Cyanobacteria biomass, 1990-2020

Information from the Phytoplankton Expert Group (PEG)

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Key Message

- The different areas of the Baltic Sea are characterized by different magnitudes of biomass of the nitrogen-fixing (diazotrophic) filamentous cyanobacteria (NFC) genera *Aphanizomenon, Nodularia* and *Dolichospermum*. During the study period 1990–2020 (June-August), the highest biomass occurred in the Northern Baltic Proper and the Gulf of Finland, whereas no or low biomass of nitrogen-fixing cyanobacteria appeared in the Bothnian Bay, the Kiel Bay and Kattegat area.
- The biomass of nitrogen-fixing cyanobacteria (NFC) may show opposing trends in different sea areas. The examples below confirm that the sea areas have to be evaluated separately:
    - Simultaneous occurrence of extremely low biomass in the Arkona Basin and Bornholm Basin versus relatively high biomass in the neighbouring Eastern Gotland Basin in 2004, 2005, 2017 and 2018.
    - High cyanobacteria biomass in the Gulf of Finland (342 µg / L) and the Eastern Gotland Basin (283 µg / L) but very low in the southern areas of the Baltic Sea (17-79 µg / L) in 2017.
- Non-parametric Seasonal Mann-Kendall test revealed statistically significant temporal trends both in the total biomass of nitrogen-fixing filamentous cyanobacteria (NFC) and in the biomasses of individual genera in separate sea areas, even though the year-to-year variability in the biomass is high:
    - Decreasing trend for *Aphanizomenon* biomass in Arkona Basin.
    - Decreasing trend for *Nodularia* biomass in the Gulf of Finland but only in July.
    - Increasing trend for sum of NFC biomass, and each separate genus in the Bothnian Sea since the mid of the 1990s.
    - Increasing trend for sum of NFC, *Dolichospermum* and *Nodularia* biomass at the Landsort Deep Station as well as to a small extent for sum of NFC, *Aphanizomenon* and *Dolichospermum* in the Bay of Mecklenburg.
    - Increasing trend for *Aphanizomenon* and *Dolichospermum* biomass in the Eastern Gotland Basin.
- The genus *Nodularia* is more common in the central and southern part of the Baltic Sea compared to the northern part – i.e. in the gulfs of Bothnia, Finland and Riga, where the genus *Aphanizomenon* dominates. *Dolichospermum* is the dominant genus only in the Kiel Bay and the Bothnian Bay where the total biomass of diazotrophic cyanobacteria is very low.

Results and Assessment

Relevance of the cyanobacteria biomass for describing developments in the environment

Nitrogen-fixing (diazotrophic) cyanobacteria are an important component of the ecosystem. By their ability to fix molecular nitrogen, the bloom-forming cyanobacteria of the genera *Aphanizomenon, Nodularia* and

Dolichospermum prevent severe nitrogen shortage and resulting starvation in all trophic levels of the ecosystem in the summer. However, human activity has imported a surplus of nutrients into the Baltic Sea for decades which turned the originally indispensable cyanobacteria into a nuisance because their nitrogen fixation counteracts the measures to reduce eutrophication, as specified in the following section.

According to Wasmund (1997), nitrogen-fixing cyanobacteria may be considered to occur in “bloom concentration” when biomass is about 200 µg / L in the mixed upper water layer from 0 m to the depth of 10 m. If this biomass is floating and enriched at the water surface it becomes visible and is also clearly perceived from satellites (Kahru & Elmgren 2014).

Policy relevance and policy references

The blooms of nitrogen-fixing cyanobacteria seem to have increased at least since the 1960s (Finni et al. 2001, Funkey et al. 2014). When occurring in large blooms, cyanobacteria indicate and contribute to eutrophication, oxygen depletion in deep waters and toxic effects. The displeasing view of the discolouring surface scum alone may impair the touristic use of the coasts in summer. The changes in cyanobacteria biomass and composition represent changes in the ecosystem with far-reaching consequences. Their trends are of high relevance and interest. This Baltic Sea Environment Fact Sheet (BSEFS) “Cyanobacteria Biomass” serves the long-term documentation of the nitrogen-fixing cyanobacteria biomass development in the different sea areas of the Baltic Sea.

The Indicator Fact Sheet “Cyanobacteria bloom index” covering semi-quantitative rank data from year 1999 to 2007 was presented by Kaitala and Hällfors (2008). Information about the spatial extent of the blooms during summer based on satellite data is available (BSEFS “Cyanobacterial blooms in the Baltic Sea”, Öberg 2018). In comparison to the semi quantitative rank data , our BSEFS presents more precise, quantitative biomass data from a greater number of sea areas, and in contrast to the satellite image data, our BSEFS gives additional information about the species composition in the water column. The species composition is relevant also because *Nodularia* and *Dolichospermum* have the potential to be hepatotoxic .Hepatotoxicity of *Aphanizomenon* has not been confirmed in the Baltic Sea, though Cox et al. (2005) have reported potential for production of the neurotoxic amino acid β-N-methylamino-L-alanine (BMAA) within the strains of Baltic Sea *Aphanizomenon* and *Nodularia*. However, BMAA levels in field samples from the Baltic Sea are low (Johansson et al., 2010; Spáčil at al. 2010).

Owing to the high ecological importance of cyanobacterial blooms, they may serve as indicators in the sense of the EU-Marine Strategy Framework Directive (European Union 2008). A new HELCOM pre-core eutrophication indicator Cyanobacterial Bloom Index (CyaBl), based on the paper by Anttila et al. (2018) is implemented (HELCOM 2018a) and used in the Second HELCOM holistic assessment (HELCOM 2018b). It attempts to combine satellite observation data with the biomass monitoring data delivered by the HELCOM Phytoplankton Expert Group (PEG). The biomass data are identical with the data used for this Baltic Sea Environment Fact Sheet, but this BSEFS gives also more comprehensive additional information on the differences in the biomasses of the genera *Nodularia*, *Aphanizomenon* and *Dolichospermum* in different Baltic Sea areas.

