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EFFECT OF EUTROPHICATION ON PHYTOPLANKTON PRODUCTIVITY AND GROWTH IN THE WADDEN SEA

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ABSTRACT

As in most estuarine areas and coastal seas the growth of phytoplankton in the Wadden Sea is regulated by underwater irradiance and nutrient concentrations. The Wadden Sea shows clear signs of eutrophication. It has been documented by the high nutrient concentrations due to the large inputs of nutrients in this area by several European continental rivers (Rhine, Ems, Weser and Elbe), by an increased phytoplankton primary production and by the observations of black spots, areas where anaerobic sediment horizons reach the sediment surface. Other indications of eutrophication are the mass occurrence of green algae (*Ulva* and *Enteromorpha* spp.) and the dominance of specific phytoplankton species like the bloom forming Prymnesiophyte *Phaeocystis* sp. In the stratified parts of the German Bight lowered oxygen values are regularly observed.

To check the validity of the presumption that both irradiance and nutrients are important for the growth of phytoplankton, methods developed by Cloern (1999) were tested for different sites in the Wadden Sea and their effects on the growth of phytoplankton tested. In this review data are presented from another study where nitrogen was tested.

Based on literature data on the Wadden Sea it can be shown that a clear increase in both phytoplankton and microphytobenthos primary production has occurred from the early-70s till the mid-80s. During the same period nutrient inputs increased several fold. It is unlikely that the underwater irradiance has changed substantially, so that most changes can be directly related to the increased nutrient inputs. The efforts to reduce the phosphate input from the European continent has been successful with regard to the objectives set during the second international Ministerial conference on the North Sea, where a 50% reduction of the anthropogenic load had been agreed upon. However, the productivity in the Wadden Sea does not seem to be affected proportionally. This is probably due to two factors: the less intensely studied role of irradiance, and the role of nitrogen as the main limiting nutrient.

INTRODUCTION

The ecology of the Wadden Sea has been studied for more than a century. Due to the presence of nearby research institutes and universities our knowledge of the Wadden Sea has greatly improved during the last 3 decades. Among these institutes are the Netherlands Institute of Sea Research at Texel (the Netherlands), the University of Groningen, Department of Marine Biology, several German Universities and Institutes like the University of Oldenburg (Institute for Chemistry and Biology of the Sea), Bremen and Hamburg Universities, the Research and Technology Institute in Büsum (a branch of the Kiel University), the Biologische Anstalt Helgoland at Helgoland and the Wadden Sea Station Sylt. The latter two now operate under the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven.

Together with several governmental institutes a very large amount of hydrographical and sedimentary data is available for the Wadden Sea. The amount of biological information, however, is limited and just exists for a few sites where long term studies were performed (Texel: Marsdiep area, Norderney, Sylt, Helgoland, Büsum, *cf.* Figure 1). Even these sites are not always representative for the Wadden Sea proper due to the sampling locations which are in the main inlets and therefore may represent coastal North Sea water as well.

Information on the ecological status of the Wadden Sea has been compiled in two so-called Quality Status Reports (QSR) on the Wadden Sea in 1993 (de Jong *et al.* 1993) and in 1999 (de Jong *et al.* 1999). In a recent publication (van Beusekom *et al.* 2001) Wadden Sea specific eutrophication criteria have been developed and critically assessed. So apart from numerous single papers on different aspects of eutrophication of the Wadden Sea the reader is referred to these three different compilations.

In this paper one aspect of the eutrophication of the Wadden Sea is discussed in detail: is the growth of phytoplankton affected by the nutrient levels in the Wadden Sea and which role does irradiance play in the expression of eutrophication?

Most of the analysis will be based on literature references, on work done at the Research and Technology Centre in Büsum, which was established in 1988 to perform multidisciplinary studies in the Wadden Sea, and at the Wadden Sea Station Sylt. Although the Wadden Sea should be treated as a unity as stressed by the trilateral agreement by the governments of the Netherlands, Germany and Denmark, data from different sites in the Wadden Sea will be compared. Large parts of the Wadden Sea are now under nature protection and all together form a very large international nature reserve. A recent description of the main characteristics of the Wadden Sea can be taken from van Beusekom *et al.* (2001). A map indicating the locations mentioned in this paper is presented as Figure 1.

