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Typology as a structuring mechanism for phytoplankton composition in the Baltic Sea

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Abstract

Phytoplankton composition is a biological quality element to be used for ecological classification within the Water Framework Directive. Seasonal proportions of diatoms, dinoflagellates, cyanobacteria and chlorophytes calculated from species-specific phytoplankton biovolumes sampled in 38 water bodies within the Baltic Sea were investigated to determine if the typology, defined by salinity, depth and retention time regimes, provided a useful separation of water bodies into groups for intercomparison of phytoplankton compositions. Variations in the phytoplankton composition could be significantly related to a combination of salinity and depth regimes. The significance of retention time as structuring mechanisms could not be properly assessed due to relatively few water bodies with long retention times. Cyanobacteria and chlorophytes were almost completely absent in the more saline and turbulent waters of the Kattegat and Belt Sea, whereas the proportion of diatoms and dinoflagellates generally increased with salinity. The significance of the depth regime relied entirely on few water bodies in the German part of the Baltic Proper that had a phytoplankton composition deviating substantially from other water bodies with similar salinity. Consequently, salinity ranges may provide a useful typology definition for segregating water bodies into distinct groups, however, other characteristics, not exploited in this study, need to be included as well to be able to distinguish different water body types based on their phytoplankton composition.

1 Introduction

The overall aim of the Water Framework Directive (WFD, Directive 2000/60/EC) is to establish good ecological status in all European waters by 2015. For the implementation of WFD all water bodies must be classified into types of similar characteristics based on the geographical, geological, morphological, physical factors governing the functioning and structure of the biological communities. The main purpose of typology is to enable type specific reference conditions to be defined, which in turn are used as the anchor of the classification system (ANONYMOUS 2003). Two main approaches can be taken in the determination of the surface water body types (HEISKANEN et al. 2004): 1) types are defined from knowledge of how physical drivers determine biological communities ('*a priori*' approach), and 2) types are distinguished by analysing survey data from reference sites ('*a posteriori*' approach).

Although the implementation of WFD is a national obligation, a common typology framework for the Baltic Sea has been established through the EU-project CHARM (SCHERNEWSKI & WIELGAT 2004). The '*a priori*' typology established in the CHARM project is based three main factors: 1) salinity, 2) residence time and 3) depth/mixing conditions. For the Baltic Sea three distinct salinity regimes were considered in agreement with the guidance from the WFD Common Implementation Strategy (CIS) working group (ANONYMOUS 2003): oligohaline waters from 0.5 to 6, mesohaline waters from above 6 to 18 and polyhaline waters from above 18 to 30. Estuaries, lagoon and archipelagos with residence time above 30 days were separated from water bodies with more frequent water exchange. Finally, water bodies were separated into shallow (<10 m) and deep (>10 m) in contrast to three CIS recommendation of three distinct classes with 30 m and 50 m as boundaries. In the Baltic Sea water bodies with depths below 10 m are frequently fully mixed and stratification often occurs at depths just below 10 m. Therefore the threshold of 10 m was also used as a surrogate measure for stratification. The aim of the CHARM project, as the next step, was to test the 'ecological relevance' of the '*a priori*' typology using biological data from national monitoring programs.

Phytoplankton is one of four biological quality elements of the WFD and taxonomic composition, abundance, biomass and plankton blooms should be considered for the ecological classification of transitional and coastal waters (Directive 2000/60/EC). Salinity is known to be a structuring mechanism for the phytoplankton composition, since estuaries and coastal areas provide a transition zone between freshwater and marine species. However, between ecosystems there can be large differences in the phytoplankton composition versus salinity. For instance RIJSTENBIL (1987) found that this transition in a Dutch delta was most pronounced for diatom species shifting from freshwater to marine species, whereas LORENZO et al. (2004) documented a shift from large diatoms and dinoflagellates in the estuaries to cyanobacteria in the offshore waters in Western Spain. Although salinity can explain some of the changes in the phytoplankton community of estuaries, it cannot account for all the spatial variation (MUYLAERT et al. 2000). Moreover, turbulent waters are known to favour large phytoplankton (MARGALEF 1979; KIØRBOE 1993), which may also effect the phytoplankton composition in relation to typology, particularly if the tidal influence is large.

