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Thresholds of Environmental Sustainability
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Threshold nutrient levels for harmful algal events in some European coastal waters.

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Executive Summary

This report evaluates an analyses of the correlation between nutrient data and harmful algal events in the Baltic Sea, Danish waters and Norwegian coastal waters.

In the Baltic Sea total nitrogen and phosphorus concentrations and inorganic phosphate and nitrate concentrations were correlated with cyanobacterial bloom data during the period 1982 – 1994. The extension of potentially harmful floating cyanobacterial blooms as observed by satellite did not correlate directly with nutrient concentrations. This suggests that phosphate concentrations in the surface layers are a poor predictor for cyanobacterial bloom formation. However, a significant linear correlation was found between the bloom area of one year and surface concentrations of total dissolved phosphorus, dissolved reactive phosphate during winter, or excess phosphate after the spring bloom for the following year. This suggests that cyanobacterial floating blooms in the Baltic Sea contribute to phosphorus enrichment in the surface waters of the open Baltic Sea.

For the Danish marine waters, nutrient concentrations were correlated with the summed number of mussel closure days per year due to DSP causative species (Dinophysis spp.) for a number of areas. Linear regression analyses yielded no significant correlations. In the future, more data will be gathered, and other types of analyses will be tested.

For Norwegian coastal waters, nutrient loads were related to the presence of potentially toxic dinoflagellates (PSP and DSP causative species) for the period 1990-2000. No significant correlations were found. Moreover, both nutrient and harmful algae data appeared to be inconsistent over time.

In none of the analyses mentioned above, significant correlations between nutrient concentrations and/or loads were found. Therefore, no threshold nutrient concentration or load could be detected. Further analyses will concentrate on the acquisition of more and better data, solving some existing inconsistencies and applying non-linear methods to the available data. Also, data outside the Nordic countries will be accessed and included in a further analyses of thresholds of nutrient concentrations for harmful algal blooms.

1. Introduction

Algal blooms that interfere with human activities are called Harmful Algal blooms. There is substantial scientific evidence that the frequency and magnitude of this kind of blooms has increased during the last few decades. There is also substantial evidence that this increase coincided with the anthropogenic increase in nutrient input in the environment, and that there is a causal relationship of phytoplankton growth and nutrient loads. However, efforts to correlate the concentrations of nutrients to the occurrence of HABs in marine coastal waters have so far failed.

The overall objective of this workpackage is to search for relationships between nutrient concentrations or loads on one hand, and harmful algal effects on the other hand. Other parts of the project deal with the relation between algal biomass and nutrient concentrations.

In marine coastal waters, threshold concentrations of nutrients for the occurrence of harmful algal blooms and events related to the occurrence of these blooms can be expected. Mechanisms for a possible threshold response has earlier been reflected upon in several theoretical studies (e.g. (Riegman 1994) (Thingstad 1990)). At low resource availabilities, resource competition is the main factor regulating phytoplankton biomass and competition. Small phytoplankton will dominate on the basis of their better surface to biomass ratio (Stolte 1996). With increasing resource concentration, the biomass of these small phytoplankton species are limited by fast-responding grazers, such as flagellates and ciliates. At this higher resource availability, part of the resources can not be exploited by these competitive species because they are grazer controlled, and other phytoplankton can dominate the community. These are usually species that are slightly less competitive for the uptake of limiting resources, but may have other features that hinder grazers from preying upon them. Most harmful algae have some kind of feature that makes them less palateble to grazers, such as spiny structures, tough cell walls, and/or toxins. Therefore, harmful algal events would only occur over a certain resource threshold. In marine coastal waters either nitrogen or phosphorus are often limiting phytoplankton production. Our study concentrates therefore on these two nutrients. Although there is reason to believe that there may be a nutrient threshold for harmful algal blooms and events, it is unlikely that all species that we call harmful have the same population behaviour. This study divides therefore the available data in different geographical areas, and different harmful algal event types.

2. Methodology

In general the following methodology was followed: In an earlier part within this workpackage, a database was constructed with harmful algal events (HAE) in European coastal waters (Deliverable 3.1.1). This database is the base for the current analysis. In order to be able to correlate the occurrence of HAE and nutrient concentrations or loads, all data were recalculated to the sum of the number of event-days per year for each location. Data were, if possible, corrected for sampling effort by normalizing for the number of measured stations and the frequency of sampling. For the areas that nutrient data were available for the same period as the HAE, data on total nitrogen (TN) and total phosphorus (TP) were averaged over a calendar year period and compared with the number of eventdays per year. As a first approach, a linear regression technique was applied to find out if the HAE data were correlated with the nutrient data. This analysis was performed for every area of interest (see below). This analysis was performed for three areas: Baltic Sea proper, Danish coastal waters, and the Norwegion coast. This choice is made on the basis of available nutrient data and their overlap with available HAE data at this stage of the project. It is expected that more data will become available for analyses at a later stage.

