Mathematical model of the nitrogen cycle in the Southern Bight of the North Sea

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Abstract

The nitrogen cycle between dissolved inorganic and organic matter, phytoplankton, zoo-plankton, non living particulate organic matter, and sediments is studied in the ecosystem formed by the Southern Bight of the North Sea.

A consistent pattern of mean annual fluxes of nitrogen based on the primary production and the zooplankton grazing is set up.

A mathematical model describing the dynamic behaviour of nutrients, phytoplankton, zoo-plankton and dissolved organic matter is proposed. The results of the simulation fairly well fit the recent observations made in the frame of the Math. Modelsea research programme.

Introduction

Marine mathematical models are based on a preliminary selection of appropriate state variables which are regarded as representative of the system and for which evolution equations are written.

These equations express that the time derivatives of the state variables are a sum of terms representing hydrodynamical effects such as diffusion, advection, *etc.* and biochemical interactions such as production, grazing, remineralization, *etc.*

As these equations are rather complex, there is a trend to treat separately the ecology and the hydrodynamics and two kinds of mathematical models can now be distinguished. The first ones are mainly hydrodynamical models at which are added some simple terms : linear, quadratic or biquadratic ''à la Lotka-Volterra''. One of the aims of these models is the problematics of the plankton patchiness.

The second ones, mainly ecological, are usually called box models. These models concern the mean concentrations of the state variables over some reasonably homo-geneous regions of space and are not affected by the detailed hydrodynamics of the sea (Nihoul, 1975).

The model presented here belongs to the second category and the box studied is coastal area of 5,370 km², with a mean depth of 15 m, off the Belgian coast and crossed by a mean flow of $40 \times 10^3 m^3/sec$ (Fig. 1).
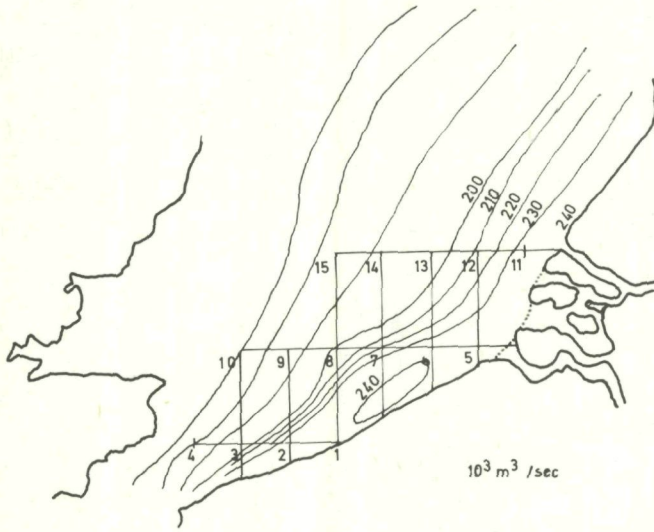

FIG. 1. Area of investigation. The stream-line pattern is given by Nihoul and Ronday (1975).

The more eastern waters are more characteristic of an open-sea ecosystem and the more northern ones, of an estuarine ecosystem due to the very heavy imput of the Rivers Rhine and Meuse.

The gyre appearing in the mathematical models of residual circulation developed by Nihoul and Ronday (1975) and confirmed by the sedimentologists who call it an outerlagoon (Gullentops, 1974) gives some consistency to the hypothesis of spatial homogeneity and thus to the box concept.

The nitrogen cycle

The obvious interest of every ecosystem analyst working on several state variables is to use the same unit for each of them. Nitrogen is chosen as basic unit for two reasons.

The first one is that nitrogen is more limiting than phosphorus. In fact, the order of magnitude of the N:P ratio in the marine phytoplankton is 16:1 (Corner and Davies, 1971) and the maximum N:P ratio observed here in the dissolved matter is 10:1 (Elskens, 1971-75). So, N is probably always depleted before P.

The second one is that nitrogen is more interesting than carbon because nitrogen only expresses the proteins for which the amino acids distribution differs little from one phytoplankton species to another, when these are grown in similar conditions and later when they are incorporated into the tissues of zooplankton and fish. Moreover, these

proteins are more rapidly destroyed than lipids and carbohydrats and thus constitute a better indicator of the turnover of living material (Lancelot, in press).

Unfortunately, all the available data are not expressed in g of N. So, it is necessary to make several unit changes which are important because they correspond to physiological states of living organisms which may vary in time and are sometimes among the most sensitive parameters of the ecosystem (Radach and Maier-Riemer, 1974).

