

## EUTROPHICATION AND ALGAL GROWTH IN THE NORTH SEA

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### ABSTRACT

The North Sea is a shallow shelf sea with an area of 0.6 million km<sup>2</sup>, surrounded by densely populated land areas. The general water circulation is counter-clockwise, and an annual freshwater input of 400 km<sup>3</sup> results in characteristic coastal water masses and currents. The North Sea receives an annual input of about 1 million tons of nitrogen (N) per year by rivers and run-off. Most of this nitrogen input is of anthropogenic origin and comes to the shallow southern part of the North Sea. The nitrate concentration of major rivers is 300–500 μM in winter and the annual mean N concentration of the freshwater discharge to the southern North Sea is about 300 μM. When diluted 23-fold, corresponding to a salinity of 33.5 if diluted with Atlantic water, the freshwater N is approximately equal to the natural N content of the Atlantic seawater. This level of anthropogenic N loading affects about 30 % of the volume flow through the central and southern North Sea. The average N/P ratio for the annual inputs of N and phosphorus (P) in 1990 was 30, which is almost twice as high as the typical ratio of 16 for marine waters. This leaves a large surplus of about 400 thousand tons of N remaining when P is depleted by algal growth in the coastal water. The excess N is exported with the coastal currents and is utilized under P limitation over an extended area. The increase in nitrate-based new production due to anthropogenic eutrophication is about 30 % for the whole North Sea. The change to P limitation of large coastal water masses is perhaps the most significant ecological change due to eutrophication. This could have particular importance for the strongly stratified waters of Kattegat and inner Skagerrak. Here nutrients advected from the southern North Sea by the Jutland Current are entrained from below the pycnocline into the euphotic zone, whereas local input of nutrients comes primarily to the upper layer. Eutrophication of stratified waters may be particularly conducive of promoting growth of flagellates, including harmful and toxic species. P limitation may aggravate this situation. Dinoflagellates are as a group characterized by slow growth, and their ecological success is assumed to reflect a compensatory high ability to survive.

A relationship between P requirement and growth rate is postulated, reflecting the general proportionality between content of nucleic acids and growth rate. Based on this, a hypothesis is put forward that suggests a shift towards greater dominance of slow-growing algae, including red tide dinoflagellates, with increasing N/P ratio of marine systems. Recent blooms of toxic Prymnesiophytes, such as the 1988 bloom of *Chrysochromulina polylepis* in Kattegat and Skagerrak, suggest another link between P limitation and harmful algae. Prymnesiophytes seem to have a good ability to grow on organic P and to be good competitors under P limitation. It is hypothesized that *Chrysochromulina* type algae are usually living in association with organic marine snow aggregates which presumably are P limited microenvironments. Massive blooms of these organisms may be exceptional events made more likely by changes due to eutrophication. Increased nutrient loading and associated P limitation may cause changes in nutrient conditions of macroscale coastal environments which resemble the conditions of their microscale habitats.

## INTRODUCTION

Coastal eutrophication is a common phenomenon in regional seas bordering densely populated land areas (Smayda, 1990). The North Sea is a recipient of run-off from areas in Europe that are strongly urbanized and industrialized and with extensive and intensive agricultural developments and practices. Build-up of nutrients in the coastal zone was identified as an issue of concern in a quality status report prepared for a North Sea ministerial meeting in 1987 (Anon., 1987). Nutrients and eutrophication in the North Sea have been treated in several recent overviews and communications (Brockman et al., 1988, 1990; Dickson et al., 1988; Gerlach, 1988, 1990; Lancelot et al., 1987, 1989; van Bennekom and Wetsteijn, 1990; Reid et al., 1990; Schaub and Gieskes, 1991).

While the North Sea is not a mediterranean sea in itself, it is as a shelf sea part of the large Arctic mediterranean sea (Worthington, 1970). This encompasses the Norwegian Sea basin including the Greenland and Icelandic Seas, as well as the Arctic basin. The dynamics of the Arctic mediterranean sea will be subject of intensified research in the coming years due to its importance for the regional and global climate (Broecker and Denton, 1990; Clarke, 1990). In this respect, comparisons with processes and dynamics of the Mediterranean Sea will be a relevant and valuable approach.

## THE NORTH SEA ECOSYSTEM: TOPOGRAPHY AND CIRCULATION

The North Sea covers an area of about 0.6 million km<sup>2</sup>. It is a relatively shallow sea with a mean depth of 74 m (ICES, 1983; Otto et al., 1990) and a general increase in depth from south to north (Fig. 1). About 1/3 of the North

Sea is made up of shallow areas of 50 m or less in the southern part and in the Kattegat. The central and northern parts have depths between 50 and 200 m except for the Norwegian Trench with maximum depth of about 700 m in the Skagerrak.

The circulation of the North Sea is characterized by a counter-clockwise flow pattern (Otto et al., 1990; Fig. 1). Atlantic water flows into the North Sea from

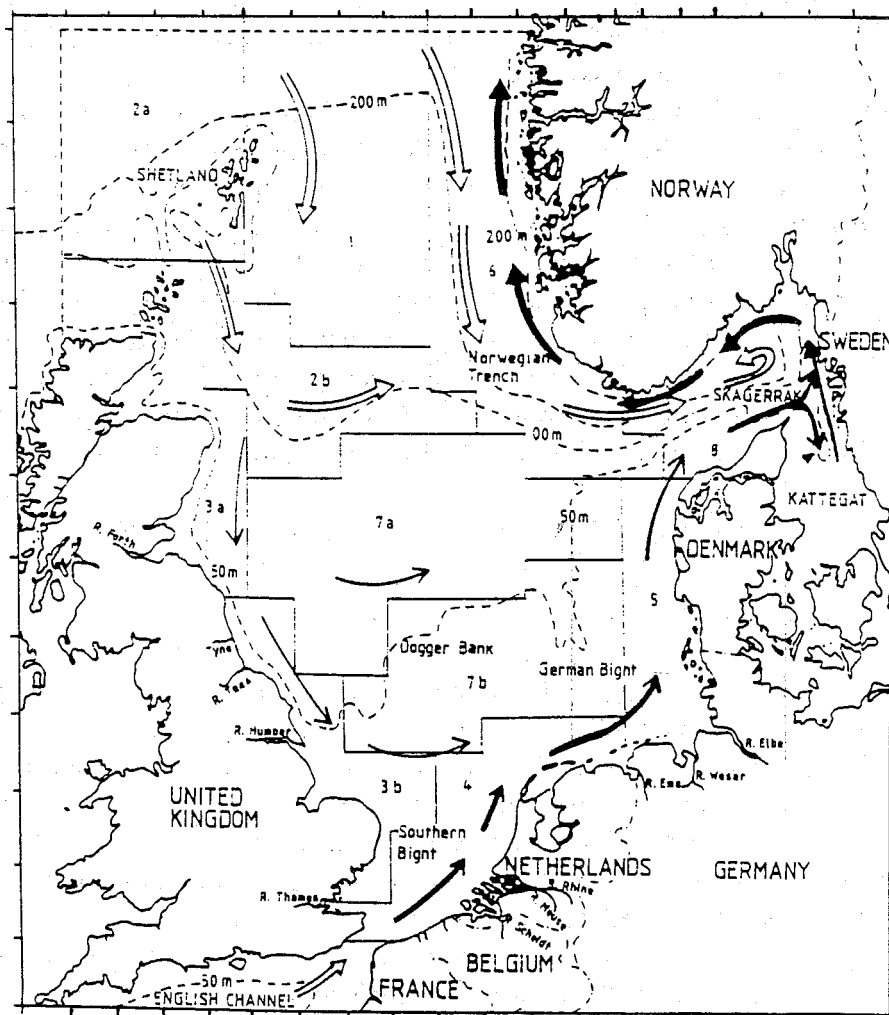


Fig. 1. Bathymetry and circulation of the North Sea. Water from the North Atlantic (open arrows) flows into the North Sea from North and through the Channel. Freshwater from major rivers contribute to a northwards flowing coastal current along the shallow southeastern North Sea. This flows as the Jutland Current into Skagerrak and Kattegat where it is entrained into the Baltic outflow and continues as the Norwegian Coastal Current. Based on Anon. (1987), Otto et al. (1990) and Svendsen et al. (1991). Also shown is the subdivision of the North Sea (ICES, 1983) which forms the basis for the subregional environmental quality status reports prepared by the North Sea Task Force (NSTF, 1991).

north of Scotland and the Shetland Isles. Much of the Atlantic inflow circulates as a trench flow through the Skagerrak (Otto et al., 1990; Svendsen et al., 1991). Atlantic water also enters the North Sea through the English Channel. This flow receives freshwater from major European rivers such as the Seine, Rhine and Elbe. It constitutes a northwards flowing coastal current along the eastern side of the North Sea and continues as the Jutland Current along the western and northern coasts of Denmark into Kattegat and Skagerrak. There is large variability with frequent blocking of the flow of the Jutland Current (Aure et al., 1990; Richardson and Jacobsen, 1990).

Due to the shallow depth and strong tidal mixing, the coastal water mass in the southern North Sea is usually vertically homogenous. As the Jutland Current passes the northern tip of Denmark there is an abrupt change to stratified conditions. The Jutland Current submerges under the lighter, brackish-water outflow from the Baltic Sea and flows below the pycnocline southwards in the Kattegat and northwards along the Swedish westcoast. There is massive entrainment of water from the deeper layer across the pycnocline into the outflowing Baltic water in the Kattegat. As a result the salinity of the Baltic outflow increases from about 8 to 25 as it progresses from the southern entrances to the northern outlet from the Kattegat (Aure et al., 1992).