2.1. The Baltic Sea Proper

The nutrient data available for the Baltic Proper were downloaded from a public database (SHARK; Svensk HavsARKiv) webaddress: http://www.smhi.se/oceanografi/oce_info_data/shark/home_order_sv.html.
Data from 0–10 meter from the station BY15 were used as being representative for the open Baltic Sea. Data on Harmful algal events were obtained in three different ways:

1. Surface chlorophyll-a concentrations obtained from the SHARK database.
2. Cyanobacterial floating layers coverage as observed from satellite. Data on total area covered by accumulations of cyanobacteria were kindly provided by Mati Kahru. Bloom area data were corrected for sampling frequency. The methodology is published in (Kahru 1997). Data have been obtained from 1982 – 1994.
3. Reports in Swedish newspapers on harmful algal events using the database "Artikelsök". In the Baltic Sea, cyanobacterial blooms are the main cause for harmful algal events. This affects mostly tourism at the east-coast of Sweden. Each summer, newspaper articles report when floating cyanobacterial layers float into land and interferes with tourism activities. The number of newspaper articles may be a measure for the magnitude of the problem in a year. Yearly averaged number of newspaper articles were obtained from he above mentioned database by applying the boolean search string "(algblomning* OR giftalg* OR alggift* OR blågrönalg*) AND year", which means: "(algal bloom* OR toxic alga* OR algal toxin* OR bluegreen alg*) AND year".
4. Directly from the HAE database described in Deliverable 3.1.1. The data on the Baltic Sea in this database are all adopted from the HAEDAT database of HAB events maintained by the Intergovernmental Oceanographic Commission (IOC). It covers events reported by different scientists in the Baltic Sea region. The disadvantage with these data is that the frequency of sampling is not known. Most likely, the sampling effort is irregular in time and space.

2.2. Denmark

Nutrient data from the Danish coastal areas were obtained from the danish national database for marine data (MADS), available at: http://www2.dmu.dk/1_Viden/2_Miljoe-tilstand/3_vand/4_mads_ny/Vandkemi2_en.asp. This database covers data from 1989 to 1994 for different stations. The data were made compatible with the HAE database by grouping the nutrient stations so that maximum overlap occurred with the different regions in the HAE database. The log transformed data of total nitrogen, total phosphorus and winter (Dec previous year, Jan, Feb) nitrate and phosphate concentrations were averaged over the different stations and over the year and after that they were transformed back. This was done to decrease the influence of extreme values and to account for the increasing variance in the data with increasing average.
There were two kinds of data in the HAE database for Denmark, data on shellfish culture closures due to too high numbers of toxic phytoplankton (97 % of summed event-days) and fish killing phytoplankton species (3 %). Only shellfish toxicity risk data were used for the analysis.

2.3. Norwegian coastal waters

For the Norwegian coastal waters, data on nutrient loads were used in stead of nutrient concentrations. The data on nutrient loads to Norwegian waters are available via the website of the "State of the Environment Norway" (www.environment.no). The data are classified in four areas:

1. Skagerrak
2. North Sea
3. Norwegian Sea

4. Barentz Sea
5. sum of the four above.

As a first approach, the occurrence of HAE in Norway was tested against the total load to Norwegian waters.

The sum of harmful algal eventdays for each year was corrected for the sampling effort at that particular year, because the number of sampled stations varied. The vast majority of the data on HAE that were available at the time of analysis consist of wild blue mussel toxicity. Both PSP and DSP toxicity data were available, but for this analysis, all mussel toxicity events were summed.

3. Results

3.1. The Baltic Sea Proper

3.1.1. Time trends

The data from station BY15 in the Baltic Sea Proper on total phosphorus show an increasing trend for the years 1969 to the end of the 1980's. From the beginning of the 1990's, a slight decreasing trend is seen. Winter concentrations of phosphate show more or less the same trend. Total nitrogen concentrations show an increase to the end of the 1990's, whereafter a tendency to a decreasing trend may be observed. Winter nitrate concentrations over the same period show a clear decreasing trend from about 1980 to 1997.

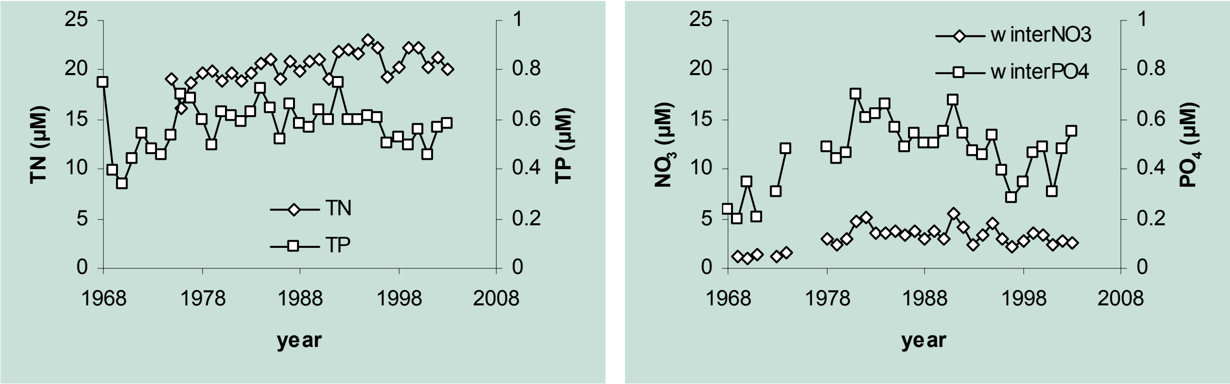


Figure 3-1 Time trends of total nitrogen and total phosphorus (left panel) and winter concentrations (average December, January and February) of nitrate and dissolved reactive phosphate (right panel) at station BY 15 in the Baltic Sea Proper (0-10 m).

