Phaeocystis globosa and the phytoplankton succession in the East Frisian coastal waters

J. Rahmel[1], M. Bätje[1], H. Michaelis[1] & U. Noack[2]

[1] *Niedersächsisches Landesamt für Ökologie, Forschungsstelle Küste;*
An der Mühle 5, D-26548 Norderney, Germany
[2] *Dr. U. Noack-Laboratorium für angewandte Biologie;*
Richthofenstr. 29, D-31137 Hildesheim, Germany

ABSTRACT: The phytoplankton succession and related abiotic variables were investigated within the frame of a monitoring programme. Results from 1985 to 1991 are presented. For the prymnesiophyte *Phaeocystis globosa*, an increase in the maximum annual abundance was observed. The appearance of this species in the phytoplankton succession followed an annually recurrent pattern. Among the starting conditions for the bloom, a coincidence with the annual DIN/P maximum was most obvious. Quantitatively, temperature and salinity showed the lowest variability at the onset of the blooms. Nutrient uptake during the increasing phase of the bloom appeared to affect nitrate concentrations more significantly than those of ammonia and phosphate.

INTRODUCTION

Since the end of the nineteen-seventies, the population dynamics of the prymnesiophyte *Phaeocystis globosa* received accentuated attention along the southern coast of the North Sea (Bätje & Michaelis, 1986; Weisse et al., 1986; Cadée & Hegeman, 1986; Lancelot et al., 1987). It was assumed that the more frequently-occurring blooms of this species indicated a eutrophication-caused change in the pelagic communities of the coastal waters. The hypothesis that the increase in nutrient input to the marine environment might have enhanced *P. globosa* blooms has also been emphasized for other geographical regions (Al-Hasan et al., 1990). In the Netherlands, trends in the occurrence of *P. globosa* blooms and their relation to coastal eutrophication have been continuously observed since the 'seventies (Cadée & Hegeman, 1991; Riegman et al., 1990). In these investigations, a relation between riverine nutrient input and phytoplankton biomass or bloom magnitude, respectively, was found – which is at least plausible for the western part of the Dutch Wadden Sea (Cadée & Hegeman, 1986; Riegman et al., 1992). Available information for the German coastal zone is mainly based on results gained from short observation periods in the 'seventies or early 'eighties (Weisse et al., 1986; Bätje & Michaelis, 1986; Eberlein et al., 1985). A continuous time-series which provides information on recent developments is not reported for the German coastal zone. Some results from this area concerning the role of *P. globosa* in the annual phytoplankton succession and its relation to the physico-chemical environment from the period 1985–1991 are presented in this paper.
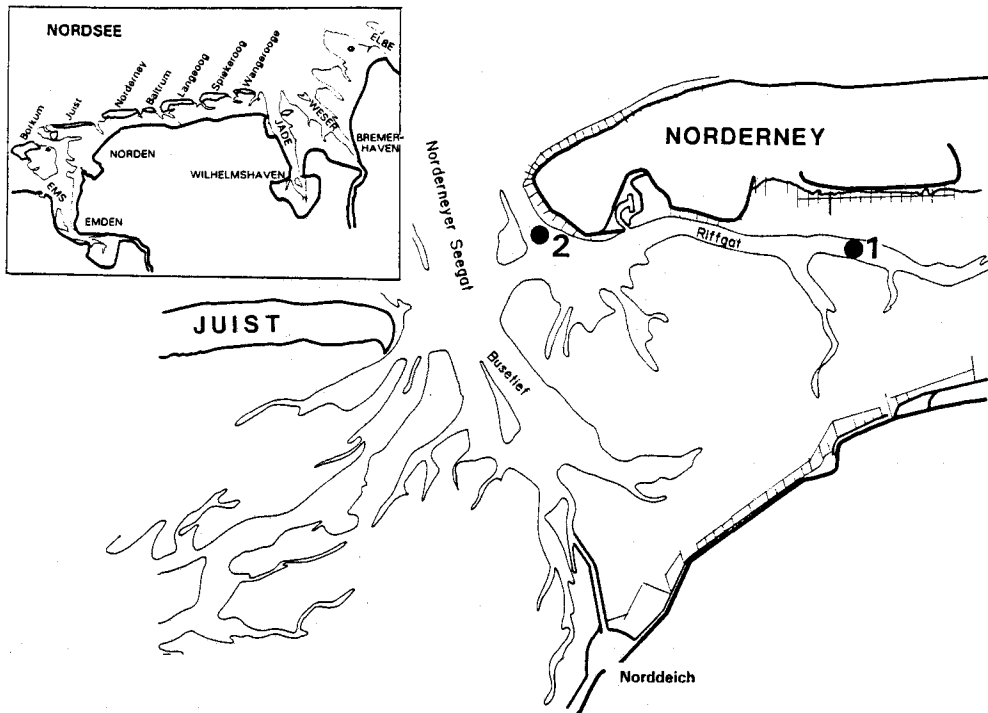
Fig. 1. Location of sampling sites