## NUTRIENTS LOADING TO THE COASTAL ZONE

### *Total annual input*

At the Second International Conference on the Protection of the North Sea in London in 1987, ministers agreed on a goal to reduce the input of nutrients by 50 % between 1985 and 1995 for those areas where nutrients cause or are likely to cause pollution. Due to this political goal and obligation, there is a large scientific and political interest in nutrient input data.

Table 1 summarizes the inputs of total nitrogen and phosphorus by country in 1985 and 1990. The 1985 data are from a compilation made by a preparatory working group for the Third North Sea Conference in the Hague in 1990 (Parcom, 1990a). The 1990 data are from a compilation made by an Ad Hoc Working Group on Input Data of the Paris Commission (Parcom, 1992; Colijn et al., 1992). The input data should be treated with some caution due to possible incompleteness and inconsistencies in reporting of data and partly also due to the political interest invested in such data.

The total annual input of nitrogen to the North Sea by rivers and run-off was about 1 million ton in 1985 and 1990. The rivers Rhine and Elbe are the two largest point sources, being reflected in the large input values ascribed to the Netherlands and Germany in Table 1. These two rivers contribute about half of the total N input by rivers and run-off to the North Sea (Anon., 1987; Parcom, 1990a). In addition, there is a considerable input of N from the atmosphere, estimated to be of the order of 400 thousand tons per year (Anon., 1987; Colijn et al., 1992).

TABLE 1

Annual inputs of nitrogen and phosphorus to the North Sea by rivers and direct discharges 1985 and 1990. Values are in thousand tons per annum. The 1985 data are from Anon. (1990) and the 1990 data are from Parcom (1992).

Country	Nitrogen		Phosphorus		N/P (atomic ratio)	
	1985	1990	1985	1990	1985	1990
United Kingdom	184	165	24.6	> 18	15	< 19
Belgium	65	30	10.2	2.0	13	31
Netherlands	402	348	45.7	24.2	18	30
Germany	256	190	17.6	11	30	36
Denmark	54	63	8.1	2.8	14	47
Sweden	49	38	1.2	1.5	84	52
Norway	79	66	4.7	2.3	35	59
Total	1089	900	112	62	20	30

Most of the N input via freshwater and the atmosphere is of anthropogenic origin. The total anthropogenic input of N to the North Sea was therefore about 1 to 1.5 million tons in 1985 and 1990. This can be compared to a transport of N in the Atlantic water that circulates through the North Sea of about 5–7 million tons per year (Brockmann et al., 1990; Colijn et al., 1992).

The total annual input of phosphorus by rivers and run-off was about 110 and 60 thousand tons in 1985 and 1990, respectively (Table 1). This trend of decline in input may be real, reflecting efforts to reduce P input by sewage treatment and use of P-free detergents.

Most of the N input is in the form of nitrate which in 1990 contributed 565 thousand tons or 62 % of the total N input by rivers and run-off (Colijn et al., 1992). Nitrate is also considered the dominant component of the atmospheric

input of N (Anon., 1987). Inorganic phosphate made up 78 % of the total P input by rivers and run-off in 1990 (Colijn et al., 1992).

#### *Nitrogen concentrations in rivers and estuaries*

The total annual input of N by rivers and run-off of about 1 million ton is carried in a total freshwater input of about 400 km<sup>3</sup> (ICES, 1983, Otto et al., 1990). Dividing the total input of N by the total amount of freshwater gives an overall mean concentration of 180  $\mu\text{M}$  of N in the freshwater. Calculations for various subregions of the North Sea reveal high concentrations in the range 140–360  $\mu\text{M}$  N for the coastal regions from the UK eastcoast to the German Bight and in the Kattegat (Table 2). The average N concentration of the freshwater discharge to Skagerrak and the Norwegian westcoast is considerably lower (58 and 18  $\mu\text{M}$ ; Table 2).

The N content of the major rivers discharging into the southern North Sea is about 500  $\mu\text{M}$  in winter (Dickson et al., 1988; Lancelot et al., 1989; van Bennekom and Wetsteijn, 1990). This is about 40 times higher than the winter nitrate concentration of Atlantic water (about 12  $\mu\text{M}$ ; Føyn 1987; Skjoldal and Rey, 1989; Danielsen et al., 1991). Mixing diagrams of nutrient concentration versus salinity typically show steep linear decrease in concentration with increasing salinity, indicating dominance of physical mixing processes in estuarine and nearshore water in winter (Fig. 2; Dickson et al., 1988; van Bennekom and Wetsteijn, 1990; Parcom, 1990a). Biological processes would generally tend to cause non-linearity in such mixing diagrams. The effect of this is usually seen in the high salinity range due to the much larger volume of water and longer time required for dilution compared to the situation in the low salinity region (Fig. 2).

There are differences in nutrient concentrations among rivers which can cause complex patterns in the coastal zone influenced by plumes from different rivers (van Bennekom and Wetsteijn, 1990). For a more gross budget calculation, however, mixing can be considered to be between two different water types: European river water with salinity of almost zero and Atlantic Water with salinity of about 35 (Table 3). A N concentration of 300  $\mu\text{M}$  for the river water, similar to the mean concentration based on the annual inputs of N and freshwater to subregions 3, 4 and 5 (Table 2), has been assumed for the calculations. A salinity of 33.5 represents 23-fold dilution of the river water. The river N is by then reduced to 13  $\mu\text{M}$  assuming conservative mixing (Table 3). A salinity of 33.5 can therefore be taken as an approximate limit for the

TABLE 2

Nitrogen loading to coastal subregions of the North Sea. The subregions are those defined in ICES (1983). Data on volume, water flow, turnover time of water and freshwater discharge were taken from ICES (1983), Otto et al. (1990) and Aure et al. (1992). Annual N input data are for 1990 as compiled by Parcom (1992) and Colijn et al. (1992). The N input expressed per second has been scaled against seawater flow and freshwater discharge, undiluted and following 18-fold dilution (corresponding to salinity of 33). The annual N input has also been scaled against subregion volume.

ICES subregion	Area	Volume ( $10^{12} \text{ m}^3$ )	Flow ( $10^6 \text{ m}^3 \text{ s}^{-1}$ )	Turnover time (y)	Freshwater discharge ( $10^3 \text{ m}^3 \text{ y}^{-1}$ )	Freshwater N input ( $10^3 \text{ tons y}^{-1}$ )	Scaled N input ( $\text{mmol m}^{-3}$ )			
							Freshwater	Diluted 18-fold		
3a	UK East coast-N	2.9	0.03	3.1	1.2	85	160	8.9	2.1	6.4
3b	UK East coast-S	0.8	0.02	1.3	0.5	80	360	20.0	7.1	9.0
4	Belgian/ Netherlands coast	1.2	0.16	0.23	3.1	380	275	15.3	22.5	5.3
5	German/ W-Danish coast	1.0	0.18	0.18	1.4	215	345	19.2	15.3	2.7
8	Kattegat Skagerrak	0.5 7.0	0.06 1.0 0.3*	0.26 0.22	1.1 1.7	69 44	140 58	7.8 3.2	9.8 0.4	2.6 0.1
6	W-Norwegian coast	12	$\approx 1$	0.38	3.5	29	18	1.0	0.2	0.1

\* Flow of the upper layer coastal current.

dilution whereby riverborne N to the southern North Sea equals the natural N content of the marine water.

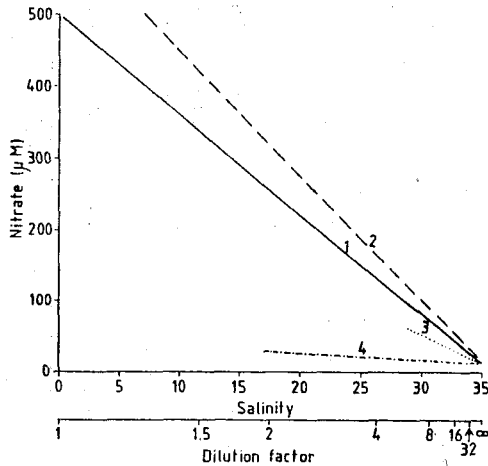


Fig. 2. Relationships between winter nitrate concentration and salinity in estuaries. The lower abscissa gives the dilution factor for freshwater diluted with seawater of salinity 35. The solid line represents the line for conservative mixing of freshwater with 500  $\mu\text{M}$  nitrate with seawater of salinity 35 and 12  $\mu\text{M}$  nitrate. Relationships for: 1) southeastern UK estuarine water, 1960–86; 2) total inorganic nitrogen in the Scheldt estuary in 1978; 3) Dutch coastal waters in 1961; 4) Dutch coastal waters in the 1930s. Based on Dickson et al. (1988) and Parcom (1990a).

### *Nitrogen loading to the coastal zone*

The input of N to the coastal areas of the North Sea can be scaled in relation to volume and flow of the recipient body of coastal water. This has been done for coastal subregions (Fig. 1) based on the subdivision used by an ICES working group estimating flushing times of the North Sea (ICES, 1983). These subregions have also been adopted by the North Sea Task Force as the basis for preparation of environmental quality status reports (NSTF, 1991).

When scaled to volume, the total annual inputs of N represent from 7 to 23  $\mu\text{moles l}^{-1}$  ( $\text{mmol m}^{-3}$ ) for the subregions comprising the southeastern UK coast, the Southern Bight, the German Bight and the Kattegat (Table 2). The average annual N loadings to these areas are of the same magnitude as the natural content of N in seawater. When scaled to flow, the annual N inputs to subregions 4 and 5 and the Kattegat are from 3 to 5  $\mu\text{moles l}^{-1}$  (Table 2), reflecting turnover times of a few months for these areas (ICES, 1983). The annual N loadings to Skagerrak and the Norwegian westcoast are considerably lower, reflecting lower N inputs and larger recipient volumes and flows (Table 2).

