https://doi.org/10.17895/ices.pub.19271795

ICES Marine Science Symposia, 219: 199–207. 2003

Has the eutrophic state of German Wadden Sea waters changed over the past 10 years due to nutrient reduction?

Norbert Ladwig, Karl-Jürgen Hesse, Franciscus Colijn, and Urban Tillmann

Ladwig, N., Hesse, K.-J., Colijn, F., and Tillmann, U. 2003. Has the eutrophic state of German Wadden Sea waters changed over the past 10 years due to nutrient reduction? – ICES Marine Science Symposia, 219: 199–207.

For a period of more than 10 years, two basic eutrophication indicators, dissolved inorganic macronutrients and chlorophyll *a*, have been measured along with physical parameters at a permanent coastal station in the northern German Wadden Sea near Büsum. despite distinctly reduced phosphorus inputs, the data have not revealed any long-term trend in nutrient winter concentrations or algal biomass compared to other available time-series in the area of investigation, i.e. River Elbe nutrient loads and nutrient concentrations in the German Bight near Helgoland. Instead, there are indices of slightly higher winter phosphate concentrations in recent years as well as a decrease in maximum annual N:P ratios due to elevated residual phosphate concentrations in spring. This is in contrast to the situation in the adjacent German Bight, where a declining trend in dissolved inorganic phosphate concentrations is observed. It is suggested that persistent high phosphate concentrations in the northern German Wadden Sea result from local sources of phosphate such as remobilization from the sediments, as well as remineralization of imported organic matter. The comparison with a comprehensive assessment of seasonal light and nutrient availability in the water column indicates that on an annual basis, phytoplankton biomass development in the northern German Wadden Sea is still insensitive to current nutrient reduction measures because of the predominant role of light limitation in this turbid environment.

Keywords: Elbe, eutrophication, German Bight, nutrients, phytoplankton, Wadden Sea.

N. Ladwig, K.-J. Hesse, and F. Colijn: Research and Technology Centre Westcoast, University of Kiel, Hafentörn, D-25761 Büsum, Germany [tel: +49 4834 604 202; fax: +49 4834 604 299; e-mail: office@ftz-west.uni-kiel.de]. U. Tillmann: Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, D-27570 Bremerhaven, Germany [tel. +49 471 4831 1470; e-mail: utillmann@awi-bremerhaven.de]. Correspondence to N. Ladwig.

Introduction

The northern German Wadden Sea forms a broad and shallow interface between the waters of the German Bight and its surrounding mainlands. The area is subjected to a direct nutrient enrichment deriving mainly from the River Elbe and, to a lesser extent, from the River Weser. Annual nutrient discharge of the Elbe is in the range 136 200 t N (total nitrogen) and 5200 t P (total phosphorus), whereas the Weser accounts for 64 600 t N and 2400 t P, respectively (average for 1994–1998) (Lenhart and Pätsch, 2001). In addition, the adjacent coastal waters of the German Bight receive a considerable amount of nitrogen and phosphorus from indirect inputs from more remote sites. For example, advective transport of continental coastal water imports nutrients from the River Rhine which may be transported into the Wadden Sea through tidal mixing. During the growth season a large fraction of nutrients enters the Wadden Sea in the form of organic particles. These inputs are difficult to quantify on an annual basis because of their inaccessibility during field assessments. Rough estimates of the particulate import based on seasonal field data and numerical simulations are in the range 240 g C m^{-2} yr^{-1} for the Western Dutch Wadden Sea (De Jonge and Postma, 1974) and 100 g C m^{-2} yr^{-1} in the North Frisian area (Dick *et al.*, 1999). In addition to these water-bound inputs, about 7600 t N is estimated to enter the Wadden Sea by direct atmospheric deposition (De Jong *et al.*, 1993).

Calculated on the basis of data from 1994, approximately 70% of the nitrogen and 55% of the phosphorus pool in the northern German Wadden Sea during winter result from anthropogenic sources (Hesse *et al.*, 1995). The high anthropogenic nutrient supply to the Wadden Sea is assumed to be responsible for direct and indirect eutrophication effects, such as the proliferation of benthic macroalgal mats (Siebert and Reise, 1997), increases in phytoplankton production (Cadée, 1986; Asmus *et al.*, 1998) and phytoplankton biomass (Schaub and Gieskes, 1991; Riegman, 1995; De Jonge *et al.*, 1996; Philippart *et al.*, 2000), and shifts in benthic communities (van Beusekom *et al.*, 2001). Because of nuisance effects of anthropogenic nutrient enrichment in the coastal zone, the continental countries bordering the North Sea agreed to reduce the anthropogenic nutrient loads in rivers by 50% in the period 1985–1995. The level was agreed upon at the "Second International North Sea Conference" in 1987. With respect to the Elbe, a 55% reduction of phosphorus loads has been achieved, but only about a 17% reduction in nitrogen loads in the period 1985–1996 (De Jong *et al.*, 1999).

