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Macroalgal mass development in the Wadden Sea: first experiences with a monitoring system

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ABSTRACT: The distribution and cover density of macroalgae (Chlorophyta, Ulvaceae) were estimated by means of aerial surveys in 1990–1992 in the Wadden Sea of Niedersachsen, an intertidal area of some 1200 km^2 situated at the German North Sea coast. Each year, up to a maximum of 15 % of the total area was covered by algae. The spatial distribution was heterogeneous. In some subregions the macroalgal carpets covered from 30 % up to 60 % of the tidal flats. The cover density was at its peak in 1990. Additionally, tentative ground truth investigations were carried out on species composition. Reviewing other reports of macroalgal mass development at various sites in Europe, it is assumed that in the German Wadden Sea the recent macroalgal blooms have to be regarded as a response to eutrophication, and will presumably remain a chronic problem for many years to come.

INTRODUCTION

In the summer of 1989 attention was drawn to a sudden outburst of benthic green algae (Ulvaceae) occurring simultaneously in the entire German Wadden Sea. Large parts of the tidal flats were covered by macroalgal vegetation, a hitherto unfamiliar occurrence, which varied from a scattered patchwork, to dense carpets of up to 25 cm thickness. Air-surveillance was commenced by both Schleswig-Holstein (Reise, pers. commun.) and Niedersachsen. In the following summers (up to 1992) the green algae have repeated their excessive growth. Accordingly, the aerial surveys have been maintained and have meanwhile resulted in a regular monitoring programme. The results for 1990–1992 from the Niedersachsen coast, i.e. the area between the Ems and the Elbe estuaries, are given in the present report.

The current situation is compared with early descriptions of the Wadden Sea vegetation (Nienburg, 1927; Linke, 1939; Gessner, 1957) and some recent studies on macroalgal mass development.

METHODS

Aerial surveys

Aerial surveys of algal cover along the coast of Niedersachsen (Fig. 1) were carried out 3 to 5 times during the summers of 1990–1992. They were performed with a single-

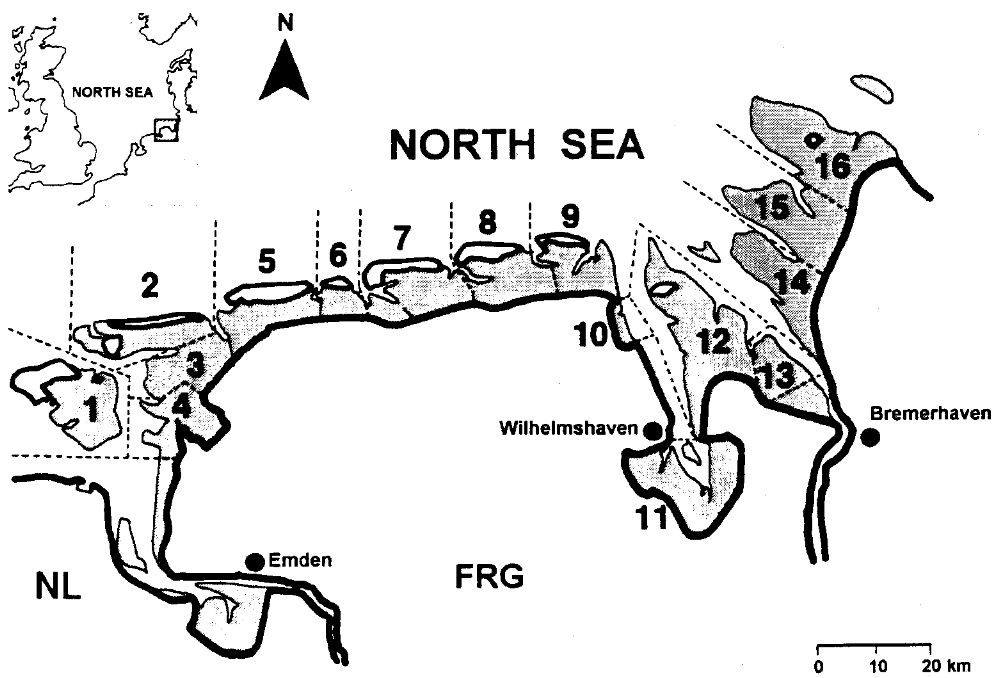

Fig. 1. The survey area (shaded), divided into 16 subregions from west to east for data interpretation purposes