The total freshwater input to the southern North Sea is about  $190 \text{ km}^3 \text{ y}^{-1}$  or  $6000 \text{ m}^3 \text{ s}^{-1}$ . When this amount of freshwater is diluted 23-fold with Atlantic water, corresponding to a salinity of 33.5, it represents a volume flow of



0.14 million  $\text{m}^3 \text{s}^{-1}$  (Table 3). This is slightly lower than the estimated flux through subregions 4 and 5 along the coasts from Belgium to Denmark (ICES, 1983; Otto et al., 1990). The N input with the freshwater represents at this

TABLE 3

Dilution of river water, nitrogen concentration and volume transport at different salinities for the coastal water mass in the southern North Sea. The calculations are based on mixing European river water with Atlantic water with salinity 35. The annual mean freshwater discharge to subregions 3–5 (from UK eastcoast to Danish westcoast) is  $6200 \text{ m}^3 \text{ s}^{-1}$  with a mean N concentration of about  $300 \mu\text{M}$  (Table 2).

Salinity	Dilution factor	N concentration ( $\mu\text{M}$ )	Flow ( $10^6 \text{ m}^3 \text{ s}^{-1}$ )
30	7	43	0.04
32	12	26	0.07
33	18	17	0.11
33.5	23	13	0.14
34	35	9	0.22
34.5	70	4	0.43

dilution and flow a N loading approximately equivalent to the natural content of N in the recipient seawater. The volume flow of  $0.14 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$  can be compared to a total flow of about  $1.5 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$  through the entire North Sea and about  $0.5 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$  through the central and southern North Sea (ICES, 1983; Otto et al., 1990). Thus about 30 % of the volume flow through the central and southern North Sea receives a N loading equivalent to the natural background N content.

The high nutrient loading to the coastal zone of the southern North Sea is reflected in elevated nutrient concentrations in winter when biological consumption of nutrients is at a minimum (Radach and Berg, 1986; Weichart 1986; Føyn, 1987; Lancelot et al., 1987, 1989; Brockmann et al., 1988, 1990; Dickson et al., 1988; Hydes and Edmunds, 1989; van Bennekom and Wetsteijn, 1990; Colijn et al., 1992). Concentrations of more than  $1 \mu\text{M}$  phosphate and  $20 \mu\text{M}$  nitrate are commonly found along the eastern coast of the North Sea (Brockmann et al., 1990; Colijn et al., 1992).

Most of the nutrient loading from rivers and run-off to the North Sea is of anthropogenic origin, reflecting the large population and activities of man in the watersheds. Exact quantification of the anthropogenic contribution is made difficult, however, by the limited amount and questionable quality of historical nutrient data (Weichart, 1991). For the river Rhine there has been an increase

in nitrate concentration from about 100 to 300  $\mu\text{M}$  between 1955 and 1985 (Fig. 3; van Bennekom and Wetsteijn, 1990). Earlier measurements indicated concentrations of about 50  $\mu\text{M}$  nitrate or less. Measurements from the Dutch coastal zone in the 1930s indicated a river concentration of about 60  $\mu\text{M}$  nitrate based on extrapolation to zero salinity (Fig. 2; Parcom, 1990a). The concentration of inorganic phosphate in the Rhine increased from less than 2 to more than 10  $\mu\text{M}$  between 1940 and 1975 (van Bennekom and Wetsteijn, 1990). For the German Bight where the river Elbe is a major nutrient source, there has been a 2- to 3-fold increase in phosphate winter concentration between 1936 and 1975-85 (Weichart, 1986, 1991).

#### *N/P-ratio and seasonality in nutrient input*

The average N/P ratio for the total annual inputs of N and P by rivers and

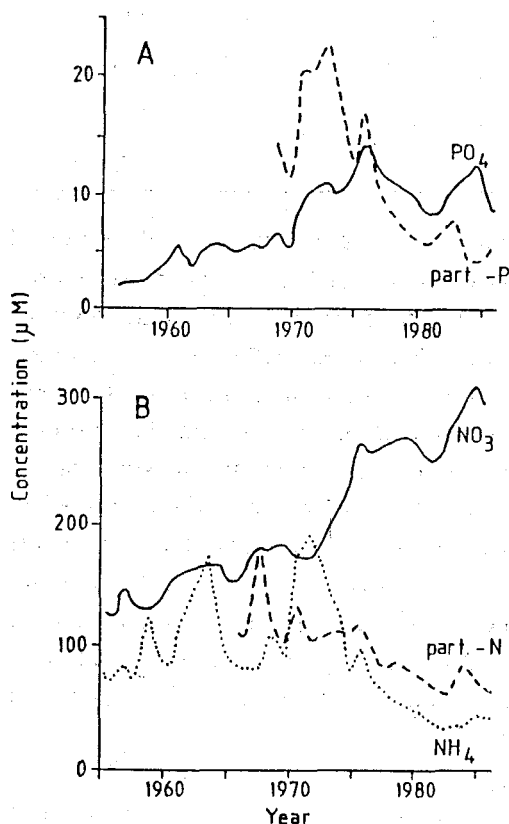


Fig. 3. Nutrient concentrations in the River Rhine from 1955 to 1987. From Bennekom and Wetsteijn (1990).

run-off in 1990 was 30 (Table 1). This is about twice as high as the Redfield ratio of 16, characteristic of marine water and plankton biomass (Redfield et al., 1963). There are considerable regional differences in the average N/P ratio of the annual inputs, ranging from less than 19 for the UK eastcoast to about 50 for Kattegat and Skagerrak (Table 1).

The high N/P ratio is probably a recent feature as indicated by temporal trends for the concentrations of the various N and P constituents in the river Rhine. After 1970 there have been marked decreases in particulate N and P and in ammonium, while inorganic phosphate has remained at a high level with no clear trend. Nitrate, in contrast, has shown a steadily increasing trend (Fig. 3; van Bennekom and Wetsteijn, 1990). These trends reflect the

combined effects of sewage treatment and agricultural practices.

Data from the river Elbe for the period 1985–89 reveal a marked difference between N and P in relation to river flow which reflects differences in sources of origin. While the concentration of phosphate decreased with increasing river flow according to a theoretical dilution curve, nitrate showed the opposite trend with a marked increase with increasing river flow (Fig. 4; Anon., 1990). This is

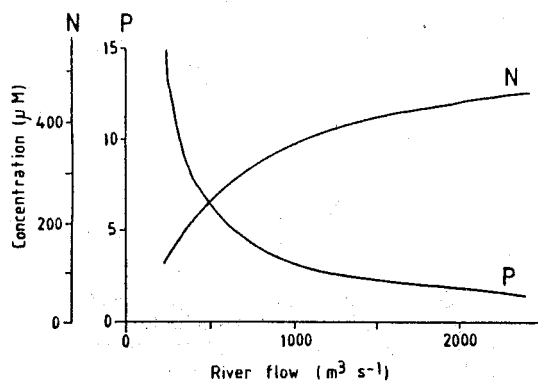


Fig. 4. General relationships between concentration of nitrate and inorganic phosphate versus water flow of the River Elbe. Phosphate behaves according to a dilution curve with constant input of P, whereas the nitrate concentration increases asymptotically with increasing river flow. Based on data from 1985–89 in Anon. (1990).

because most of the nitrate originates from agriculture, being washed off from the land when precipitation is highest in winter and spring. Total N and P showed similar but less clear trends to those of nitrate and phosphate (Anon., 1990). This difference in behaviour results in a marked seasonality with high N/P input ratio in winter and spring due to the high nitrate input at high river flow. The N/P ratio is considerably lower in summer and autumn when the river flow is low (Fig. 4).

## NUTRIENT CONSUMPTION IN THE COASTAL ZONE

### *A conceptual model*

A conceptual model for nutrient consumption and phytoplankton growth in the coastal zone of the southern North Sea is shown in figure 5. Turbidity due to suspended material from rivers and resuspended sediments limits the production in the nearshore shallow areas. The light penetration generally increases as the turbidity decreases in the offshore direction (Peeters et al., 1990). In shallow offshore areas such as the Dogger Bank, the restricted depth of mixing allows growth of phytoplankton even during the winter (Brockmann et al., 1990; van Bennekom and Wetsteijn, 1990).

Due to the high turbidity and heavy nutrient input, the nearshore coastal zone typically has a surplus of nutrients and the growth of phytoplankton is limited by light. The extent of this is largest in winter when the amount of incoming light is low and the discharge of freshwater and nutrients is high. There are similarities in the basic patterns of nutrient consumption and algal

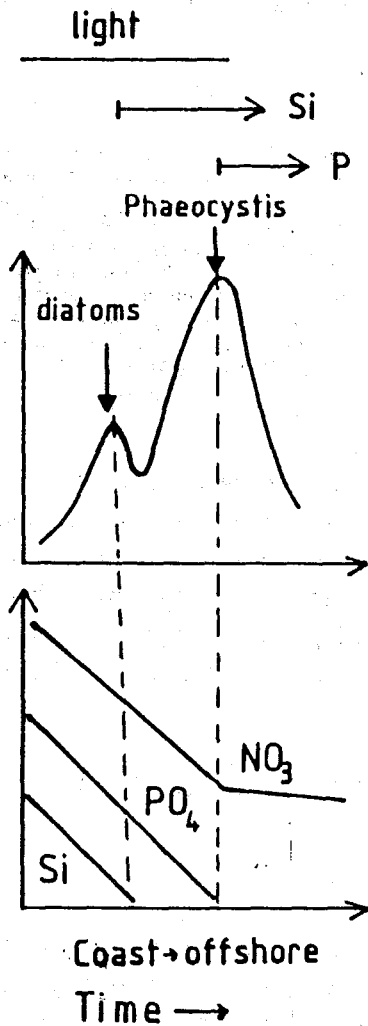


Fig. 5. A conceptual model for algal growth and nutrient consumption in the coastal zone of the southern North Sea. Excess nutrients from riverine input and high turbidity cause light limitation of the algal growth in the nearshore coastal zone. During spring there is increased nutrient consumption, first by diatoms limited by silicon, followed by massive blooms of *Phaeocystis pouchetii* limited by phosphate. The excess nitrate from eutrophication is exported with the coastal currents and utilized at lower rate under P limitation over an extended area. Nutrient patterns similar to the temporal ones in spring occur along coast-offshore mixing gradients.

growth between the temporal development in spring and summer in the alongshore direction of the coastal current and the development in the offshore direction of progressive dilution of the coastal water.