Assessment

The first Baltic Sea Environment Fact Sheet on the cyanobacteria biomass was published in 2011. Just like the earlier Indicator Fact Sheet “Cyanobacteria bloom index” (Kaitala & Hällfors 2008), it concentrates on the open sea. However, owing to the COMBINE strategy, also coastal stations are considered. The situation near the coast may be different from that in the open sea. Therefore, clusters of coastal stations have been kept apart from open sea stations if they were separated by a long distance (> 70 km). When the distances between the coastal and open sea stations were less than 70 km, the data were combined.

Stations were pooled by sea areas (Fig. 1) in order to get representative data. This pooling also included stations which are rarely sampled (in the Bornholm Basin and the southern parts of the Eastern Gotland Basin), but which are not specified in Fig. 1. The data were treated as explained in the “Technical information” below. The seasonal means of the total biomass of NFC in the summer period (June-August) are presented in Fig. 1. In the Bothnian Sea, cyanobacteria blooms may last until October; therefore, the season is defined in this area from June to October. Recently, blooms have still occurred in September and even later also in some other areas. In order to facilitate comparison with earlier reports, we nevertheless considered only the period from June to August. As shown in earlier fact sheets of the PEG, phytoplankton trends may be even opposite in the different sea areas (e.g. Jaanus et al. 2007). Therefore, separate diagrams were produced for all areas for which data were available that met the methodology.

In this BSEFS on Cyanobacteria biomass, only nitrogen-fixing species of the genera *Aphanizomenon*, *Nodularia* and *Dolichospermum* are considered, since these are the main genera that form blooms in the Baltic Sea. Specific information on these three cyanobacteria genera is shown in Fig. 2 and 3. Statistically significant temporal trends of variability of biomass of particular genera and their sum in the separate areas are presented in Tab. 1 together with the mean biomasses for the period 1990-2020 (or the period with the longest continuous time series with gaps not longer than one year).

Bothnian Bay

In the Bothnian Bay, the cyanobacteria biomass is usually very low. Monthly averages do not exceed 50 µg / L. During the period 1991-2020, two maxima of cyanobacteria biomass were observed. The first maximum was caused by the high (126,81 µg / L) *Aphanizomenon* biomass at the coastal RA1 station in August 2005, and second at the same station in July 2014 (119 µg / L). *Dolichospermum* predominates in this region, with an average share of 63% in the total biomass of diazotrophic cyanobacteria, while the share of *Aphanizomenon* is 34% and *Nodulari*a is only 3%. Long-term mean NFC biomass in the Bothnian Bay is only 8 µg / L, wherefore results are not presented in a separate figure.

Bothnian Sea

In the Bothnian Sea (including data also from stations located in the Quark), nitrogen-fixing cyanobacteria are more relevant than in the Bothnian Bay. In this region there is a tendency for an earlier bloom start (cf. Kahru and Elmgren 2014), but moderate cyanobacteria biomass is also found in autumn (monthly means of 100-150 µg / L and up to 360 µg / L in the individual autumn samples). Therefore, we used the period from June to October for this area. Starting with very low cyanobacteria biomass in the mid of the 1990s, biomass has increased more or less continuously (Andersson et al. 2015, Kuosa et al. 2017). Moreover, in contrast to earlier years, cyanobacterial blooms were also observed in the northern part of the Bothnian Sea (Lehtinen et al. 2019). Also, the statistical analysis (see Metadata – Technical information – 6. Methodology of data manipulation) of the time series of data collected for this BSEFS indicates a significant upward trend in the biomass of diazotrophic cyanobacteria in the Bothnian Sea, which concerns all of the genera (Tab. 1). It should be noted that the biomass of diazotrophic cyanobacteria at stations located in the Quark is much lower (long-term mean is 28 µg / L, and maximum biomass 132 µg / L in August 2017) than at stations located in the proper of the Bothnian Sea (long-term mean 83 µg / L, maximum biomass 686 µg / L in August 2017 and 546 µg / L in August 2020).

Gulf of Finland

In the Gulf of Finland, very high biomass occurred with single peak values from 2000 to 7470 µg / L in the late 1990s and in the beginning of the 2000s, in 2008 and again since 2013. The blooms have mainly been dominated by *Aphanizomenon* with the exception of the year 1999, when *Nodularia* contributed more to the total cyanobacterial biomass. Seasonal Mann-Kendall tests of temporal trends for the Gulf of Finland data collected for this BSEFS show that there is no significant change in the biomass of diazotrophic cyanobacteria in the period 1993-2020. Only in July, a downward trend was observed for the genus *Nodularia*, which anyway represents only 14% of the mean biomass of cyanobacteria in this basin. In 2021, the database for the Gulf of Finland was enriched with 150 records from the period 1991-2019 (footnote 15). The added data concerns the stations already existing in the BSEFS 'Cyanobacteria biomass' dataset. Influence of the added data was particularly noticeable in 2008, when the total biomass of cyanobacteria increased from 282 to 488 µg / L, due to high-biomass blooms of *Aphanizomenon* in July at station 3 (7062 µg / L).

Archipelago Sea and Åland Sea

The Finnish coastal station "Nau 2361 Seili intens" was the only station situated in the Archipelago Sea. Its data alone was not sufficient fulfil the requirements explained in the Metadata section **"**Methodology and frequency of data collection". Thus, data for Archipelago Sea is not presented. The same concerns data from the Åland Sea.