Several long-term monitoring studies have been carried out in the River Elbe (e.g. Gaumert, 1991; ARGE Elbe, 2001), the East-Frisian Wadden Sea (e.g. Hanslik *et al.*, 1998; De Jong *et al.*, 1999; Rahmel *et al.*, 1999), and the open German Bight (e.g. Hagmeier, 1978; Radach and Berg, 1986; Weichart, 1986; Gillbricht, 1988, 1994; Radach and Bohle-Carbonell, 1990; Körner and Weichart, 1991; Hickel *et al.*, 1992, 1993, 1994; Hickel, 1998; Gaul, 2000). These studies give some insight into changes in the trophic state of the systems during recent decades. In order to investigate the long-term variability of plankton and nutrients in the more estuarine part of the northern German Wadden Sea, the Research and Technology Centre Westcoast (FTZ) of Kiel University started a monitoring programme in 1991. This initiative coincided with the period when intensive political programmes for nutrient reduction in the main freshwater sources of the area were implemented as a consequence of the massive *Chrysochromulina* bloom in summer 1988.

To evaluate the effects of nutrient reduction efforts in the northern German Wadden Sea, we examined the evolution of two basic eutrophication-related indicators, dissolved inorganic nutrients (nitrogen, phosphorus) and chlorophyll *a* (as a proxy for phytoplankton biomass) at the permanent station of Büsum Mole during the past decade (1991–2000). The dynamics of these indicators are then considered with respect to cause–effect relationships and interpreted taking into consideration some other information available for the area, especially information concerning the role of light limitation for phytoplankton growth and internal nutrient sources.

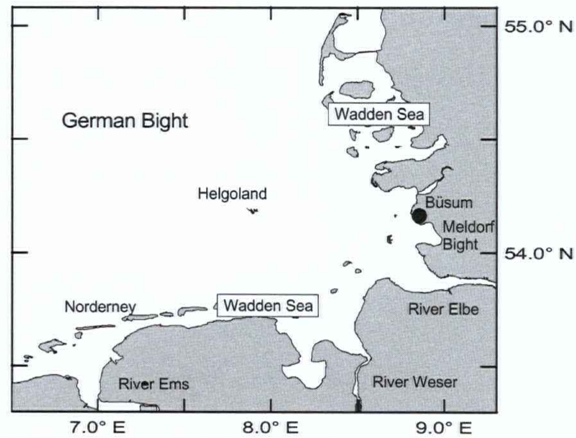

Figure 1. Map of the German Bight showing the area of investigation with the position of the permanent station Büsum Mole (large dot).

Material and methods

In the period 1991–2000, surface samples were taken weekly at the eastern mole of Büsum port (Figure 1) during the growth season (April–September) or fortnightly in winter (October–March). Sampling was implemented at high tide in order to reduce tidal influences. Water depth at this station is ca. 10 m at high tide. Subsamples for inorganic dissolved nutrient determination (DIN = nitrate + nitrite + ammonia, DIP = phosphate) were filtered through glass microfibre filters (GF/C, Whatman) and immediately analysed in accordance with Grasshoff *et al.* (1983). For chlorophyll *a* analysis, 200–2200 ml of the sample was filtered through Whatman GF/C filters, which were stored deep frozen (–20°C) before undergoing spectrophotometric analysis according to Lorenzen (1967). Records of temperature and salinity were made with a WTW probe (LF 191, Wissenschaftlich-Technische Werkstätten) calibrated for salinity. Vertical profiles revealed that the water column is permanently well mixed owing to high tidal current speeds of up to 1.5 m s^{-1} (K. Rickleffs, pers. comm.). It is therefore assumed that the samples are representative of the entire water column.

The spatial distribution of nutrients as well as primary production data were evaluated within the framework of two integrated projects, TRANSWATT (Transport, Transfer and Transformation of Biomass Elements in Wadden Sea Waters) and KUSTOS (Near Coastal Fluxes of Energy and Matter in the German Bight). For further information, see Sündermann *et al.* (1998).

Several additional time-series were made available from other institutions for this analysis. From the long-term monitoring station in the Elbe at Hamburg (Seemannshöft) we obtained observations of total phosphorus and dissolved phosphate, total nitrogen and dissolved inorganic nitrogen compounds from 1985 until 2000 (ARGE Elbe, Arbeisgemeinschaft für die Reinhaltung der Elbe, Hamburg). Furthermore, the AWI/BAH (Alfred-egener-Institut für Polar- und Meeresforschung/Biologische Anstalt Helgoland, Bremerhaven) provided nutrient data from the permanent station at Helgoland Roads for the period 1962–1996. Data of winter nutrient trends in the open German Bight were provided by the BSH (Federal Maritime and Hydrographic Agency, Hamburg).

Results

1. Nutrient concentrations

A quasi-synoptic picture of inorganic nitrogen distribution in winter (February 1994) illustrates the influence of the Elbe discharge on the nutrient distribution in the inner German Bight and the German Wadden Sea (Figure 2). Steep gradients occurred, with maximum concentrations of more than 300 µM DIN in the River Elbe and more than 50µM DIN offshore.