Silicate is a nutrient required by diatoms for formation of their silicious tests. Although the silicate concentration in major rivers such as the Rhine, Scheldt

and Elbe is high (100–300  $\mu\text{M}$ ), there has been no marked increase due to eutrophication paralleling those of N and P (Radach and Berg, 1986; Anon., 1987; van Bennekom and Wetsteijn, 1990). Thus silicate is typically the first nutrient to become limiting in spring, causing the termination of the spring diatom bloom in the coastal waters (Gieskes and Kraay, 1975; Lancelot et al., 1989; Peeters et al., 1990). The remaining N and P allow further growth of algae not requiring Si, and massive blooms of the colony-forming phytoflagellate *Phaeocystis* spp. typically occur in spring and early summer (Gieskes and Kraay, 1975, 1977; Cadée and Hegeman, 1986; Weisse et al., 1986; Lancelot et al., 1987, 1989; Bauerfeind et al., 1990).

Reflecting the high N/P ratio of the riverine nutrient input, P is typically the second nutrient to become limiting. This has been clearly demonstrated in data from the late 1980s. Lancelot et al. (1989) reported an extensive data set from the spring 1988 which showed remaining inorganic N concentrations of 10–40  $\mu\text{M}$  upon depletion of phosphate in the Belgian, Dutch and German coastal waters. Data from a monitoring station on the west coast of Denmark from 1984 to 1989 showed a consistent pattern with nitrate concentration of 20  $\mu\text{M}$  or more remaining when phosphate was depleted in spring and early summer (Parcom, 1990b). Bauerfeind et al. (1990) reported 10–20  $\mu\text{M}$  excess nitrogen remaining when phosphate was depleted by spring blooms in the southeastern North Sea in 1985 and 1986.

The spring growth of phytoplankton is limited by light until phosphate is depleted. The excess N, being mainly nitrate originating from the land run-off during winter and spring, is used at a lower rate when P limitation occurs (Fig. 5). The consumption of the surplus nitrate is then dependent on new supplies of P. Remineralization in bottom sediments and in the water column is one source of P for continued biological production, but this would also supply remineralized nitrogen in the form of ammonia which might be used preferentially over nitrate by phytoplankton. The excess nitrate is therefore exported with the currents and utilized over an extended area.

#### *Phosphorus limitation and new production*

The large excess of N in the present anthropogenic inputs by rivers and run-off has drastically altered the ecological characteristics of the coastal waters. There has been a change from a more balanced situation with a probable tendency towards N limitation in former, pristine times, to the present situation with marked P limitation in spring and summer due to eutrophication. Assuming an N/P ratio of 16 for the primary consumption of the nutrients, 420

thousand tons of the total annual input of N would remain when P has been utilized (Table 1). Due to the seasonality in the input concentrations (Fig. 4), the imbalance between N and P is even stronger for the discharges during winter and spring.

In terms of marine production, a distinction is made between new production and recycled production (Dugdale and Goering, 1967). New production is typically based on nitrate being mineralized over the annual cycle and/or supplied from the deep water. Recycled production is typically based on ammonium being recycled by excretion from grazing zooplankton or microbes in the microbial loop. The input of nutrients from rivers and run-off give rise to new production in the sea. Due to the excess N, new production in terms of N is decoupled from that in terms of P. New production in terms of P would occur until the input of P is depleted (Fig. 5). The further consumption of nitrate would represent new production in terms of N, but since it is driven by recycled P, the corresponding algal growth would represent recycled production in terms of P.

It is possible to construct a rough N budget for the North Sea to illustrate the quantitative importance of the mainly anthropogenic nutrient input from rivers and run-off. The annual transport of N into the North Sea from the Atlantic has been calculated to be about 7 million tons based on estimates of volume flow and N content of water masses (Lee, 1980; ICES, 1983; Colijn et al., 1992). An alternative estimate of about 4 million tons was given by Brockmann et al. (1990) (Table 4).

The transport through the Channel is about 350 thousand tons (Brockmann et al., 1990; Colijn et al., 1992).

Despite the great number of studies, there is still much uncertainty concerning the level of primary production of the North Sea. Reid et al. (1990) gave estimates of 200, 250 and 150–200  $\text{g C m}^{-2} \text{y}^{-1}$  for the net primary production in the southern, central and northern North Sea, respectively. Joint and Pomroy (1992) arrived at much lower estimates for the central North Sea, about 100  $\text{g C m}^{-2} \text{y}^{-1}$ , based on a comprehensive study over 15 months within the UK NERC North Sea Project. Their study covered the area south of 56° N. Assuming similar production levels in the central and northern North Sea, 100 and 200  $\text{g C m}^{-2} \text{y}^{-1}$  would seem to represent a low and a high estimate for the average annual production of the North Sea. These estimates are equivalent to a total annual production of 7 and 14 million tons of N, respectively, assuming a C/N ratio of 8 (Table 4).

Much of the total production is recycled production. An estimate of new nitrate-based production of 4 million tons is obtained by assuming that an upper

layer of 50 m thickness is depleted of  $10 \mu\text{M}$  nitrate during the growing season. This is equivalent to a production of  $56 \text{ g C m}^{-2} \text{ y}^{-1}$  and is probably an overestimate rather than an underestimate of the true new production.

About 80 % of the total input of approximately 1 million tons of N by rivers

TABLE 4

Summary of major elements of the nitrogen budget of the North Sea ecosystem.

Budget component	N ( $10^3$ tons)	Reference
<i>Input</i>		
Atlantic	7000	Lee, 1980; ICES, 1983; Colijn et al., 1992.
	4100	Brockmann et al., 1990.
Channel	350	Colijn et al., 1992.
Baltic	200	Anderson and Rydberg, 1988; Brockmann et al., 1990.
Rivers and run-off	1000	Table 1.
Atmosphere	400	Anon., 1987.
<i>Consumption/primary production</i>		
New production, 0–50 m	4000	see text
Anthropogenic new production	1400	
Total production	7000	Joint and Pomroy, 1992.
	14 000	Reid et al., 1990
<i>Transport by Jutland Current</i>		
Anthropogenic N	400	see text

and run-off comes to the coastal areas of the southern North Sea (Table 1). Much of this input is consumed by increased algal growth in this zone. Thus Joint and Pomroy (1992) estimated the annual production to be 199 and 261  $\text{g C m}^{-2} \text{ y}^{-1}$  in subregions 4 and 5 in the Southern Bight and the German Bight, respectively (Fig. 1). The volume flow through these subregions is about  $0.15\text{--}0.20 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$  and the turnover time is about 4 months (ICES, 1983; Otto et al., 1990). The flow of the Jutland Current is of similar magnitude (Otto et al., 1990), corresponding to a 20- to 30-fold dilution of the mean annual freshwater input to the coastal zone of the southern North Sea (Table 3).

The transport time of water from the Jutland Current through the Kattegat and Skagerrak system is likely to be variable and is of the order of one to several months (Aure et al., 1990, 1992). The total transport time from the

southern North Sea to the northern exit along the Norwegian west coast is therefore typically more than 4 months. This is sufficient time in general to allow biological consumption of the nutrients supplied by riverine inputs before they exit from the North Sea.

The new production due to input of N by rivers and run-off can therefore be taken to be equal to the total input of about 1 million tons N per year. This is about 25 % of the natural new production of the whole North Sea (Table 4). Taking also the atmospheric input into account, the increase in new production is probably more than 30 %.

The predominantly man-made increase in new production is concentrated to the coastal zones of the southern and eastern North Sea. This is also the nursery grounds of juvenile herring which spawns along the coasts of Scotland and England in autumn. The larvae are transported with the currents to nursery grounds on the eastern side of the North Sea (Corten, 1990; Daan et al., 1990). It is likely that eutrophication has effects on the feeding conditions and production potential for fish. The relationship between eutrophication and fish production is complex, however, with both negative and positive effects being possible. The fish catch from Skagerrak has shown a marked increase since 1930 and the biomass yield per area is much higher than the average for the North Sea (ICES, 1987). Considering the large magnitude of the coastal eutrophication and the general link between new production and fisheries, it is possible that the high fishery yield is partly an effect of eutrophication.

Reduction in nutrient input will have different effects for N and P. A Dutch analysis concluded that reduction in P would lower the magnitude of algal growth in the coastal zone whereas reduction in N would lead to a reduction in the affected area (NSTF, 1990). This is in accordance with the conceptual model in figure 5 where P is the primary limiting nutrient (after silicate) and the excess N is being exported with the currents and utilized under P-limited conditions over an extended area.

## EUTROPHICATION IN THE STRATIFIED ENVIRONMENTS OF KATTEGAT AND SKAGERRAK

### *Transport of nutrients from the southern North Sea*

Following the bloom of *Chrysochromulina polylepis* in May/June 1988, there has been an increased awareness of the possible large role of the Jutland Current as a transport route of nutrients from the southern North Sea. In late



April prior to the bloom in 1988, a large body of water with high nitrate content, relatively low phosphate content and virtually depleted silicate content was found in Kattegat and inner Skagerrak (Aksnes et al., 1989; Skjoldal and Dundas, 1991). Based on hydrographical characteristics this water was identified as originating from the southern North Sea. About 100 000 tons of nitrate was present as remaining excess N following silicate depletion by spring growth of phytoplankton and transport with the Jutland Current (Aksnes et al., 1989). A few selected vertical profiles from the west coast of Denmark and Kattegat in April 1988 demonstrate the excess nitrate (Fig. 6).