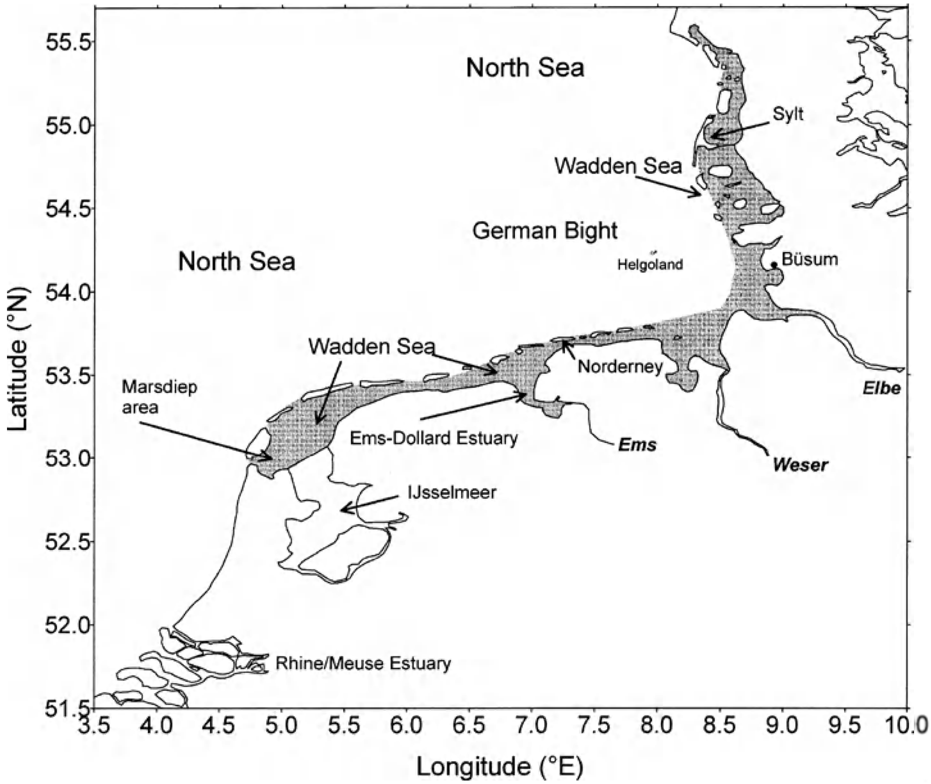


Figure 1: Map of the international Wadden Sea (hatched area) with locations mentioned in the text.

NUTRIENTS IN THE WADDEN SEA

The numbers of papers and reports on the concentrations of the dissolved inorganic macro-nutrients phosphate, nitrate, nitrite, ammonium and silicate is large. For the Dutch western parts of the Wadden Sea studies already started in the late forties (for dissolved phosphate: Postma 1954) and early sixties (for dissolved nitrogen compounds: Postma 1966). During the seventies detailed information in the western part and less frequent observations for the whole of the Dutch Wadden Sea, up to the Ems-Dollard estuary are given by Helder (1974) on nitrogen compounds and de Jonge and Postma (1974) on dissolved phosphate. Recent overviews were published by van der Veer *et al.* (1989), Philippart *et al.* (2000) and Philippart and Cadée (2000). In the German part of the Wadden Sea studies were performed by Hickel (1989), Martens (1992), Hesse *et al.* (1992) and Hanslik *et al.* (1998). Van Beusekom *et al.* (2001) give an overview of nutrient concentrations in the entire Wadden Sea.