Northern Baltic Proper

The acquisition of data for the Northern Baltic Proper made it possible to include the area in the BSEFS. The biomass of nitrogen-fixing cyanobacteria is very high in this area, both in terms of monthly mean values (5-1831 µg / L), seasonal means (100-944 µg / L, Fig. 1, Fig. 2) and long-term mean (433 µg / L, Tab. 1). In the taxonomic composition, *Aphanizomenon* (75%) comprises the larger share, then *Nodularia* (18%), and *Dolichospermum* (only 8%). In the Northern Baltic Proper area, the highest biomass values always occurred in July, very often exceeding 1000 µg / L. The highest biomass (2102 µg / L) was recorded in July 2017 at the H1 station. Mann-Kendall tests of temporal trends for the Northern Baltic Proper data show that there is no significant change in the biomass of diazotrophic cyanobacteria in the period 1994-2020.

Gulf of Riga

In the Gulf of Riga, high seasonal average biomass value in year 2015 was mainly based on peak values from 4 August (1981 µg / L). In 2017, the highest biomass was recorded on 6 July, almost exclusively based on *Aphanizomenon* (1360 µg / L at station 165). In 2018, cyanobacteria biomass was three times lower than in 2017 and by half lower than the long-term mean. In the following years, the biomass of cyanobacteria (mainly *Aphanizomenon,* which on average accounts for 93% of the total biomass of diazotrophic cyanobacteria) increased again. Despite the observed fluctuations of cyanobacterial biomass in the Gulf of Riga, statistical analyses of the data from 1993-2020 period do not indicate any significant trend for the biomass of all three considered cyanobacterial genera, or for each of them individually.

Western Gotland Basin

The cyanobacteria biomass at the Landsort Deep station (BMP H3), situated in the northern part of the Western Gotland Basin, appears relatively low for methodological reasons. This was the only station where the upper 20 m were sampled in contrast to 10 m in the other open sea regions. As cyanobacteria prefer the upper water layers, the inclusion of the lower layer of the euphotic zone reduces the depth-integrated average. The cyanobacteria biomass per m^3 might be up to double, especially for the strongly buoyant *Nodularia*, if only the upper 0-10 m water layer would be considered. In 2019, the peak biomass (528 µg / L) was found on 31 July and it was the second highest peak from 1990. The first one (551 µg / L) was recorded on 7 July 1999. Thus, the size of the biomass of both peaks is comparable, while the quality composition of both peaks is diametrically different. In 1999 *Nodularia* constituted 2%, *Aphanizomenon* 87% and *Dolichospermum* 11% of the biomass peak of diazotrophic cyanobacteria, 20 years later the proportion looks respectively 70% : 28% : 2%. This phenomenon is also reflected in the results of statistical analyses (Tab.1), which indicate a significant upward trend for the biomass of *Nodularia.* Additionally, there is a slight increase for the biomass of *Dolichospermum* at the Landsort Deep. The total biomass of diazotrophic cyanobacteria, where *Aphanizomenon* contribute on average 76% of the biomass, has statistically significant increasing trend for the period 1994-2020, probably due to the increasing trend for *Nodularia*.

Eastern Gotland Basin

Data from the Eastern Gotland Basin were contributed by Finland, Germany, Lithuania, Estonia, Poland and Sweden. Nevertheless, the amount of data basis is rather low, although supplemented from year to year. The biomass peak of the genera considered was recorded on 28 June 2018 (975 µg / L). The average biomass of cyanobacteria in 2019 (386 µg / L) decreased slightly in comparison to 2018. It should be noted that Eastern Gotland Basin was the second region of the Baltic Sea, next to the Gulf of Finland, where the biomass of diazotrophic cyanobacteria decreased in 2019. In 2020 the biomass of NFC decreased again to a value close to the long-term mean (220 µg / L). The highest biomass (889 µg / L) in 2020 was observed on 15th July. Along the coasts in southern part of Eastern Gotland Basin, sometimes the local standards of cyanobacterial toxins concentration were exceeded, which resulted in the temporary closure of the bathing areas (ICES 2013, 2015, 2016, 2017, 2021). Such events occurred when sudden strong winds and water currents pushed the masses of the bloom developed in the central Baltic Sea towards the south. Statistical analyses do not indicate any trends in total filamentous cyanobacteria biomass. On the other hand, there is detected upward trend of *Aphanizomenon* and *Dolichospermum* biomass (Tab. 1).

Gdańsk Basin

The Gdańsk Basin was added as a separate area to the BSEFS in 2018, based on the available data series from the period 2002–2018 (Fig. 1 and Fig. 2h). Cyanobacteria biomass from the stations BMPL1, BMPL5 and BMPL6 (sampled within the Polish National Monitoring Programme governed by the Chief Inspectorate of Environmental Protection, footnote 11) was combined with nearby stations sampled occasionally by NMFRI (footnote 1) and the University of Gdańsk (footnote 12). Long-term mean of cyanobacteria biomass in the Gdańsk Basin is lower than for the Northern Baltic Proper and the Gulf of Finland but higher than for the other Baltic Sea areas. The highest peak values were observed in 2009 (4693 µg / L) and 2010 (6621 µg / L). Among the genera observed in that region *Aphanizomenon* dominated (on average 64% of total cyanobacteria biomass), although in some years the contribution of *Nodularia* (2008, 2010, 2016) and *Dolichospermum* (2010, 2019) was significant. As in the case of the Gulf of Riga, Gulf of Finland and the Northern Baltic Proper, no trends in the biomass of diazotrophic cyanobacteria were found in the Gdańsk Basin (Tab. 1). This may be related to a short time series of data (18 years) and a low number of data (n=211) for the Gdańsk Basin.

As well as in the southern part of Eastern Gotland Basin, also in the Gdańsk Basin were observed surface accumulations of cyanobacteria off the coast. Therefore, the presence of cyanobacterial toxins has been regularly monitored in Polish coastal waters since 2001. Extreme concentrations (i.e. exceeding 15,000 µg / L) of nodularin (hepatotoxin produced by *Nodularia spumigena*) were determined both in 2004 (25,852 µg / L) and 2009 (42,333 µg / L) when the seasonal mean of cyanobacteria biomass was above the long-term mean, and in 2012 (45,000 µg / L), 2015 (35,280 µg / L) and 2018 (30,000 µg / L) (ICES Report: 2013, 2015, 2016, 2017, 2021; Mazur-Marzec et al. 2006) when the seasonal mean of cyanobacteria biomass was significantly below the long-term mean. This indicates that the long-term cyanobacteria biomass data collected from the central part of the Gdańsk Basin do not fully reflect the actual magnitude of cyanobacterial blooms and the risks they pose.