engined aeroplane from a constant height of 200 m. The mappings were done at about low tide when the intertidal flats were completely exposed. Each time, two flights were necessary to cover the whole Niedersachsen coast. Topographic maps (1:50 000) were used for the plots. As standard maps do not represent the dynamic morphology of the tidal flats and the channel system properly, they were corrected in advance and completed by information from the most recent aerial photographs available. Mapping was done independently by two trained persons, observing the area through the windows of the aeroplane. The localized intertidal algal stands were plotted manually onto the maps. Different cover densities (1–5 %, 6–20 %, 21–50 %, 51–80 %, >80 %), estimated from visual impression of colour and texture, were indicated by different hachures. Varying thicknesses of the algal mats could not be distinguished from the air. The final result was gained by comparison, combination, and interpolation of the two parallel plots. The areas of each cover scale were measured from the resulting maps using a digitizer. The share of the tidal flats covered by algae was calculated for each subregion and for the entire area (1200 km^2).

The validity of the cover density assessments was examined in July 1991 by local ground truth observations in 7 localities near the islands Borkum, Spiekeroog, and Mellum (subregions 1, 8 and 12). Again the cover density was estimated visually. In five cases the estimations were well in accordance with the assessments from the aerial survey which was performed 7 to 10 days in advance. In one case the aerial estimation was higher, in one case lower than the ratings on the spot. Because of these differences, only two categories, i.e. 1–50 % and >50 %, were used in the final evaluation (Fig. 2).