MATERIAL AND METHODS

The results presented here are derived from two permanent phytoplankton monitoring stations in the area of Norderney, East Frisian Islands, Germany (Fig. 1). Sampling frequency was weekly during the vegetation period, and fortnightly during the winter months. The water column at these locations is vertically mixed, due to tidal action. Samples were taken at high tide from surface water and immediately analyzed for temperature and salinity. Subsamples were filtered and stored for the determination of the content of suspended matter. Nutrient analysis was conducted according to the methods of Grasshoff et al. (1983). Colonies of *P. globosa* and large phytoplankton cells were counted in a tray as described in Newell & Newell (1963). The quantification of the smaller phytoplankton under the inverted microscope followed the method of Utermöhl (1958).

RESULTS

For an assessment of the development and magnitude of *P. globosa* blooms, data have been available since 1982. Taking into account the maximum annual abundance of the colonial phase of the species life cycle, an increase can be detected (Fig. 2). In particular the strong blooms in 1989 and 1991 with abundances of 38 500 and 49 000 colonies l^{-1}, respectively, reinforce this tendency. For single cells, this increase is less pronounced. The period during which mass developments (abundances of more than
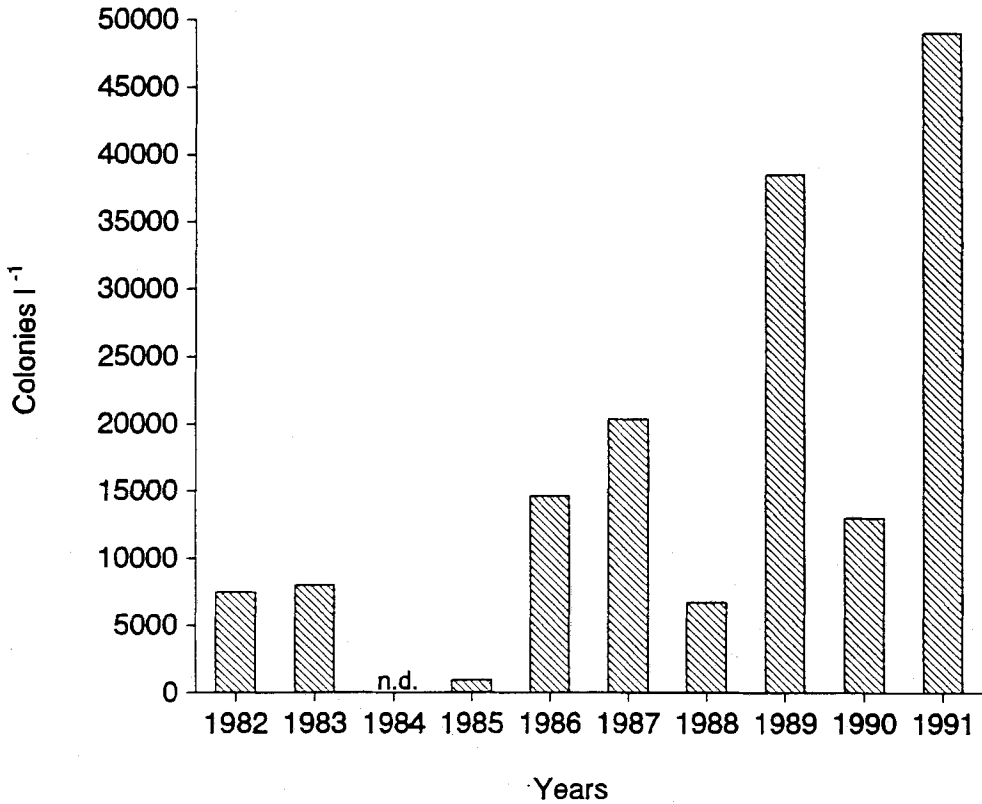
Fig. 2. Increase in the maximum annual abundance of *P. globosa*

1000 cells ml^{-1}) of the species can be observed varies between 27 and 68 days per year. From 1982 to 1991 no significant change in the duration of the bloom period could be observed.