Bornholm Basin

Cyanobacteria biomass in the Bornholm Basin was generally rather low (76% of considered data is below 100 µg / L) in comparison with the northern regions of the Baltic Proper. However, in 2019, the mean biomass of cyanobacteria increased above the long-term mean (105 µg / L), and on 15 July, for the first time since 2015, even exceeded (337 µg / L) the bloom value established in Wasmund (1997). In this blooming event *Nodularia* dominated (with 86% of total diazotrophic biomass). In 2020, all values of diazotrophic cyanobacteria biomass were again below the bloom value. When the continuous data series for the period 1997-2020 is taken into account, there is no statistically significant trend for the Bornholm Basin.

Arkona Basin

In the Arkona Basin, cyanobacteria biomass seems to decrease during the investigation period. Indeed, the lowest mean biomass was found in 2017 with a seasonal maximum of only 110 µg / L on 13 August. However, in the following years the biomass of diazotrophic cyanobacteria increased again and in 2019 exceeded the long-term mean and in 2020 reached a value equal to the long-term mean. Statistical analysis of data from the Arkona Basin does not show significant trend for cyanobacteria biomass but only decreasing trend for genus *Aphanizomenon* (forming 57% of the biomass of cyanobacteria on average).

Bay of Mecklenburg and Kiel Bay

In the Bay of Mecklenburg, blooms are not usual, but they may reach the coasts occasionally, e.g. in 2003 and 2006, when beaches had to be closed because of nuisance cyanobacteria blooms. Differences occurred between samplings from 0-10 m depth and samplings from the surface only. Samplings of the upper 10 m in the open sea revealed cyanobacterial biomass exceeding 100 µg / L in the years 2006, 2010 and 2011 in the series from 2004 to 2013 presented by Schneider et al. (2015). The surface samples from coastal and open sea stations showed biomass peaks in 1993, 1994, 2006, 2013 and 2016 (Fig. 2 b). In 2018, high cyanobacteria biomass of 588 µg / L was found at the Mecklenburg coast only on 17 July and was dominated by *Nodularia* (Wasmund et al. 2019), similarly to the maximum recorded on July 16, 2019 amounting to 370 µg / L. On the 1st July 2020 appeared cyanobacteria bloom with biomass of 327 µg / L at O22 station. The bloom consisted mainly of *Aphanizomenon* (53%) and *Dolichospermum (*41%). The Seasonal Mann-Kendall test carried out for the Bay of Mecklenburg showed statistically significant upward trends in the biomass of a total NFC, *Aphanizomenon* and *Dolichospermum* (Tab. 1).

Data from the Bay of Mecklenburg and Kiel Bay were considered for the first time in the BSEFS report in 2015. Data were delivered by State Agencies (footnotes 3 and 13) and from the coastal monitoring of the IOW (station Heiligendamm = “HD”; see Wasmund et al. 2019). All these data originated from surface samples (about 1 m depth); the few samples from 0-10 m depth were excluded from the analysis in order to prevent mixing of different methods.

The cyanobacterial biomass in Kiel Bay, starting in 2000, was generally low (maximum summer average 140 µg / L in 2012), although the individual biomass values in July exceeded 760 µg / L at station 7. Also, in 2016 and 2020, the biomass of cyanobacteria in June was 220 (at station 7) and 270 µg / L (at station 59, Fig. 1,) respectively. The biomass peak samples were almost exclusively dominated by *Dolichospermum*. The Seasonal Mann-Kendall test carried out for the Kiel Bay doesn’t reveal any statistically significant trends in cyanobacteria biomass.

Kattegatt

As in the case of Bothnian Bay, also Kattegat data are not presented because of generally low cyanobacteria biomass, which indicates that heavy cyanobacteria blooms usually do not occur in that sea area. Only at the end of July 2008, a bloom with biomass peaks of up to 400 µg / L occurred at the two Kattegat stations, but monthly and seasonal means were much lower. However, a new data series (2010-2020) from the southern part of the Kattegat, added in 2021, reveals that very intense blooms of diazotrophic cyanobacteria incidentally occur in this area as well. For example, in July 2012, there was a *Dolichospermum* bloom exceeding 4300 µg / L, and in August 2015 and 2016 a mass appearance of *Nodularia* with a biomass exceeding 380 and 6000 µg / L, respectively. Apart from these exceptional years, in the remaining years the seasonal average was in the range of 0,5-30 µg / L. Similar single bloom events took place in the Little Belt in August 2012 (1448 µg / L) and 2019 (5033 µg / L) as well as in July 2020 (217 µg / L) and consisted almost only of *Nodularia*.

General remarks for the Baltic Sea

From the above considerations it follows that due to high variability, no clear Baltic Sea -wide trends were generally detected in the biomass of diazotrophic cyanobacteria during the period 1990–2020. However, a non-parametric Seasonal Mann-Kendall test (Hirsch and Slack, 1984) revealed some statistically significant temporal trends both in the total biomass of NFC and in the biomasses of individual genera in separate sea areas (Tab. 1). An increase in total biomass of diazotrophs was confirmed in the Bothnian Sea, in the Bay of Mecklenburg and in the northern part of the Western Gotland Basin. For *Dolichospermum* and *Nodularia* only increasing trends were found (Eastern Gotland Basin, Bay of Mecklenburg, Bothnian Sea and Western Gotland Basin), while for *Aphanizomenon* the analysis revealed both increase (Bay of Mecklenburg, Eastern Gotland Basin and Bothnian Sea) and decrease (Arkona Basin) in biomass values.