High nutrient concentrations and excess nitrate in the Jutland Current and in Kattegat and inner Skagerrak have been observed on many occasions during the period from winter to early summer in subsequent years (Aure et al., 1990; Skjoldal and Aure, 1990; Svendsen et al., 1991b; Aure, Føyn and Skjoldal, unpubl. results). Figure 7 shows vertical profiles from two stations in Kattegat and at the west coast of Sweden which demonstrate Jutland Current water with excess nitrate of about  $5 \mu\text{M}$  remaining in late May 1990. These observations as well as the results from a monitoring station on the west coast of Denmark (Parcom, 1990b) suggest that high nutrients levels and excess nitrate in the Jutland Current have been regular features in recent years.

Since there is low phytoplankton activity in mid-winter, part of the riverine input of nutrients in late autumn and early winter is transported with the Jutland Current into Skagerrak and Kattegat prior to being consumed by the spring growth of algae. Part of the excess N which remains following depletion of P, is also transported downstream with the Jutland Current. The nutrient concentrations in the Jutland Current are expected to be strongly dependent on the time of the year and the interplay between meteorological conditions and biological processes.

An estimate of the transport of nutrients from the southern North Sea into Skagerrak and Kattegat by the Jutland Current is given in Table 4. Assuming a flow of  $0.15 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$  and mean concentrations of 15 and  $10 \mu\text{M}$  nitrate for January–February and March–May, respectively, a transport of 400 thousand tons of N is obtained. While this may be on the high side for transport of anthropogenic inorganic N, it is probably not too high for the total transport including particulate and dissolved organic N. A similar estimate of about 400 thousand tons of N transported with the Jutland Current into Kattegat was given in Barth and Nielsen (1989).

### Eutrophication and conditions for algal growth

The Kattegat and inner Skagerrak have probably been fairly low productive areas in the pristine condition. It is a strongly stratified system with a marked

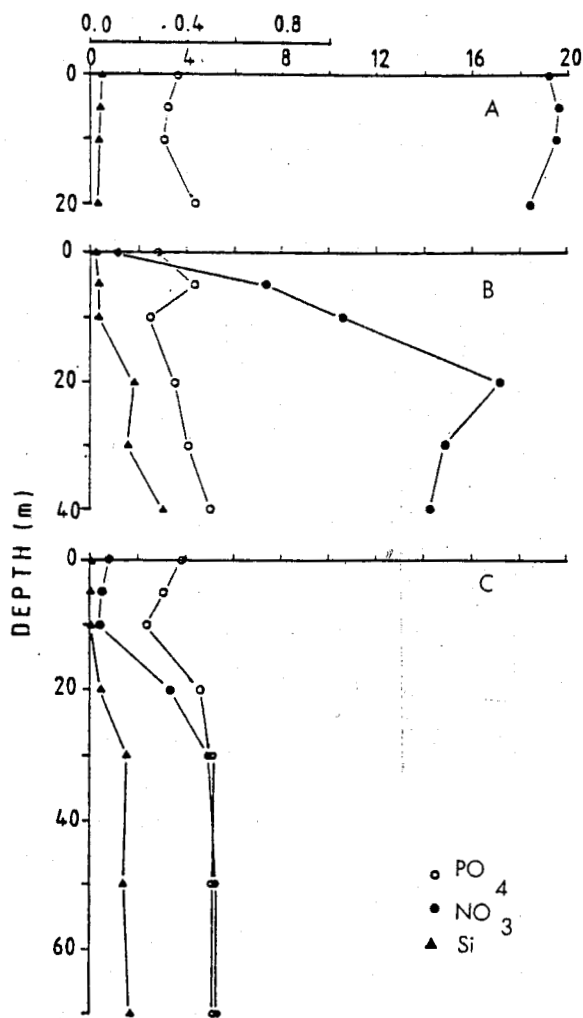


Fig. 6. Vertical profiles of phosphate (upper scale,  $\mu\text{M}$ ), nitrate and silicate (lower scale,  $\mu\text{M}$ ) off the west coast of Denmark (A), in the northern Kattegat (B), and in the southern Skagerrak northwest of Denmark. Data from late April 1988 prior to the bloom of *Chrysochromulina polylepis* (Skjoldal and Dundas, 1991).

halocline separating the Baltic outflow and the Norwegian coastal current from the underlying water from the North Sea or the Atlantic (Fig. 1; Otto et al.,

1990; Aure et al., 1992). Following the spring bloom, the water transported from the southern or central North Sea into Skagerrak and Kattegat would have been nutrient-depleted surface water. This water would then have submerged under the fresher and lighter surface layer to give a situation with low nutrient

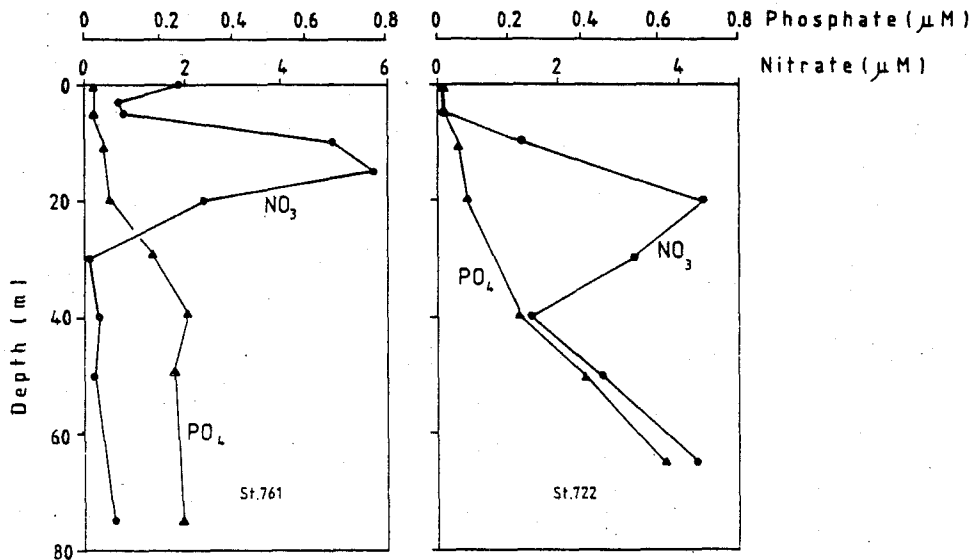


Fig. 7. Vertical profiles of phosphate and nitrate from north of Denmark (St. 761) and inner Skagerrak (St. 722) showing an intermediate layer of Jutland Current water with high nitrate content. Data from R/V "G.O. Sars" cruise during the ICES SKAGEX campaign, late May 1990.

water below the pycnocline. It is therefore likely that entrainment did not bring up much nutrients into the upper layer in summer and autumn.

This situation has now changed dramatically. The Jutland Current carries a heavy load of nutrients, characterized by a large nitrate excess in spring and early summer. This water submerges and the nutrients are being entrained into the upper layer. The nutrients advected from the southern North Sea with the Jutland Current are therefore entering the euphotic zone from below. The effects of these nutrients and the distorted nutrient ratios are therefore expected to be strongest on the algae in the pycnocline region where there typically is a chlorophyll maximum following the spring bloom in the upper layer (Richardson and Kullenberg, 1987; Rosenberg et al., 1990; Richardson and Christoffersen, 1991; Skjoldal and Dundas, 1991).

A possible scenario for the bloom of *Chrysochromulina polylepis* in 1988 was that it developed as a pycnocline population over an extended area in Kattegat and inner Skagerrak. Due to strong outflow of Baltic water and entrainment,

both algae and nutrient-rich water were mixed up into the upper layer where the toxic bloom developed. Excess nitrate and P limitation did probably contribute to the toxic mode of this bloom (Skjoldal and Dundas, 1991).

In addition to nutrients advected by the Jutland Current to the deeper part of the euphotic zone, there is also local supply of nutrients by rivers and run-off (Table 1) that goes into the upper layer of Kattegat and inner Skagerrak. Due to its limited size, the combined effect of advected and local nutrient enrichment is strongest in Kattegat where increases in nutrients levels and primary production and a decrease in oxygen level have been documented over the last two decades (Ærtebjerg, 1987; Anderson and Rydberg, 1988; Wassmann, 1990). Oxygen depletion of the deeper layer has occurred several times in recent years. The annual primary production in southern Kattegat has recently been found to be about  $290 \text{ g C m}^{-2} \text{ y}^{-1}$  (Richardson and Christoffersen, 1991).

## PHOSPHORUS LIMITATION AND GROWTH OF HARMFUL ALGAE

### *P* limitation algal growth rate and occurrence of dinoflagellates

Margalef (1978) described in a diagram a general relationship between algal types and degree of mixing and nutrient level. Along the diagonal of this diagram, from high mixing and high nutrient level to low mixing and low nutrient level, there is a general shift in dominance from diatoms to small flagellates. Red tide dinoflagellates were considered to occur in the rare situations when there was a combination of low mixing and high nutrient level. This general relationship points to the possibility that eutrophication of stratified waters, such as Kattegat and inner Skagerrak, may be particularly conducive of promoting growth of toxic dinoflagellates. Dinoflagellate blooms have been a common occurrence in these waters during the last decade, with massive blooms of *Gyrodinium aureolum* in the autumn as the most conspicuous events (Dahl and Tangen, 1990). DSP toxicity in blue mussels along the Skagerrak coasts caused by *Dinophysis* spp. has also become a more or less constant problem (Dahl and Yndestad, 1985; Dahl, pers. comm.).