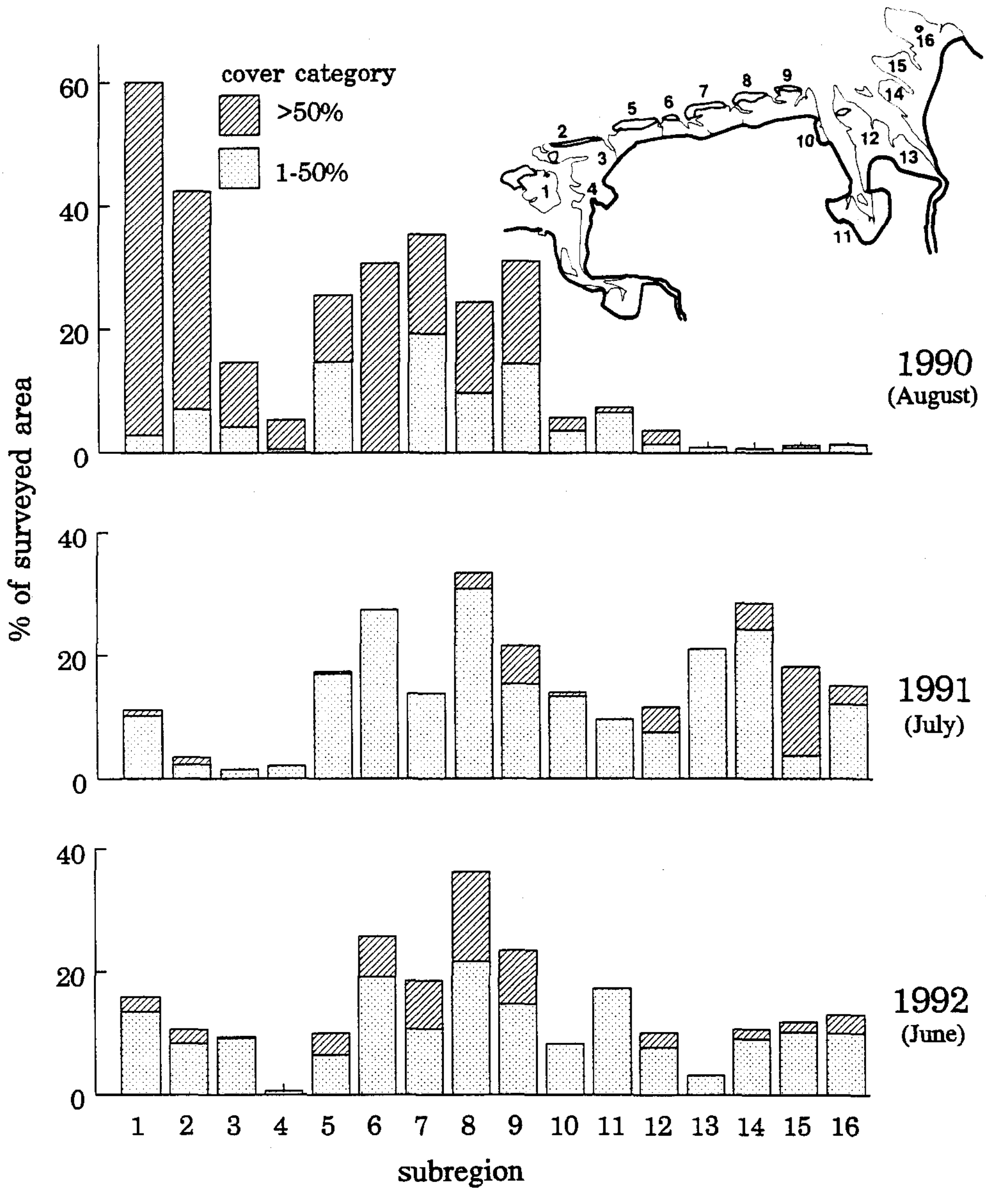

Fig. 2. Spatial distribution of benthic macroalgae in the intertidal area of Niedersachsen (Germany) 1990–1992

Species composition

Already during the first outburst of macroalgal growth in 1989, samples for taxonomic determinations were collected in July from 16 locations near Norderney and Baltrum (subregions 5 and 6). The material was completed by collections in July 1991 from 7 locations (subregions 1, 8, 12) and July 1992 from 8 locations (subregion 5). From each station a random collection, partly preserved (4 % formalin in seawater) and partly fresh thalli, was determined to species and, in some cases, to subspecies level.

Descriptions of substrata and the effects of macroalgae on sediment and benthos are based on qualitative field observations.

RESULTS

Spatial, seasonal and interannual variability of coverage

As an example, Figure 3 represents the results of two surveys in the tidal flat region behind four of the East Frisian Islands in July and August 1991. The location and extension of the algal fields are given without indication of cover densities. Not only the size of the algal fields changed from one month to another, but also their position was subject to considerable shiftings.

Figure 2 illustrates how the maximum coverage of algal mats was distributed over the 16 subregions of the survey area in the years 1990–92. Only the two cover categories <50 % and >50 % are considered. The areas of dense algal cover shifted from the western and middle subregions in 1990, to the middle and eastern subregions in 1991 and 1992. In 1990 (August) the maximum coverage was recorded on the tidal flats of the western-most East Frisian islands Borkum (subregion 1) and Juist (subregion 2), with 60 % and 40 % coverage, respectively; however, high densities of algae also occurred in the intertidal of the other islands (subregion 5–9). This was the most intense algal development observed within the three years. In 1991 (July) and 1992 (June), the area between Norderney and Wangerooge (subregion 5–9) supported the major part of the algal crop. Furthermore, the tidal flats between the Jade and Elbe estuary (subregion 11–16) were more severely affected than in 1990.

With the exception of the long-lived mussel beds and some *Lanice*-populations which were covered annually, the vegetation pattern in each subregion changed every year. Constantly low algal cover was registered in subregion 4: a sheltered, muddy bay without suitable substrata for macroalgae.

The seasonal dynamic of the macroalgal development as derived from the aerial surveys differed from year to year, with regard to both the onset of growth, and the duration of the vegetation period. In 1990 (5 monthly surveys), growth started early in May, and the mats largely survived until late September. In 1991 (3 monthly surveys) the growing period began in June and most of the coverage had already disappeared by late August. In 1992 (5 monthly surveys), algal development recommenced in May, but – different from 1990 – the stands became rather scarce by September. The peak of algal cover was recorded in late August for 1990, in July for 1991 and for 1992 already in June.