The analysis of the annual cycle of the phytoplankton reveals a pattern which is displayed in Figure 3. The *P. globosa* spring bloom either follows, or intersects with, the spring diatom bloom. A minor diatom bloom follows the *P. globosa* bloom. This sequence of phytoplankton groups can be found almost every spring. During May and June higher abundances of the heterotrophic dinoflagellate *Noctiluca scintillans* may appear. The remaining part of the annual cycle is less regular. For the first diatom bloom, a considerable year-to-year variability concerning the dominant species could be stated (Table 1). *Brockmanniella brockmannii* and *Skeletonema costatum* are the more frequently occurring species. Additionally, during the second diatom bloom different species may become dominant. Among these is *Asterionella glacialis*, for the majority of the survey years. Autumn diatom blooms are not a common feature of the annual cycle. They may appear during some years, however. The *P. globosa* spring bloom usually starts from the beginning of April to early May (Table 2). The annual maximum is mainly found in early May. Further mass developments of this species also occur during summer. Their magnitude is, in general, less significant than that of the first peak.
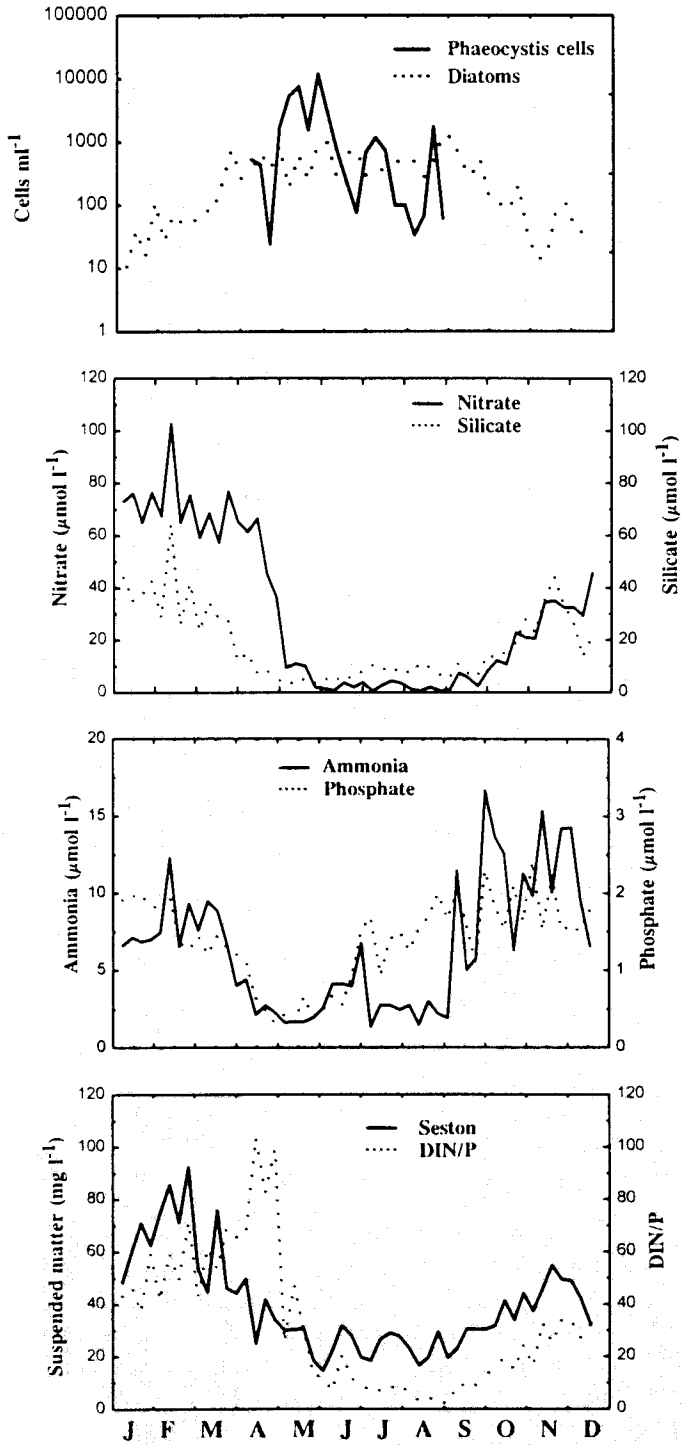
Table 1. Dominant species during the first diatom blooms in the annual cycle at the Norderney plankton survey station, 1985–1991