In a recent paper (Ladwig *et al.* 2003) the development of nutrient concentrations in a part of the German Wadden Sea was described over the last decade. This study showed that in areas which are under the direct influence of main river outflows (cf. Elbe river) no change in the phosphate and nitrogen concentrations could be observed over the last decade. This is consistent with the main conclusions from the QSR 1999 (de Jong *et al.* 1999). It was noted that nutrient concentrations in the Wadden Sea during winter depend to a large extent on salinity levels. Therefore, actual concentrations cannot be directly compared unless they are standardised to a certain salinity. Details of the concentration salinity method, based on conservative behaviour of nutrients in winter, are given in de Jong *et al.* (1993). The analyses in the 1993 and 1999 QSRs are based on winter concentrations normalised to standard salinities of 10 and 27 psu. The clearest decrease was observed for phosphate which decreased by about 50% in most of the Wadden Sea. Phosphate input via the IJsselmeer (Figure 1) even decreased by 90%. In the western Wadden Sea and Danish Wadden Sea winter phosphate concentrations of about 1 μM are observed which gradually increase towards the estuaries of Weser and Elbe where concentrations of 2–4 μM prevail. No equivalent decrease was observed for nitrogen, although ammonium showed a clear downward trend in the Ems, Weser and Elbe estuaries, presumably due to the progressive implementation and technical improvement of waste water treatment plants. Nitrate showed an upward trend in the western Dutch Wadden Sea and a downward trend in the Ems, Weser and Elbe estuary. Winter nitrate concentrations in the Wadden Sea (27 psu) range between 20–110 μM but are about 50 μM in most parts. These concentrations are clearly higher than the background concentrations of 3 μM dissolved inorganic nitrogen (DIN) and 0.2–0.3 μM PO_4 in summer and 7 μM DIN and 0.4–0.5 μM PO_4 in winter (van Raaphorst *et al.* 2000).

Most studies on the eutrophication focus on winter nutrient concentrations (e.g. de Jong *et al.* 1999). An alternative approach to assess the eutrophication status of the Wadden Sea was proposed by van Beusekom *et al.* (2001). They used the shape of the seasonal cycle of ammonium and nitrite as a measure of eutrophication (remineralisation intensity) and focused on the autumn values. The above authors showed that during the eighties and nineties the major part of the variability in ammonium and nitrite was attributable to variations in riverine nitrogen input. Van Beusekom *et al.* (1999, 2001) stressed the importance of organic matter import from the North Sea into the Wadden Sea as a major nutrient source for the eutrophication of the Wadden Sea.

Despite the import of organic matter into the Wadden Sea and the high remineralisation rates in summer, the seasonal cycle of nitrogen compounds shows minimum values during summer and maximum values during winter (van Beusekom and de Jonge, 2002). This shows that the balance between nitrogen uptake by phytoplankton and phytobenthos and nitrogen release by remineralisation processes is shifted towards the primary producers. In autumn, when light conditions deteriorate, an ammonium maximum develops, indicating a shift in the balance towards remineralisation.

TURBIDITY IN THE WADDEN SEA

Long term data sets on turbidity in the Wadden Sea are only available from the NIOZ Station in the Marsdiep tidal inlet (Cadée and Hegeman 1991). Information on suspended loads is available from several governmental and research institutes in the Netherlands, Lower Saxony and the Island of Sylt. For the area of the Wadden Sea which is influenced by the Ems estuary, frequent data are available from the mid-seventies till the early eighties (Colijn 1982). Mostly simultaneously with the nutrient measurements (see previous section) SPM (suspended particulate matter) has been measured. Several authors have shown the effects of tidal currents and phases on the SPM concentrations (Postma 1954; Colijn 1982). The importance of SPM for the regulation of underwater irradiance is obvious in tide-influenced areas where fine sediments are transported by tidal currents, and resuspended by currents and wind/wave effects (Colijn 1982; de Jonge and van Beusekom 1995). Therefore euphotic zones are limited to a few metres at most, but more often with improved under-water light conditions in summer as opposed to winter with much more wind-driven resuspension of sediments (de Jonge and van Beusekom 1995, Tillmann *et al.* 2000). An overview of euphotic depths in the Schleswig-Holstein part of the Wadden Sea was presented by Ladwig (1997). Calculations showed that the euphotic depth ranged between 1.5 to 6.6 metres depth (May–July 1994, May–August 1995), thereby considerably affecting the primary production in the northern German Wadden Sea.

PRIMARY PRODUCTION OF PHYTOPLANKTON IN THE WADDEN SEA

As compared to nutrient measurements the number of measurements on primary production of phytoplankton is relatively small. At a few sites measurements have been performed such as at the NIOZ pier at Texel in the Marsdiep area of the western Wadden Sea (Cadée and Hegeman 1993), in the Ems-Dollard estuary (Colijn and Ludden 1983), in the eastern German Wadden Sea at two locations: Büsum (Tillmann *et al.* 2000) and the Sylt–Rømø Wadden Sea (Asmus *et al.* 1998). However the only long-term time series available is the one measured at the NIOZ pier because it covers, albeit with different methods, a period of about 30 years. The data series shows that during the seventies the annual primary production of phytoplankton amounted to approximately 150 $gC.m^{-2}$. In the 1980s and 1990s this primary production increased about twofold to more than 300 $gC.m^{-2}$. These high values are consistent with the high values measured in the outer part of the Ems estuary where occasionally values up to 400 $gC.m^{-2}$ were observed (Colijn and Ludden 1983). In the German Wadden Sea at Büsum approximately 150 $gC.m^{-2}$ was measured (Tillmann *et al.* 2000), whereas in the Sylt–Rømø area annual values increased from about 50 to 160 $gC.m^{-2}$ between 1980 and 1995 (Asmus *et al.* 1998).