The results of aerial surveys during the times of maximum extension (Table 1), give an impression of the interannual variability of algal cover. The total area (cover density 1–100 %) was approximately the same size every year: about 180 km^2 or 15 % of the surveyed area, respectively. However, with regard to the vegetation density, distinct interannual differences can be defined. The major coverage was recorded in 1990, when almost 70 % of the overgrown area supported an algal cover of the categories 4 or 5 (>50 %). In 1991 and 1992, only some 20 % of the vegetation was that dense. In 1991,

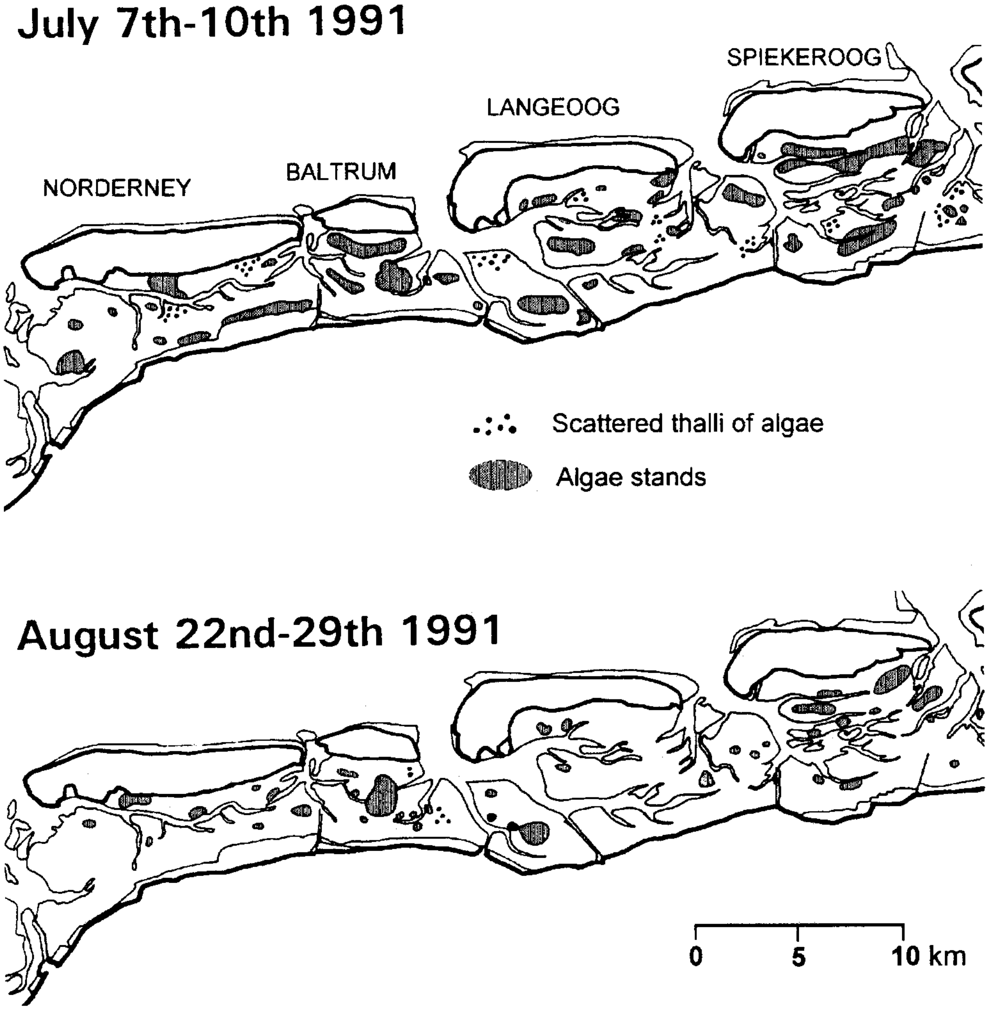

Fig. 3. Two examples of aerial survey results in the East Frisian part of the Wadden Sea. Areas covered by algae are given without indication of different cover densities

only approximately 50 % of the area involved was more than 20 % covered. In 1992, the 20 % cover category was surpassed by 70 % of the algal mats.