Mean fluxes of nitrogen in the southern North Sea

To begin with, one must establish a "frozen picture", a general pattern of mean nitrogen fluxes between the various components of the marine system (Fig. 2).
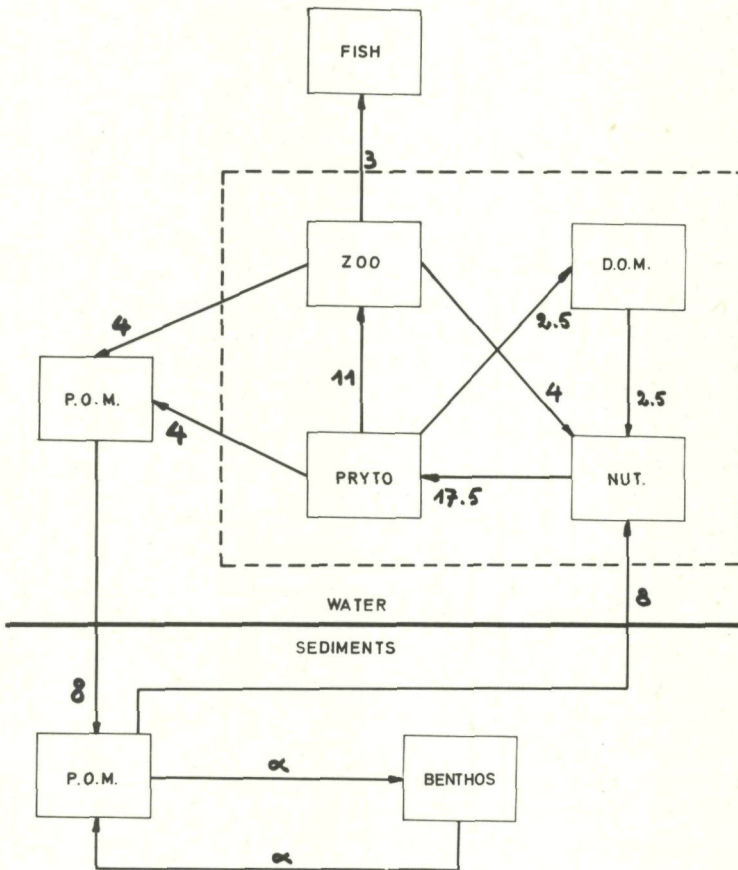

FIG. 2. Mean fluxes of nitrogen in the Southern Bight of the North Sea. All the data are expressed in g N/ m²/ year.

This pattern is based upon two fundamental fluxes ; the first one is the primary production evaluated by Mommaerts (1974, 1975) at 17.5 g $N/m^2/year$ and the second one is the zooplankton grazing estimated by Daro and Bossicart (in press) at 11 g $N/m^2/year$.

For the phytoplankton, it is assumed (Parsons and Seki, 1970) that an average of 15 % of the total nitrogen fixed by the primary production is released as soluble material. So, there is a flux of 2.5 g $N/m^2/year$ between phytoplankton and the dissolved organic matter. In order to balance the ecodynamics of the phytoplankton, one has to postulate, by difference, a flux of natural mortality of 4 g $N/m^2/year$ between phytoplankton and non-living particulate organic matter.

For the zooplankton, one can adopt a balance for *Calanus sp.* given by Steele (1974) estimating that, "of nitrogen digested, 35.7 % are excreted in soluble form, 37.5 % lost as fecal pellets and 26.8 % invested in growth". Moreover, the hypothesis is set forward that the soluble excretion is entirely constituted by ammonia. So, there is a flux of 4 g $N/m^2/year$ to the particulate organic matter, of 4 g $N/m^2/year$ to the dissolved nutrients and of 3 g $N/m^2/year$ available for the higher levels of the food chain.

It is admitted that all the soluble organic matter is remineralized and that the fraction which reenters the particulate organic matter as bacteria can be neglected. Finally, all the particulate organic matter is supposed to drop to the bottom and being recycled into the sediments. This is probably realistic because the residence time of non-living organic matter follows the ratio H^2/A_v where H is the depth and A_v the vertical eddy diffusity which is equal to 0.26 day. This is less than the minimum time lag for remineralization of 2 days cited by Ketchum and Corwin (1965).

This mean pattern of the nitrogen cycle must be regarded as a first working hypothesis and perhaps does not represent the real ecosystem for two reasons. The first one is that the two basic fluxes are not direct data but are estimated from the measurement of an optimum rate of *in vitro* primary production by the C^{14} techniques, and from the estimation of food requirements of some species and stages of zooplankton. The second reason is that the other fluxes are derived from the basic ones by very simple rules of proportionality. The nitrogen circulation will only realistic when all the fluxes are measured directly and independently.