The results of testing the data series until 2020 confirm the direction of change for cyanobacterial biomass reported earlier for different parts of the Baltic Sea – Bornholm and Arkona Basin (Wasmund et al. 2011), Northern Baltic Proper (Suikkanen et al., 2013; Huseby et al., 2019), the Gulf of Finland (Suikkanen et al., 2013) and Bothnian Sea (Andersson et al. 2015; Lehtinen et al. 2016, Kuosa et al. 2017). Most of observations indicate rather fluctuations in surface blooms instead of continuous long-term trends (e.g. Kahru et al. 2018).

Large variations between different areas may occur. For example, cyanobacterial biomass was exceptionally low in the Arkona Basin and Bornholm Basin in 2004, 2005, 2017 and 2018 but high in the Eastern Gotland Basin at the same time. The basin-wide differences in bloom distribution are also known from satellite images (Kahru and Elmgren 2014, Kahru et al. 2018, Öberg 2018). This stresses the importance of dividing the Baltic Sea into sub-regions and treating them separately.

Although the satellite images give valuable information on the spatial differences in cyanobacteria abundances, numerous discrepancies between satellite observations and ship-based biomass data (biomass analysed from water samples) exist. For example, the high biomass in the Arkona Basin in 1998 and 2008 is not reflected in the number of days with cyanobacteria observed in the satellite images (Öberg 2018). Also, at station Landsort Deep there is only little systematic correlation between the actual cyanobacteria biomass and satellite surface data, probably because of deep maxima of *Aphanizomenon* which cannot be adequately recorded by satellites. Satellites may detect the blooms only under specific weather conditions (clear sky) whereas water samples taken with ship-based measurements are not so selective. If wind mixes the cyanobacterial biomass into the water, surface accumulations will not form even though cyanobacterial biomass was high. On the other hand, calm winds may enable surface blooms to become visible even though actual cyanobacteria biomass was not exceptionally high.

As shown in Fig. 2 and Tab. 1, *Aphanizomenon* is dominating in the northern regions of the Baltic Sea whereas *Nodularia* is mostly dominating in the southern Baltic Sea. This may reflect a north-south salinity gradient. *Aphanizomenon* seems to prefer lower salinity than *Nodularia* irrespective of the coasts. Lehtimäki et al. (1997) found that *Aphanizomenon* from the Baltic Sea grows best at salinities of 0 to 5 psu while the optimum salinity for *Nodularia* bloom development is 5–13 psu (Sivonen et al. 1989, Lehtimäki et al. 1994). Moreover, observations of Pliński & Jóźwiak (1999), and Mazur & Pliński (2003) showed that growth of the hepatotoxin-producing *Nodularia* is strongly temperature-dependent and is optimal at 25–28°C. Lehtimäki et al. (1997) narrows this range of optimal growth for *Nodularia* to 20-25°C, indicating that it is still higher than the temperature optimum for Aphanizomenon (16–22 °C). *Aphanizomenon* seems to be able to utilise upwelled nutrients, while *Nodularia* seems even negatively affected by upwelling events (Munkes et al. 2020).

Dolichospermum is less important quantitatively (1-17% of mean cyanobacteria biomass, depending on area). The exceptions are the Bothnian Bay and Kiel Bay, where *Dolichospermum* biomass accounts for about 60% of the total biomass of the analyzed NFC, and Kattegat, where in some events *Dolichospermum* is able to create almost monogenic blooms.