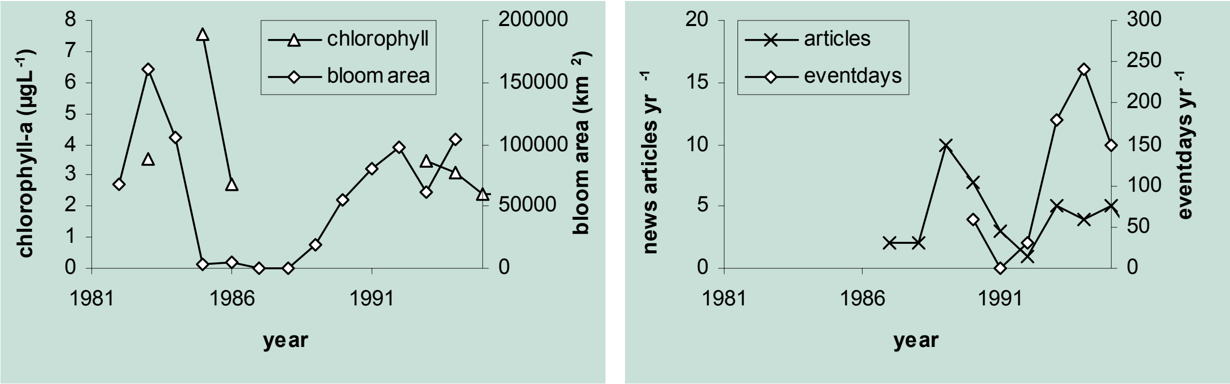


Figure 3-2 Time trend of algal blooms indicators. Left panel: Average chlorophyll-a from 0-10 m deep at station BY 15 and estimated cyanobacterial bloom area in the Baltic Sea proper (Kahru 1997) for each year. Right panel: number of newspaper articles in Swedish newspapers and sum of eventdays from the HAE database.

The data available for the four different measures for harmful algal bloom events were varying in frequency. Most data exist at this moment on the area of cyanobacterial floating layers (Kahru 1997), which are available for 1982 1994. The data show no time trend over this period, but two distinct periods with large area blooms can be distinguished, and a period with hardly any floating blooms (1985-1988) between. This has earlier been explained by climatic factors (Kahru 1997). Chlorophyll-a concentration data from the same station were more scarce, and did not vary in the same way as estimated bloom area. During 1985 and 1986 chlorophyll concentrations were high, whereas floating blooms were virtually absent. The two other types of harmful event indicators, newspaper articles and sum of eventdays from the HAE database both showed minima during 1991 and 1992, which were not observed in the bloom area data. No overall trends could be observed, partly because of the low number of data. For further analyses, the estimated bloom area data were used, because they were available over the longest period.

The estimated bloom area seems to covary with winter phosphate concentration although winter phosphate minima and maxima seem to occur one or two years later than minima and maxima in estimated bloom area. Bloom area seemed to covary less with winter nitrate concentrations and winter nitrate/phosphate ratios (Figure 3-3).

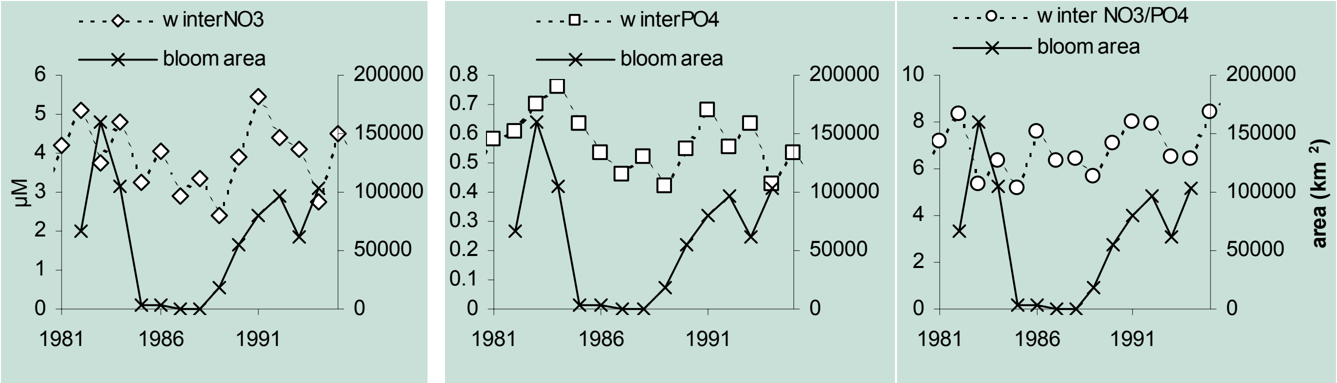


Figure 3-3 Time trends of winter surface concentrations (average Dec year before, Jan, Feb; 0-10 m) of nitrate, phosphate and the nitrate/phosphate ratio for the years 1981-1995 at BY15, together with cyanobacterial bloom area for 1982-1994.

The patterns of covariation between estimated bloom area and TN, respectively TP and TN/TP ratio were similar to those of winter phosphate. Only TP seemed to covary with bloom area, and also here there seemed to be a one year delay between bloom area and TP concentrations (Figure 3-4).