River Elbe

The long-term development of concentrations of phosphorus and nitrogen compounds (total-P, DIP, total-N, DIN) at the Elbe monitoring station Seemannshöft (Hamburg) clearly reveals a decrease since intense point-source reduction measures were put in place at the end of the 1980s (Figure 3). Both

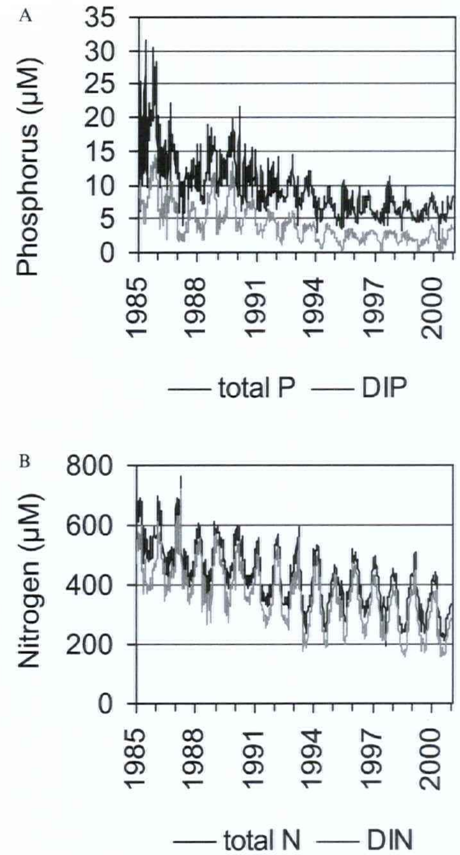

Figure 3A, B. Development of total phosphorus (total P), phosphate (DIP), and total nitrogen (total N), dissolved inorganic nitrogen (DIN) levels at the Elbe monitoring station Seemannshöft, Hamburg (data: ARGE Elbe).

total-P and DIP data show that levels have been successfully reduced by approximately 60–70%. A reduction of about 50% can be observed for nitrogen (ARGE Elbe, 2001).

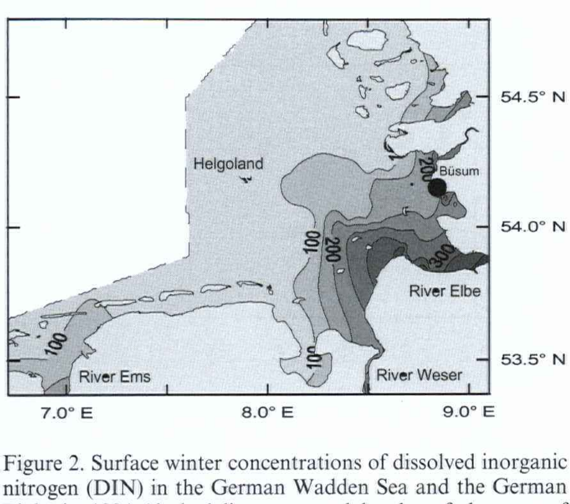

Figure 2. Surface winter concentrations of dissolved inorganic nitrogen (DIN) in the German Wadden Sea and the German Bight in 1994 (dashed line = seaward border of the area of investigation; data: TRANSWATT/KUSTOS).

German Bight

The salinity-normalized mean winter phosphate concentrations in the German Bight (Figure 4) decreased over the past decade to levels (< 0.6 µm P at 34 PSU) close to those observed by Kalle in 1935/36 (Kalle, 1937; Weichart, 1986; Körner and Weichart, 1991; Gaul, 2000). However, no similar decrease was observed for inorganic nitrogen. A comparison with historical reference values for nitrogen is hindered by the lack of reliable analytical methods in the 1930s as well as a lack of adequate monitoring activities before the 1970s.

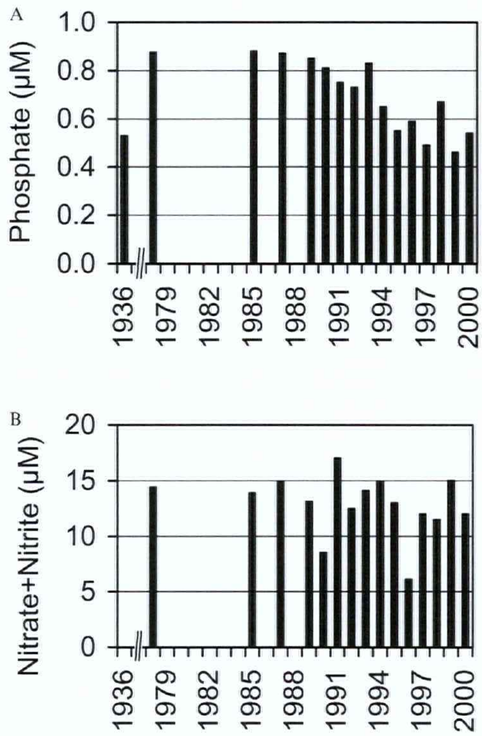

Figure 4A, B. Mean surface winter concentrations of dissolved inorganic phosphate and dissolved inorganic nitrogen compounds (sum of nitrate + nitrite) at salinity 34 in the German Bight (data: BSH).

Wadden Sea

The data set at the monitoring station of Büsum Mole does not allow for the establishment of a nutrient/salinity correlation for each of the different winter seasons, because sampling was restricted to a single point with a restricted sampling frequency.

However, in order to evaluate whether there is a similar trend in the northern Wadden Sea as that observed in the open German Bight and the Elbe water, the Wadden Sea data of winter nutrient concentrations (December–February) at Büsum Mole were split into two 5-year periods and plotted against salinity (Figure 5). Neither data set revealed any significant relationship between nutrient concentrations and salinity, and no temporal decline over a broad range of salinities was evident. Rather, the available winter phosphate concentrations had a significant tendency to be higher during the 1996–2001 period than the preceding 5-year period from 1991 to 1995 (t-test: $p = 0.008$). No statistically significant differences were found for DIN.