Nevertheless, the proposed nitrogen cycle could be consistent which can be checked in two ways. The first one concerns the fish. From data given by the I.C.E.S. (1970), the fish stock in the North Sea can be estimated at 0.16 g N/m^2. If the annual food requirement of fish is supposed to be 15 times its yield (Randers, 1973), a value of 2.5 g $N/m^2/year$ is obtained which is very close to the flux of the net secondary production. The second way concerns the sediments. If one assumes that the nitrogen in the sediments is in equilibrium and that the benthic food chain is selfsufficient, the flux of sinking particulate organic matter must be equal to the regeneration of dissolved nitrogen from the sediments. Indeed the value of 8 g $N/m^2/year$ falls within the range of fluxes from sediments as estimated by Vanderborght *et al.* (1975).

Mathematical model of the nitrogen cycle

The state variables which are selected here are the dissolved nutrients X_1, the phytoplankton X_2, the zooplankton X_3 and the dissolved organic matter X_4, all expressed in g N/m^2. Their evolution equations are the following :

$$\dot{X}_1 = F_{01\,Scheldt} + F_{01\,Belgian\ coast} + (F_{01\,South} - F_{10\,North}) + F_{01sediments} + F_{31} + F_{41} - F_{12} \qquad (1)$$
$$\dot{X}_2 = F_{12} - F_{24} - F_{23} - F_{20} \qquad (2)$$
$$\dot{X}_3 = F_{23} - F_{31} - F_{30fecal\ pellets} - F_{30fish} \qquad (3)$$
$$\dot{X}_4 = F_{24} - F_{41} \qquad (4)$$

in which :

— $F_{01\,Scheldt}$ is the imput of the Scheldt estuary. The very few available data roughly show that this imput has a winter maximum of 1,500 g N/sec and a summer minimum of 100 g N/sec (Janssen and Meuris, 1975). Thus, the simplest way of expressing it is $F_{01\,Scheldt} = 0.013\ (1 + 0.8 \cos \omega t)$ in g $N/m^2/day$ with $\omega = 2\pi/365$ and t, the time in days. (5)

— $F_{01\,Belgian\ coast}$ is the terrigeneous import from the belgian coast which is assumed, by lack of more precise information, to be constant and of the same order of magnitude as the Scheldt imput ; $F_{01\,Belgian\ coast} = 0.013$ g $N/m^2/day$.

— $(F_{01\,South} - F_{10\,North})$ is the difference between the nitrogen importation from the Channel and the exportation to the North which is equal to -7 g $N/m^2/year$. Direct measurements in the Dover Straight show that the first term varies from 15,000 g N/sec in winter to 300 g N/sec in summer (Janssen and Meuris, 1975) while the second one is assumed to be proportional to the concentration of dissolved nitrogen inside the box. Therefrom :

$$(F_{01\,South} - F_{10\,North}) = 0.13(1 + 0.66 \cos \omega t) - 0.038\ X_1 \text{ in g } N/m^2/day \qquad (6)$$

— the flux $F_{01sediments}$ of dissolved nutrients diffusing from the sediments is constant and equal to 0.022 g $N/m^2/day$.

— F_{12} is the primary production which can be written :

$$F_{12} = C_1\ f(t)\ T(t)\ X_2\ (\frac{X_1}{0.5 + X_1})\ L \qquad (7)$$

The primary production linearly depends on the phytoplankton biomass, the temperature $T(t)$ and the photoperiod (*i.e.* the fraction of the day during which the incident light is a available for the photosynthesis) $f(t)$.

It is controlled by the dissolved nutrients following a Michaelis-Menten's law with a half saturation constant equal to 0.5 g N/m^2.

The light influence is expressed by Steele's relationship integrated on depth

$$L = \frac{e}{K_e H} [\exp (- \frac{I_{av}(t)}{I_{opt}} e^{-K_e H}) - \exp (- \frac{I_{av}(t)}{I_{opt}})] \qquad (8)$$

with $I_{av}(t)$, the photosynthetic available radiation at the sea surface ; I_{opt}, the optimum light intensity rated by Mommaerts (1974) at 10^5 $J/m^2/hr$; K_e, the light extinction coefficient expressed by Riley's law :

$$K_e = K'_e + 0.096\ X_2 + 0.283\ X_2^{2/3} \text{ in } m^{-1} \qquad (9)$$

The self shading inhibition is taken into account but this effect is not predominant here because of the very high mean level of turbidity of the sea water ($K_e' \sim 0.6/m$).