Seasonal succession of phytoplankton is another highly important mechanism to consider for phytoplankton composition. Generally the spring bloom in temperate and boreal coastal and offshore waters is dominated by diatoms, shifting towards dinoflagellates and cyanobacteria during summer with diatoms reappearing as the dominating taxonomic group during the autumn blooms (SMAYDA 1980; BIANCHI et al. 2002). However, deviations from this pattern have been reported (e.g. OLLI & HEISKANEN 1999; TAMELANDER & HEISKANEN 2004). Thus, phytoplankton composition as a biological quality element has to take the seasonal shifts into account if such indicator should be useful for ecological classification.

The objective of this study was to investigate if the phytoplankton community structure indicators at different seasons over a wide range of water bodies within the Baltic Sea would verify the typology defined in the CHARM project. This objective was achieved by calculating the mean proportions of different taxonomical groups for the different water bodies and investigating differences in these indicators between the three considered typology definitions.

2 Material and methods

A comprehensive phytoplankton database has been compiled within the framework of the CHARM project covering almost the entire Baltic Sea. The database contains bio-volumes at species level with additional taxonomical, morphological, functional and size group distribution for the different species recorded. In addition, hydrophysical and – chemical measurements from the same samples have been collected from the contributors and combined with the phytoplankton data. The CHARM phytoplankton database included data from 1970 to 2001, however, with the largest amount of data sampled within the last two decades.

In the present study, data from 38 distinct water bodies, including estuaries, coastal and open waters, were selected (Fig. 1) covering the period from 1990 to 2001 when the data coverage was reasonable high and the quality of data presumably better. Due to differences in the national monitoring programs, water bodies were represented by 1 up to 13 stations (Table 1). Stations within water bodies were included only if there were at least 10 samples taken at that particular station. The samples were partitioned according to seasons that varied between the different basins of the Baltic Sea. The definition of seasons was partly extracted from HELCOM (2002) as given in Table 2.

For each phytoplankton sample the proportions of diatoms, dinoflagellates, cyanobacteria, chlorophytes and other species out of the total sample bio-volume were calculated. If a specific taxonomical group was not present in the sample, the zero value was replaced by a sufficiently small bio-volume for the purpose of data transformations below before calculating the proportion. Based on these five taxonomical groups six indicators were examined: 1) proportion of diatoms in spring, 2) proportion of diatoms in autumn, 3) proportion of dinoflagellates in spring, 4) proportion of dinoflagellates in summer, 5) proportion of cyanobacteria in summer and 6) proportion of c*hlorophytes* in summer. Proportions of the taxonomical groups (denoted *P*) were transformed by means of the logistic function in order to obtain data that was approximately normal distributed and unboundedthe logistic function in order to obtain data that was approximately normal distributed and unbounded.

Figure 1: The investigated 38 water bodies within the Baltic Sea comprised a combination of estuaries, coastal and open waters. The numbers refer to the specific water bodies listed in Table 1.

Since the monitoring data was unevenly distributed in time and between stations, mean values for the different indicators were calculated employing a general linear model (e.g. McCullagh & Nelder 1989) taking spatial and temporal variations into account:

Logit(P)=water body + station(water body) + year + month

where *water body* described the mean proportion for the 38 water bodies, *station(water body)* described the variation between monitoring stations within the water body, *year* described the interannual variation common to all water bodies (1990-2001) and *month* described differences between months of sampling. Mean levels of the transformed observations for the 38 water bodies were calculated as marginal means from this model, i.e. producing mean values that were not biased by skewed sampling in time or space. This implied that the mean values for water bodies were represented by the mean level of all monitoring stations within the water body.