2. Nutrient ratios and chlorophyll *a* concentrations

In addition to absolute levels of nutrient concentrations, the molar N:P ratio can be used as an index for changed nutrient conditions. Chlorophyll *a*, as another basic eutrophication indicator, is analysed for the Büsum Mole time-series exclusively.

Wadden Sea

Annual cycles of the molar DIN:DIP ratio at Büsum Mole exhibit a clear seasonal pattern with pronounced maxima (> 200:1) in the aftermath of the phytoplankton spring bloom (March–May) and

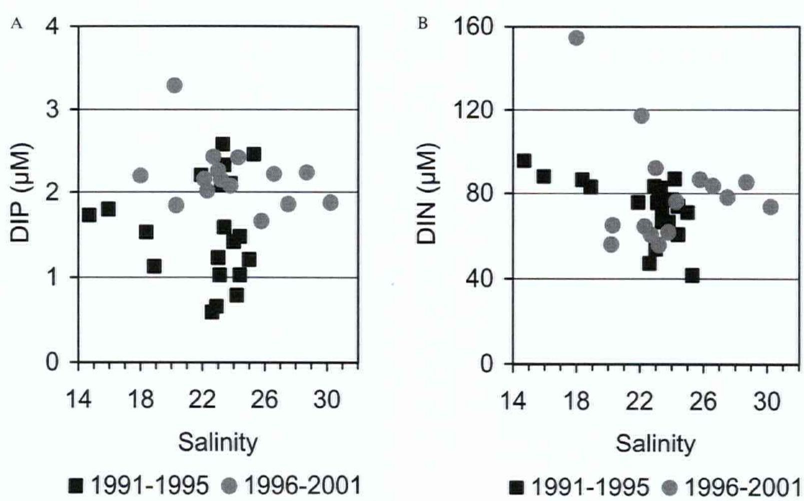

Figure 5 A, B. Winter concentrations of dissolved inorganic phosphorus and nitrogen at different salinities at the Büsum Mole station (northern German Wadden Sea).

minima (< 16:1) in summer (Figure 6A). During the annual cycle, phosphorus compounds are exhausted at first, followed by an annual minimum in nitrogen concentrations in summer which causes a reversal from high to low DIN:DIP ratios below 16:1. The temporal development at the permanent station of Büsum Mole reveals that there are recurrent low DIN:DIP maxima (< 100:1) in recent years (1998–2000).

The reason for the observed lower annual DIN:DIP maxima in the Wadden Sea near Büsum is an increase in the annual minima of phosphate concentrations during the last 3 years of the time-series (1998–2000), while the respective DIN concentrations remained more or less stable (Figure 7). These years were usually preceded by mild absolute winter temperatures.

River Elbe

In contrast to the Wadden Sea, the maximal ratios in the Elbe, which occur at the same time of year, show an inverse trend (Figure 6B). In the second half of the 1980s, annual DIN:DIP maxima in the Elbe were below 400:1. Since 1992 the DIN:DIP ratio has regularly exceeded 400:1, with a maximum in 1999 (> 1000:1). This development is assumed to be a result of the more pronounced phosphate reduction in the river compared to that of inorganic nitrogen.

German Bight

With respect to the long-term development of DIN:DIP ratios in the German Bight near Helgoland the annual maxima show a similar trend as in the River Elbe with extreme ratios of more than 6000:1 occurring in the past decade (e.g. 1994) (Figure 6C). These high values are caused by the pronounced phosphate exhaustion during the spring bloom and presumably also by the reduced phosphorus inputs from the Elbe.

2. Chlorophyll *a* concentration at Büsum Mole

A comparison with another indicator of eutrophication, chlorophyll *a*, revealed that no statistical relationship of chlorophyll *a* concentrations with