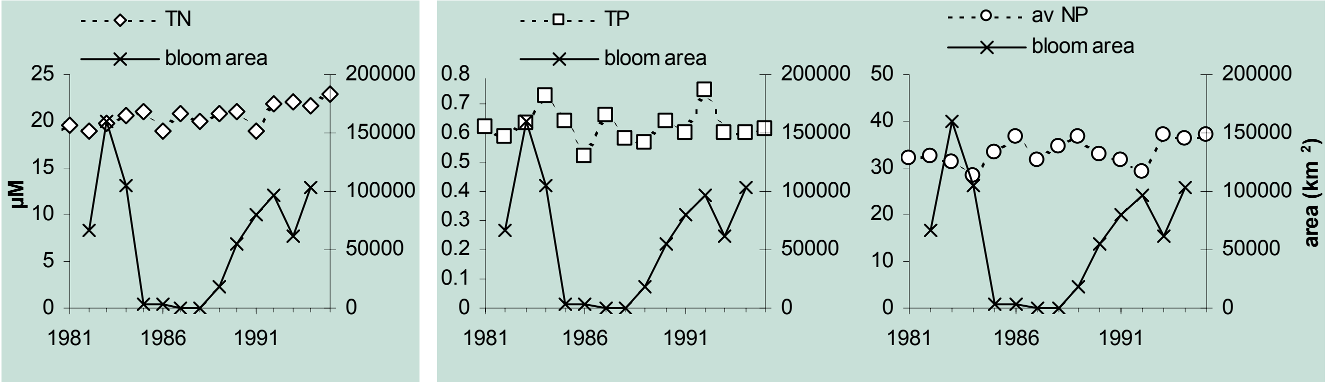


Figure 3-4 Time trends of yearly averaged surface concentrations (Jan-Dec; 0-10 m) of total nitrogen, total phosphorus and the ratio of TN/TP for the years 1981-1995 at BY15, together with cyanobacterial bloom area for 1982-1994.

Excess phosphate, defined as the concentration of phosphate that theoretical is available after the spring bloom (calculated as winterPO4 – winterNO3/16), showed approximately the same pattern as winter phosphate. The measured phosphate concentration in the month May, which should be after the spring bloom, showed somewhat lower values in general (Figure 3-5).

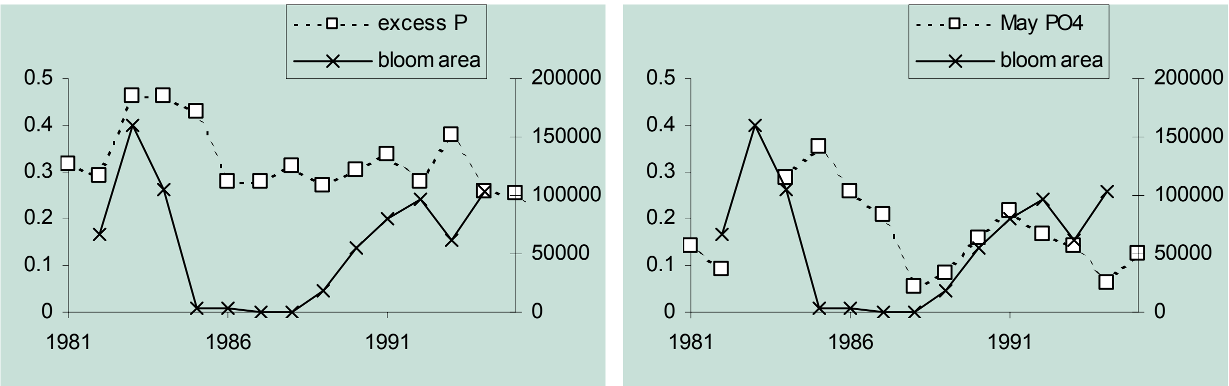


Figure 3-5 Time trends of yearly averaged surface concentrations of excess phosphate (winter phosphate - winter nitrate/16; left panel) and phosphate concentrations in may (after the spring bloom) for the years 1981-1995 at BY15, together with cyanobacterial bloom area for 1982-1994.

3.1.2. Correlations of bloom indicators with nutrient concentrations.

The covariation between estimated bloom area during different years and nutrient concentrations is made more clear in 2-dimensional plots. Bloom area correlated significantly (linear regression) with surface (0-10 m) phosphate concentrations during the next winter, but not with surface concentrations from the previous winter or with surface nitrate concentrations during the previous or next winter (Figure 3-6).

