The impact of Odra river waters on the seasonal and spatial distribution of primary production and chlorophyll *a* concentrations in the Pomeranian Bay in 1996–1997*

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Abstract

Primary production and chlorophyll *a* concentrations were measured in March and May 1996, July and October 1997. The study was carried out in the coastal zone adjacent to the mouths of the Świna and Dziwna, which together drain over 80% of the waters carried by the river Odra, and in the open Pomeranian Bay.

Chlorophyll *a* concentrations in the entire Pomeranian Bay varied between 0.8 and 16.5 mg m^{-3}. The minimal daily *in situ* primary production measured in March was 19.3 mgC m^{-2} d^{-1}, the July maximum was 1238.6 mgC m^{-2} d^{-1}. The potential primary production ranged from 1.5 to 59.2 mgC m^{-3} h^{-1}. The rate of

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photosynthesis expressed as the assimilation number (AN) varied from 0.3 to 6.6 mgC mgchl^{-1} h^{-1}.

The waters of the river Odra reinforce eutrophication in the coastal zone of the Pomeranian Bay. The photosynthetic rate there is usually higher than in open bay waters.

1. Introduction

Measurements of primary production and chlorophyll *a* concentrations in the phytoplankton of the Pomeranian Bay were conducted as part of the project 'Impact of the Odra (Oder) river waters on the ecosystem of the Pomeranian Bay'. The studies were focused principally on the spatial distribution of the above parameters and their seasonal variability with respect to the trophic conditions obtaining during the study.

The Pomeranian Bay and the Gulf of Gdańsk are particularly exposed to the consequences of inorganic and organic pollutant discharges, nutrients included. These consequences were very much reinforced during the flood in southern Poland in 1997, the effects of which were observed hundreds of kilometres away in the Odra and Wisła estuaries (Pastuszak *et al.* 1998, Gromisz *et al.* 1999).

Permanently elevated nutrient concentrations in the vicinity of river mouths and discharges of allochthonous organic matter, including phytoplankton, lead to raised chlorophyll *a* concentrations; consequently, primary production is higher in these waters than in the open sea (Renk *et al.* 1976, Siegel *et al.* 1994, Ochocki *et al.* 1995a,b, Renk 1997).

The extent, rate and direction of riverine water spread, and therefore the transport of all substances contained in these waters, are governed by hydro-meteorological factors (Pastuszak 1996, Pastuszak *et al.* 1998). They are decisive with respect to the distribution and concentration of chlorophyll, and to primary production in bays and beyond them (Rosenberg *et al.* 1986, Cederwall & Elmgren 1990, Renk 1991, 1992, 1997, Pollehne *et al.* 1995, Kaczmarek *et al.* 1997).

2. Material and methods

Four cruises of r/v 'Baltica' took place in the Pomeranian Bay in 1996–1997: in March and July 1996, and in May and October 1997. Together with physico-chemical measurements, primary production and chlorophyll *a* concentrations were assessed, the latter being considered an indicator of phytoplankton biomass.

Primary production

The *in situ* primary production was measured directly in seawater under natural irradiation and temperature conditions. The potential primary production was measured in a thermo-incubator under constant, artificial light conditions – *ca* 250 kJ m^{-2} h^{-1} (PAR), and at temperatures corresponding to the average temperature in the euphotic layer. In both cases the ^{14}C isotope method (Steeman-Nielsen 1952) was applied; a detailed description of this technique can be found in BPMEC (1980, 1988) and in Evans *et al.* (1987). It is should be noted that 0.07–0.2 dm^3 of aq. $NaHC^{14}O_3$ were added to each sample (activity 100–300 kBq).

The *in situ* incubation was done in 100 cm^3 glass bottles at 0.5, 2.5, 5, 10, 15 and 20 m depth, usually for 4 hours around midday. The estimations of potential primary production were done in 50 cm^3 glass bottles over a period of 2 hours. Directly after incubation the mixtures were passed through GF/F glassfibre filters, which were then exposed for 3–5 min. to conc. HCl fumes and placed in marked plastic scintillation vessels. After the cruise each bottle was filled with 6 cm^3 of Ready Value scintillation cocktail, and the activities of the filters were measured on a 6000 IC Beckman scintillation counter.

Chlorophyll *a*

The fluorometric method by Holm-Hansen *et al.* (1965) was used to measure chlorophyll *a* concentrations; for details, see Evans & O'Reilly (1983).