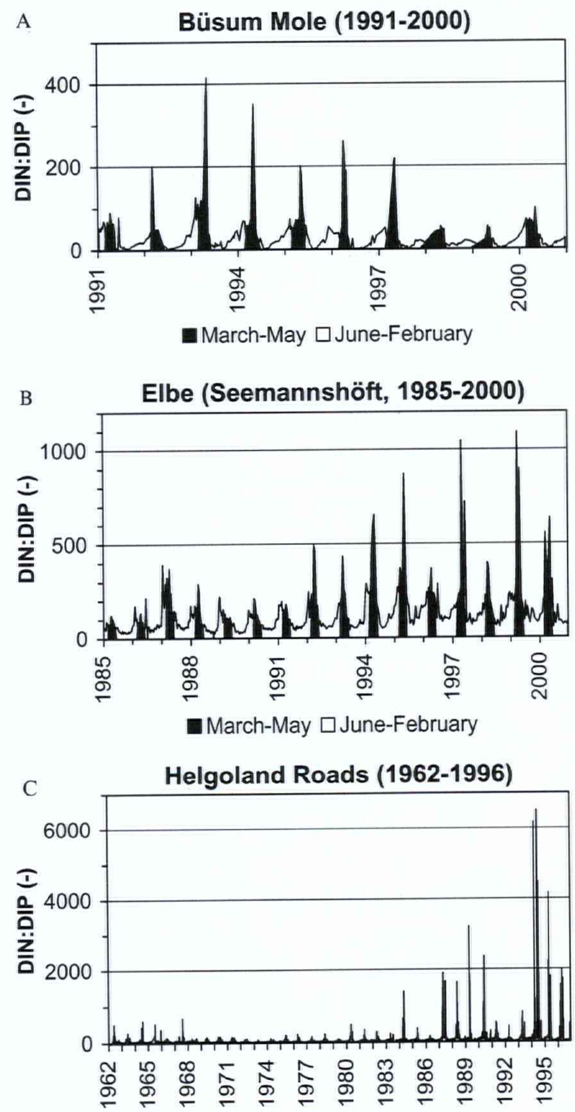

Figure 6A–C. Annual cycles of molar DIN:DIP ratios in the northern German Wadden Sea (Büsum Mole), River Elbe (Seemannshöft, Hamburg), and German Bight (Helgoland Roads). Periods of phytoplankton spring bloom (March–May) indicated in black in A and B; different scales and periods (data: ARGE Elbe, BAH/AWI).

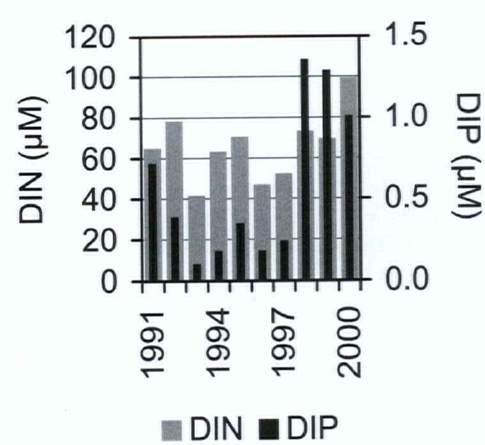

Figure 7. Concentrations of dissolved inorganic nitrogen and phosphorus at the Büsum Mole station during the annual N:P maximum after the phytoplankton spring bloom.

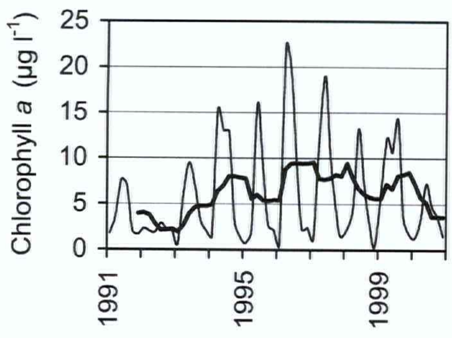

Figure 8. Bimonthly averaged chlorophyll *a* concentrations at Büsum Mole from 1991 to 2000 (bold line indicates a running mean of one year).

the nutrient conditions was found at the Wadden Sea station (Figure 8). There is a pronounced interannual variability both in the running means for each year and in the annual maxima of the bimonthly averaged chlorophyll *a* values lacking any significant trend. Despite the increase in residual phosphate concentrations after the spring bloom, a corresponding increase in chlorophyll *a* concentrations is lacking.

Discussion

The long-term observations made at the Büsum Mole station have not shown any decrease in winter nutrient concentrations over the past 10 years (1991–2000) (Figure 5), whereas the input from the River Elbe has been reduced considerably in the same period (Figure 3). This was unexpected for the area of investigation, which is clearly under the sphere of influence of the River Elbe and contrary to the trend observed in the East-Frisian Wadden Sea near Norderney, where a decrease in dissolved inorganic phosphorus and nitrogen concentrations was found (Rahmel *et al.*, 1999).This, together with the observation of elevated minimum (or residual) phosphate concentrations in the final 3 years of the decade (1998–2000), suggests an additional source for nutrients in the region (see section "Phosphorus release from the sediments" below), which counteracts the effects of successful reduction efforts in riverine nutrient inputs. Sedimentary release may be among the possible causes overriding the reduction in riverine phosphorus discharge.

Furthermore, phytoplankton development (measured as chlorophyll *a* concentration) does not exhibit any trend during the investigated period from 1991 to 2000 (Figure 8). The lack of a significant nutrient/phytoplankton relation in the Wadden Sea poses the question whether light limitation is more effective on phytoplankton primary production in the area of investigation than limitation by inorganic nutrients (see section "Light limitation of phytoplankton primary production" below).

1. Phosphorus release from the sediments

A common feature of the northern German Wadden Sea is an annual late summer maximum (August/September) of dissolved ortho-phosphate derived from P released from the sediments (e.g. Hesse *et al.*, 1992; Dick *et al.*, 1999) (Figure 9A). Contrary to this, the annual cycle of dissolved inorganic nitrogen (Figure 9B) rather follows the normal pattern for temperate zones with high winter concentrations and minima in summer. The excess phosphate remobilized from the Wadden Sea sediments stems from the decomposition of both autochthonous and allochthonous organic material (Postma, 1961; Hesse *et al.*, 1992; Dick *et al.*, 1999). Annual particulate organic matter imported from the adjacent German Bight into the northern Wadden Sea is estimated to be in the range 120 000 t POC yr^{-1} (Dick *et al.*, 1999). Part of the remineralized P is temporarily stored as insoluble iron-bound DIP in the sediments. Release is induced by a shift in the redox potential due to an increase in organic load and temperature during the growth season. The amount of excess DIP mixed out into the adjacent German Bight is in the range 1700 t DIP yr^{-1} (Dick *et al.*, 1999).

