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"Estuarine Eutrophication"

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ESTUARINE EUTROPHICATION

A. Scope. Estuarine system is by definition, as an interface between terrestrial and marine systems, a highly dynamic and variable environment. Since biota respond to both Energy and Variability in a similar way as the classic dose curve, the amount of energy and variability in most estuarine situations is already on the high end, where diversity and production prosper but further excesses in either cause reduction in diversity and changes in state.

Anthropogenic eutrophication, or strong natural events, upset the dynamic equilibrium with the difference being that strong natural events tend to be 'pulse' forcing whereas anthropogenic forcing tends to 'pulse and trend' forcing which does not allow for full recovery between 'pulses'.

Specifically, eutrophication upsets the estuarine equilibrium by increasing the chemical potential energy (nutrient loading) but not the physical potential energy (available to spatially disperse the nutrients). This causes a distortion to which the resident biota can not adjust. In other words, the assimilation of high organic/nutrient inputs requires coupling between physics and the food web: physical flushing disperses the input over a larger area while biological assimilation disperses the chemical potential energy within the food web.

B. Problems. A number of inter-related problems arise from the anthropogenic distortion of natural equilibrium. Here we mention them and then in the next section review some of the relevant dynamics involved that would need to be correctly simulated in any serious modelling exercise.

1. The overall issue is the impact on the biota, which implies habitat loss or degradation such that the original estuarine community is replaced with a less diverse, less stable, higher entrophic community that is sustained by the input levels of energy (nutrients) and variability but can not succeed itself to a lower entrophic state. This degeneration is often irreversible on long time scales and its recognition by management or the public generally occurs after the fact. The sub-issues are:

2. Insufficient physical flushing. By discharging too much in one place or area (as with a river discharge) the physics can not disperse the raw discharge (nutrients) or the intermediate products (carbon) such that the local system accumulates/buries organic (and pollutant) matter. Physical dispersion of these intermediate products takes an even greater time (e.g. resuspension of sediments).

3. Biological assimilation. As the energy/variability tolerances are exceeded, the community diversity falls and the routes of carbon through the food web lessen. That is, opportunistic primary producers are favored that can tolerate the new levels of energy and variability, however, by evolutionary definition the higher components of the food web are not adapted to utilizing them. Consequently the lower entrophic community exports more energy. Eventual adaptation would be a possibility but would be at a longer time scale than the rate change of the abiotic environment (e.g. estuary fills up with rich organic mud and becomes a marsh).

4. Chemical assimilation. The pollution manager thinks of the natural system as assimilating the waste (pollutants) discharged into them as if the estuary were a huge beaker in a chemistry laboratory. In fact, chemical conversions within the system are a strong mechanism for creating sinks for pollutants substances discharged to a system. Unfortunately physical and biological dispersion play a critical role in maximizing these conversions.

5. Sedimentary balance. The role of the sediment (particularly the fine fraction) plays a key role in the functioning of the system and hence its ability to disperse, transport or bury pollutants or pollutant products (carbon) within/through the system. The suspended load inhibits photosynthetic radiation, transports flocculated substances, deposits on the bottom, etc.

6. Management. The public reacts much more strongly to threats to its own health than to that of a natural system mostly through ignorance. The policy maker may be equally poorly informed and be strongly motivated by other pressures to not consider preservation of natural systems. Consequently, the reaction to 'environmental' problems of an estuary is mostly adaptive and only starts to be counteractive when the public heath safety is threatened (toxic fish, no swimming, etc.). What is sorely missing is the realization by the public and policy that the best economic investment is in the health of the natural system, which if preserved could provide more economic and 'quality' benefits than if destroyed. The proof of this lies in the hands of earth-systems scientists, who have the capacity to compute objective 'economic' comparisons.

C. Dynamics. What follows is a mention of some of the major dynamics involved in eutrophication in estuaries that need to be considered in any quantitative assessment. For the most part, nitrogen will be used as the eutrophifying agent.

1. Sources and Sinks. It is good to review the sources and sinks of nitrogen before proceeding with the dynamics that process it through the system.
External Sources include:
- Direct discharge of dissolved inorganic and organic forms from the river.
- Fixation from the atmosphere
- Acid deposition from the atmosphere
- Import from the ocean.

