is 2 cal/cm^2/min, with the net amount , substracted from reflected, being 1.3. On this basis, the amount reaching the earth's surface at our latitudes at noon on a summer day is about 800 Kcal/m^2/h.

The experimental measurements made by the automatic weather stations located at the lagoons are wholly compatible with these estimates. Figure 5 shows the daily average sunshine, wind, humidity and temperature rates for August and the monthly average rates for June-November 1988 period, as recorded in the Orbetello Lagoon.

The conversion of the light energy reaching the lagoon into thermal energy implies a heat exchange between the lagoon water and the surrounding environment, i.e. all the adjoining systems (air, sediment, sea water etc.) The surrounding environment transmits heat to the lagoon, where the temperature then rises; if the water temperature rises, and becomes higher than the surrounding environment 's, then the lagoon dissipates the surplus heat back to it. The first process is characteristic in Spring and Summer, when the lagoon is in a heating stage, while the second process takes place in the colder season.

A second type of energy conversion is chemical, i.e. through the chlorophyllian photosynthesis, with the growth of living plants.

Experimental measurements of primary production conducted on the lagoons at peak production periods showed 1 mg-C/m^3/h for phytoplankton,.and 100 mgC/gr wet weight/h for macroalgae. In the winter period, estimates of 0.5 Kg/m^2 (fresh weight) were made for the macroalgae biomass, while in the summer fresh weight figures of 10 Kg/m^2 were often recorded in many areas of most of the studied lagoons. This means that using Odum conversion factors (13), calculations in the range of 5 to 100 Kcal/m^2/h can be made of the energy conversion due to the photosynthesis of non-microscopic algae (energy from phytoplankton growth is considered to be negligible).

This means that in the lagoons a maximum variable amount of about 12% of the light energy is converted into organic matter; which is similar to the level estimated by Odum (13).

The amount of light energy reaching the lagoon area but not converted into the biomass is mainly converted into heat, which is accumulated in the lagoon waters, thus increasing internal entropy. However, in order to maintain the entropy of the system at the lowest possible level, the local environment must be able to dissipate the surplus energy and the entropy produced in irreversible processes to the external environment.