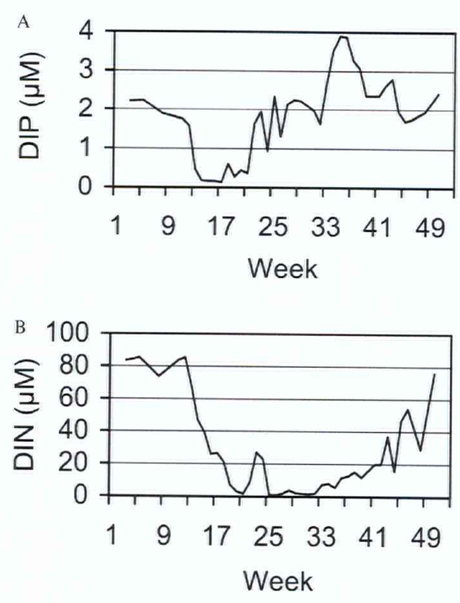

Figure 9A, B. Annual cycle (1996) of dissolved phosphate (DIP) and inorganic nitrogen (DIN) at the Büsum Mole station.

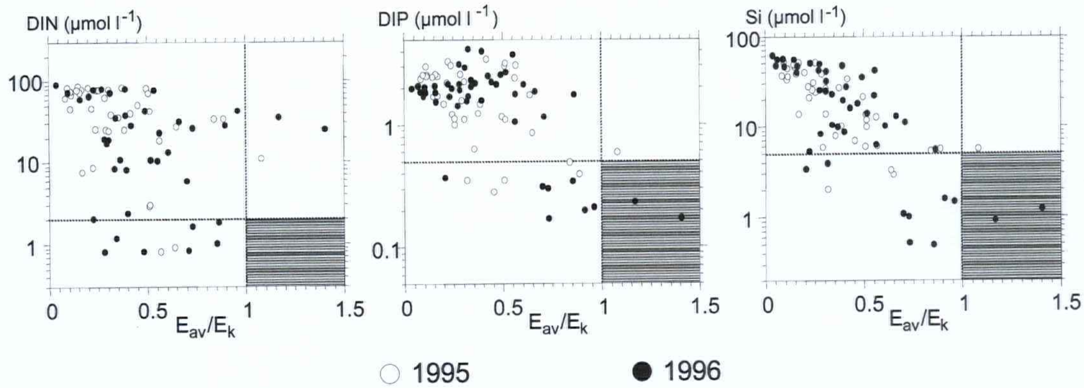

Figure 10. Ratio of the daily average light availability (E_{av}) and the measured light saturation onset parameter (E_k) with ambient nutrient conditions. The shaded area defines the region for which $E_{av}/E_k > 1$ (light saturation) and nutrient concentrations are below half-saturation constants for phytoplankton nutrient uptake as published in the literature (modified after Tillmann *et al.* (2000) with permission from the Journal of Plankton Research).

It is suggested that sedimentary phosphate remobilization may affect winter phosphate levels and also occurs in spring. Remineralization of the organic load in the Wadden Sea sediments may not be totally completed during winter. The amount of phosphate release from this process may be triggered by winter temperatures. In addition, the degree of sediment remobilization is related to stochastic wind-induced sedimentary shear stress during winter time. As already mentioned, the last 3 years were characterized by mild absolute winter temperatures which may have contributed to a higher phosphate remobilization from the sediment.

2. Light limitation of phytoplankton primary production

For two annual cycles (1995, 1996) the importance of light limitation versus inorganic nutrient control of phytoplankton growth in the Wadden Sea was assessed by Tillmann *et al.* (2000). In Figure 10, periods of ambient light limiting conditions in the mixed water column are compared with periods when nutrient concentrations dropped below published half-saturation constants for nutrient uptake. It turned out that light limitation prevailed at most sampling days and that nutrient limitation under light saturated conditions (shaded area in Figure 10) was likely to occur only for DIP and Si (silicate) on 2 days in April 1996 (Tillmann *et al.*, 2000). Comparable observations have been made by Cloern (1999) and Lohrenz *et al.* (1999) in several estuaries in the USA.

Conclusions

In contrast to the long-term decrease of inorganic nutrient inputs from the River Elbe and the decrease observed in the German Bight, a similar development could not be revealed for the northern German Wadden Sea near Büsum. As shown for winter nutrient concentrations, effects of reduction measures are not measurable at this site during the period 1991–2000. Phosphorus release from the sediments is assumed to counteract the reduction efforts in this part of the Wadden Sea. Mild winter temperatures in recent years may have caused the observed increase in phosphate concentrations in the period 1996–2001. Nutrients are still available in excess with respect to the requirements of phytoplankton growth in the area.

Phytoplankton development is rather controlled by limited light availability. Hence, the long-term development of phytoplankton biomass at Büsum Mole, as shown by means of the chlorophyll *a* concentration (Figure 8), does not show any change during the period 1991–2000. Similar observations have been made previously in the Dutch part of the western Wadden Sea (Marsdiep). Here, phytoplankton primary production remained high, although phosphate concentrations declined (Cadée and Hegeman, 1993).