External Losses include:
- Export to the ocean
- Burial in sediments
- Denitrification and loss to the atmosphere
- Absorption on particles (phosphorus)

2. New Nitrogen. A simple but very important aspect about a closed system is that it recycles all of its mass. Any new mass that happens in the system will be converted to growth or exported. Therefore, only the production based on any extra or 'new' nitrogen can be removed as a harvestable yield without damaging the system. Any of the above listed sources of N would be considered as new nitrogen.

- f-ratio. The degree to which a system is exposed to new nitrogen is given by the f ratio, which gives the % of new production

  f = new production/total production, or

  f = new production/[new production + regenerated production]

  when f is low (f ~ 0.1) an oligotrophic system is indicated and when it is high (f ~ 0.8) a eutrophic system is indicated.

3. Photosynthetic Quotient (PQ). The cycle of nitrogen within the system is initiated by photosynthetic uptake, which can occur in any of its inorganic forms, ammonia, nitrite, and nitrate. Any new nitrogen acts to bring in more CO2 through the photosynthetic equation. However, the amount of oxygen produced depends on the organic substance generated, carbohydrate, lipid or protein.

- The Photosynthetic Equation is simple form is

$$6CO_2 + 6\,H_2O \Rightarrow 6CH_2O + 6O_2$$

- PQ = moles of O2 released/moles of CO2 utilized.

- PQ = 1 if carbohydrates are produced, as CH2O

- PQ = 1.2 if lipids are produced, as CH2

- PQ = 1.8 if NO3 is needed for proteins, as NH2

- PQ = 0.8 if NH4 is used instead of NO3, then some of the O2 that would have been released is used to oxidize the NH4

- In general, PQ < 1 if oxygen is used during photosynthesis and PQ > 1 when oxygen is released during photosynthesis

- A nitrogen regenerating system is based on NH4, which is released by excretion and easily, re-assimilated. Consequently, it can have a PQ ranging from 0.8 to 1. Whereas a new-nitrogen system is based on NO3 and will have a PQ ranging from 1 to 1.8.

- Fishing from an N-regenerating system will reduce the pool of N and limit production. Whereas, fishing from a new-N system would be sustainable up to the level where N harvest = new N.

4. Regeneration of Nutrients. The reverse of photosynthesis is the oxidation or decomposition of photosynthetically produced substances. This involves primarily Carbon, Oxygen, Hydrogen Nitrogen and Phosphorus. Each of these has a different cycle and only the last two are limiting. In a surface marine environment, we might consider the surface phytoplankton community as a closed system with respect to N and P. The other three elements are cycled through much larger systems (air/atmosphere and water/ocean) and thus are not limiting nor in a closed mass cycle for surface phytoplankton. For this reason N and P are 'nutrients' or limiting substances (Leibig's Law of the Minimum).

- The Organic Oxidation governs the chemical ratios of recycled photosynthetically produced substances.

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 106O_2 \Rightarrow 106CO_2 + NH_3 + H_3PO_4 + 106H_2O$$

and the ammonium can be further oxidized,

$$16NH_3 + 32O_2 \Rightarrow 16HNO_3 + H_20$$

- If there were no other chemical transformation processes then the substances that have been through the photosynthetic process would remain in the same proportion – often referred to as stoichiometric ratios. Of course with external sources and other processes this is not true, but the ratios are useful, as pointed out by Redfield. For example, decomposition of photosynthetic material should have an oxygen/carbon molar ratio of 276/106 or 2.60, or 1.3 for O2:C; and the carbon/nitrogen molar ration would be 106/16 or 6.63.

The ratios are determined based on molar dimensions, but can be converted to weight ratios, for example, the C:N of 6.63 converts to a weight ratio 6.18 by multiplying by the ratio of their gr-at weights 14/15.

- Nitrogen Turnover refers to the reuse of N in surface production. In an oligotrophic system N is turned over many times and in a dystrophic (too much N input) system N is turnover only several times. The more that N is turned over, the higher is its effective C:N ratio, meaning that more C is sequestered from the atmosphere by the same amount of N.