The water samples for determining chlorophyll *a* were subsampled from the same water volume as for the determination of nutrients, phytoplankton and its production, bacteria and their production, and for zooplankton studies. A water volume of 0.1–0.3 dm^3 was filtered through GF/F glassfibre filters (ϕ 42 mm). The filters with phytoplankton were stored in darkness at $-20°$C until the chlorophyll could be extracted in a land-based laboratory (3–5 weeks later). Extraction was done with 8 cm^3 of a 90% aqueous solution of acetone in darkness for 24 hours at 4°C. After the extract had been centrifuged, its fluorescence was measured before and after adding 2 drops of 5% HCl, a Turner Designs fluorometer (model C 10–005 R) being used for this purpose. This instrument was calibrated against the Sigma C–5753 chlorophyll standard.

The interpretation of the primary production results was based mainly on hydrochemical data collected during the cruises (Pastuszak *et al.* in preparation).

3. Results

Primary production

The values and distributions of *in situ* primary production in seawater under 1 m^2 of euphotic layer at the stations (Fig. 1) in the various seasons in 1996–1997 are given in Fig. 2. The average potential production of phytoplankton sampled at 0, 5 and 10 m in particular months is illustrated in Fig. 3.

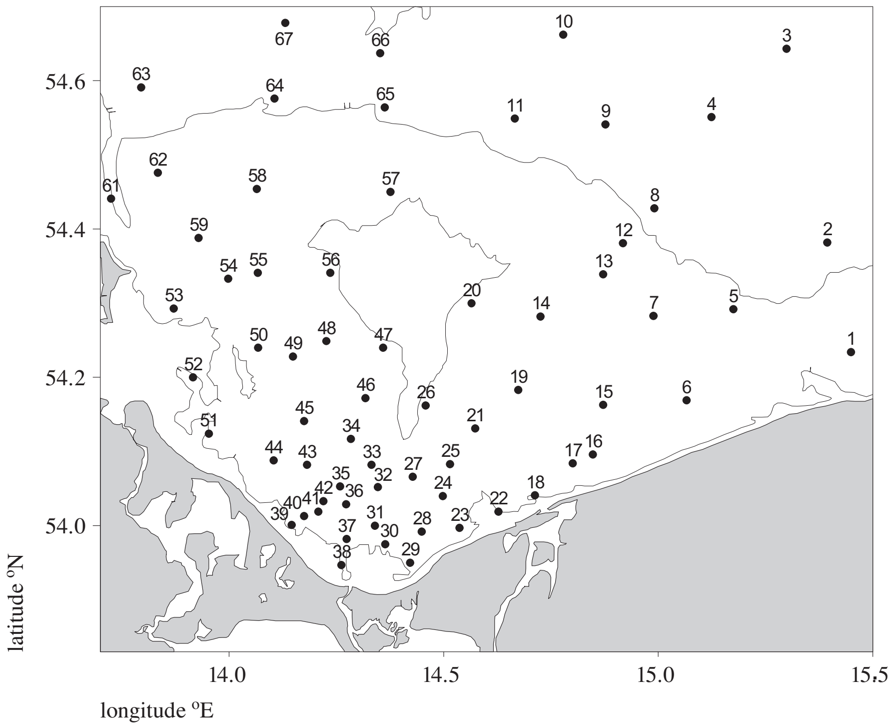

Fig. 1. Location of stations where primary production and chlorophyll *a* concentration were measured

Both the *in situ* and potential primary productions were highly variable in March, changing from *ca* 19 to 889 $\mathrm{mgC\,m^{-2}\,d^{-1}}$ and from 1.5 to 35 $\mathrm{mgC\,m^{-3}\,h^{-1}}$ respectively. The highest *in situ* and potential productions were recorded in the south-western part of the Bay, with the exception of the mouth of the Świna (station 38).

May was conspicuous for the considerable variability in primary production in both in- and offshore waters, the respective values ranging from 250 to 940 $\mathrm{mgC\,m^{-2}\,d^{-1}}$ and from 200 to 740 $\mathrm{mgC\,m^{-2}\,d^{-1}}$. Production (*ca* 250 $\mathrm{mgC\,m^{-2}\,d^{-1}}$) was very low at the station off the mouth of the