Species composition, substrata preference. and effects

In addition to the results of the aerial surveys, only preliminary and tentative ground truth data are available, with hardly any information on spatial and seasonal variation. Sampling for taxonomy and observations of substrata and effects were restricted to only a few spots in the intertidal area of the Niedersachsen coast.

Table 1. Maximum macroalgal cover recorded by aerial surveys in the summers of 1990–1992 on the intertidal flats of Niedersachsen (Germany)

Cover category	Area covered (km^2)		
	1990 (August)	1991 (July)	1992 (June)
0 %	1040	1040	1058
1– 5 %	11	13	24
6– 20 %	26	84	36
21– 50 %	22	53	70
51– 80 %	125	34	37
81–100 %	3	3	2
total cover	187	187	169
% share of surveyed area	15 %	15 %	14 %

Concerning species composition, predominantly representatives of the family Ulvaceae were identified in the algal mats. Three of a total of 20 species belonged to the genus *Ulva*, 12 taxa (including subspecies) to the genus *Enteromorpha*. The following mat-forming species were regarded as being dominant: *Enteromorpha prolifera* subsp. *prolifera* and subsp. *radiata*, *Enteromorpha intestinalis*, *Ulva lactuca* and *Ulva scandinavica*. A complete list of species is given in Table 2. The samples did not contain remainders of unidentified thalli.

The macroalgae of the intertidal soft bottom live attached to empty mollusc shells, to shells of living bivalves *(Cerastoderma edule, Macoma balthica, Mytilus edulis)*, and to the tubes of the polychaete *Lanice conchilega*. Additionally, algal thalli can be anchored passively in the sediment by means of burrowing activities of the lugworm, *Arenicola marina*. Algae growing on mussel beds *(Mytilus edulis)* are either attached to the shells *(Enteromorpha* spp.), or fixed with byssus threads *(Ulva* spp.).

Apparently the different substrata are colonized by distinct algal communities, i.e. *Mytilus* beds mainly by *Ulva* spp., and *Lanice* colonies by *Enteromorpha* spp.

Table 2. Benthic macroalgae in the intertidal area of Niedersachsen (FRG). Dominant, excessively growing species area indicated by **bold type**

Chlorophyta	*Enteromorpha clathrata* (Roth) Greville
Ulva scandinavica Bliding	*Enteromorpha torta* (Merl. in Jürg) Reinb.
Ulva lactuca L.	*Enteromorpha flexuosa* (Wulfen ex Roth) J. Ag.
Ulva rigida C. Ag.	*Enteromorpha ahlneria* Bliding
Enteromorpha prolifera (O. F. Müller) J. Ag.	*Percursaria percursa* (C. Ag.) Rosenv.
subsp. *prolifera* Bliding	*Blidingia marginata* (J. Ag.) P. Dang.
subsp. *radiata* (J. Ag.) Bliding	*Rhizoclonium riparium* (Roth) Harvey
Enteromorpha linza (L.) J. Ag.	Phaeophyta
Enteromorpha linziformis Bliding	*Ectocarpus siliculosus* (Dillw.) Lyngb.
Enteromorpha compressa (L.) Greville	Rhodophyta
Enteromorpha intestinalis (L.) Link	*Porphyra umbilicalis* (L.) J. Ag.
Enteromorpha ralfsii Harvey	
Enteromorpha kylinii Bliding	

A moderate algal cover may provide food and shelter for epifaunal crustaceans *(Gammarus spec., Crangon crangon, Carcinus maenas)* and small fish *(Pomatoschistus microps)*. A noxious effect on the macrobenthos could be detected when the sediment under thick algal carpets turned into anoxia: Bivalve molluscs *(Cerastoderma edule, Macoma balthica)* left the sediment, where they died or fell prey to birds. Most of the annelids disappeared except *Capitella capitata* and tubificides which apparently dominated the remaining benthos community.

Moreover, algal mass production causes severe effects on the draining system of the intertidal flats. Drifting algal material tends to gather in the small tidal creeks which, by the decaying matter, are turned into black gullies. During ebb tide, they discharge reduced suspended matter into the main channels, visible from the air as black plumes.