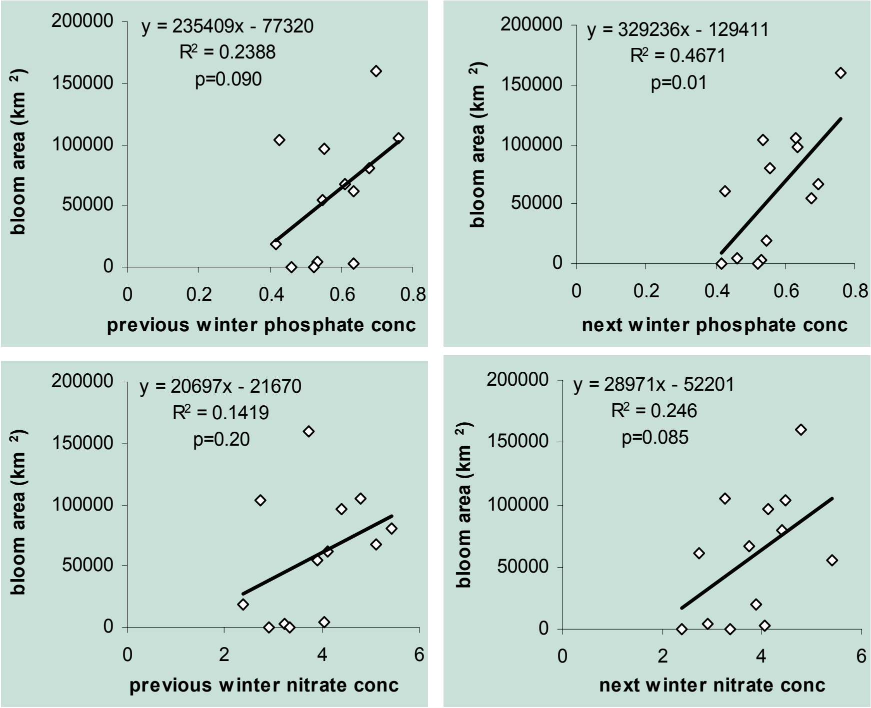


Figure 3-6 Correlations between cyanobacterial bloom area and this and next years surface (Jan-Dec; 0-10 m) concentrations of phosphate and nitrate (in µM). At a 0.05 level, only the correlation with next winters phosphate concentration is significant.

The covariation between bloom area and yearly averaged total phosphorus was very much similar. Only the correlation (using linear regression) between bloom area and next years average TP was significant (Figure 3-7). Both results suggests that cyanobacterial blooms contribute to the next years total dissolve phosphorus concentrations in the surface layer.

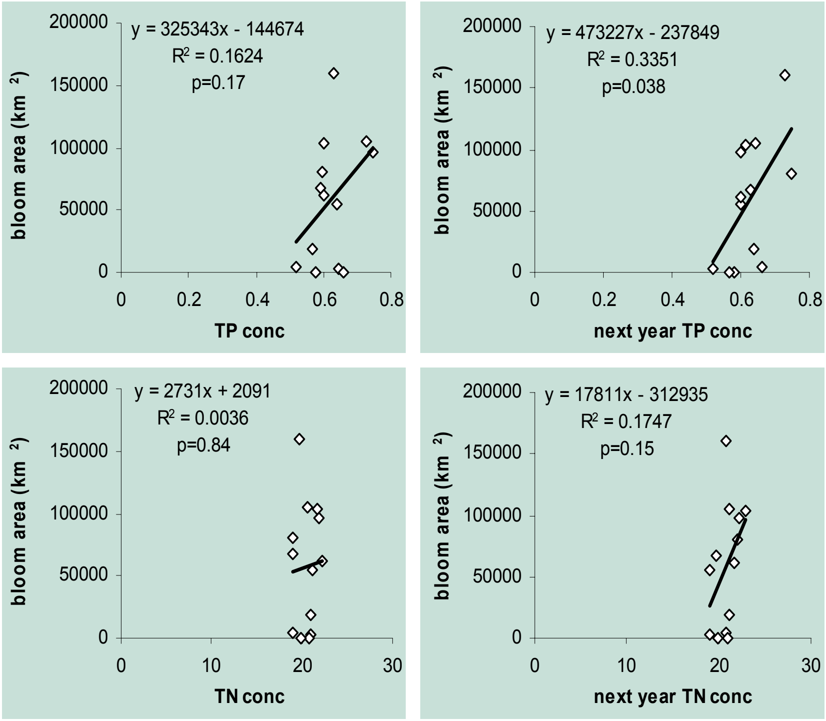


Figure 3-7 Correlations between cyanobacterial bloom area and concentrations of total surface (Jan-Dec; 0-10 m) yearly averaged total phosphorus and nitrogen (in µM) from the same year (left panels) respecively next year (right panels). At a 0.05 level, only the correlation with next years TP is significant.

The amount of phosphate that is available for cyanobacterial blooms is sometimes called “excess phosphate”. This is the concentration of phosphate theoretically left over after the spring bloom. This definition assumes that spring bloom algae take up phosphate relative to nitrate according to the Redfield ratio (1:16 mol:mol) and that phosphate uptake is halted once nitrate is depleted. The excess phosphate was calculated for every year as:

excess phosphate = winter phosphate – winter nitrate/16

Plotting these values against estimated bloom area of the same year, no significant linear relationship seems to occur. However, estimated bloom area did correlate with excess phosphate during the next year, analogous to the above described results.