Meteorological and oceanographic data allow to simulate $f(t)$, $T(t)$ and $I_{av}(t)$ by

$$f(t) = 0.5 (1 - 0.33 \cos \omega t) \quad \text{unitless} \tag{10}$$

$$T(t) = 13 (1 - 0.38 \cos \omega t) \quad °C \tag{11}$$

$$I_{av}(t) = 240 (1 - 0.78 \cos \omega t) \quad \text{kcal}/m^2/\text{day} \tag{12}$$

— F_{24} represents the release of soluble material by the phytoplankton which is worth 15 % of the primary production, by hypothesis

$$F_{24} = 0.15 F_{12} \tag{13}$$

— F_{23} is the zooplankton grazing which is proportional to the zooplankton biomass and the temperature. It depends on the phytoplankton following a Michaelis-Menten law with a half-saturation constant equal to 0.5 g N/m^2

$$F_{23} = \frac{C_2 T(t) X_2 X_3}{0.5 + X_2} \tag{14}$$

— $F_{30fecal\ pellets}$ is the flux of solid excretion of the zooplankton which is proportional to its biomass and to the grazing as suggested by Cushing (1969), Parsons et al. (1967) and applied to mathematical models by O'Brien and Wroblewski (1973).

$$F_{30fecal\ pellets} = C_3 F_{23} X_3 \tag{15}$$

— F_{20}, F_{30fish}, F_{31} and F_{41} respectively are the phytoplankton natural mortality, the fish predation on the zooplankton, the soluble excretion of zooplankton and the remineralization of the dissolved organic matter. They are expressed by:

$$F_{20} = C_4 T(t) X_2 \tag{16}$$

$$F_{30fish} = C_5 X_3 \tag{17}$$

$$F_{31} = C_6 T(t) X_3 \tag{18}$$

$$F_{41} = C_7 T(t) X_4 \tag{19}$$

The parameters C_1, C_2, ... C_7 which appear in eq. (7) and eqs (14) to (19) are estimated by optimizing techniques (Pichot and Runfola, 1974) in such a way, that after integration of the evolution equations, the mean values of the state variables and of the fluxes are obtained. The values of these parameters are given in Table I.

TABLE I

Biological parameters

Notation	Description	Estimated value
C_1	Saturated growth rate of phytoplankton	0.05 /day x °C
C_2	Saturated grazing rate of zooplankton	0.055/day x °C
C_3	Solid excretion rate of zooplankton	3 m^2/g N
C_4	Mortality rate of phytoplankton	0.045/day x °C
C_5	Predation rate of fish on zooplankton	0.09 /day
C_6	Soluble excretion rate of zooplankton	0.014/day x °C
C_7	Mineralization rate ofdissolved organic matter	0.021/day x °C

Results

In Figs 3, 4, 5 and 6 the comparison between the result of the simulation and the 1974 data, respectively for the dissolved nutrients, the phytoplankton, the zooplankton and the net primary production are shown.

For the dissolved nitrogen (Fig. 3), there is a good agreement till August followed by high peak due to ammonia and not yet clearly explained. Janssen and Meuris (1974) think this is related to the exceptional climatic conditions in the autumn of 1974. The torrential rains increased the mean flow of the Scheldt times causing a sort of cleaning action which resulted in a dilution of suspended matter and organic decomposition products in the Southern Bight.
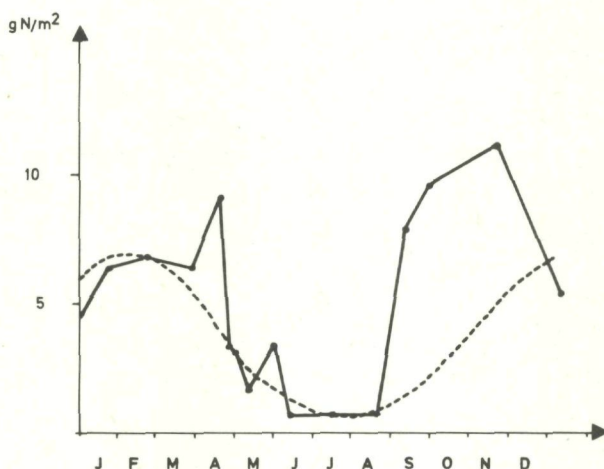

FIG. 3. Total dissolved nitrogen. ——— Observations made by Janssen and Meuris (1975) ; - - - result of the simulation.

For the phytoplankton (Fig. 4) and the net primary production (Fig. 6), the proposed model simulates fairly well the spring bloom as far as the less conspicuous autumnal outburst.