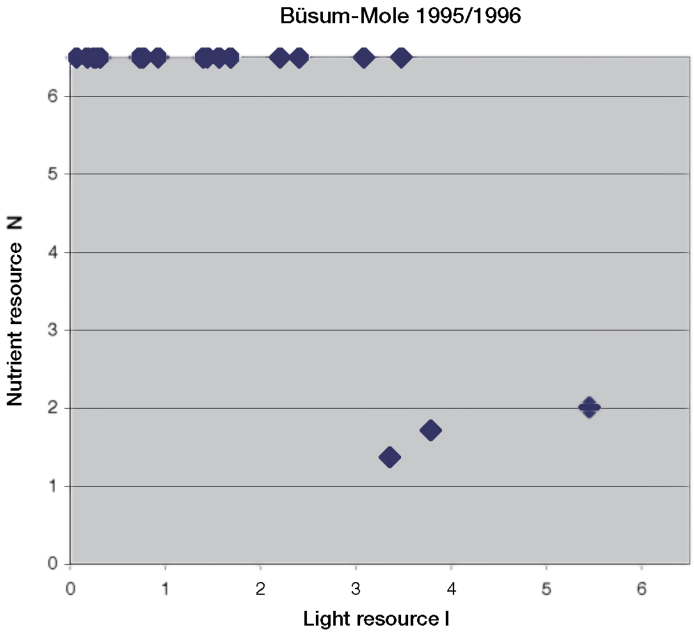
The information available strongly suggests that nutrient concentrations may have played a crucial role in the enhancement of primary production in the Wadden Sea. However this does not imply that a simple nutrient reduction will result in a proportional change in primary production, due to the complexity and non-linearity of the relationships between nutrients, phytoplankton growth and productivity and species composition (Philippart and Cadée 2000). Moreover, until now only phosphate inputs have been reduced substantially, whereas input of nitrogen compounds has been stabilised and slightly decreased (de Jong *et al.* 1999).

A COMPARISON BETWEEN NUTRIENT AND IRRADIANCE REGULATED GROWTH OF PHYTOPLANKTON

Investigations on the light regime in the Wadden Sea and the increased eutrophication of the Wadden Sea suggest that nutrients and light regime are the main factors regulating growth of phytoplankton (and microphytobenthos) in the marine environment (Colijn 1982). Especially in turbid regions the role of irradiance gets more and more important, i.e. becomes the main limiting factor for the growth of phytoplankton. In a direct comparison between light and nutrient regulated growth of phytoplankton in the German Wadden Sea Tillmann *et al.* (2000) showed that during most of the year, except during very few days in summer, light availability in the water column is the limiting factor for phytoplankton growth. In his study on limiting factors Cloern (1999) has developed a simple empirical model which enables a test on the growth conditions of a generalised phytoplankton community. Based on growth dependency from underwater irradiance levels and nutrient concentrations and assumed half saturation constants for nutrient uptake and light dependent phytoplankton growth, he calculated the ranges of nutrient and irradiance where one of both factors gets limiting. This procedure was also used for growth of phytoplankton in the Wadden Sea and tested for several sites with nitrogen (nitrate) and irradiance as parameters (Colijn and Cadée 2003) (Figure 2). The results of this analysis showed that over large areas of the Wadden Sea underwater irradiance levels limit the growth of phytoplankton and that only occasionally nitrogen reaches levels low enough to limit the phytoplankton growth. The different sites showed small differences: at the most western part (Marsdiep inlet) over a two-year period only two of 23 observations showed a potential nutrient limitation; in the turbid part of the Ems estuary (the Dollard) no signs of nutrient limitation could be recognised; in the outer more transparent part of the Ems estuary two values showed nutrient limitation during 1994; data from the German part of the Wadden Sea show comparable results: the station at the island of Norderney showed signs of a more intensive nutrient (nitrogen) limitation: four values during 1990 were indicating nutrient limitation. Again the more turbid station Büsum only showed three values over a two-year period which indicated nitrogen limitation. This is in close agreement with the results presented in Tillmann *et al.* (2000).