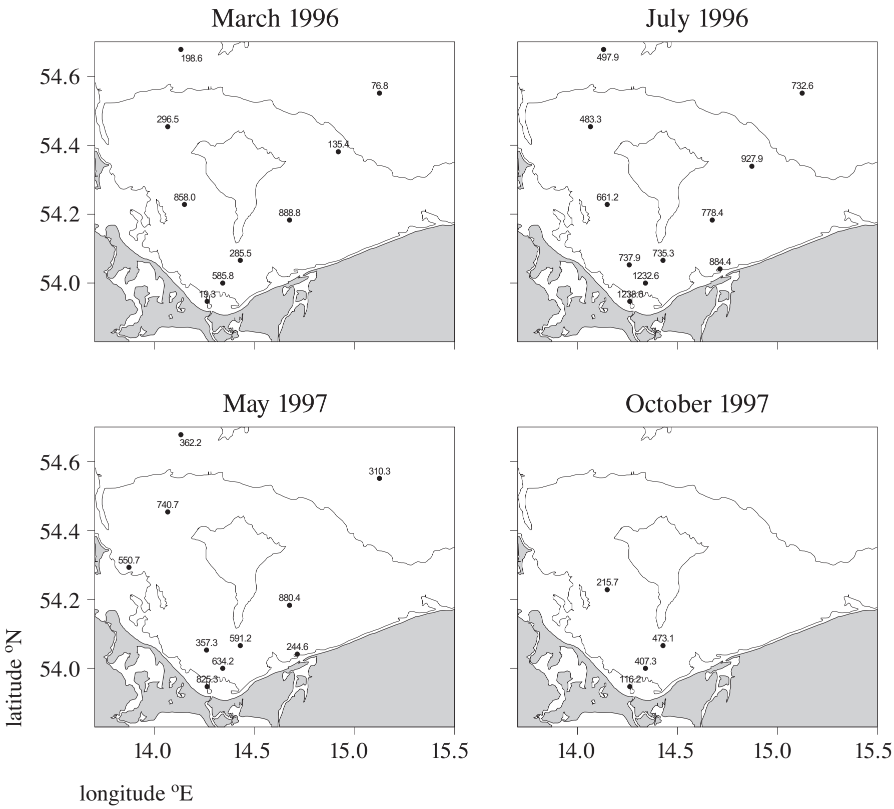

Fig. 2. Daily *in situ* primary production [mgC m^{-2} d^{-1}] in particular months in 1996–1997

Dziwna. The average potential primary production in May calculated for the 0–10 m layer also exhibited considerable spatial variability and a wide range of values (from 1.5 to 15 mgC m^{-3} h^{-1}).

In July the lowest *in situ* production was 500 mgC m^{-2} d^{-1} while the highest reached *ca* 1250 mgC m^{-2} d^{-1}. The highest values were recorded near the mouth of the Świna (stations 38 and 31); in general, *in situ* production was higher in the eastern part of the Bay than in the west. In most cases the July pattern of potential plankton production was similar to that of the *in situ* production. Potential production was highest in the vicinity of the Świna. Like the *in situ* production, potential production was higher in the eastern part of the Bay than in the west. The overall range of potential production was 4.8–60 mgC m^{-3} h^{-1}.

It is difficult to characterise the autumn *in situ* production owing to the very limited number of measurements. All that can be said is that it was relatively low, close to or below the lowest values measured in May;