For the zooplankton (Fig. 5), the difference which appears at the end of August could be due to the predation of chaetognaths on herbivores which is not taken into account here.
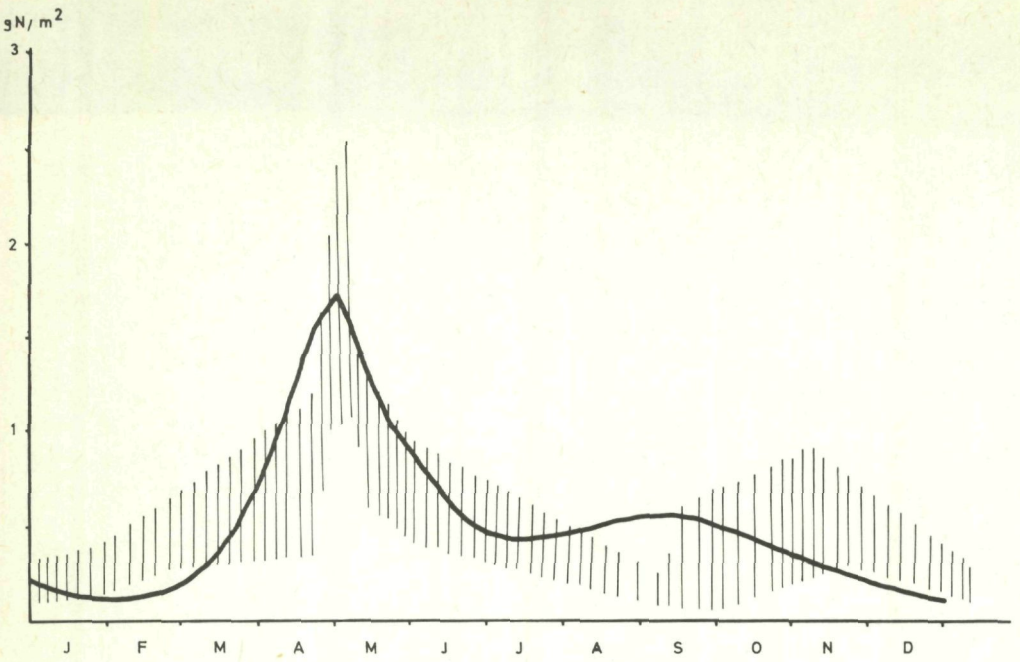
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FIG. 4. Phytoplankton biomass. Vertical lines : range of values observed by Lancelot (in press) ; ——— result of the simulation.

FIG. 5. Zooplankton biomass. Vertical lines : range of values observed by Daro and Bossicart (in press) ; ——— result of the simulation.
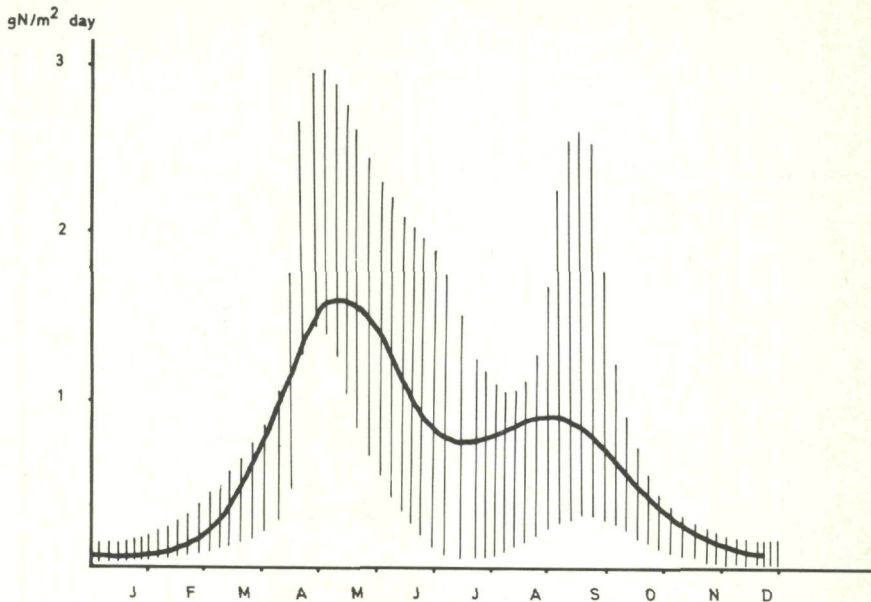
gN/m^2 day

FIG. 6. Net primary production. Vertical lines: range of values observed by Mommaerts (1975); ——— result of the simulation.

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