CONCLUSIONS

Long term observations at a few sites in the Wadden Sea show that a long term increase in nutrient concentrations (especially nitrate and phosphate) and in phytoplankton and phytobenthos production has taken place. Values increased in the seventies and stabilized in the eighties. After phosphorus reduction measures a decline towards values recorded during the fifties was observed. However, a decline in primary production of phytoplankton has not yet been observed at the only long term monitoring location in the Marsdiep (Dutch Western Wadden Sea). This might well be due to the effects of the still high nitrogen values and the relatively high turbidity in the Wadden Sea. At present, limiting factors for the growth of phytoplankton are primarily the high turbidity


Büsum-Mole 1995/1996
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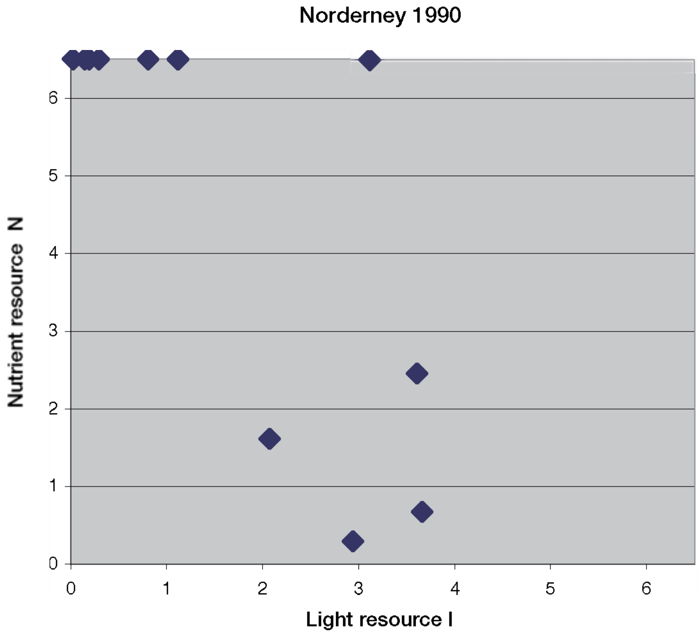
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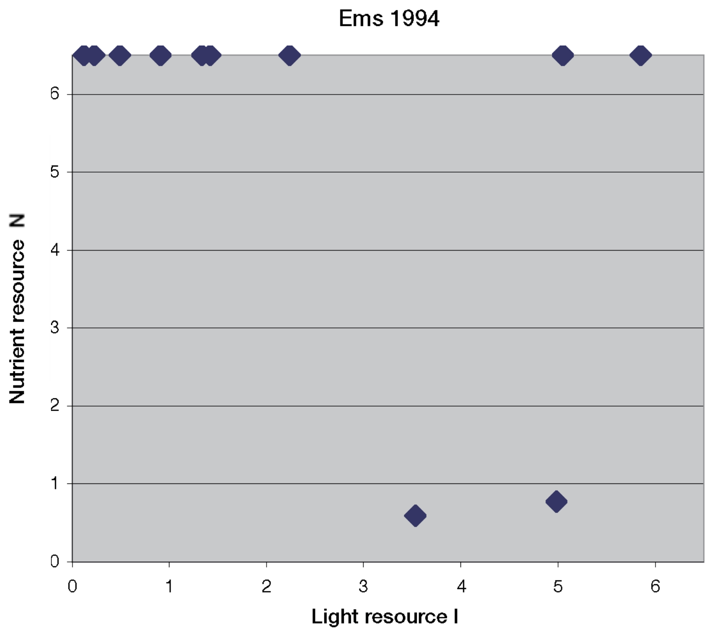
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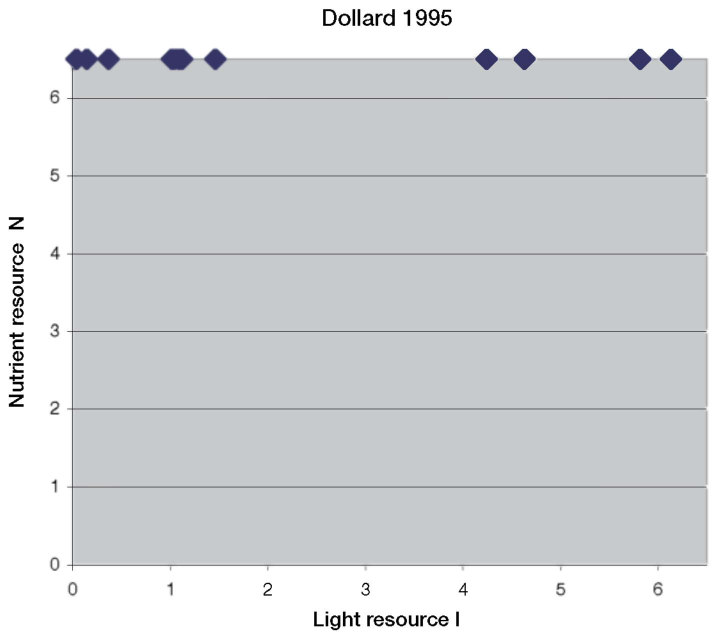
Dollard 1995