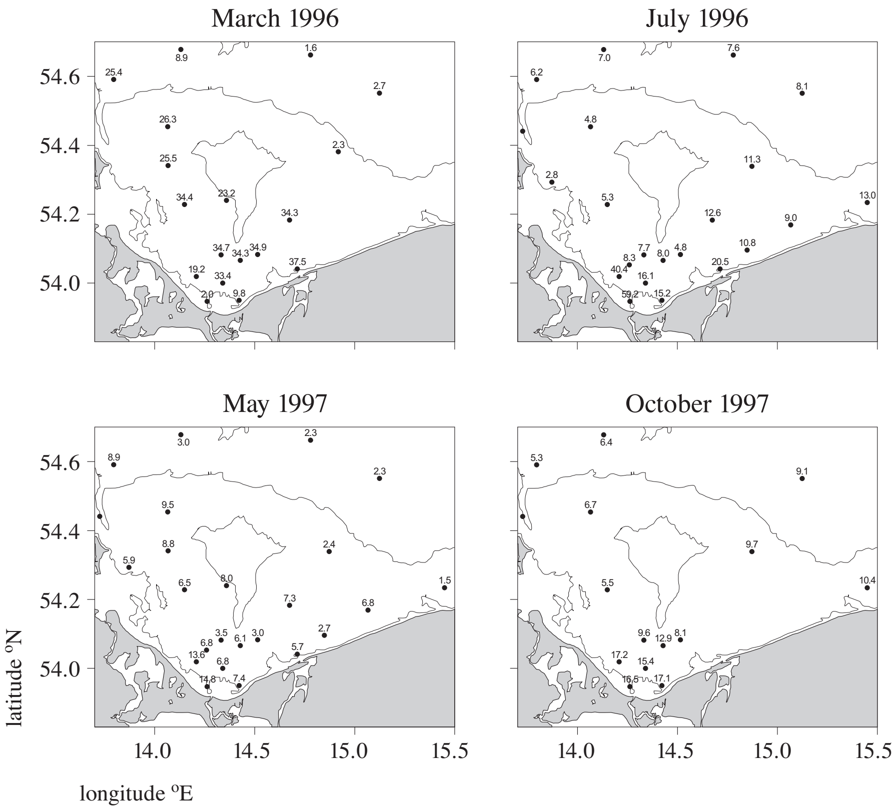

Fig. 3. Average potential primary production [$\mathrm{mgC\,m^{-3}\,h^{-1}}$] at 0.5, 5 and 10 m depth in particular months in 1996–1997

the water temperature in May was comparable to that in October. The measured *in situ* production ranged from 116 to 473 mgC $\mathrm{m^{-2}\ d^{-1}}$, the minimum being at station 38 near the mouth of the Świna. The October potential primary production varied from 5 to 17 mgC $\mathrm{m^{-3}\ h^{-1}}$, the lowest values being recorded in the north-western part of the Bay.

Chlorophyll *a*

Figure 4 illustrates the distribution of average chlorophyll *a* concentrations at 0, 5 and 10 m depths in the various seasons. Because there were 2–3 times more measurements of chlorophyll *a* than of primary production, the distribution of the former's concentrations could exceptionally be presented in the form of isolines.

In March 1996, as was the case with the production, the differences between the chlorophyll concentrations in the south-western and north-eastern

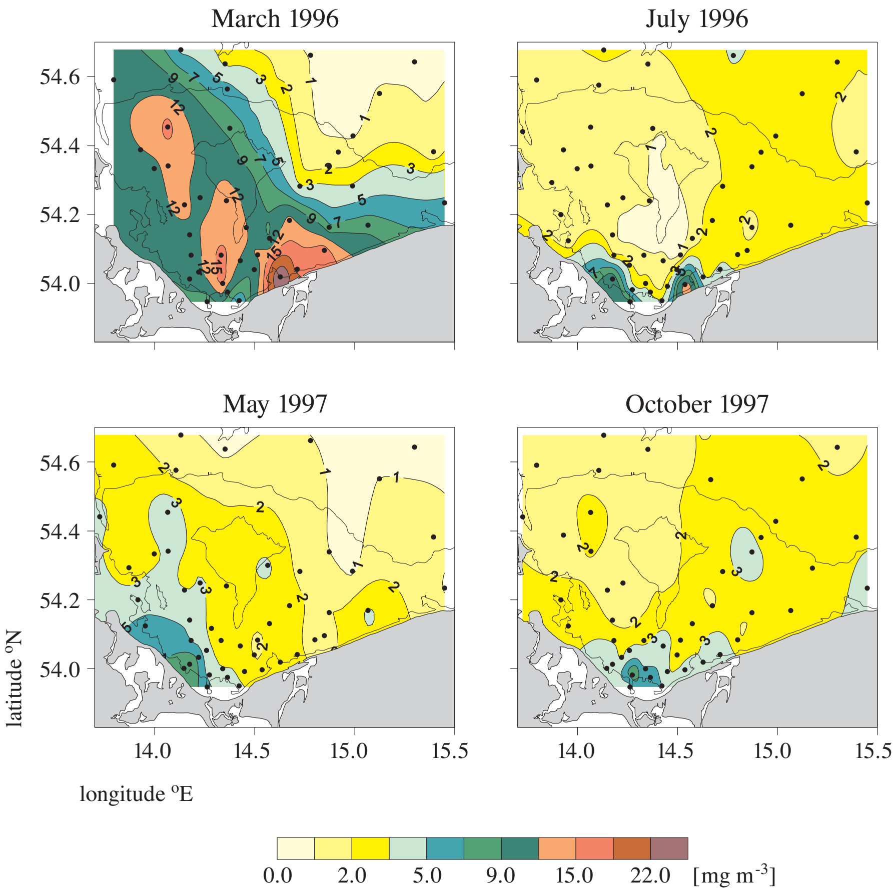

Fig. 4. Average chlorophyll *a* concentrations [mg m^{-3}] at 0.5, 5 and 10 m depth in particular months in 1996–1997

parts of the Bay were considerable, their respective values ranging from 5 to 27 mg m^{-3} and from 1 to 5 mg m^{-3}.