As an example, assume that a system has can regenerate 50% of its N and has an f ratio of .67. We begin with a 10 moles of new N which produces 66.3 moles of C. After one turnover, we have 5 moles of N which produces an additional 33.1 moles of C, the next turnover produces 16.6 moles, then 8.3, etc. The original 10 moles of N produce about 130 moles of C or an effective C:N of 13. Consequently, an oligotrophic system can support a much higher biomass on the same amount of new nitrogen.

Typical effective C:N values for the three levels of eutrophication are >20 for Oligotrophic, 15 – 20 for Eutrophic, and < 15 for Dystrophic. The weight ratios are about 7% less, but can be useful in evaluating a system. For example, it was estimated that in 1994 the Northern Adriatic produced 131 x 109 molC/yr with 15.8 x 109 molN/yr of new N discharged by the Po River (Hopkins, 1998). This is a C:N ratio of 8.3 and suggests that the N turnover is low, or that the system is not efficiently regenerating its nitrogen.

- Summary of Eutrophic & Oligotrophic characteristics:

EUTROPHIC		OLIGOTROPHIC
High New Production	>Yield>	Low New Production
Shorter Food Chain	>Yield>	Longer Food Chain
Low N Efficiency	<Recycling<	High N Efficiency
Low Food-Web Efficiency	>Waste>	High Food-Web Efficiency

5. Biomass Turnover. Another useful indicator is the length of time it takes the primary producers to generate their own biomass. This is usually expressed as the ratio of Production/Biomass (P/B), or the fraction of the Biomass produced per day. Inverted it express the Biomass turnover time. Terrestrial Production is about an order of magnitude greater than Marine Production, and the Terrestrial Biomass is even higher. Terrestrial Turnover is about a year and that of Marine is about a day. Marine producers must be able to reproduce their biomass quickly to offset high losses (sinking, grazing, etc) and because Terrestrial producers must put more production into maintaining (respiration) their high biomass.

6. Photosynthetic Control. Of the quantities needed for photosynthesis, light and nutrient are the most limiting and therefore (Leibig's Law) are the controlling variables. The dependency of growth on the amount of light or nutrient is similar. Both follow a fairly linear relationship when light or nutrient are in small quantities and then level off at a saturation level. In the case of light, some decrease in growth is experienced for very high intensities (photo-inhibition). These dependencies are well explained in the attached copy from Text by Lalli and Parsons. Here only a few points will be emphasized.

- The light basically is used to provide chemical potential energy to drive both the light and dark reactions. It does this by exciting an electron of a chlorophyll molecule to an unstable state. The energy available from this electron as it returns to its normal energy level is used to add a P atom back to ADP to from ATP which then drives the photosynthetic reactions and in doing so returns to the ADP form.

This light-chemical battery has an energy-input limit Pmax where more light will not drive the photosynthetic reaction any faster. Consequently light is limiting at both ends. Each species has its particular response curve.

Because the level of light varies with time the solar input (time of day, season, weather) and with the plankton cell's position in the water, its integrated response over time is difficult to estimate.

- The growth curve for nutrients is similar to that of light having an approximately linear response to initial increases in nutrient and reaching a level of saturation. This change is caused by, first, the ability to acquire nutrients from the ambient water (concentration in water) and, second, by the its capacity to utilize the nutrients internally (concentration in the cell). Interspecies competition is determined by the steepness of the initial slope and by the saturation maximum, refer to Fig. 3.7.

- When the limitation and characteristics of the light response is added, there are many permutations of the number of 'niches' available for species in the marine habitat. Again the diversity is restricted at both ends, at high and low levels of nutrient the diversity drops as fewer species are accommodated.

7. Carbon Pathways. One of the system reactions to distorted supplies of new nutrient is to change in the way carbon is processed in the system. Very important is the emerging evidence that the microbial loop can actually compete with the higher trophic levels and sequester a large part of the carbon making it not available to move 'up' the food chain. (See attached article by Azam, 1998).

HAVE A EUTROPHIC DAY!!