8

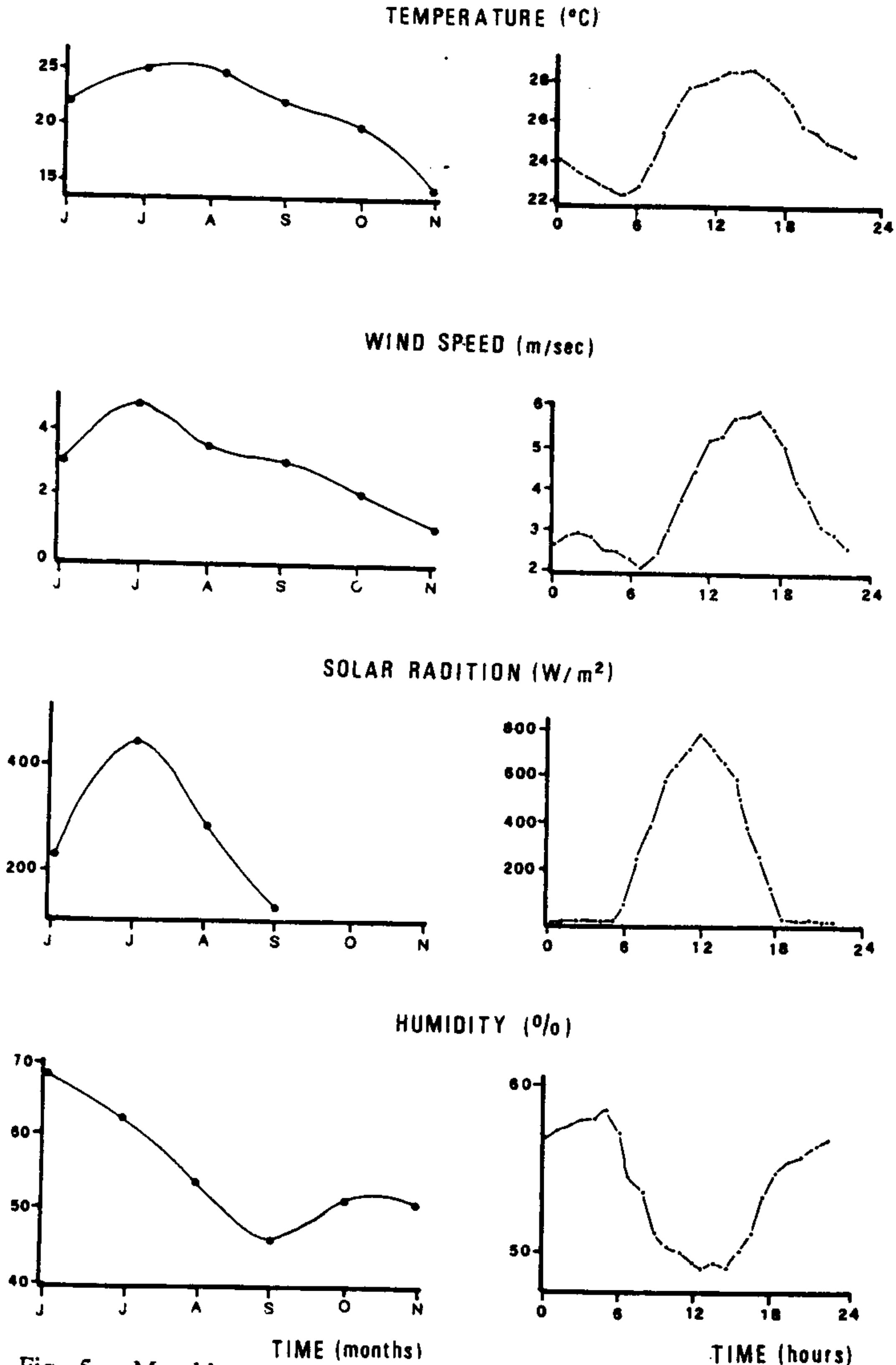

Fig. 5 - Monthly averages and diel variations (at August)of the main metereological parameters in the Lagoon of Orbetello in 1988.

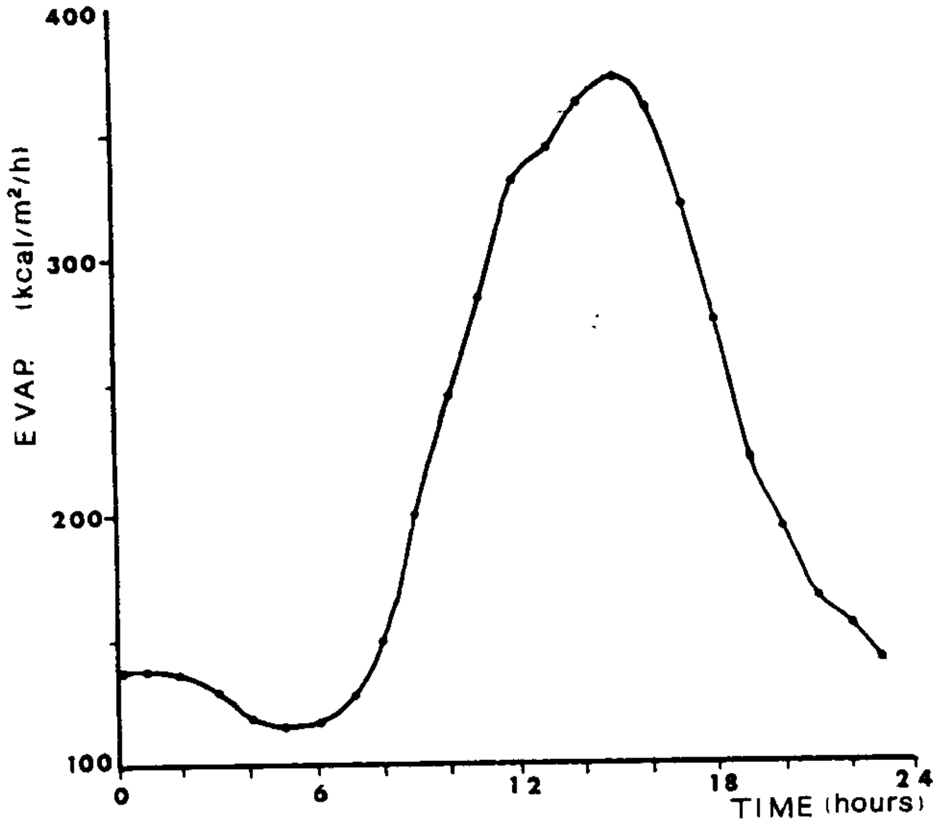

Fig. 6 - Diel variations of evaporation at August 1988 in Orbetello Lagoon.