The mean proportions for the six indicators were (transformed values) analyzed with respect to typology (salinity, depth and retention regimes) by means of a three-way analysis-of-variance. The significance of the different factors was investigated by means of F-test (type III test) using a 5% significance level. Mean levels for the 3 salinity regimes, the 2 depth regimes and 2 retention regimes were similarly calculated as marginal means from the analysis-of-variance.

Table 1: Typologies for the water bodies investigated and the number of phytoplankton samples taken and stations sampled within each water body (1990-2001). Salinity and depth regimes for the different water bodies were derived from the monitoring data, whereas retention regimes were determined by investigating the location of stations on the typology maps in SCHERNEWSKI & WIELGAT (2004).

No.	**Water body**	**Typology**			**#stations**	**#samples**		
		Sali	Depth	Retent.		Spring	Sum.	Aut.
1	Bothnian Bay Finnish coast	oligo	deep	<30 d	1	8	52	4
2	Bothnian Sea Finnish coast	oligo	deep	<30 d	1	8	19	3
3	Inner archipelago	oligo	deep	<30 d	5	31	56	7
4	Tvärminne coast	meso	deep	<30 d	1	43	58	19
5	Coast east of Helsinki	oligo	shallow	<30 d	2	40	108	31
6	Huovari	oligo	deep	<30 d	13	98	165	33
7	Narva Bay	oligo	deep	<30 d	3	38	46	13
8	Gulf of Finland	oligo	deep	<30 d	11	173	392	116
9	Tallinn Bay	oligo	shallow	<30 d	7	133	350	89
10	Pärnu Bay	oligo	shallow	<30 d	3	68	141	41
11	Gulf of Riga coastal	oligo	shallow	<30 d	6	61	104	37
12	Gulf of Riga open-part	oligo	deep	<30 d	4	86	93	53
13	Curonian Lagoon	oligo	shallow	>30 d	8	130	176	100
14	Lithuanian coast	meso	deep	<30 d	8	53	71	56
15	Bight of Gdansk coastal	meso	shallow	<30 d	4	48	59	10
16	Bight of Gdansk open-part	meso	deep	<30 d	2	29	39	9
17	Coast off Swinoujscie	meso	deep	<30 d	4	63	103	67
18	Oderhaff	oligo	shallow	>30 d	2	64	99	58
19	Greifswalder Bodden	meso	shallow	<30 d	1	47	68	51
20	Prohner Wiek/Bodden	meso	shallow	<30 d	3	74	100	68
21	East of Rügen	meso	deep	<30 d	3	85	146	76
22	West of Rügen	meso	shallow	<30 d	11	164	278	174
23	Der Grabow	oligo	shallow	<30 d	2	23	44	19
24	Warnow estuary	meso	shallow	<30 d	5	40	85	50
25	Warnemünde coast	meso	deep	<30 d	1	54	76	51
26	Mecklenburg Bight	meso	deep	<30 d	3	95	149	86
27	Western Baltic open-part	meso	deep	<30 d	3	47	64	42
28	South Little Belt	meso	deep	<30 d	1	52	65	51
29	Great Belt	meso	deep	<30 d	2	44	72	54
30	The Sound	meso	deep	<30 d	1	34	63	42
31	Kolding Fjord	poly	shallow	<30 d	1	33	74	42
32	Vejle Fjord	poly	shallow	<30 d	1	56	114	65
33	North Little Belt	meso	deep	<30 d	2	74	112	71
34	Horsens Fjord	poly	shallow	<30 d	1	60	91	67
35	Århus Bight	poly	deep	<30 d	1	79	108	76
36	Mariager Fjord	meso	deep	>30 d	1	86	183	95
37	Coastal Kattegat	poly	shallow	<30 d	2	95	147	111
38	Skive Fjord	poly	shallow	<30 d	1	93	147	73

Residuals from the analysis-of-variance were examined for normality (Kolmogorov-Smirnov test), independence and variance homogeneity. Standardized residuals were calculated from the analysis-of-variance and water bodies exceeding the 95% confidence limits of the normal distribution (±1.96) were identified. Mean levels and their confidence limits of the transformed observations were back-transformed to proportions using the inverse logistic function. Consequently, the back-transformed values corresponded to median levels on the proportion scale.