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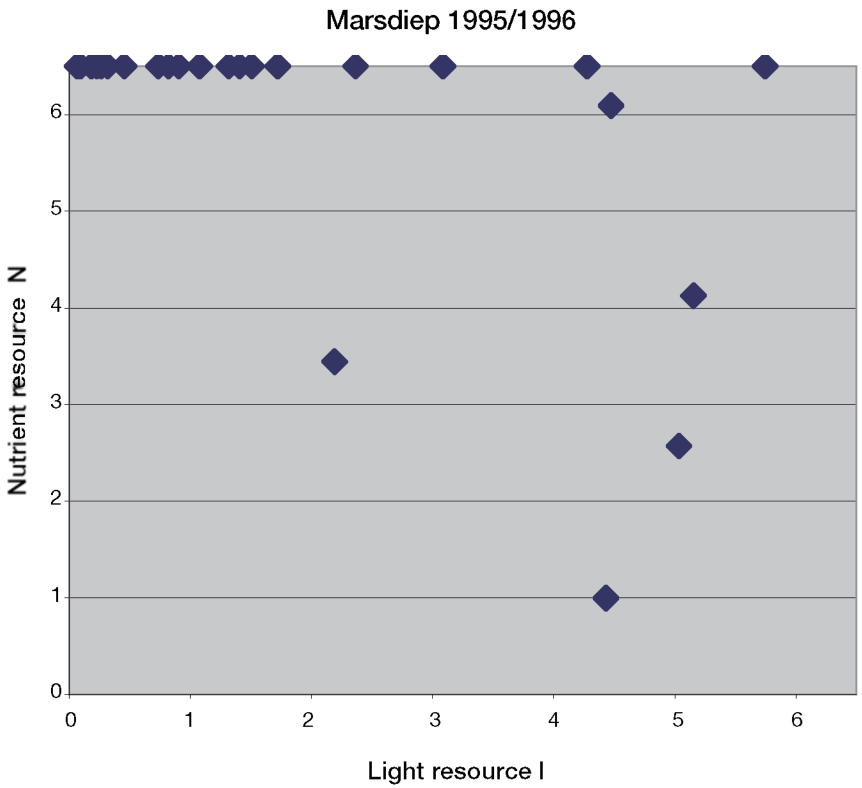

Figure 2: Irradiance and nitrogen limited growth of phytoplankton based on Colijn & Cadée (2003). For every month the mean dissolved nitrogen concentration and the mid-month irradiance has been calculated. The factor nutrient resource is the ratio of the dissolved nitrogen concentrations and an assumed Ks value for growth of phytoplankton on nitrate. The factor light resource is calculated as the ratio of surface global irradiance and the vertical attenuation coefficient (recalculated from SPM-values or secchi disc observations using conversions by Tillmann *et al.* 2000) (for further details see Cloern, 1999. (all nutrient resource values > 6.5 are plotted as 6.5).

and secondarily the availability of nitrogen compounds. Still, primary production is high enough to reduce the nutrient concentrations to levels far below the winter concentrations. This indicates that on an annual level, a decreased nutrient input will decrease the annual primary production, but that the effect will be damped by the light regime.

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