Thermal dissipation towards the atmosphere takes place (e.g. by irradiation with the formation of thermal currents) when the air temperature is lower than the water temperature (a condition which generally occurs at night during the summer). Dissipation may take place towards sediment, when sediment temperature is lower, or towards other means of access to the lagoon such as the sea or canals.

It should be pointed out that heat dissipation from water towards sediment involves only a very thin layer of sediment, as shown by the experiments of Bucci et al. (1) for Orbetello and Hull et al. (2) for the Pontine Lagoons. Heat dissipation by conduction is negligible, generally being under 0.5% of the total thermal energy exchange.

The most important type of energy dispersion during the Summer is evaporation (Fig. 6), which has been indirectly calculated for the Orbetello Lagoon on the basis of meteorological data, using an empirical formula (14).

Nevertheless, there are objective barriers to the dissipation of the entropic surplus to the outside environment in the lagoon systems studied, when the meteorological conditions described above prevent dissipation. Under these conditions, the lagoon environment has a higher temperature than the air, and thus gives off heat to the air. Low winds, low hydrodynamics and high humidity lead to the formation of a sort of "lid" over the lagoon which is thus insulated from the surrounding environment. The re-aeration process in the water is therefore slowed down and can no longer support the aerobic process of mineralization. This triggers fermentation, which leads to the anaerobic pattern of the sulphur cycle. In other words, the physical conditions causing thermodynamic instability of the ecosystem coincide with the conditions leading to the terminal biochemical processes of dystrophy.

4. CONCLUSIONS

The occurrence of anoxic events should be interpreted in the context of the theories developed by Prigogine (15) and discussed with others (16,17) in the field of the thermodynamics of irreversible processes in open systems far from equilibrium.

The hypertrophic lagoon is an open system with specific physiographical characteristics which , under certain meteorological conditions, is no longer able to convert energy and at the same time properly pump out entropy. If the external energies of the system such as turbulence and hydrodynamism governed by steady winds are lacking, adequate dissipation of the energy surplus can no longer take place, and a dystrophic crisis may begin. The accumulation of entropy in the system is not compatible with the ecological structure, which reacts by undergoing the extreme condition of dystrophy, leading to anoxic crisis with the death of aerobic fauna.

The reorganization of the system's ecological structure on a far less complex level can be considered as the final autoregulating mechanism. The lower organizational structure of the new population is compatible with the lower dissipation capacity and the high internal entropy, which was unsupportable for the previous population.

From a strictly biological point of view, colonizing of the lagoon environment by anaerobic bacteria is not necessarily negative, but it is in an evolutionary point of view however, since it involves the temporary reversal of the evolutionary process: a highly organized community such as aerobic vertebrated is replaced by sulphur cycle bacteria and also in the ecological as this reversal is the result of damage to the environment.

A situation where the deterioration of the aerobic process leads to the increase of the anaerobic pattern can therefore be interpreted as a population

11

structure regulating mechanism, since the physical conditions having a negative effect on surplus energy dissipation increases the production of hydrogen sulphide, which has a considerable effect on biotic selection of the ecosystem.

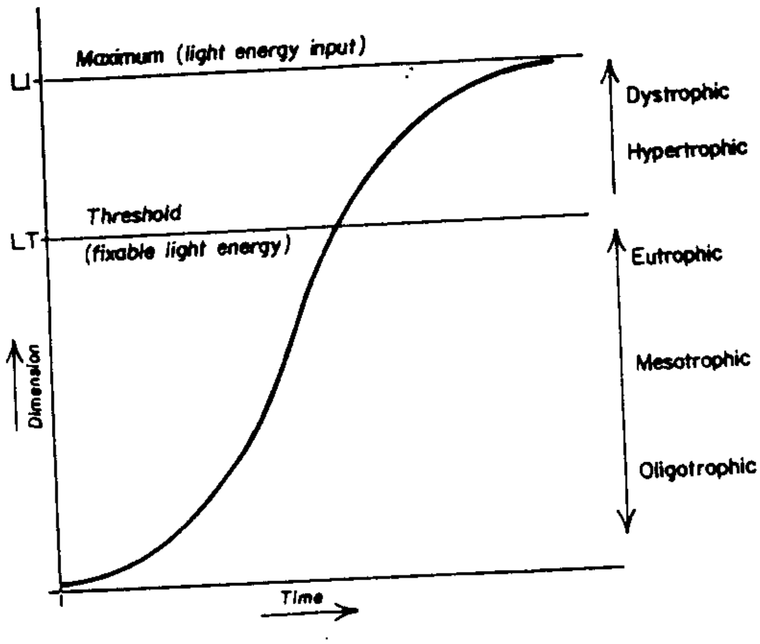

Fig. 7 - Biological productivity.