Table 2: Definition of seasons employed in the present study. Water body numbers refer to the list in Table 1.

Baltic Sea regions	**Water body no.**	**Spring**	**Summer**	**Autumn**
Gulf of Bothnia	1-2	Apr-Jun	Jul-Sep	Oct-Nov
Baltic Proper, Gulf of Riga, Gulf of Finland	3-23	Mar-May	Jun-Sep	Oct-Dec
Belt Sea, Sound, Kattegat	24-38	Feb-Apr	May-Aug	Sep-Nov

3 Results

The variation in the considered indicators with respect to typology could be attributed to differences in salinity and depth regimes, whereas the retention time did not have any significant effect on the proportions investigated (Table 3). Discarding retention as explanatory factor did not induce any changes in the significance of the two other factors. Salinity regimes was the most significant source of variation between the water body indicators, except for the proportion of dinoflagellates in spring that varied significantly with depth regimes only. The depth regime also had a significant effect on the proportion of diatoms in autumn, dinoflagellates in summer and cyanobacteria in summer. However, the explanatory power was low for all indicators but the summer proportion of cyanobacteria and chlorophytes, where a substantial part (65%) of the variation could be attributed to differences in salinity regimes (Table 3).

Only the proportion of dinoflagellates in spring did not pass the Kolmogorov-Smirnov test for normality. For this specific indicator data from Der Grabow, East and West of Rügen cropped out with a much smaller proportion than predicted by the typology. The two water bodies, Der Grabow and East of Rügen, were also exceeding the 95% confidence limits for the residuals for some of the other indicators, most pronounced for spring diatoms from Der Grabow having a standardized residual of -3.67, corresponding to a probability of 0.0001 that this observation belongs to the same distribution.

Diatoms were generally favoured by high salinities in both spring and autumn, as was dinoflagellates in summer (Fig. 3). The median proportion of cyanobacteria and *chlorophytes* in summer was approximately 4% for oligohaline water bodies decreasing to less than 1% for mesohaline waters and almost non-observable for polyhaline waters. Dinoflagellates in spring and summer as well as diatoms in autumn had relatively higher proportions for deeper water bodies, whereas the proportion of cyanobacteria in summer was higher in the shallow water bodies