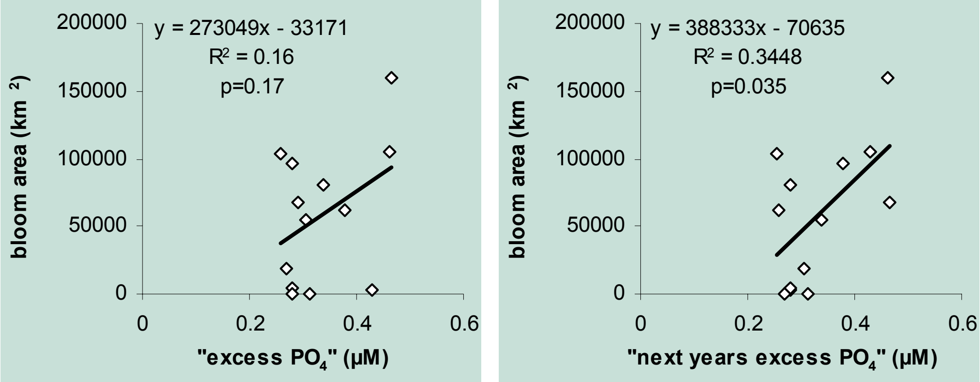
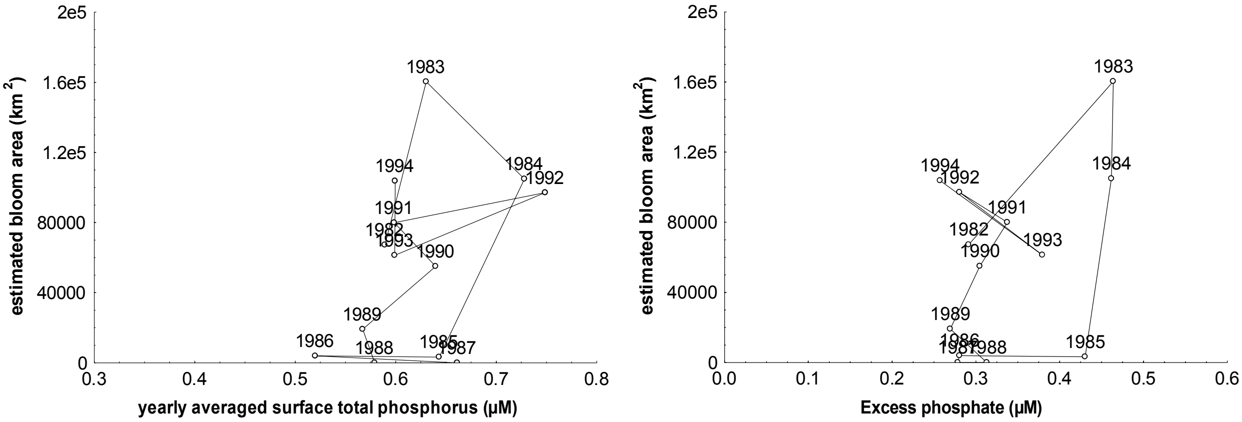


Figure 3-8 Variation of cyanobacterial bloom area with "excess phosphate" during the same year calculated as (winterphosphate – winternitrate/16) (left panel) and excess phosphate during the year after (right panel) Only the correlation with next years excess phosphate was significant using linear regression.

Bloom areas were not correlated significantly with nutrient concentrations prior to the bloom. Apparently, other factors dominate the formation of floating cyanobacterial blooms in the Baltic Sea, presumably temperature and solar irradiation. However, cyanobacteria consume phosphorus, and phosphate has to be available in order to have a bloom in a certain year.

On the other hand estimated bloom areas were correlated with winter phosphate, total phosphorus, and excess phosphate in the year after the bloom (Figure 3-6, Figure 3-7, upper right panels, Figure 3-8, right panel). This suggests that cyanobacterial blooms positively affect the phosphate concentrations in the surface layers.



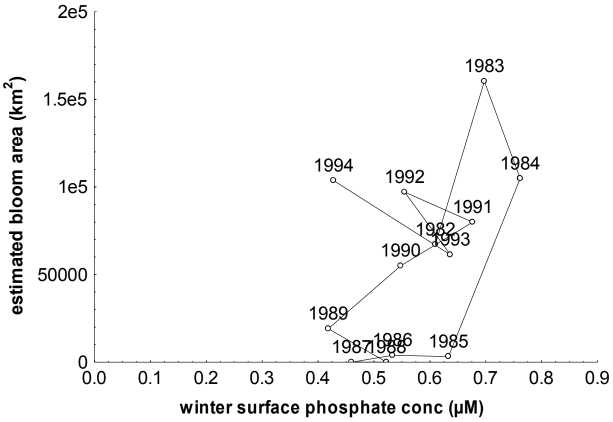


Figure 3-9 Trajectory plots of estimated bloom area against yearly averaged surface total phosphorus (upper left panel), excess phosphate after the spring bloom (upper right panel) and winter surface phosphate concentrations (lower left panel).

This is also shown in the trajectory plots for surface concentrations of total phosphorus, excess phosphate, and winter phosphate (Figure 3-9). These plots show hysteresis, rather than a straightforward correlation between phosphate and bloom area.

In shallow lakes, often the reverse trend is observed, i.e. a delayed response of phytoplankton blooms after a decrease in nutrient concentrations. In the period between 1982 and 1991, cyanobacterial bloom area does not seem to respond to nutrient concentrations, but rather the reversed effect if observed. A hypothetical scenario is that from 1983 to 1987, phytoplankton blooms decreased due to unfavourable climatic conditions such as relatively cool and windy summers. As a response to this, less phosphate is retained in the surface layer (here calculated for 0-10 m), causing on average a decrease in total phosphorus, reactive phosphate and excess phosphate during that period. From 1989, cyanobacterial blooms increased again, followed by an increase of total phosphorus, reactive phosphate and excess phosphate up to 1991. After 1991, there is variation in both bloom area and nutrient concentrations, but no obvious trend.