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Data

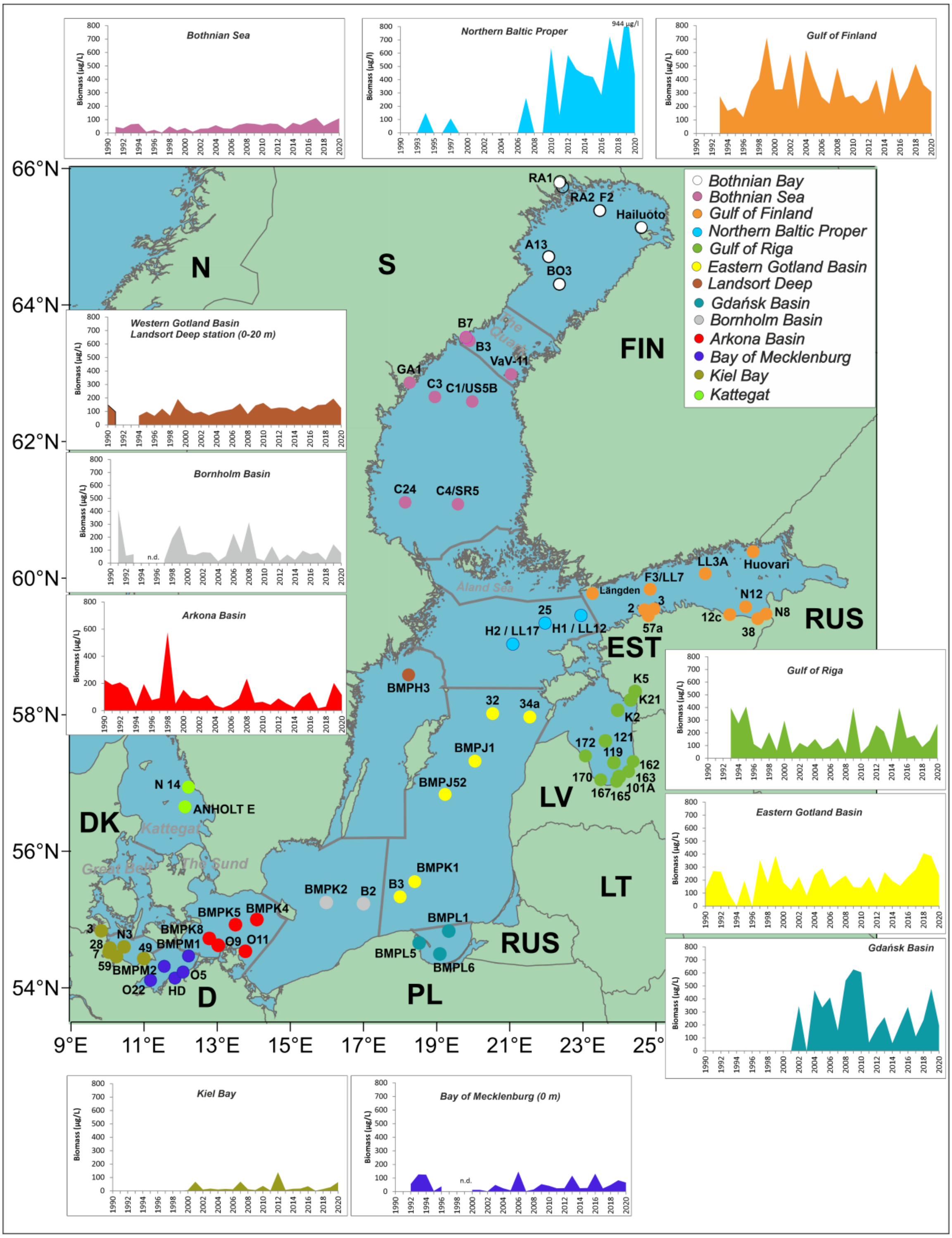

Fig. 1: Map of the regularly sampled stations, containing one graph on diazotrophic cyanobacteria biomass per area (seasonal mean biomass in µg / L); details see in Fig.2. Stations in Bothnian Bay and Kattegat tested but results not presented. “n.d.” = no sufficient data.

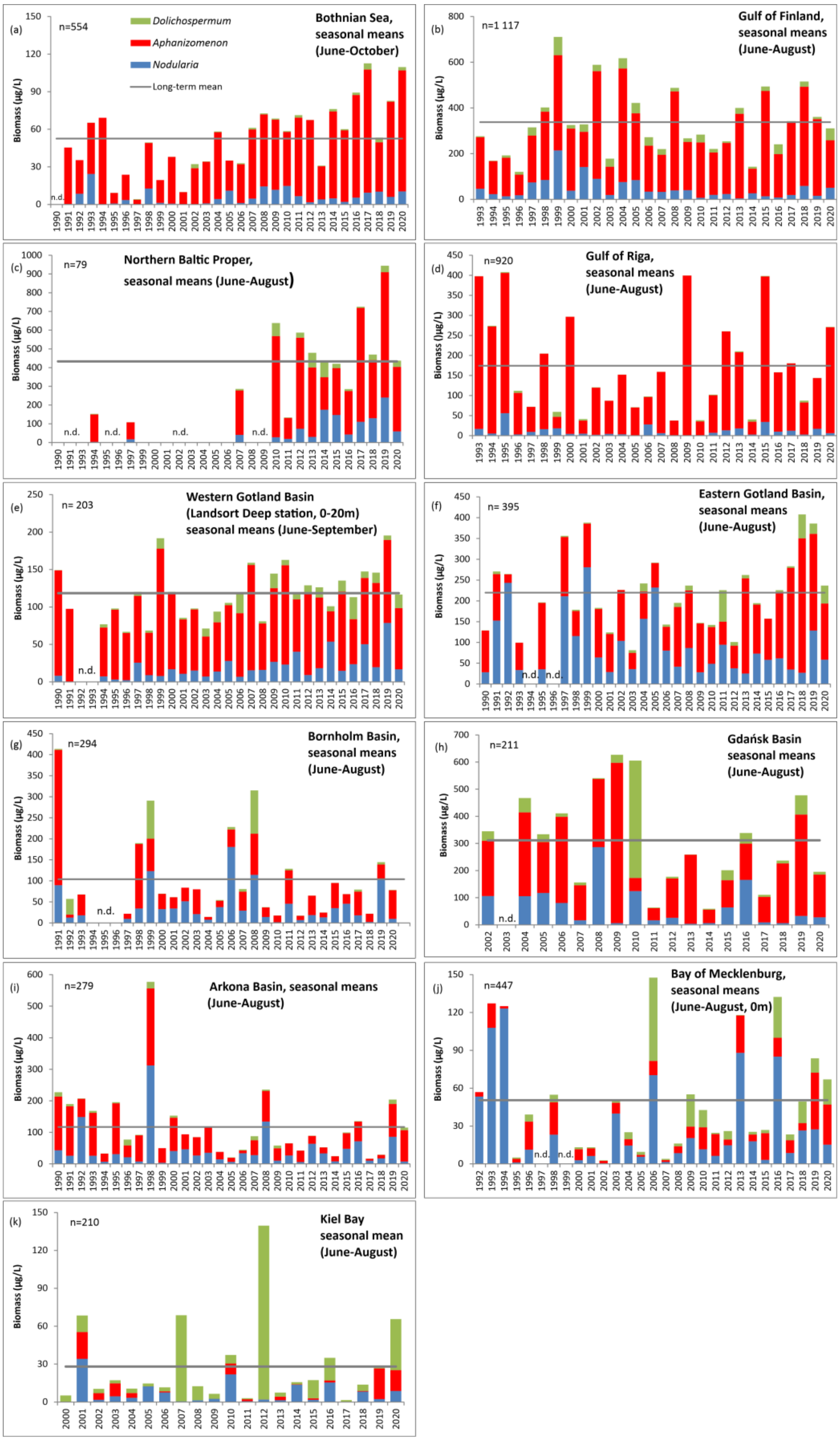

Fig. 2: Mean biomass (wet weight, µg / L) of the three bloom-forming cyanobacteria genera in the different Baltic Sea areas (a-k) during their blooming period (note the different scales for the separate diagrams). The long-term mean per area (all species together) is indicated by a horizontal line. “n” is total number of samples analysed for this region, “n.d.” = no sufficient data or no data at all.