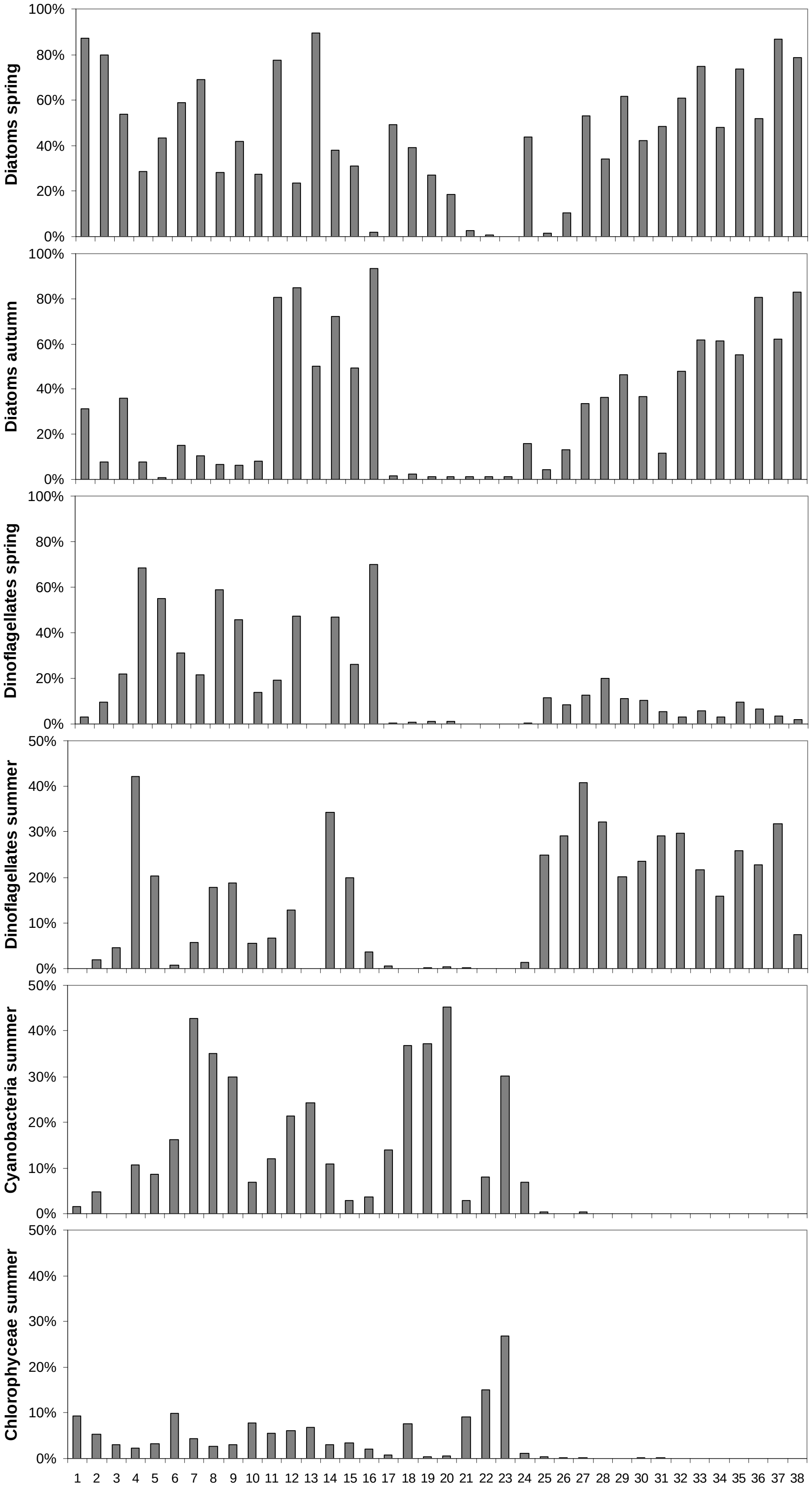

Figure 2: Estimated median proportions of indicators after back-transformation for the 38 water bodies identified by numbers given in Table 1. Note the difference in scaling on the lower three graphs.

Table 3: Analysis-of-variance for mean proportions (transformed values) of the different indicators (n=38 water bodies) analyzed for variation attributable to the typological features of the different water bodies (df=degrees of freedom, F=F test statistic, P=probability of no variation with respect to factor).

Indicator	Factor	df	F	P
Diatoms spring	Salinity regime	2	4.12	0.0253
(R^2=0.23)	Depth regime	1	2.03	0.1636
	Retention	1	1.93	0.1742
Diatoms autumn	Salinity regime	2	4.00	0.0278
(R^2=0.24)	Depth regime	1	5.14	0.0301
	Retention	1	1.60	0.2152
Dinoflagellates spring	Salinity regime	2	0.76	0.4748
(R^2=0.23)	Depth regime	1	6.26	0.0175
	Retention	1	1.91	0.1761
Dinoflagellates summer	Salinity regime	2	4.23	0.0231
(R^2=0.35)	Depth regime	1	5.06	0.0313
	Retention	1	2.32	0.1372
Cyanobacteria summer	Salinity regime	2	30.23	<0.0001
(R^2=0.65)	Depth regime	1	6.25	0.0176
	Retention	1	2.28	0.1405
Chlorophytes summer	Salinity regime	2	30.87	<0.0001
(R^2=0.65)	Depth regime	1	2.33	0.1364
	Retention	1	1.69	0.2026

4 Discussion

In this study we have shown that the phytoplankton composition could be related to differences in salinity and depths/mixing conditions. The significance of retention time could not be adequately investigated as there were only three water bodies with a high retention time giving little power to the statistical test. Although salinity is a well-known structuring factor for the phytoplankton community, this study confirms this across a wide range of different ecosystem as opposed to the majority of reported studies from the literature analysing data from a specific localised area, typically estuaries.