3.1.3. Thresholds for harmful algal events in the Baltic Proper

At this stage of analysis, there is no clear threshold nutrient concentration for the occurence of cyanobacterial floating blooms in the Baltic Proper. This is partly due to the relatively low variation in nutrient concentrations over the considered period. Since the cyanobacterial bloom area only correlated with next years phosphorus concentrations, it cannot either be concluded that nutrient concentration is the proximate causal factor for formation of the bloom.

3.2. Denmark

The analysis of data for Danish coastal waters is still in progress, and should therefore be taken with caution. Further analysis will include corrections for possible differences in sampling effort of the HAE events, and algoritms in order to increase the compatibility between areas.

None of the relationships between nutrients and HAE was significant at $p=0.05$ level. Some preliminary trends can be observed however. In Limfjorden and Roskilde fjord, harmful algal events seem to covary with winter phosphate, and to a lesser extent winter nitrate concentrations. We have not been able to test for threshold values statistically yet, but for example, in Roskilde fjord, all years with no observed harmful algal events coincided with winter phosphate concentrations of lower than ca. 45 μg P L^{-1}. This might indicate a threshold value for this particulate area. In Limfjorden area, HAE occurred at winter phosphate concentrations as low as 5 µg P L^{-1}, although a higher number of HA eventdays were observed at higher winter phosphate concentrations.

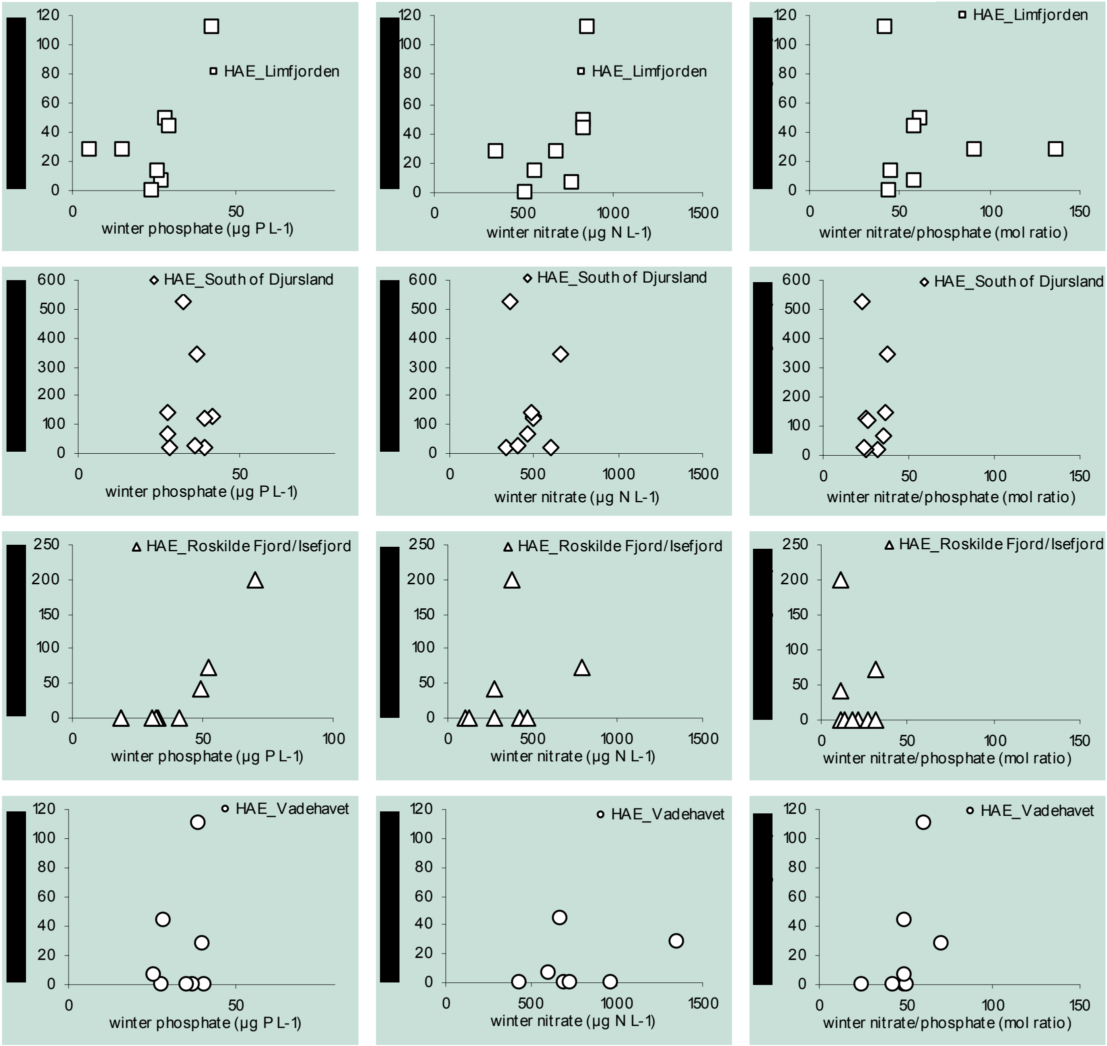


Figure 3-10 Preliminary results for the correlations between harmful algal events (mussel culture closures) and winter phosphate (left panels), nitrate (mid panels) and N/P ratios (right panels) in four different regions of the Danish coast.