Tab. 1: Results of Mann-Kendall tests of temporal trends in time series of total NFC, *Nodularia*, *Aphanizomenon* and *Dolichospermum* biomass and mean values for them during the particular testing periods.

Area	MK statistic	p-value	Significance code	Slope (change/ unit)	Median	Mean biomass [µg/L]	% of NFC biomass
Mann-Kendall tests of temporal trends in time series of total biomass of NFC							
Bothnian Sea (1991-2020)	587	0,0002	+++	1,55	36,62	48	100
Gulf of Finland (1993-2020)	92	0,3304		2,06	279,64	336	100
Northern Baltic Proper (2007-2020)	6	0,7976		3,79	290,64	436	100
Western Gotland Basin (Landsort Deep Station, 1994-2020)	185	0,0178	+	1,74	96,61	119	100
Bornholm Basin (1997-2020)	1	0,9858		0,01	44,53	95	100
Gulf of Riga (1993-2020)	1	0,9930		0,02	115,67	171	100
Eastern Gotland Basin (1990-2020)	69	0,4174		0,86	147,86	216	100
Gdańsk Basin (2002-2019)	4	0,9205		0,85	214,72	316	100
Arkona Basin (1990-2020)	-168	0,0736		-0,73	48,33	117	100
Kiel Bay (2000-2020)	4	0,9433		0,01	5,25	28	100
Bay of Mecklenburg (1992-2020)	260	0,0107	+	0,24	16,94	50	100
Mann-Kendall tests of temporal trends in time series of *Nodularia* biomass							
Bothnian Sea (1991-2020)	276	0,0316	+	0,00	0,00	5	10
Gulf of Finland (1993-2020)	-112	0,2540		0,00	17,25	48	14
Northern Baltic Proper (2007-2020)	19	0,3752		2,96	27,29	80	18
Western Gotland Basin (Landsort Deep Station, 1994-2020)	288	0,0006	+++	0,33	11,35	21	18
Bornholm Basin (1997-2020)	-68	0,2631		-0,24	14,55	43	45
Gulf of Riga (1993-2020)	-75	0,4327		0,00	2,78	11	6
Eastern Gotland Basin (1990-2020)	-108	0,2363		-0,14	32,53	91	42
Gdańsk Basin (2002-2019)	-60	0,2308		-1,04	18,99	68	22
Arkona Basin (1990-2020)	16	0,8633		0,00	10,73	46	39
Kiel Bay (2000-2020)	-15	0,7044		0,00	0,17	7	24
Bay of Mecklenburg (1992-2020)	133	0,1522		0,01	6,17	31	62
Mann-Kendall tests of temporal trends in time series of *Aphanizomenon* biomass							
Bothnian Sea (1991-2020)	595	0,0002	+++	1,32	31,43	42	88
Gulf of Finland (1993-2020)	138	0,1238		2,65	209,31	263	78
Northern Baltic Proper (2007-2020)	20	0,3720		3,44	202,00	327	75
Western Gotland Basin (Landsort Deep Station, 1994-2020)	57	0,4806		0,39	69,98	88	74
Bornholm Basin (1997-2020)	9	0,8812		0,13	28,21	43	45
Gulf of Riga (1993-2020)	19	0,8702		0,25	108,91	158	92
Eastern Gotland Basin (1990-2020)	211	0,0243	+	1,52	67,94	115	53
Gdańsk Basin (2002-2019)	22	0,6170		2,01	134,24	202	64
Arkona Basin (1990-2020)	-264	0,0104	-	-0,91	26,88	67	57
Kiel Bay (2000-2020)	20	0,6787		0,00	0,00	5	17
Bay of Mecklenburg (1992-2020)	290	0,0091	++	0,16	5,54	12	23
Mann-Kendall tests of temporal trends in time series of *Dolichospermum* biomass							
Bothnian Sea (1991-2020)	666	0,0000	+++	0,00	0,00	1	2
Gulf of Finland (1993-2020)	105	0,3323		0,06	13,09	25	7
Northern Baltic Proper (2007-2020)	-1	0,9451		0,00	10,30	30	7
Western Gotland Basin (Landsort Deep Station, 1994-2020)	297	0,0029	++	0,07	3,73	9	8
Bornholm Basin (1997-2020)	47	0,4809		0,00	0,11	10	10
Gulf of Riga (1993-2020)	-125	0,2030		0,00	0,16	2	1
Eastern Gotland Basin (1990-2020)	291	0,0046	++	0,04	1,74	10	5
Gdańsk Basin (2002-2019)	39	0,3254		0,14	6,93	46	14
Arkona Basin (1990-2020)	16	0,8745		0,00	0,09	4	4
Kiel Bay (2000-2020)	31	0,5543		0,02	1,56	17	59
Bay of Mecklenburg (1992-2020)	370	0,0008	+++	0,07	0,76	8	15

Metadata

Technical information

1. Data source: Danish, Estonian, Finnish, German, Latvian, Lithuanian, Polish and Swedish national monitoring data (see list of authors and Footnotes). Main sampling locations are presented in Fig. 1. Original purpose of the data: Phytoplankton monitoring programs in the frame of HELCOM COMBINE.

2. Description of data: Biomass data (wet weight in µg / L) in integrated samples (0-10 m; 0-20 m at the Landsort Deep station; surface = 0-1 m in Bay of Mecklenburg; 0-5 m at the Polish high-frequency coastal station BMPL5). Sampling at the Finnish high-frequency coastal stations "Hailuodon ed int.asema", "Suomenl Huovari Kyvy-8A", "UUS-23 Längden" and "Vav-11 V-4" reached from surface to the depth of 2x Secchi depth (usually 0-8 m, maximum depth is 10 m); they could be integrated into the existing data series without problems. Genera included in index: *Nodularia*, *Aphanizomenon* and *Dolichospermum* (previously *Anabaena*) (see Fig. 3).