It is concluded that efforts made towards nutrient reduction have not yet had a measurable impact on the trophic state in the primary steps of the food web in this part of the northern German Wadden Sea. However, nothing can be concluded with respect to changes in the absolute amounts of particulate organic matter entering the area from the adjacent German Bight, but it seems likely that these amounts are still high enough to exceed the sedimentary buffer capacity in the region.

Acknowledgements

Special thanks to Britta Egge, who prepared the Büsum Mole time-series data. We are indebted to

Michael Bergemann, Justus van Beusekom, Uwe Brockmann, Horst Gaul, and Wolfgang Hickel for providing valuable nutrient data sets. Thanks also to the anonymous referees for their comments on this article. Part of the study was supported by a grant from the German Ministry for Education and Research (grant no. 03F0130) and of the Federal Environmental Agency (grant no. 29825233).

References

Arbeitsgemeinschaft für die Reinhaltung der Elbe (ARGE Elbe). 2001. Wassergütedaten der Elbe. Zahlentafel 2000. Wassergütestelle Elbe, Hamburg. (In press.)

Asmus, R., Jensen, M. H., Murphy, D., and Doerffer, R. 1998. Primary production of microphytobenthos, phytoplankton and the annual yield of macrophytic biomass in the Sylt-Rømø Wadden Sea. *In* Ökosystem Wattenmeer, pp. 367–391. Ed. by C. Gätje and C. Reise. Springer-Verlag, Berlin.

Beusekom, J. E. E. van, Fock, H., De Jong, F., Diel-Christiansen, S., and Christiansen, B. 2001. Wadden Sea Specific Eutrophication Criteria. Common Wadden Sea Secretariat. Wilhelmshaven, Germany. 116 pp.

Cadée, G. C. 1986. Increased phytoplankton primary production in the Marsdiep area (western Dutch Wadden Sea). Netherlands Journal of Sea Research, 20: 285–290.

Cadée, G. C., and Hegeman, J. 1993. Persisting high levels of primary production at declining phosphate concentrations in the Dutch coastal area (Marsdiep). Netherlands Journal of Sea Research, 31: 147–152.

Cloern, J. E. 1999. The relative importance of light and nutrient limitation of phytoplankton growth: a simple index of coastal ecosystem sensitivity to nutrient enrichment. Aquatic Ecology, 33: 3–15.

De Jong, F., Bakker, J. F., Dankers, N., Dahl, K., Jäppelt, W., Madsen, P. B., and Koßmagk-Stephan, K. (Eds.). 1993. Quality Status Report of the North Sea, Subregion 10, The Wadden Sea. Wilhelmshaven: Common Wadden Sea Secretariat. 174 pp.

De Jong, F., Bakker, J. F., van Berkel, C. J. M., Dankers, N. M. J. A., Dahl, K., Gätje, C., Marencic, H., and Potel, P. (Eds.). 1999. Wadden Sea Quality Status Report. Wadden Sea Ecosystem No. 9. Common Wadden Sea Secretariat, Trilateral Monitoring Group. Wilhemlshaven, Germany. 259 pp.

De Jonge, V. N., and Postma, H. 1974. Phosphorus compounds in the Dutch Wadden Sea. Netherlands Journal of Sea Research, 8: 139–153.

De Jonge, V. N., Bakker, J. F., and van Stralen, M. 1996. Recent changes in the contributions of River Rhine and North Sea to the eutrophication of the western Dutch Wadden Sea. Netherlands Journal of Aquatic Ecology, 30: 27–39.

Dick, S., Brockmann, U. H., van Beusekom, J. E. E., Fabiszisky, B., George, M., Hentschke, U., Hesse, K.-J., Mayer, B., Nitz, T., Pohlmann, T., Poremba, K., Schaumann, K., Schönfeld, W., Starke, A., Tillmann, U., and Weide, G. 1999. Exchange of matter and energy between the Wadden Sea and the coastal waters of the German Bight: estimations based on numerical simulations and field measurements. Deutsche Hydrographische Zeitschrift, 51: 181–219.

Gaul, H. 2000. MURSYS – Nährstoffkonzentrationen in der küstennahen Zone und in der Deutschen Bucht (GAUSS-Fahrt Nr. 345 , Februar). http://www.bsh.de/Meeresumweltschutz/Mursys/Gaumert, T. 1991. Trend-Entwicklung der Nährstoffe im Elbwasser von 1980 bis 1989. Wassergütestelle Elbe/ARGE Elbe, Hamburg, 23 S.

Gillbricht, M. 1988. Phytoplankton and nutrients in the Helgoland region. Helgoländer Meeresuntersuchungen, 42: 435–467.

Gillbricht, M. 1994. Phytoplankton and the physical environment in the Helgoland region. Helgoländer Meeresuntersuchungen, 48: 431–443.

Grasshoff, K., Ehrhardt, M., and Kremling, K. (Eds.). 1983. Methods of Seawater Analysis. Verlag Chemie, Weinheim, New York. 317 pp.

Hagmeier, E. 1978. Variations in phytoplankton near Helgoland. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 172: 361–363.

Hanslik, M., Rahmel, J., Bätje, M., Knieriemen, S., Schneider, G., and Dick, S. 1998. Der Jahresgang blütenbildender und toxischer Algen an der niedersächsischen Küste seit 1982. Umweltbundesamt, Forschungsbericht 102 04 248, Berlin. 234 pp.