DISCUSSION

Mass development of macroalgae reaching 30, 40 or even 60 % coverage in certain subregions is without doubt a phenomenon new to the Wadden Sea. Up until the 1980s, the multicellular algae represented a constant but modest element of this ecosystem. This can be derived both from early reports (Nienburg, 1927; Linke, 1939; Gessner, 1957) and from about 40 more recent surveys referring to areas of the Niedersachsen coast (e.g. Koeman, 1975; Michaelis, 1969, 1987; Meyer & Michaelis, 1980) in many of which one author of the present study has gathered his own experience since 1967. Although Nienburg and Gessner (locis citatis) mentioned the phenomenon of "tidal-flat blooming" caused by explosive spring growth of green algae, these blooms were probably (though figures are not available) of limited expansion. Along the Niedersachsen coast, algal development in all studies – from the 1940s until the late 1980s – was far from exerting noxious effects. Reviewing the state of knowledge up to the end of the 1970s, van den Hoek et al. (1979) attributed only a subordinate role to the multicellular algae in the Wadden Sea. However, they already indicated early symptoms of a possible increase caused by the rising nutrient load. Also Michaelis (1978) related gigantic growth which he found in thalli of *Ulva, Enteromorpha* and *Porphyra* spp., to eutrophication; and Reise (1983), in 1979 observed an increasing abundance of green algae in Schleswig-Holstein. During benthic surveys in the 1980s, this increase also became obvious in Niedersachsen (Michaelis et al., unpubl.)

Since the early 1970s, "green tides" of macroalgae, principally *Ulva* and *Enteromorpha*, have been reported from various sites of the European coasts: from the Swedish side of the Kattegat (Rosenberg, 1992), the Island of Funen in Denmark (Funen County Council, 1991), different places around the British Isles (Perkins & Abbott, 1972; Joint, 1978; Lowthion et al., 1985), the French coast of the Channel (Desprez et al., 1992; Piriou & Ménesguen, 1992) and the Adriatic Sea (Viaroli et al., 1992).

The abundance and biomass of macroalgae is controlled by many factors which can be principally connected to 3 groups: physical control (hydrodynamic forces, climate), chemical control (nutrient supply), and biological control (grazing, substrata). Whereas physical and biological factors primarily regulate the seasonal and interannual variability and the spatial distribution of macroalgal growth (Warwick et al., 1982; Piriou & Ménesguen, 1992), nitrogen overload is regarded as being the key factor for mass development in many coastal areas of the Baltic Sea (Cederwall & Elmgren, 1990), in

Danish waters near the Island of Funen (Funen County Council, 1991), on the coast of Brittany (Piriou & Ménesguen, 1992), and in the coastal lagoons of the Adriatic Sea (Pugnetti et al., 1992; Viaroli et al., 1992). We assume that this also holds true for the Wadden Sea of Niedersachsen. The time series from two phytoplankton monitoring stations near Norderney (see Fig. 1 in Rahmel et al., 1995) is too short to document an increase in nutrient concentrations, but the annual nutrient cycles show certain peculiarities which are characteristic for eutrophied Wadden Sea areas. The occurrence of the summer phosphate peak (Rahmel et al., 1995) which has also been reported by Hickel (1989) for the Wadden Sea of Sylt, may serve as an example.

Macroalgae may also influence the nutrient cycle. From nutrient data of the stations near Norderney it is obvious that the DIN (dissolved inorg. nitrogen) summer medians