Fig. 3: Genera included in index, from left: *Nodularia* (taken by Irina Olenina), *Aphanizomenon* (taken by Susanne Busch) and *Dolichospermum* (previously *Anabaena*, taken by Helena Höglander).

http://nordicmicroalgae.org/taxon/Nodularia%20spumigena?media_id=Nodularia%20spumigena_8.JPG&page=2

http://nordicmicroalgae.org/taxon/Aphanizomenon?media_id=Aphanizomenon_5.jpg

http://nordicmicroalgae.org/taxon/Dolichospermum%20lemmermannii?media_id=Dolichospermum%20lemmermannii_2.jpg&page=2

3. Geographical coverage: Entire Baltic Sea (see Fig. 1).

4. Temporal coverage: Summer 1990-2020 (June-August, in the Bothnian Sea June-October). Note that the years 1992-1993 are missing from the Landsort Deep station, 1994 and 1996 from the Eastern Gotland Basin, 1994-1996 from the Bornholm Basin, 1997 and 1999 from the Bay of Mecklenburg and 2003 from the Gdańsk Basin, 2008 and 2009 from the Northern Baltic Proper. Even if data from one month were available, they were excluded because only one month was not representative for the investigation period. Some time series started later, e.g. from Bothnian Sea and Bornholm Basin 1991, from Bay of Mecklenburg in 1992, from Gulfs of Finland and Riga in 1993, from Gdańsk Basin in 2002 and Kiel Bay in 2000, from Northern Baltic Proper 2007.

5. Methodology and frequency of data collection: Information based on national monitoring samples analysed and identified by phytoplankton experts, using the mandatory HELCOM methods (HELCOM 2021).

Additional explanation on the counting procedure using size classes was given by Olenina et al. (2006). Sampling frequency varies in dependency of the national monitoring cruises. At least one sample per month has to be available to allow the calculation of the seasonal average. This precondition could also be fulfilled by pooling nearby stations. Only in a few exceptions, mentioned in the Assessment section, data are presented despite missing data from one month out of three. The total number of samples is indicated in each diagram in Fig. 2.

6. Methodology of data manipulation: The precondition of at least one sample per month could be fulfilled in the representative open sea stations by combining the different national monitoring data. In coastal areas under the responsibility of only one country, many data (from Lithuania, Poland and Finland) had to be rejected because of too low sampling frequency. Other more coastal data (from Gulfs of Bothnia, Finland and Riga, see Fig. 1) are included, as they were close to the open sea stations and their sampling frequency was high (Fig. 2).

From the single data, monthly means were calculated, which served as basis for calculation of seasonal mean values.

The temporal trends for the investigated groups of filamentous cyanobacteria (*Nodularia*, *Aphanizomenon*, *Dolichospermum* and the sum of all NFC) were tested with a non-parametric Seasonal Mann-Kendall test (Hirsch and Slack, 1984) with autocorrelation set to one and using month as a class variable. All data series collected until 2020 were used to test each of the Baltic Sea regions separately (Tab. 1).

Analysis was performed using the software Multitest (http://www.miljostatistik.se/mannkendall.html, Linköping University). We have used following the M-K tests offered by this software:

- Ordinary M-K tests for monotone trends in univariate time series (for separate month or station etc.)
- Multivariate M-K (Hirsch and Slack, 1984) tests for common monotone trends in multiple time series (for all months or for all stations).

Quality information

1. Strength and weakness (at data level): The main strength is the availability of comparable multi-decadal genus-specific biomass data. The main weaknesses are the low number of sampling stations and the low seasonal coverage in the sampling frequency. Monitoring cruises into the open Baltic Sea are expensive and can be conducted only a few times per year by the countries involved. This undersampling problem, occurring generally at ship-based sampling, is dramatic if high patchiness occurs. Especially the buoyant cyanobacteria are inhomogeneous in their horizontal and vertical distribution. The vertical inhomogeneity is tackled by the integrated sampling down to 10 m, or at specific stations down to 20 m depth (Landsort Deep) or 2 times Secchi depth (Finnish coastal stations). The equipment is however not designed for representative sampling of surface scums. The combining of the different national data taken at the central HELCOM stations improves the total sampling frequency to reach the minimum requirements.

2. Reliability, accuracy, robustness, uncertainty (at data level): Data on the reliability and precision are not available. A ring test of HELCOM-PEG, conducted in 2012, gave information on the precision of *Nodularia* countings in dependence of the counting procedure (Griniene et al. 2013). The phytoplankton proficiency test (Vuorio et al. 2015), which was participated by many HELCOM PEG members, included identification test for *Aphanizomenon flosaquae* and *Nodularia spumigena*, and counting test for *Aphanizomenon* sp. Similar phytoplankton proficiency test provided in 2020 included test for *Dolichospermum lemmermannii* identification. The uncertainties concerning sampling are discussed above; they have natural reasons. The microscopical counting is a robust method of high accuracy. In contrast to indirect methods (satellites, pigments etc.), the objects can directly be recognized, counted and measured. Moreover, the contribution of the different species can be evaluated. The calculation of biomass from the counting results is highly reliable since common biovolume formulas (Olenina et al. 2006) and a regularly updated biovolume file (http://www.ices.dk/ data/Documents/ENV/PEG_BVOL.zip) are used.

3. Further work required (for data level and indicator level): In order to assure a sufficient sampling frequency, the combined efforts of different countries to sample at least the central key station in each sea area have to be maintained or better to be extended. This is especially important when these data will be used to follow up the Baltic Sea Action Plan, the Marine Strategic Framework Directive and the Water Framework Directive. The basic data for this Environment Fact Sheet are integrated into a Cyanobacteria Bloom indicator, called “CyaBl”, for the implementation of the Marine Strategic Framework Directive. In order to be able to utilize the ICES database for the long-term trend analyses, the database should be updated annually, and kept harmonized concerning taxonomy and biovolume calculation formulae since the beginning of the study period (since year 1990). At the moment, data for this BSEFS has been collected yearly from the national PEG representatives.

FOOTNOTES

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