Hesse, K.-J., Hentschke, U., and Brockmann, U. 1992. A synoptic study of nutrient and phytoplankton characteristics in the German Wadden Sea with respect to coastal eutrophication. *In* Marine Eutrophication and Population Dynamics. 25th European Marine Biology Symposium, Ferrara, pp. 45–53. Ed. by G. Colombo *et al.* Olsen and Olsen, Fredensborg.

Hesse, K.-J., Tillmann, U., and Brockmann, U. 1995. Nutrient-phytoplankton relations in the German Wadden Sea. ICES CM/T, 8. 13 pp.Hickel, W. 1998. Temporal variability of micro- and nanoplankton in the German Bight. ICES Journal of Marine Science, 55: 600–609.

Hickel, W. 1998. Temporal variability of micro- and nanoplankton in the German Bight. ICES Journal of Marine Science, 55: 600–609.

Hickel, W., Berg, J., and Treutner, K. 1992. Variability in phytoplankton biomass in the German Bight near Helgoland, 1980–1990. Hydrobiological Variability in the ICES Area, 195: 249–259.

Hickel, W., Eickhoff, M., and Spindler, H. 1994. Changes in the German Bight pelagic environment during three decades. ICES CM 1994/E, 18. 8 pp.

Hickel, W., Mangelsdorf, P., and Berg, J. 1993. The human impact in the German Bight: eutrophication during three decades (1962–1991). Helgoländer Meeresuntersuchungen, 47: 243–263.

Kalle, K. 1937. Nährstoff-Untersuchungen als hydrographisches Hilfsmittel zur Unterscheidung von Wasserkörpern. Annalen der Hydrographie und Maritimen Meteorologie, 65: 1–18.

Körner, D., and Weichart, G. 1991. Nährstoffe in der Deutschen Bucht, Konzentrationsverteilung und Trends 1978–1990. Deutsche Hydrographische Zeitschrift. Ergänzungsheft Reihe A, 17. 41 pp.

Lenhart, H., and Pätsch, J. 2001. Daily nutrient loads of the European continental rivers for the years 1977–1998. Berichte aus dem Zentrum für Meeres- und Klimaforschung. Reihe B: Ozeanographie, 40. 146 pp.

Lohrenz, S. E., Fahnenstiel, G. L., Redalje, D. G., Lang, G. A., Dagg, M. J., Whitledge, T. E., and Dortch, Q. 1999. Nutrients, irradiance, and mixing as factors regulating primary production in coastal waters impacted by the Mississippi River plume. Continental Shelf Research, 19: 1113–1141.

Lorenzen, C. J. 1967. Determination of chlorophyll and pheopigments: spectrophotometric equations. Limnology and Oceanography, 12: 343–346.

Philippart, C. J. M., Cadée, G. C., van Raaphorst, W., and Riegman, R. 2000. Long-term phytoplankton–nutrient interactions in a shallow coastal sea: algal community structure, nutrient budgets, and denitrification potential. Limnology and Oceanography, 45: 131–144.

Postma, H. 1961. Transport and accumulation of suspended matter in the Dutch Wadden Sea. Netherlands Journal of Sea Research, 1: 148–190.

Radach, G., and Berg, J. 1986. Trends in den Konzentrationen der Nährstoffe und des Phytoplanktons in der Helgoländer Bucht (Helgoland Reede Daten). Berichte der Bioligischen Anstalt Helgoland, 2: 1–63.

Radach, G., and Bohle-Carbonell, M. 1990. Strukturuntersuchungen der meteorologischen, hydrographischen, Nährstoff- und Phytoplankton-Langzeitreihen in der Deutschen Bucht bei Helgoland. Berichte der Biologischen Anstalt Helgoland, 7: 1–425.

Rahmel, J., Bätje, M., Jakobs, R., and Michaelis, H. 1999. Nutrient trends in the East-Frisian Wadden Sea (Germany). Senckenbergiana maritima, 29 (Suppl): 119–123.

Riegman, R. 1995. Nutrient-related selection mechanisms in marine phytoplankton communities and the impact of eutrophication on the planktonic food web. Netherlands Journal of Sea Research, 32: 63–75.

Schaub, B. E. M., and Gieskes, W. W. C. 1991. Eutrophication of the North Sea: the relation between Rhine river discharge and chlorophyll *a* concentration in Dutch coastal waters. *In* Estuaries and Coasts: Spatial and Temporal Intercomparisons, pp. 85–90. Ed. by M. Elliot *et al.* Olsen and Olsen, Fredensborg.

Siebert, I., and Reise, K. 1997. Grünalgenausbreitung im Wattenmeer. Umweltbundesamt, Forschungsvorhaben 102 04 245, Berlin. 152 pp.

Sündermann, J., Hesse, K.-J., and Beddig, S. (Eds.). 1998. Abschlußbericht der BMBF-Verbundprojekte TRANSWATT und KUSTOS. Bd. 1, 2. 511 pp.

Tillmann, U., Hesse, K.-J., and Colijn, F. 2000. Planktonic primary production in the German Wadden Sea. Journal of Plankton Research, 22: 1253–1276.

Weichart, G. 1986. Nutrients in the German Bight, a trend analysis. Deutsche Hydrographische Zeitschrift, 39: 197–206.