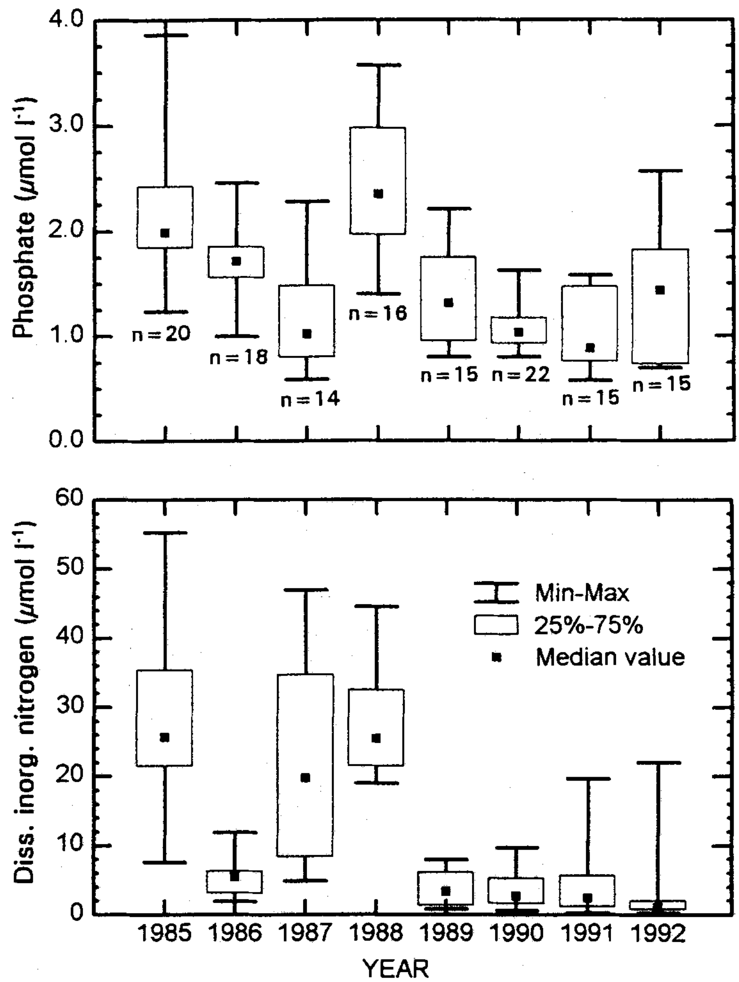

Fig. 4. Variability of dissolved inorganic nitrogen compounds and phosphate in surface water samples at two monitoring stations near Norderney (for methods see Rahmel et al., 1995)

(July–August) of the "macroalgae years" (1989–1992) differ significantly from those of the former years (Fig. 4). From 1985 to 1988, the monthly medians vary between 5.4 and 25.7 μmol l^{-1}, while in 1989–1992 they are in the range of between 1.2 to 3.4 μmol l^{-1}. For phosphate, relatively low concentrations (0.9–1.4 μmol l^{-1}) were also measured in the years 1989–92, but a significant reduction of this nutrient could not be observed. During the years without mass occurrences of macroalgae, means of 1.0–2.4 μmol l^{-1} were found. Is it possible that the macroalgae, known to have very high N uptake rates (Wallentinus, 1984), caused the decrease of DIN?

The effects of macroalgal mass development on the environment are severe. In the Niedersachsen Wadden Sea, like in many other places investigated (Perkins & Abbott, 1972; Nicholls et al., 1981; Reise, 1983), the bottom fauna under thick algal carpets undergoes a fast succession, coincident to the detailed description given by Pearson & Rosenberg (1978) for macrobenthic response to organic pollution. Mass mortality of bivalves is the most obvious effect, but polychaetes and meiofauna besides suffer from oxygen deficiency and toxic hydrogensulfide in the sediment. As observed during this study, surface areas of tidal flats which have become anoxic by green algal cover and breakdown, recover within a few days or weeks. More severe effects are expected on the small creeks of the draining system, the bottom of which is turned into anoxic conditions as a result of the decay of accumulated algal masses. Flatfish, e.g., are much more sensitive to low oxygen concentrations than the infauna and they leave when the oxygen saturation drops under 10–25 % (Baden et al., 1990).

As a final conclusion: The algal growth in the Wadden Sea greatly resembles the cases described from elsewhere in Europe – with regard to the dominant species, the nutrient interactions and the effects. A common feature is that representatives of the genera *Ulva* and *Enteromorpha* are the main species causing mass production, that mass production always occurs in bays, fjords or lagoons which are highly polluted but also provide shelter from strong currents and wave action, and that mass production has become an event occurring regularly every summer. By drawing an analogy, it is suggested that in the Wadden Sea green algae will remain a problem and a severe ecological factor for a long period to come.

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