Year	First diatom bloom	Second diatom bloom
1985	*Odontella aurita* *Brockmanniella brockmannii*	*Cerataulina bergonii* *Asterionella glacialis*
1986	*Thalassiosira minima* *Asterionella kariana*	*Skeletonema costatum* *Nitzschia delicatissima*
1987	*Asterionella glacialis* *Brockmanniella brockmannii*	*Asterionella glacialis* *Skeletonema costatum*
1988	*Skeletonema costatum* *Chaetoceros* sp.	*Asterionella glacialis* *Rhizosolenia delicatula*
1989	*Skeletonema costatum* *Brockmanniella brockmannii*	*Rhizosolenia* sp. *Asterionella glacialis*
1990	No major bloom observed	
1991	*Thalassiosira nordenskiöldii* *Ditylum brightwellii*	*Rhizosolenia* sp. *Nitzschia seriata*

Table 2. Variability of the initial conditions of the *Phaeocystis* bloom, 1985–1991. Only results from sampling dates right before and after the blooms onset are included. AVG = arithmetic mean, STD = standard deviation, V_r = relative variation coefficient (%). Concentrations of nutrients are given in $\mu mol\ l^{-1}$

Variable	n	AVG	MEDIAN	STD	V_r
Week	27	15.92	15.57	2.22	2.68
Temperature	27	9.52	10.10	2.00	4.04
Salinity	27	30.67	31.07	1.87	1.17
Ammonia	26	2.33	1.71	1.78	14.94
Nitrate	27	44.32	40.60	30.25	13.14
Phosphate	27	0.60	0.60	0.37	11.80
Silicate	26	8.02	4.89	10.01	24.48
DIN/P	27	129.01	79.00	135.53	20.22

The course of the spring blooms is closely related to the annual dynamics of the physico-chemical environment. This relation still emerges in the generalizing scheme given in Figure 3. During winter, the cell numbers are low. The occurring species are mainly diatoms. Inorganic nutrients are available in high concentrations. From the median values of the DIN/P ratio and the molar ratio of silicate versus phosphate, nutrient conditions of DIN : Si : P of 49 : 19.5 : 1 can be calculated. Along with the diatom spring bloom the concentrations of silicate, phosphate and ammonia decrease. Nitrate, however, is not as severely affected by this event. This causes the establishment of the annual maximum of the molar ratio of dissolved inorganic nitrogen compounds versus dissolved

Fig. 3. Phytoplankton succession and the relation to abiotic factors. The results presented are weekly median values from 1985 to 1991