The most pronounced salinity effect was observed for cyanobacteria and chlorophytes. A considerable portion of the chlorophytes encountered was comprised of freshwater species and the highest proportions of chlorophytes were typically seen in water bodies affected by large freshwater inputs from Oder, Vistula, Nemunas, Daugava, Neva and Kemijoki. The presence of chlorophytes in the Baltic coastal waters is not solely related to riverine discharge points, since the proportion of chlorophytes in the Inner archipelago, Gulf of Finland open-part, Gulf of Riga open-part, Lithuanian coast, Bight of Gdansk open-part and in particular, West of Rügen and Der Grabow, had relatively high proportions of chlorophytes. Thus, the presence of chlorophytes in the Baltic Sea is not only due to dilution of freshwater species in the river plumes.

In the more saline and turbulent waters of Kattegat and Belt Sea chlorophytes and cyanobacteria almost completely disappear, and this may be related to the stabilisation of the water column. The Kattegat and Belt Sea are separated from the Baltic Proper by two shallow sills. While the Kattegat and Belt Sea are dominated by strong advective transports and a high degree of mixing across the pycnocline, the rest of the Baltic Sea has a much more stable water column. Thus, the sharp decline in the proportion of chlorophytes and cyanobacteria in Figure 3A could be due to a combination of changing salinity and turbulence conditions. In fact, salinity may be a pseudo explanatory factor since turbulence and salinity conditions are correlated.