The May 1997 chlorophyll *a* concentrations ranged from 1 to 9 mg m^{-3}; these tended to decrease offshore and reached a maximum west of the Świna mouth.

In July 1996 the chlorophyll *a* concentrations lay in the 1–3 mg m^{-3} range over the entire Pomeranian Bay. The only exception was the area west of the Świna mouth and stations 23 and 29, where the concentrations fluctuated between 9.5 and 15.2 mg m^{-3}.

In October 1997 the lowest measured concentration of this pigment was 1.5 mg m^{-3}, the highest one – 10 mg m^{-3}. The chlorophyll concentration decreased quite distinctly in the offshore direction, although there were some exceptions like stations 13 and 38.

4. Discussion

According to the March distributions of primary production and chlorophyll *a*, the entire Pomeranian Bay could be divided into north-eastern and south-western subregions. In the former, winter stagnation was holding back phytoplankton growth, whereas in the latter the spring bloom had already started, despite very low, even negative, temperatures (Pastuszak *et al.* 1996). These authors indicated that the nutrient concentrations measured in the south-western subregion, in particular those of inorganic nitrogen and silicon, were several times higher there than in the north-eastern subregion. A hydrochemical situation like this would favour a phytoplankton bloom and thus give rise to much higher oxygen concentrations (by *ca* 06–1 $\mathrm{cm^3\,dm^{-3}}$) in the south-western part than in the north-eastern area .

The highest *in situ* phytoplankton production, $> 800\,\mathrm{mgC\,m^{-2}\,d^{-1}}$, was reported at stations 49 and 19, which values must have been due to large chlorophyll concentrations and a high photosynthetic rate. The potential production measured at the same stations and the calculated assimilation numbers (AN) (Fig. 5) were some of the highest measured in this period, their respective values being 34 and $2.6\,\mathrm{mgC\,mgChl^{-1}\,h^{-1}}$. Nutrient concentrations at these stations were also high. The trophic conditions were therefore propititious for phytoplankton production, and the high chlorophyll *a* concentrations indicated that photosynthesis there must have been intense for some time already.

Chlorophyll concentrations were highest at station 22 ($27\,\mathrm{mg\,m^{-3}}$); unfortunately, however, measurements of both types of production are not available from there. With an optimum nutrient supply and favourable light conditions, higher chlorophyll concentrations as a rule go hand in hand with higher plankton production (Woźniak *et al.* 1989, Renk & Ochocki 1998). However, there are exceptions, *e.g.* station 38 where at relatively high chlorophyll concentrations ($7.01\,\mathrm{mg\,m^{-3}}$) and at very high nutrient concentrations the primary production was unexpectedly low ($19.3\,\mathrm{mgC\,m^{-2}\,d^{-1}}$). In all probability, this was not the result of poor irradiation conditions ($5\,\mathrm{MJ\,m^{-2}\,d^{-1}}$) there. This inference is drawn from the fact that at other stations, where solar irradiation energy doses were 2.5 times lower, the chlorophyll concentration was indeed lower, but production was one order of magnitude higher (*e.g.* st. 67, where the irradiation was $2\,\mathrm{MJ\,m^{-2}\,d^{-1}}$, chlorophyll – $4.56\,\mathrm{mg\,m^{-3}}$, pp – $199\,\mathrm{mgC\,m^{-2}\,d^{-1}}$). The relative shallowness of this station (~ 9.5 m) should not have been the cause of such an effect either – 80–90% of the entire euphotic layer production takes place in the top 10 m layer (Ochocki *et al.* 1995b). The same thing was observed in the case of potential production as long as there was saturation irradiation. This is a direct indication of the fact that irradiation was not