In addition to nutrient enrichment per se, eutrophication often leads to altered nutrient ratios. Flagellates are generally favoured by eutrophication due to silicon limitation of diatoms (Gieskes and Kraay, 1977; Officer and Ryther, 1980; Radach and Berg, 1986; Aksnes et al., 1989; Conley and Malone, 1992).

Phosphorus limitation may also be of importance for the species composition of phytoplankton. Much of the P in small organisms is used for synthesis of

nucleic acids. Since the concentration of RNA is proportional to growth rate for a wide range of organisms (Sutcliffe, 1970; Båmstedt and Skjoldal, 1980), a relationship between P content of biomass and organism size is to be expected. Figure 8 shows a calculated relationship between P content and body size based

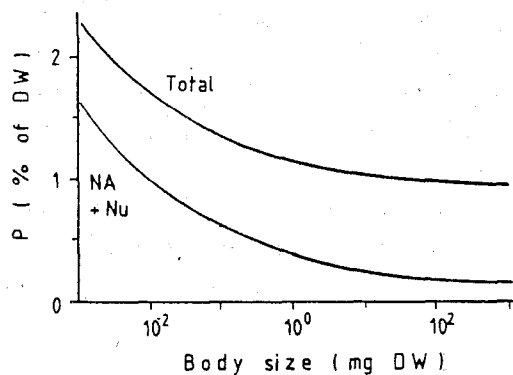


Fig. 8. Relationships between phosphorus content (% of dry weight) and body weight of zooplankton for total P and P contained in nucleic acids and nucleotides. Calculated from general relationships between contents of RNA, DNA and ATP versus body weight (Skjoldal and Båmstedt, 1977; Båmstedt, 1979; Båmstedt and Skjoldal, 1980). A protein-rich biomass with protein:lipid ratio of 9:1 and an ash content of 10 % have been assumed. N and P contents of protein, lipid and carbohydrate were taken from Ikeda (1977).

on relationships between concentrations of RNA, DNA and adenine nucleotides versus body size of zooplankton (Skjoldal and Båmstedt, 1977; Båmstedt, 1979; Båmstedt and Skjoldal, 1980). This relationship shows that zooplankton smaller than about 50  $\mu\text{g}$  dry weight body size has more than half its P content contained in nucleic acids and nucleotides. 50  $\mu\text{g}$  corresponds to the size of a medium-sized copepod such as *Pseudocalanus*. For bacteria and ciliates a strict relationship between RNA concentration and growth rate has been demonstrated, with RNA content being about as high as the protein content of the fastest growing bacteria (Leich, 1968). Similar compilation of data for algae has not been done, but available data suggest fairly high contents of nucleic acids (Dortch et al., 1983).

Planktonic food chains are characterized by small organisms being eaten by larger ones. Due to the general size dependency of metabolism and growth, faster growing organisms are typically eaten by slower growing organisms. One would therefore expect a decreasing relative P content of the biomass as one goes up a planktonic food chain from algae through herbivores to carnivores, with excess P in the diet being excreted at each step in the food chain (Fig. 9). Evidence for this is found in excretory N/P ratios which typically are lower than the N/P ratios of zooplankton biomass (Ketchum, 1962; Le Borgne et al., 1983). Due to the theoretical coupling between P content and growth rate, one can hypothesize a relationship between the average N/P ratio for a system and characteristics of the food chain. Small fast-growing algae, such as bloom

diatoms and small flagellates, have assumedly a high demand for P in order to produce high content of nucleic acids. If a system is shifted from N limitation to P limitation, characterized by an increase in the average N/P ratio, it may be more difficult for fast growing algae to realize their growth potential. This may cause a shift in competitive advantage towards more slowly growing algae (Fig. 10). To this category belong many dinoflagellate species which have characteristically low growth rates (Banse, 1982).

The ecological success of slow growing algae must, by default, be that they are good survivors. This points to the need for defense mechanisms which act to reduce grazing and microbial attacks and lower their mortality rate. Chemical agents and bad taste can be important factors for this purpose (Huntley et al., 1986; Estep et al., 1990). Although little is known about the functions of toxins in algae, they are likely to have ecological implications and to be involved in

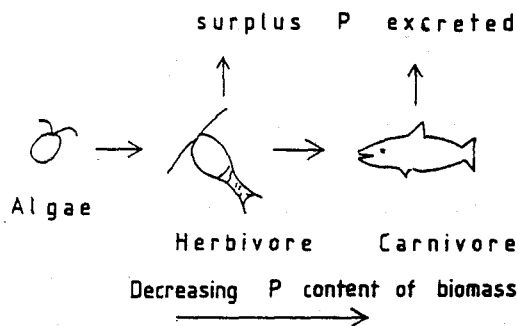


Fig. 9. Simplified pelagic food chain where large eats small. The P content of biomass decreases up the food chain and surplus P in diet due to nucleic acids is excreted at each step.

evolutionary selection. This may have contributed to the high number of toxic species among the generally slow-growing dinoflagellates.

The above arguments point to a possible link between frequency of occurrence of toxic dinoflagellates and P limitation caused by eutrophication. This may be particularly the case in stratified environments where the physical conditions from the outset favour growth of flagellates (Holligan, 1989). Although not yet proven in specific cases, the substantial degree of eutrophication and the associated shift to P limited conditions are likely to have caused a shift in species composition in Kattegat and inner Skagerrak. An increased frequency of toxic dinoflagellates is a possible effect of such a change.

#### *Blooms of Prymnesiophytes*

The most well-known species in the group of Prymnesiophytes are *Phaeocystis* spp. They occur as both unicellular flagellates and non-motile

colonies in mucus. Massive blooms of *Phaeocystis* occur in the coastal region of the southern North Sea in spring and summer (Lancelot et al., 1987, 1989). The magnitude and duration of these blooms have probably increased due to eutrophication (Cadeé and Hegeman, 1986). Another colony-forming prymnesiophyte, *Corymbellus aureus*, has also formed blooms in the southern North Sea in the 1980s (Gieskes and Kraay, 1986).

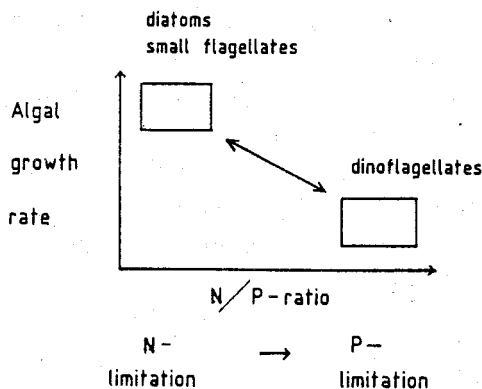


Fig. 10. Hypothetical relationship between N/P ratio of marine systems and algal growth rate and algal types. Due to high demand for P for synthesis of nucleic acids, fast-growing algae such as diatoms are favoured by low N/P ratio. Increase in the N/P ratio towards P limitation is postulated to favour slow-growing algae such as dinoflagellates, including toxic species.

The bloom of *Chrysochromulina polylepis* in Kattegat and Skagerrak in May/June 1988 (Aksnes et al., 1989; Dahl et al., 1989; Skjoldal and Dundas, 1991) was one of the rare occasions when algae of this genus have been noted to form a bloom, and the first occasion when they were noted to form a toxic bloom (Estep and MacIntyre, 1989). A species of a closely related genus, *Prymnesium parvum*, has, however, quite commonly formed toxic blooms in brackish water aquaculture ponds in various regions. This species has since 1988 formed toxic blooms in late summer in a fjord in Rogaland in southwestern Norway (Skjoldal and Aure, 1989; Kaartvedt et al., 1991; Aure and Rey, 1992).

*Prymnesium parvum* and *Chrysochromulina polylepis* produce a similar toxin called prymnesin. This is a general membrane destructing toxin which has a broad range of effects on organisms (Underdal et al., 1989; Skjoldal and Dundas, 1991). For both *P. parvum* and *C. polylepis* it has been shown experimentally that nutrient limitation and in particular P limitation, induces the production of toxin (Shilo, 1981; Edvardsen et al., 1990). Estep and MacIntyre (1989) hypothesized that prymnesin was used as a short-range chemical weapon whereby the algae disrupted neighbouring cells in order to utilize the released nutrients. They suggested the term dasmotrophy for this process.

The bloom of *Chrysochromulina polylepis* in Kattegat and Skagerrak was associated with nutrient-rich water with high N/P ratio that had been advected

from the southern North Sea (Skjoldal and Dundas, 1991). P limitation was a possible factor causing the algae in the bloom to become toxic. The toxic blooms of *Prymnesium parvum* in Rogaland have been restricted to the upper layer of a fjord strongly influenced by freshwater discharge. This freshwater contains very little inorganic phosphate and the upper layer in the fjord is P limited with excess nitrate present (Skjoldal and Aure, 1989; Aure and Rey, 1992).

Common denominators for the blooms of these two species have been that they occurred in strongly stratified environments with high N/P ratio and likely P limitation. This suggests that these algae are efficient competitors under P limitation, and dasmotrophy and phagotrophy may be important nutritional mechanisms in this respect. Under P limited conditions the ability to utilize organic phosphorus compounds may also be an important competitive advantage. Ability to utilize and grow on organic phosphorus compounds seems to be a wide-spread property among the group prymnesiophytes (Veldhuis and Admiraal, 1987; Boekel and Veldhuis, 1990, S.R. Erga, pers. comm.).

A second species of *Chrysochromulina*, *C. leadbateri*, formed a toxic bloom in a freshwater influenced fjord in northern Norway in May 1991 (Rey, 1991). A possible causative factor for this bloom was conditioning of the water by an overwintering stock of about 1 million tons of herring which reduced oxygen levels in the fjord and probably left excretory products in the water (Rey and Aure, 1991). Thus a natural eutrophication event was perhaps involved in the case of this bloom.