phosphate (DIN/P ratio). This maximum generally coincides with the start of the *P. globosa* bloom.
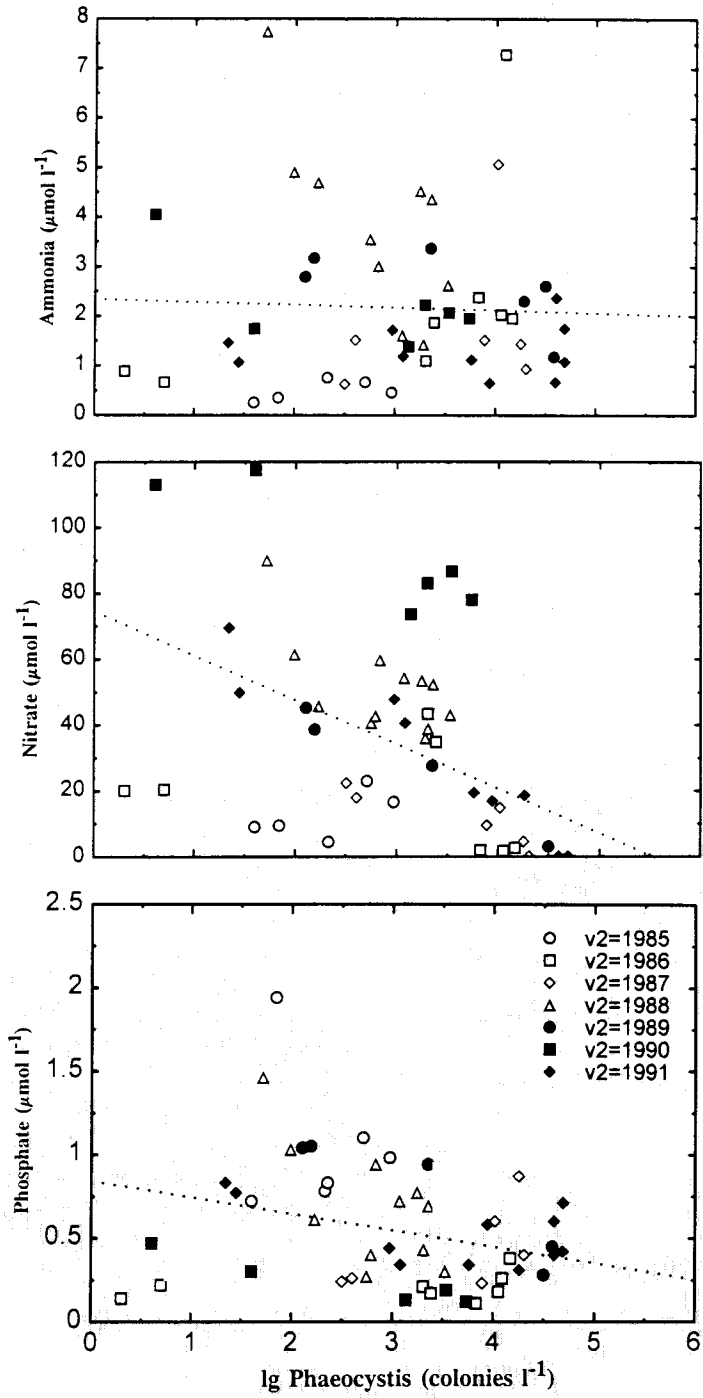
Along with the increase in the abundance of *P. globosa* goes a significant diminution of the nitrate concentrations. This consumption, combined with an increasing phosphate content during summer, results in low DIN/P ratios. Quantitatively, the initial environmental conditions for the *P. globosa* spring bloom proved to be rather variable. The results which are displayed in Table 2 show that the variability of its timing, as well as that of the temperature and salinity range, is moderate. The values for the nutrients show a deviation from the mean which is significantly higher.

More detailed information on the nutrient dynamics during the *P. globosa* spring blooms of several years is given in Figure 4. For this purpose, results received during the period between the start and the maximum of the bloom are pooled. The ammonia concentrations remain almost unaffected by the rising of the abundance of *P. globosa*. For nitrate and phosphate, a reduction is indicated by the regression line. In spite of this common trend, differences can be observed. Nitrate is almost depleted in the course of the mass development of *P. globosa* (Spearman rank order correlation: $r_s = -0.596$, n = 55, $p < 0.005$). The concentrations can decrease by two orders of magnitude. The phosphate levels do not change as dramatically; the reduction to almost undetectable concentrations is not as common as with nitrate. During several years, phosphate even seems to recover at maximum abundances of *P. globosa* (Spearman rank order correlation: $r_s = -0.280$, n = 55, $p < 0.05$). The different behaviour of the two nutrients holds especially true for the years with strong blooms, like 1989 and 1991.

DISCUSSION

Between 1982 and 1991, a tendency to an increase in the magnitude of the *P. globosa* blooms could be observed. These results are to some extent in agreement with reports from the western Dutch Wadden Sea. Cadée & Hegeman (1986) describe an increase in the abundance of *P. globosa* and in the duration of the blooms in the period 1974–1985. Concerning the development of the duration of the blooms, there is a difference between the results of both time-series. At Norderney, no prolongation could be detected. Based on the comparably short time series, however, it is difficult to conclude whether the observed increase in the bloom magnitude at the Norderney stations is able to be indicative of a long-term trend. It has further to be considered that the tendency is valid for the maximum abundances, which implies that the sampling frequency may have influenced the results. During 1982–1988, the actual maxima may have been missed – while they were sampled in 1989 and 1991. Historical data on the abundance of *P. globosa* in the area of the East Frisian Islands are reported by Mielck (1932) and Wulff (1935). Maximum values given by these authors amount to 2300 or 1300–5640 colonies l^{-1}, respectively. It is not clear, however, whether these values actually represent abundances at maximum bloom development. Despite these uncertainties the observed tendency should not be ignored but rather be considered as an indication of a change in the system.