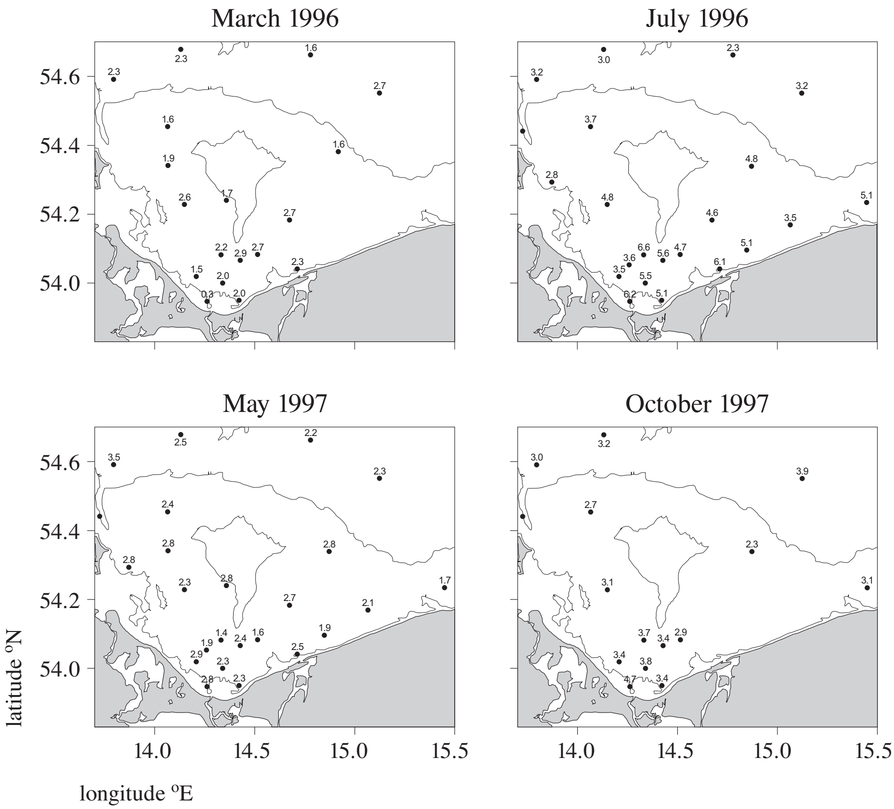

Fig. 5. Average assimilation numbers [mgC mgChl^{-1} h^{-1}] at 0.5, 5 and 10 m depth in particular months in 1996–1997

the main factor limiting photosynthesis. The ratio of potential production in volume and time units to chlorophyll concentration in the same volume unit is called the assimilation number (AN). This number, an index of the photosynthetic rate, was exceptionally low (0.33 mgC mgChl^{-1} h^{-1}) (Fig. 5). At the other stations the assimilation number ranged from 1.5 to 3 mgC mgChl^{-1} h^{-1}. Such a low photosynthetic rate could mean that the majority of plankton cells in the whole population were dead, or that the phytoplankton species composition could have altered. The explanation of this phenomenon may also lie in the presence of some organic or inorganic inhibitor (Ochocki *et al.* 1987). The very high concentrations of nutrients recorded there, in particular nitrates (*ca* 30 μmol dm^{-3}) and ammonia (13 μmol dm^{-3}), could have had an inhibiting effect (Renk *et al.* 1992).

The vicinity of station 31 was also characteristic as one of relatively high *in situ* production; moreover, one of the highest potential productions was recorded there. Although the assimilation number was not the highest, that area exhibited high chlorophyll *a* concentrations, which underscores its peculiarity, as indicated by physico-chemical studies and the phytoplankton composition (Gromisz *et al.* 1999, this volume).

The distribution of potential phytoplankton productions (Fig. 3) was the same as those of *in situ* productions and chlorophyll *a* concentrations; in most cases, primary productions in the SW subarea was one order of magnitude higher than in the NE subarea. This must have been caused by great differences in chlorophyll concentrations between these two subareas, and not by assimilation numbers, as the latter did not suggest such great spatial differences. This means that the potential phytoplankton production in March, except off the Świna mouth, was much more uniform over the entire Bay (min. AN – 1.59 mgC mgChl^{-1} h^{-1}, max. AN – 2.92 mgC mgChl^{-1} h^{-1}) than would appear from the *in situ* and potential productions, or from chlorophyll *a* concentrations.

The May 1997 chlorophyll *a* concentrations were distinctly different east and west of Dziwnów. Except at station 6, concentrations E and NE of Dziwnów are several times lower than W and NW of that place. This picture remains in quite good agreement with the distributions of hydrological and hydrochemical parameters in that month (Pastuszak *et al.* 1998).

The May *in situ* and potential productions differed greatly in the north-east of the Bay and its other sectors (Figs. 2 and 3). Both productions were lower in the eastern and northern subregions of the Bay.