Prymnesiophytes have a characteristic haptonema, a small threadlike appendage which they presumably use to attach themselves to surfaces (Estep and MacIntyre, 1989). During the blooms in Rogaland, *Prymnesium parvum* has been observed to attach themselves to a range of substrates including sublittoral macroalgae (Johnsen and Lein, 1989; Kaartvedt et al., 1992).

*Chrysochromulina* spp. are commonly present in water samples from a range of environments, but they rarely occur in high abundance or form blooms (Estep and MacIntyre, 1989). It is a possibility that these algae are adapted to live in association with organic aggregates and marine snow particles where they use their haptonema to attach themselves. Such particles are likely to be microenvironments characterized by P deficiency. P leaks rapidly out from cells which goes in lysis, and detritus in surface waters contain little P (Sakshaug et al., 1983; Skjoldal and Wassmann, 1986). Bacteria have typically a high P content (Bratbak, 1985; Martinussen and Thingstad, 1987; Vadstein et al., 1988) and efficient uptake of inorganic phosphate (Bratbak and Thingstad, 1985; Thingstad, 1987). When detrital aggregates are being colonized, the bacteria



will utilize phosphate in the water surrounding the particles, making these probably P deficient microenvironments (Fig. 11). Marine snow aggregates have been shown to be microenvironments with high biological activity resulting in oxygen depleted conditions (Alldredge and Cohen, 1987; Alldredge

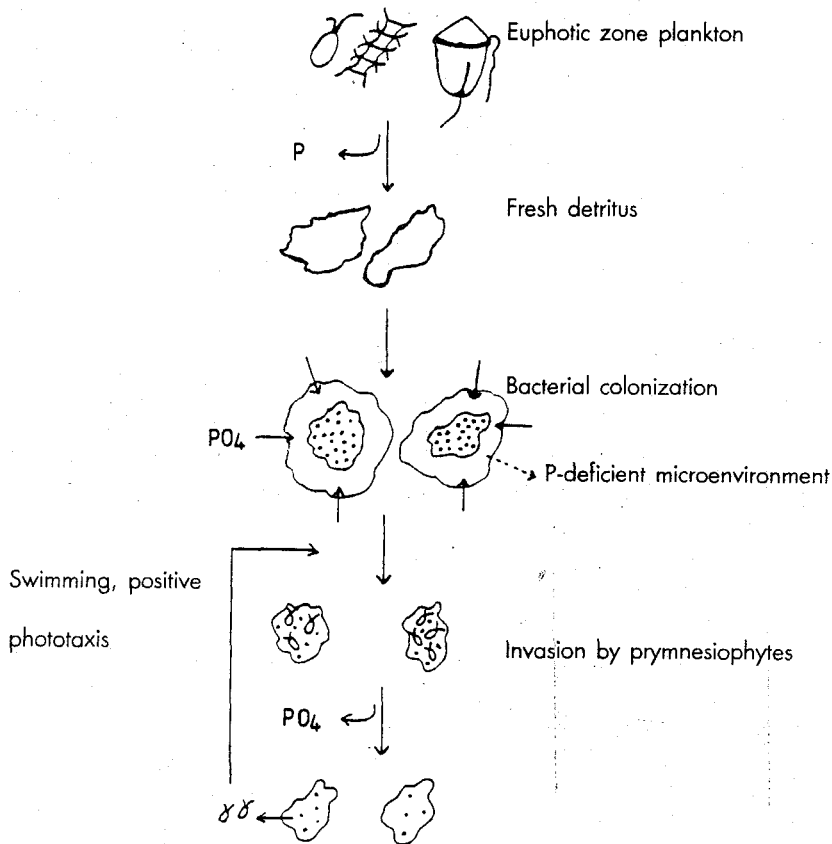


Fig. 11. Hypothetical association of *Chrysochromulina* type algae with organic marine snow aggregates. P leaks rapidly from organisms upon death and detritus is poor in P. Bacteria colonizing detritus have a high P requirement, causing a P deficient microenvironment. *Chrysochromulina* use their haptonema to attach to the aggregates and may secure nutrients by phagotrophy and dasmotrophy (Estep and MacIntyre, 1989). As the aggregates sink below the euphotic zone the algae detach and swim upwards guided by positive phototaxis to attach to new particles.

and Gotschalk, 1990).

Hypothetically, *Chrysochromulina* type algae may use their haptonema to attach themselves to such organic aggregates. Here they can use their phagotrophic ability and possibly toxin induced dasmotrophy to obtain nutrients from bacteria and other components of the microbial community. As the

particles slowly sink deeper than the euphotic zone, the *Chrysochromulina* cells can detach themselves and swim upwards guided by positive phototaxis to attach themselves to new particles (Fig. 11).

While the scheme in figure 11 remains to be verified, it points to the possible role of habitat scale in plankton ecology. Some algae may be adapted to live in restricted environments such as estuaries on the mesoscale and marine snow particles on the microscale. One consequence of eutrophication may be a change in the nutrient conditions of a macroscale coastal environment to resemble those of smaller scale environments such as marine snow. The bloom of *Chrysochromulina polylepis* in Kattegat and Skagerrak in 1988 may be an example of such a change in scale-related environmental properties caused by eutrophication.

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ABEL: Are there questions for Doctor Skjoldal ?

AUBREY: In the community that studies toxic dinoflagellates there seems to be a debate as to whether the worldwide incidence of toxic dinoflagellates is increasing or not, whether it is really an increase or whether we are just observing them a lot better and identifying them a lot better right now. I would be interested in your opinion on this matter, and also perhaps your opinion as to what might be causing the increase in the toxicity.

SKJOLDAL: The first point I can only comment very generally. I think we are, of course, being more aware; we have cases of fish or other organisms very sensitive to poisonous algae, but I also have a feeling that among algal experts there is some consensus that there is a real increase in the frequency of harmful algae blooms, and I think if you link this with the clear evidence for many coastal regions around the world that we have eutrophication we have now an increase in nutrient input that we know, leads to an increase in the growth of algae. I think that it is to be expected that in general increased growth of algae in the sea will also lead to an increase in the occurrence of harmful algae, even if we do not employ any selectivity for them at all.

SHERMAN: I think we owe Doctor Skjoldal a debt of gratitude for his elegant presentation and explanation of a very growing problem. I simply have a comment that we have been puzzled in the area of the north-east coast of the U.S. and that we have some information on increasing frequency and extent of harmful algae blooms, and I simply would say that for the first time, since fishing statistics have been carried over the last some seventy years, we have had to close the fishery a hundred miles off shore because of the presence of toxic algae in mollusk. We have reason to want to support your efforts in looking at the nitrogen, phosphorus ... the origins of this problem because I think what you are telling us is that this has serious implications in how we treat waste water in our plants. Thank you.

ABEL: I couldn't help; I wonder could you discuss at all the possible role of the nitrogen's cycle itself, may be with the exception of the one over late talking about ammonia; there wasn't much mention about the possible relative values of ammonia, nitrite, and nitrate.

**SKJOLDAL:** Well, I think there are many complex linkages here. First of all that denitrification is an important process and we have shown in an autumn situation that perhaps as much as fifty percent of the nitrate that comes out by river Elba and also other rivers is being used by denitrification; now that denitrification is respiratory degradation of organic material using nitrate instead of oxygen and it can take place in sediments, it can probably also take place in organic aggregates, but it points to the link we have here with the organic load that also comes out with the rivers and these things are linked also the estuaries, these strongly polluted estuaries, can be in some way considered as a biological treatment plant by being dredged and all kind of manipulation we are influencing how this system function as a biological treatment plant, and perhaps that is what we should do; we should, perhaps, try to manage some of the estuaries as treatment plant in order to reduce the problem for rest of the coastal zone rather than, perhaps, to try to clean all of them, at least in the first place.

**ABEL:** Are there other questions?

**HYLLEBERG:** I have three small questions. The first one is how do you calculate what is normal concentration of nitrate in sea water, considering the difference between surface and bottom and the eddy variation?

**SKJOLDAL:** Well, the winter value in surface water of the Atlantic source is around twelve micromills and that is the normal winter mixing that brings up nutrients from the deeper water ... results in those concentrations.

**HYLLEBERG:** So it's the winter value you use?

**SKJOLDAL:** Yes, I used that for comparison here. Of course, there is an unknown datum that ... dissolve organic nitrogen that seems to be larger then we previously thought it was. We don't know what it is; so there is a problem there; also with ... there are some trends for the Kattegat area that shows that whereas during the last fifteen years has been an increase in inorganic components in the winter values, the total has increased even more, indicating that eutrophication leads also to a mark increase in the organic components, and I don't know if any have studied or analysed what these are.

**HYLLEBERG:** Thank you. The other question is about the river Rhine: you showed that nitrate went up and ammonia down; what explanation for this, is it better water quality, more nitrification or what is it?

**SKJOLDAL:** Well, I cannot really answer that. I think it has to do with the sewage treatment; that a lot of the particulate material has been taken out and ammonia and phosphate are being controlled and partly reduced whereas a

nitrate which originates from the agricultural practises both an increased use of fertilizers and also with different use of the land leads to increased leakage of nitrate into the fresh water and into the sea.

**HYLLEBERG:** Does this mean that total nitrogen that leaves is constant, I mean when one goes down and the other one up, there is no change.

**SKJOLDAL:** I think I have seen a curve for the Rhine that the increase in nitrate is balanced by the decrease in ammonia and particular nitrogen of the total input of nitrogen is fairly stable whereas the total for phosphorus has shown a decreasing trend in ...

**HYLLEBERG:** Then the last one, it's also short. My question is ... is there any direct proof of increased productivity in the North Sea ? I don't doubt your statement that the North Sea has become eutrophied, but I wonder is it possible to go out and show by primary productivity measurements that values are higher now than they used to be. I know they have tried it in the Baltic and they failed and that's one of the most eutrophic areas, they claim.