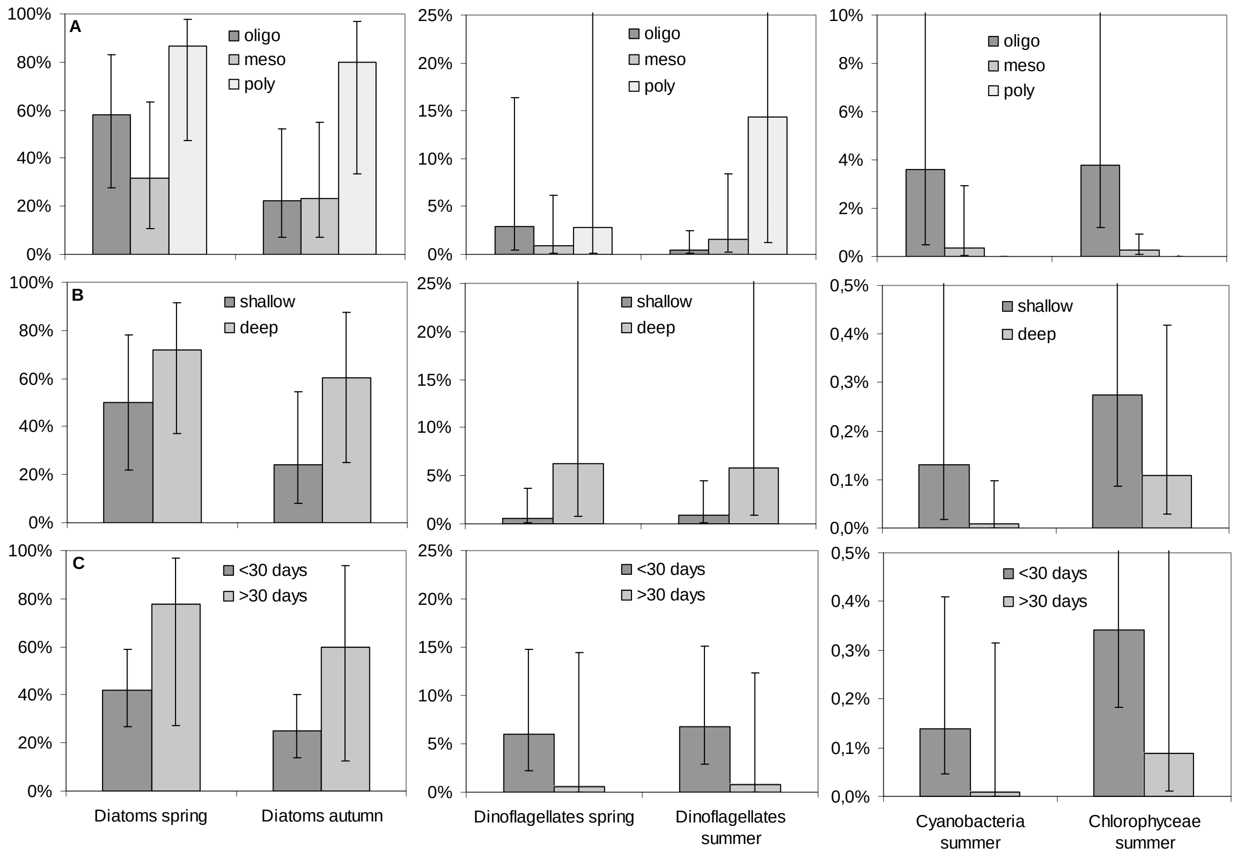

Figure 3: Estimated median proportions of indicators after back-transformation for the three typologies A) salinity, B) depth and C) retention time. Error bars show the 95% confidence limits for the mean level. Note that the scaling differs between the indicators.

The proportion of diatoms in spring and autumn as well as the summer proportion of dinoflagellates were related to the salinity level, although only diatoms in autumn and dinoflagellates in summer reflected a monotone gradient with respect to salinity. The proportion of diatoms in spring in oligohaline waters was relatively higher than in mesohaline waters but lower than in polyhaline waters. Several of the oligohaline water bodies were dominated by freshwater species in spring as documented in WASMUND et al. (1999) and this may have given rise to this non-monotone relationship with salinity, i.e. a decreasing trend for freshwater diatoms and increasing trend for marine diatoms with salinity resulting in a minimum proportion of spring diatoms in mesohaline waters.

Cyanobacteria had a relatively higher proportion in shallow waters during summer, but not sufficient to account for the observed change in the dinoflagellates proportion from shallow to deep waters. The depth-related changes in diatoms proportions are opposite to those in CARSTENSEN et al. (2004). In fact, the significance of depth regime for all six indicators was associated with German water bodies from the Baltic Proper region that reflected a very different composition in general. These water bodies were dominated by cyanobacteria, chlorophytes and other species, whereas diatoms and dinoflagellates were almost absent. However, this strongly deviating composition corresponded partly to the results in FEUERPFEIL et al. (2004) where diatoms disappeared after the spring bloom.

The three considered typology regimes could only account for a minor part of the total variation in the six indicators only, and the unexplained remaining variation within typologies suggests that the phytoplankton composition is indeed governed by other factors as well. Turbulence is an obvious typology classification parameter, and bioassay experiments have shown that pulses of nitrogen may favour diatom growth (ÖRNÓLFSDÓTTIR et al. 2004) and it is therefore likely that nutrient conditions and N/P/Si ratios may also have a structuring mechanism for the phytoplankton community.

Validation of different types by evaluating the within-type variability of biological communities would require good quality biological data from unimpacted sites (HEISKANEN et al. 2004). As most of the coastal water bodies, where the data for this study was compiled from, are impacted by human pressures (HELCOM 2002), it is difficult to distinguish between the impact of pressures (such as anthropogenic nutrient loading) and the type-specific physical and morphological factors that shape the structure of phytoplankton communities.

In conclusion, for classification of ecological status by means of phytoplankton taxonomic composition it is necessary to consider different salinity regimes. We did not analyse if other boundary values for the salinity regimes would provide a clearer grouping of the investigated water bodies. Still considerable variation remains within the employed salinity regimes, some of which appear to be systematic, suggesting that additional characteristics for sub-grouping may be required for comparing phytoplankton composition across the wide range of ecosystems in the Baltic Sea.

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