The distributions of nutrients in May were striking, as the whole Bay could be divided into two subregions, there being depletion of nitrates in the north-east and of phosphates in the north-west and west (inshore water included). Both nutrients can limit primary production, but it is hard to confirm this solely on the basis of production measurements. It is well known that the absolute primary production under the same or similar trophic, temperature and light conditions depends very much on the initial biomass of the producer, *i.e.* phytoplankton abundance. In order to meet this requirement, assimilation numbers were calculated (Fig. 5). Comparison of these assimilation numbers does not show up such distinct differences between these subregions as was the case with primary production or chlorophyll *a* (from 1.4 to 3.4 mgC mgChl^{-1} h^{-1}) neither is there any clear division of the Bay into two subregions. High and low ANs were recorded in both parts of the Bay, which means that nitrates and phosphates did not distinctly and unequivocally limit primary production at any given stage of phytoplankton growth. There was one case when AN was higher than average at >3 mgC mgChl^{-1} h^{-1}, and five cases when AN was lower than average at <2 mgC mgChl^{-1} h^{-1}. The latter cases were detected in the coastal zone, *i.e.* no further than 6 Nm offshore. In the remaining 18 cases, AN was between 2 and 3 $\mathrm{mgC\,mgChl^{-1}\,h^{-1}}$.

The July results were much less varied, the distribution being typical of summer in coastal waters (Ochocki *et al.* 1995a,b). Production and chlorophyll *a* concentrations were highest in the coastal zone, off the Świna and Dziwna mouths, and these values coincided with the highest nutrient concentrations. The highest photosynthetic rate was recorded north and east of the Świna mouth and east of the Dziwna mouth, which must have been connected with the trophic conditions there.

In the northern part of the Bay, where only traces of nitrogen and phosphorus were measured, the assimilation numbers were 2–3 times lower. The production potential was much greater in the coastal zone as compared with the open waters (northern part of the Bay).

In autumn, the chlorophyll distribution in the open Bay waters was relatively uniform with average values around 2 $\mathrm{mg\,m^{-3}}$. The area near the Świna mouth was characterised by much higher concentrations of this pigment, which were as high as 10 $\mathrm{mg\,m^{-3}}$ at station 37. However, the *in situ* primary production there was much lower in autumn than in spring, despite the similar temperature. Thus, environmental conditions at stations 38, 31 and 27 seem to be more favourable for production in May than in October. Analysis of the trophic and physical conditions in the two seasons shows up the lack of phosphates in May and the quite high nutrient concentrations in October. The lower water transparency in May limited the thickness of the photosynthetic layer. The water temperature in both seasons was comparable, the differences being no greater than 2°C. In two cases chlorophyll concentrations were higher in autumn (stations 31 and 27) and in one case (station 38) in spring. One should therefore expect photosynthesis to be more effective and primary production to be higher in autumn. The potential primary production measured at the same time, and AN in particular (Fig. 5), do in fact confirm a higher rate of phytoplankton production in the zone adjacent to the Świna mouth in autumn than in spring. Hence, the cause of this low real production in October was not chemical. Rather, it was an energy factor connected with the solar irradiance (the temperature was comparable in both seasons). The low doses of energy in October, especially at station 38, resulted in a sevenfold lower production there, and a 1.5 times lower production at stations 31 and 27 as compared with the spring values. Production was lower despite the favourable nutrient conditions in autumn. The respective irradiations at these stations in spring and autumn were as follows: st. 27 – 25.3 and 8.8 $\mathrm{MJ\,m^{-2}\,d^{-1}}$, st. 31 – 22 and 6.6 $\mathrm{MJ\,m^{-2}\,d^{-1}}$, st. 38 – 15.2 and 2.5 $\mathrm{MJ\,m^{-2}\,d^{-1}}$.

A more detailed analysis of the dependence between the photosynthetic rate, and nutrients and temperature, with the application of photosynthetic light curves and mathematical calculations, is presented in Renk *et al.* 1999 (this volume).

The results, in particular chlorophyll *a* concentrations and the assimilation numbers, indicate that there are considerable differences in phytoplankton biomass and photosynthetic rate in the open Pomeranian Bay