**SKJOLDAL:** Well, I chose for this presentation to keep it simple and I have not gone into a thorough review of all kind of measurements done at this. So, really, I can't answer you, but I think the evidence from nutrients side is quite clear: there has been an increased input of nutrients and the nutrients are being used in the sea. Denitrification and microbial decomposition of organic material can account for some of this, but the major part goes into producing algal biomass that then is being transported in the system either with the currents or to the bottom sediments. There have been reports that the benthic biomass of the Dogger Bank area has changed since I think the 30's or 50's with changes that look like those you would expect from eutrophication. From mesocosmic experiments done, for instance, in the ... (poor recording) ... tanks in Rhode Island those are the responses you get when you load a system with nutrients, if it is a shallow system a lot of the increases ends up in increased benthic biomass. So, viewed from the input side and from the nutrients side, I feel it's a strong case for that, there is an increased productivity and of course we shouldn't disregard that; that can also be beneficial effects for the North Sea. The productivity or the harvesting of fish has increased and so that might also be a positive side of this, but the negative, of course, is that in periods of stratification the increased growth of algae, the increased organic material and then sediments down into shallow waters that are temporarily stratified can quickly deplete that water from oxygen and so you get the kill of benthic communities and bottom fish.

ABEL: Doctor Minas, do you have a question?

MINAS: Just related to the last question. Have you tried to evaluate nutrients consumption and perhaps to comprehend some productivity measurements because we do often this kind of ... should it be possible in some regional, in some special places where the system is not so complex, in some areas should it be relatively easy? No?

SKJOLDAL: Yes. I agree with you, and I think that is a useful approach. We are not gone far into that yet.

MINAS: I think this is so different system from our Mediterranean system; much more complicated but you do have higher nutrients; we have nothing and you have too much. It should be also very difficult to speak in terms of new production, because sometimes all the system is perturbed ... have you done speculation or consideration on new production? Because the regeneration raises on the bottom, because you have shallow depths, it should be ... what is ... have you budget also regeneration at the sediment?

SKJOLDAL: We have started some work and a typical feature is that when you go into waters about twenty meters deep off the west coast of Denmark you very often find the maximum chlorophyll close to the sediments and I would think that nutrient leaking out of the sediments is one source of that, but this new production ... we have here a large surplus of nitrates so there is a large input of a new nutrient in that sense, but the consumption of a nitrate is being controlled by the phosphorus cycle; so it's a different situation from the typical way ... if you get pulses of nitrate in either from below or by an upwelling event you get all free nutrients at the same time, typically.

MINAS: You have to create new definitions.

SKJOLDAL: Yes, and of course the recycling of phosphorus that is one of the sources for consumption of nitrate also recycles nitrogen, so that is one reason that the consumption of nitrate in a way goes slowly because there is also ammonium being recycled that are carrying much of the production. We think that is the main reason why we see this nitrate's signal so strong and so consistent that in a way nitrate is conserved because phosphorus limits its further utilization.

ABEL: Well, Norway has possibly the most successful exam and culture program in the world, in farming millions of salmon each year; do you find the affluents from this farms provide the high source of nutrients?

**SKJOLDAL:** Both, yes and no, I think. If the farms are located in unfavourable situation that can contribute, but in general terms when the plants are located in more dynamic coastal waters that impact isn't so a lot.

**ABEL:** Is it not flashy?

**SKJOLDAL:** Yes. In general it is, but it can cause local problems; then you are particularly concerned with the possibility that you get resting forming species nurtured by the local nutrients and resting spores are falling out and then you get the problem back.

**ABEL:** Are there other questions of Doctor Skjoldal? Then I'd like to offer the floor to Doctor Vagn Hansen who wants to make an announcement. ... Thank you very much Doctor Skjoldal for most illuminating lecture.



SYMPOSIUM " MEDITERRANEAN SEAS 2000 "

G. Multer, H. Minas, H. Skjoldal, K. Sherman, K. Vagn Hansen, T. Zunini Sertorio, U. Lie, J.P. Bethoux, L. Laubier, M. Tufano, A. Eleftheriou, C. Chiantore, B. Galil, R. Danovaro, J. Hylleberg, N. Della Croce, M. Fabiano, H. Bryden, C. Bas, N. Drago, G. Relini, R. Abel, R. Ambrogi, A. Manganaro, A. Occhipinti, G. Albertelli, M. Hernández-Avila, C. Dorman, D. Aubrey, G. Sestini, E. Özsoy.

*Santa Margherita Ligure, 25 - 27 September, 1991*

## CLOSING THE SYMPOSIUM

DELLA CROCE: The late hour calls for conciseness. First and foremost, I would like to thank and express my gratitude to my friends and colleagues LIE, DORMAN, MINAS, VAGN HANSEN, BASCOM and ABEL who chaired and pleasantly looked after the six sessions of the Symposium and, likewise, all the invited speakers who scientifically enlivened these three days.

The presented papers were extremely interesting: if it hadn't been so, three days of papers and discussions would have been too much to absorb. I definitely believe that the papers were extremely significant, touching different aspects of the problem and suggesting how, concerning the Mediterranean, notwithstanding all the historic, economic and political events of past years, centuries and civilizations, there still is room for consideration and action. It's a great pleasure for me to thank you for this contribution.

When a new Institute is born, it carries all the frailty of its being but also the potential of its future, and your presence here today is a great and valid help. As I said on the day of the inauguration of the Institute's new premises, this is the only Marine Environmental Sciences Institute of the Italian university structure and, as such, it has clear intentions and ambitions – fanciful, perhaps – which stem from the awareness of lost time and missed opportunities that our Nation has witnessed in the context of its cultural requirements concerning mediterranean matters. The closeness of French universities and laboratories such as those of Villefranche, Nice, Marseille and Banyuls, should be a stronger stimulus for a wider and more integrated cooperation, in order to recover the dialogue which in the new European framework must overcome the present



linguistic differences that somehow interfere in the relations with our French friends and colleagues.

Tomorrow morning at 9.00 a.m. the Council shall meet including new member Dr. HERNÁNDEZ-AVILA and, if they wish, all the invited speakers who will still be here with us may attend as well.

The idea of the meeting is that of ascertaining the degree of interest on the topic of Mediterranean Seas. I think that this topic – I have no idea what the auditorium thinks – is full of difficulties because putting together seas such as the Arctic, Caribbean, Roman and Asiatic is rather utopic: on the other hand – considering what I learnt these days – I have the impression that the topic may be dealt with. I truly hope that, as the first objective, we shall be able to clarify which are the diverse scientific concepts that unify the mediterranean seas.

At 12.00 we shall be the guests of the Mayor of Santa Margherita Ligure at Villa Durazzo; during the cocktail, a souvenir medal shall be awarded to each one of us.

Before closing this last session, I wish all of you a nice and safe trip back to your countries. Once more thanks for your contribution and "arrivederci".

## THE SYMPOSIUM " MEDITERRANEAN SEAS 2000 "

### DECLARES

this meeting to be an unqualified success because of the scientific excellence of the papers presented and the learned discussions that followed each paper. Our knowledge of the Mediterranean has been greatly enhanced by meeting and talking with our scientific peers and hearing new scientific data.

We wish to thank Prof. Della Croce and his associates and students for putting forward this concept and organizing this first meeting. Especially for inviting us all to this delightful location S. Margherita Ligure at an excellent hotel with its classic hospitality.

We hope that Prof. Della Croce and his associates will ensure publication of the papers, possibly including the discussion, so that some formal record of our proceedings will exist.

We recommend that similar meetings be held in future years that bring together scientists of all nations interested in scientific studies of the Mediterranean Sea and all other marginal seas. The mutual understanding and cooperation will be of value to all countries bordering these seas.

Dr. Lucien Laubier of France was invited to organize and direct the next meeting, which he accepted. He will be assisted and advised by Prof. Della Croce and whichever members of this Scientific Board he wishes to make use of.

The Scientific Board is specifically asked to consider:

- (1) the long range objectives of future symposia and the possible establishment of a scientific association, as well as a scientific journal, for the Mediterranean and other semi-enclosed seas;
- (2) suitable meeting places for future symposia;
- (3) encouraging participation of scientists and scientific institution of countries bordering these seas;
- (4) programs involving and requiring the participation of scientists and scientific institutions of several countries;
- (5) cooperation and net-working among the participating institutions, including exchange of scientists and students;
- (6) cooperation with international and regional scientific bodies.

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*Santa Margherita Ligure, 27 September, 1991*

Signed by: U. LIE, K. VAGN HANSEN and N. DELLA CROCE

## ACKNOWLEDGMENTS

It is with great pleasure that I express my deepest gratitude to Prof. S. PONTREMOLI, Rector of the University of Genoa for his interest and precious help. To Prof. G. ALBERTELLI, to Prof. M. FABIANO and to Prof. T. ZUNINI SERTORIO for their constructive, active and continuous cooperation and participation. To doctorate students M. BOYER, R. DANOVARO, S. FRASCHETTI and M. TUFANO and to graduating students M. CHIANTORE, M. KNOOP and F. SAGUATO for their helpful assistance in the organization and during the Symposium. To V. ARATA, L. GAOZZA, D. LAZZARI and M. MAIORANA for the care with which they solved all the upcoming problems. My special thanks go to Dr. M. PETRILLO for his diligent, continuous and painstaking cooperation which made it possible to print the Proceedings of the Symposium in such short time.

Furthermore, I would like to thank the Cassa di Risparmio di Genova e Imperia, the Cassa di Risparmio di La Spezia, the Municipality of Santa Margherita Ligure, the National Research Council, the Intergovernmental Oceanographic Commission and the Region of Liguria for the funds we received.

Prof. N. Della Croce

*Santa Margherita Ligure, 28 December, 1992*