Fig. 4. Decrease of dissolved nutrients during the growth phase of several *P. globosa* blooms. The regression line is calculated for pooled data from both stations. Symbols indicate different years from 1985 to 1991

Legend (from bottom panel):
○ v2=1985
□ v2=1986
◇ v2=1987
△ v2=1988
● v2=1989
■ v2=1990
◆ v2=1991

lg Phaeocystis (colonies l^{-1})

Y-axes: Ammonia (μmol l^{-1}); Nitrate (μmol l^{-1}); Phosphate (μmol l^{-1})

The coastal waters of the East Frisian Islands are tidally mixed all year round and show a broad salinity range. At the Norderney stations, salinities varying between 23.4 and 34.6 ‰ could be measured. This indicates that the stations are exposed to influences from different hydrographical regimes. Although an unpredictable series of events is rather to be expected in such an unstable environment, a recurrent pattern was observed – at least for the early stages of the annual cycle of the phytoplankton. This diatom-*P. globosa*-diatom succession also occurs in Dutch and Belgian coastal waters (Cadée, 1986; Lancelot et al., 1991). Its annual appearance in the East Frisian coastal waters is very reliable for March–May. For the remaining part of the year, such a clear pattern in the annual cycle of the phytoplankton could not be observed. Cadée (1986) describes a generalized model of the annual phytoplankton cycle in the Marsdiep. It displays a threefold reiteration of the diatom-*P. globosa* sequence. This model does not seem to be valid for the Norderney stations.

The conditions which trigger the *P. globosa* blooms have to some extent been discussed by Weisse et al. (1986). Among them, the influence of organic substances – either originating from the preceding diatom bloom or from terrestrial sources – has been considered. It was also assumed that certain nutrient or temperature conditions might be essential factors for the start of the mass development. So far, the role of terrigenous substances is still speculative, while the potential of *P. globosa* to extract phosphate from organic matter has been proven (Veldhuis et al., 1987; van Boekel & Veldhuis, 1990). The role of temperature in the spring phytoplankton succession has also been mentioned by Cadée & Hegeman (1986). According to their results, no relation could be detected between temperature and the onset of the spring increase of *P. globosa*. At Norderney, the temperatures at the start of the bloom ranged from 5.0 to 12.8 °C. Although the variability of the temperature conditions is low compared to that of the nutrients (Table 2), it has to be considered that the extreme values cover about one quarter of the annual temperature spectrum. These field observations are slightly different from results which Grimm & Weisse (1985) received from laboratory studies. They found that *P. globosa* did not show any appreciable growth at temperatures lower than 7 °C. The influence of nutrients on the appearance of the species has been discussed by several authors (Bätje & Michaelis, 1986; Veldhuis et al., 1986; Lancelot et al., 1991). Characteristic for all these descriptions is the observation of different concentrations of reactive silicate, phosphate, ammonia and nitrate. While the first three nutrients become significantly reduced during the first diatom bloom, nitrate concentrations are not affected that much. This oppositional development leads to elevated DIN/P levels.

As shown in the results, drastic changes in the concentrations of some dissolved inorganic nutrients occur during the *P. globosa* bloom. The most pronounced deviation from the pre-bloom situation can yearly be observed for nitrate. This finding is also supported by the fact that the negative correlation between *P. globosa* abundance and nitrate concentration is closer than with other nutrients. Provided that nutrients are able to become limiting resources in the turbid waters of the Wadden Sea, a shortage of nitrate might be most probable during blooms of this phytoplankton species. Lancelot & Mathot (1987) reported that its growth was N-limited during the spring bloom in Belgium coastal waters. This conclusion is supported by the results of Riegman et al. (1990), who detected a severe nitrogen limitation at the peak of the *P. globosa* bloom in the Marsdiep area, in the Netherlands. Other authors (Veldhuis et al., 1986; Hesse et al., 1992) identified

phosphate as the limiting nutrient. In the case of Veldhuis et al. (1986), this contradiction might be due to the fact that his conclusions are based on a method which is not a good indicator for phosphorus limitation in *P. globosa* blooms (van Boekel & Veldhuis, 1990). Beyond the methodological problems, it has to be considered that both studies from the Dutch coastal waters were conducted in different marine environments. Veldhuis et al. (1986) worked at a greater distance from the coast, while Riegman et al. (1990) sampled at a station which was influenced by the nutrient cycles of the Wadden Sea. There, an enhanced P supply due to remineralisation and resuspension might be expected. It has to be examined whether the result of the latter study can be extrapolated to the German Wadden Sea. As to the question whether or not nutrients can become limiting resources in this area at certain times of the year: this is still not solved, and further investigations on the topic are needed.

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