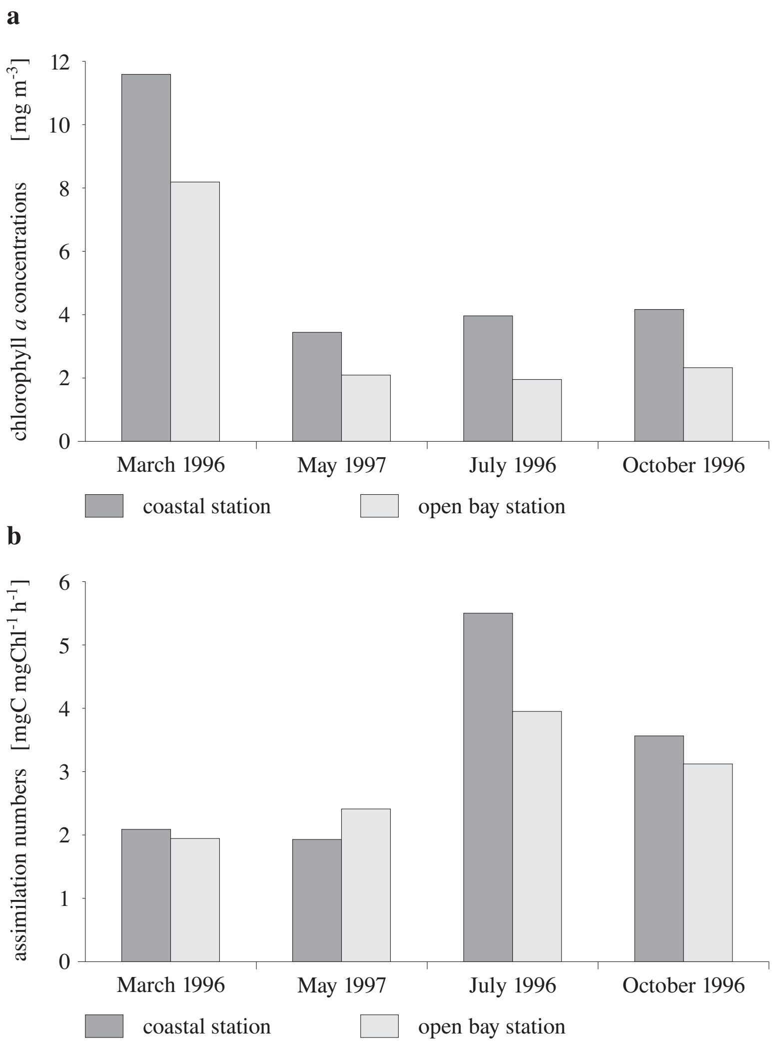

Fig. 6. Average chlorophyll *a* concentrations [$\mathrm{mg\,m^{-3}}$] (a) and assimilation numbers [$\mathrm{mgC\,mgChl^{-1}\,h^{-1}}$] (b) in the inshore and open waters of the Pomeranian Bay in particular months in 1996–1997

as compared with its inshore waters. Latitude 54.2°N was assumed to be the line dividing the open sea from inshore waters, and the average chlorophyll concentrations and assimilation numbers for these zones in the various months are shown in Fig. 6. The greatest differences in the two parameters between these zones were observed during intensive summer phytoplankton growth (July) when nutrients are depleted in the open Bay waters, hence the average assimilation numbers and chlorophyll *a* concentrations were much lower than the open Bay values. Moreover, in all the months except May, when the mean AN was lower in the coastal zone then in the open Bay, chlorophyll *a* concentrations and ANs were always lower in open Bay waters. In May, as has already been mentioned, the hydrochemical situation was very unusual (Pastuszak *et al.* 1996): phosphates were depleted in inshore waters, and nitrates exhausted in the open bay waters. The fact that mean ANs in the former area were lower than in the latter would indicate that a lack of phosphate retarded photosynthesis to a greater degree than a lack of nitrates. A similar phenomenon has been observed in other bays of the Baltic Sea. According to Graneli *et al.* (1990), Piirsoo (1993) and Renk (1997), the scarcity of phosphates is responsible for limiting primary production in the Gulfs of Finland, Bothnia, Riga and Gdańsk.

5. Conclusions

- Values and distributions of chlorophyll *a* and primary production are closely connected with the dynamics and physico-chemical parameters of the Pomeranian Bay waters.
- In March 1996 there was a distinct phytoplankton bloom in the south-western part of the Bay. The primary production and chlorophyll concentrations in the north-eastern part of the bay was indicative of winter conditions at that time. Photosynthesis was inhibited in the vicinity of the Świna mouth (station 38), most probably because of chemical factors in the water.
- In July 1997, the distribution and concentrations of chlorophyll were typical of summer, the photosynthetic rate being 2–3 times lower in the northern part of the Bay in comparison with the Świna and Dziwna mouths. The summer photosynthetic rate (AN) was 2–3 times higher than the winter figure in the entire Pomeranian Bay. Seasonal variability in phytoplankton production is typical at these times and is governed mainly by the temperature and phytoplankton species composition.

- *In situ* production off the Świna mouth was higher in spring than in autumn 1997, despite the comparable temperatures in both seasons and the scarcity of phosphorus in May. Light was the main factor limiting *in situ* production in autumn.
- Riverine waters exert a distinct eutrophic impact on inshore waters as far as latitude 54.2°N. Chlorophyll concentrations and the photosynthetic rate in this area are usually higher than in the open bay waters regardless of season. Phosphate scarcity in the inshore bay waters is the main factor limiting the photosynthetic rate there.

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