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A definition of "critical eutrophication" in the marine environment

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Resumen: El término "Eutroficación", originalmente diseñado para el medio lacustre, es ahora empleado frecuentemente en el estudio de la fertilidad marina. Debido a que las definiciones limnológicas de este término no son directamente aplicables al medio marino, se definió un nuevo término cuantitativo aplicable a este medio.

"La eutroficación crítica ocurre cuando el flujo neto de nutrientes biolimitantes que son incorporados en la biomasa de plantas es tal que la rapidez de producción de materia orgánica nueva excede la rapidez neta de aporte del oxígeno (proveniente de intercambio local aire/agua y de fotosíntesis) necesario para oxidarla".

The terms "Eutrophication", "Eutrophic" and "Oligotrophic", frequently appear in the scientific literature. Most textbooks carefully avoid defining these terms, nebulously referring to "nutrient rich water" as eutrophic and "nutrient poor water" as oligotrophic. Several texts refer to the classical works on Limnology by Hutchinson, though these terms appear to date from publications in 1917 and 1918 by Naumann and Thienemann (Kelly and Naguib 1984). Hutchinson (1957), referring to eutrophication, makes a statement which is worthwhile repeating: "As is usual in the formative period of any science, the terminology employed at first is somewhat unsatisfactory". Despite these words of caution 30 years ago, the terms flourished and are now in very general use in marine environmental science (for which they were never intended).

If eutrophication may be loosely envisaged as a process related to an enhancement of aquatic fertility, one would expect a definition to contemplate causes, manifestation and effects. Early Naumann-Thienemann-Hutchinson definitions considered effects, particularly the depletion of hypolimnetic oxygen (for eutrophy) or a uniform distribution in the water column for oligotrophy. Hutchinson (1957) based his limnological definition on rates of hypolimnetic oxygen loss (0.004 - 0.03 mg cm^{-2} day^{-1} for oligotrophic lakes, 0.05 - 0.14 mg cm^{-2} day^{-1} for eutrophic lakes with intermediate values termed as mesotrophic). Such a definition is not applicable to the open sea. Plankton abundance may be used to loosely define eutrophic and oligotrophic conditions as a manifestation of nutrien supply (Parsons and Takahashi 1973) but again the problem is where to draw the line between one phenomenon and the next.

The entire eutrophication concept was extensively reviewed by an UNESCO workshop in Tunisia in 1982 (Kelly and Naguib 1984), but the group was unable to reach a concise definition of the term. An example of an all-embracing (but nevertheless vague) definition is given by Sournia (1978): "Eutrophication is the consequence of an increased input of nutrients, leading to increased primary production, depletion of oxygen in deep water and eventual denitrification". A similar, but more explicit definition is given by Margalef (1982) who describes eutrophication as "...the enrichment of waters with nutrients at a rhythm which cannot be compensated by their definite elimination by total mineralization, in such a way that the degradation of the organic material produced causes a severe depletion in the concentration of oxygen in deep waters".

Even these definitions may be rather ambiguous in practice. In tropical oceanic upwelling areas, such as the Pacific equatorial upwelling region or the Costa Rica Dome, very high nutrient concentrations in the euphotic zone may not induce the massive phytoplankton blooms characteristic of natural eutrophication (Thomas 1979). Are these regions eutrophic?.

Similarly, phytoplankton living in the deep chlorophyll maximum of otherwise oligotrophic tropical oceans, appear to have an abundant nutrient supply but are probably light limited (see Fasham *et al.* 1985). On the other hand, some apparently eutrophied tropical coastal lagoons support huge phytoplankton populations, despite negligible water column nutrient concentrations as a result of very efficient recycling (Mee 1978). Clearly, any satisfactory definition of eutrophication should not be based on nutrient availability, but must contemplate the balance between the *rate* of incorporation of nutrients into the plant biomass and the net rate of supply of oxygen to the water column (mainly during photosynthesis and by surface diffusion and bubble entrainment) for oxidizing the organic material formed. As a water column becomes increasingly eutrophied, the photosynthetic biomass will tend to be concentrated toward the surface, diffusive loss of oxygen (produced during photosynthesis) will be greater and there will be an increased oxygen deficiency in the system.

I propose the following general definition for the term critical "Eutrophication" in order to quantify where deterious effects of nutrient enrichment begin:

"Critical Eutrophication" occurs when the net flux of limiting nutrients incorporated into the plant biomass is such that the rate of production of new organic matter exceeds the net rate of oxygen supply (from local air/water exchange and photosynthesis) required to oxidize it.

This simple definition is designed to incorporate the concepts discussed previously, to focus on kinetic processes, and to provide a conceptual description of eutrophication in both the freshwater and marine environments. A few points require additional comment:

1. The concepts of nutrient fluxes to the plant biomass and "limiting nutrients" have been extensively reviewed in the recent literature. Use of the term "flux" avoids the idea of static reservoirs or that eutrophication will always require a large excess of nutrients in the euphotic zone.

2. The "production of new organic matter" in this case refers to the gross primary productivity. Any external flux of organic material will also contribute to an increased oxygen demand (a sewage input to an estuary, for example) but only organic material produced as a result of fertilization of the water column is considered as part of the eutrophication process. The external source of organic matter may also cause a spectacular depletion of the dissolved oxygen content of the water column with disastrous ecological consequences. Such a water body would be termed as "Dystrophic".

3. Only two sources of oxygen are considered in the present definition. No mention is made of oxygen introduced by advection, which would maintain sub-surface waters fairly well oxygenated in many upwelling areas. This omission is, of course, quite intentional as subsurface horizontal advection may import water from oxygen-rich areas but also spread the organic matter locally produced over wide areas. Thus, in the marine environment, eutrophication may not result in a local area of severe oxygen depletion, even though the net local budget (of the local rate of oxygen supply to the water column less that equivalent to the gross primary productivity) is negative. Eutrophic areas of the ocean are thus net oxygen consumers and oligotrophic areas are net contributors. The presence of an oxygen minimum in the ocean does not necessarily signify eutrophication in the immediately overlaying waters. This consideration somewhat complicates the evaluation of marginal cases of eutrophication in the ocean.

The definition proposed above has one drawback. The problem is that no simple time and space frame on which the processes occur can be specified. For example, a spring bloom of phytoplankton may cause a short-term oxygenation of the euphotic zone. Some of this oxygen would escape to the atmosphere. As the bloom decays or is grazed, oxygen would be consumed and an oxygen minimum may develop. The net process would be defined as critical "eutrophication" though the time frame reauired should be sufficient to cover the entire cycle from production to remineralization. The space frame would be that defined by the Lagrangian movement of the primary producers and their degradation products.

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