3.3. Norwegian coastal waters

So far, the analysis has been restricted to nutrient loads, because data on nutrient concentration were not available over a time span corresponding to the HAE data. The time trend of nutrient loads can be divided in two periods, before and after 2000. Before 2000, both nitrogen and phosphorus loads are more or less contant. The same is true from 2000 and further. However, from 1999 to 2000, phosphorus loads approximately doubled, and nitrogen loads increased with about 10 to 20 thousand tons (Figure 3-11). There is at this moment no satisfying explanation for this sudden increase. Some inconstency between the data before and after 2000 could not be excluded.

Moreover, the sum of eventdays per station for Norwegian coastal waters also shows a jump, from 1993 to 1994. This coincides with a change in the monitoring programme. In the year 1994, number of stations were added. Even though the eventdays were normalized per station, the jump is still observed. Both inconsistencies need to be solved before a further data analysis can be done.

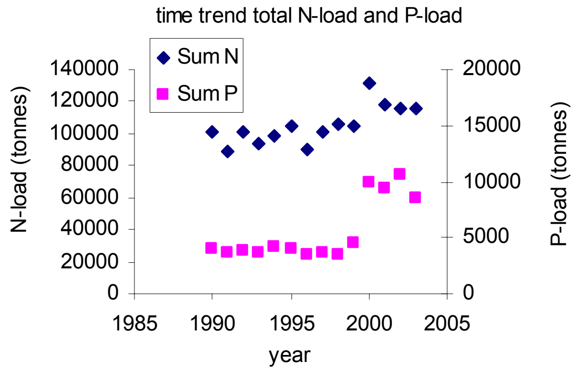


Figure 3-11 Time-trend of nitrogen and phosphorus loads into Norwegian coastal waters.

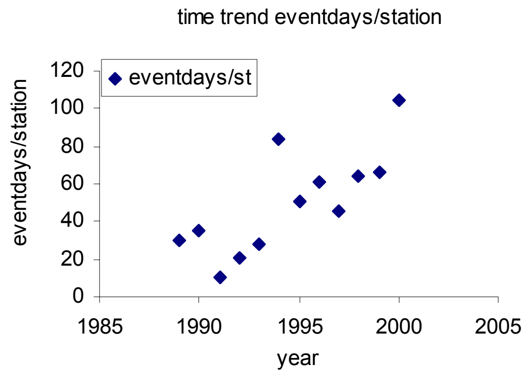


Figure 3-12 Time trend of the sum of harmful algal eventdays per sampling station in Norwegian waters.

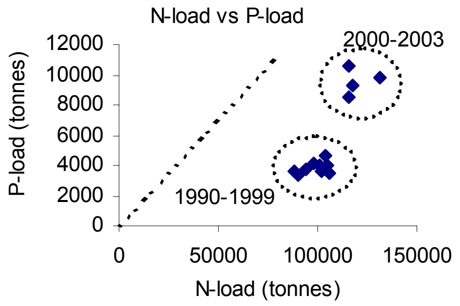


Figure 3-13 Nitrogen versus phosphorus loads to Norwegian coastal waters. The two periods are separated on the basis on their differing P-loads.

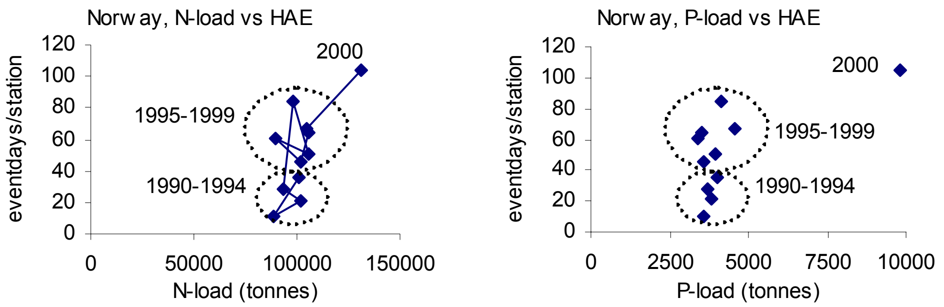


Figure 3-14 The sum of HA eventdays per station as a function of nitrogen (left panel) and phosphorus (right panel) load in Norwegian coastal waters.

4. Conclusions

The correlation between nutrient concentrations or loads and harmful algal events was studied in three different coastal areas: the Baltic Sea, Denmark, and the Norwegian coast. The number of data used in the analysis appeared in most cases to be limited by the availability of data on harmful algal events. Trends were studied using linear regression. In most cases, the variation in nutrient concentrations and/or loads showed relatively low variation over the years, and no clear trends were observed. In Norwegian coastal waters, inconsistent data prevent further analysis. In some regions in the Danish waters, the presence of potentially toxic phytoplankton seemed to covary with nutrient data, but no significant relation was found. In the Baltic Sea, however, cyanobacterial blooms measured as accumulated area over one year correlated with surface concentrations of total phosphorus, winter phosphate and excess phosphate of the following year. This result indicate that surface phosphate concentrations in the Baltic Sea are influenced by cyanobacterial blooms. This is opposite to the hypothesis that nutrient concentrations influence the occurrence of HAE.
Further studies will focus on obtaining new data from these and other regions, and analyzing the data with non-linear regression techniques.

5. Acknowledgements

Jacob Carstensen is acknowledged for extracting the Danish coastal waters nutrient data and Mati Kahru for the data on (Kahru 1997)cyanobacterial bloom areas in the Baltic Sea.

6. References

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