The conclusions discussed so far can, in our view, when taken as a general theory, be applied to any ecosystem. The phenomenon is especially applicable to shallow acquatic environments, where these conditions most commonly occur, both due to natural causes and to heavier dependence on man-made flows. The tendency to increase biological productivity seems to be incompatible with the evolution of fauna and flora in the environment.

It thus seems useful for practical applications to introduce a concept of a productivity "threshold", which in order to be defined requires a general method for assessing the surplus energy status from the point of view of ecological stability rather than simply biological production.The proposed solution involves the correlation of the characteristics of light energy to production and to the dissipation capacity of the ecosystem, which depends on its physical, morphological, hydrodynamic, weather and climatic factors. The simplified graph in figure 7 shows a classical biological carrying capacity curve, as showed in Odum(13). We propose to define the maximum and optimum dimension levels theoretically introduced by the author as LI and LT. Line LI defines the level of active light energy falling on the site, and line LT defines the level of usable energy under stable conditions, calculated on the basis of the minimum dissipation capacity of the system (determined by the sum total of external energies involved). An uncontrolled nutrient input leads the vegetal population to increase until all the available light energy is photosynthetically converted into biomass. The cost of manteinance of this population at low internal entropy is very high and involve external energies that ensure all detritus produced by respiration be mineralized. As we discussed before this doesn't happen easily at the same rate of the production and the anaerobic degradation cause the ecosystem instability and dystrophy. So it is the minimum (prolonged for an unknown time) amount of the external energies that determine the dissipation capacity and the productivity threshold. The ecosystem can be defined with the classical terms of oligotrophic and eutrophic, depending on whether the productivity is, respectively, far from or close to the level of usable energy; the system will be hypertrophic and dystrophic if population is higher or much higher than this level. It should also be recalled that in quantitative terms LI and LT are not constants, but rather variables over time, since it is the sum total of the external forms of energy that may undergo considerable changes and thus determine the optimal production level.

The general theory outlined above supplies plausible explanations for historically documented dystrophy episodes in the past, and the increasing frequency of dystrophy at the present time.

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REFERENCES

1 M. Bucci and others, RT/PAS/89/18 (1988) 1-205.
2 V. Hull, M. Falcucci and I. Cignini, (in preparation)
3 G. Giaccone, M. Princi and L. R. Longo, Ingegneria Ambientale, 6 (1976) 572-578.
4 G. Izzo, Oebalia, XV-1 (1989) 441-451.
5 G. Izzo, C.Creo and A. Signorini, Oebalia, suppl. XVI (1990) in press.

13

6 B.B. Jorgensen, Marine Biology, 41 (1977) 7-17.
7 B.B. Jorgensen, Nature, 296 (1982) 643-645
8 D.B. Nedwell and J.W. Abram, Microbial Ecology, 5 (1979) 67-72.
9 B.B. Jorgensen, Limnology and Oceanography, 22-5 (1977) 814-832.
10 J. Sorensen, D. Christensen and B.B. Jorgensen, Appl. and Env. Microbiology, 42 (1981) 5-11.
11 D.B. Nedwell, in: Advances in Microbial Ecology, Plenum Press, New York and London, 7(1984) 93-131.
12 D.M. Gates, Metero. Monogr., 6 (1965) 1-26.
13 E. Odum, Fundamentals of Ecology, W.B. Saunders Co.Philadelphia, London,
Toronto, 1971.
14 V. Ferrara and F. La Camera, RT/PAS/89/6 (1989) 1-299.
15 I. Prigogine, Etude termodynamique des phenomenes irreversibles, Desoer,Liegi 1947.
16 I. Prigogine, G. Nicolis and A. Babloyantz, Physics Toaay, 25 (1972) 23-28.
17 I. Prigogine, G. Nicolis and A. Babloyantz, Physics Today, 25 (1972) 38-44.

14