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Patterns of phytoplankton composition in coastal lakes differed by connectivity with the Baltic Sea

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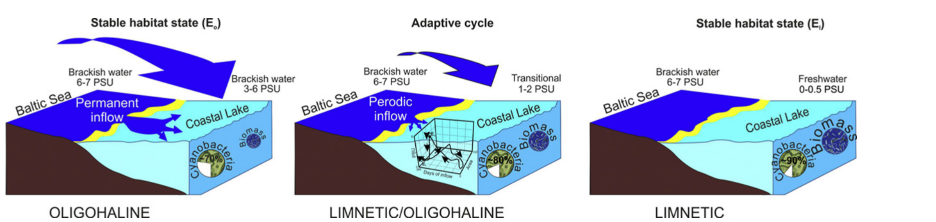
HIGHLIGHTS

- Hydrological connectivity, salinity, and TP are key factors structuring phytoplankton patterns in coastal lakes.
- Cyanobacteria and Cryptophyta were indicator groups, preferring freshwater habitats.
- Dissimilarities in biovolume of phytoplankton is indicator of the state of coastal lakes.
- Salinity level affects local adaptive states of phytoplankton communities in coastal lakes.
- Hydrological connectivity with the sea promotes internal heterogeneity of coastal habitats.

GRAPHICAL ABSTRACT



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ABSTRACT

The study was aimed to analyse reactions of the major groups of phytoplankton to the mixing regime of fresh and brackish waters in coastal lakes and the associated changes in physicochemical properties of lake waters. For this purpose, on the basis of data collected from 6 coastal lakes located along the southern coast of the Baltic Sea, differing in intensity of intrusion of brackish sea water: limnetic, L (2), limnetic/oligohaline, L/O (2), and oligohaline, O (2), we assessed the associations of major phytoplankton groups with environmental conditions. Statistical analyses revealed that the structure of phytoplankton groups significantly differed among three lakes types, and the variation in these variables was best explained by water temperature, total phosphorus, salinity, PO_4^{3-}, transparency, dissolved oxygen, and NO_3^-. Relative phytoplankton biomass showed significant differences among the O–L/O–L lake types and formed the following proportion 1:2:3.5. Cyanobacteria constituted a dominant algae group in the lakes, showing the decreasing trend from 86.5% in the L to 69.3% in the O lakes. The indicator value analysis showed that all the studied lakes were dominated by algae preferring freshwater habitats, among which Cyanobacteria and Cryptophyta were indicator groups. Redundancy analysis showed that increasing salinity has got a negative effect on Cyanobacteria and Bacillariophyta biomass, and did not stimulate the development of any algal group.

In the coastal lakes we observed 2 distinct stable states (limnetic and oligohaline) as well as transitional phases between them: (1) seaward drift (limnetic-oligohaline) with increasing salinity, and (2) landward drift (oligohaline-limnetic) with decreasing salinity. Algal communities showed the most distinct differences in biomass in limnetic and oligohaline states. These observations suggest that the structure and biomass of

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phytoplankton may respond gradually on the level of hydrological connectivity, or may respond abruptly creating two alternative stable states: limnetic and oligohaline.

1. Introduction

Coastal water bodies (lagoons and lakes) are specific and unique aquatic ecosystems, cowhich are contact sites of the inland water bodies with the sea. The ecosystems are subject to continuous changes, representing various types of lakes: completely isolated from the sea, periodically isolated or permanently linked with the sea (Netto and Fonseca, 2017; Obolewski et al., 2018). For individual coastal water bodies, the degree of hydrological connection and rise in sea level determine their size and ecological status (Obolewski, 2009; Netto et al., 2012). In the case of water bodies located on the coasts of oceans, the degree of hydrological connection makes it possible to distinguish 3 major types of ecosystems: open lagoons (intensive connection with the sea), intermittently open/closed lagoons (only in some periods fully open), and permanently closed lakes (with no permanent open connection with the sea) (Netto and Fonseca, 2017). Nevertheless, since the salinity gradient has been considered as one of the main descriptive environmental factors used to follow the spatial distribution patterns of biota, the Venice System (1959) is the most widely-used and accepted classification of marine waters. However, its application to brackish inland waters has been criticized as static and descriptive (Den Hartog, 1974). Thus, too wide range of the limnetic (< 0.5 PSU) and oligohaline (0.5–5.0 PSU) costal lakes classes as well as unstable salinity conditions in for hydrobiological observations required additional subdivisions of the oligohaline class into α-oligohaline (0.5–3.0 PSU) and β-oligohaline (3.0–5.0 PSU). Obolewski and Bąkowska (2017), apart from the limnetic and oligohaline types of coastal habitats, introduced the limnetic/oligohaline type of the brackish inland ecosystems, particularly applicable for the lakes along the coast of the southern Baltic Sea (6.0–7.0 PSU).

Hydrological connectivity between a coastal lake and the sea impacts the changes of habitat conditions in the water body. The seaward and landward drifts of water generate the appearance of highly stressful environmental factors for the communities inhabiting the lakes (eg. El-Kassas et al., 2016; D'ors et al., 2016; Majewska et al., 2017). One of the most prominent characteristics of limnetic/oligohaline habitats is the lack of stability in salinity, with its diurnal, seasonal, and annual fluctuations (Taupp and Wetzel, 2014). The lakes linked with the sea by river mouths are characterized by a high dynamics of abiotic conditions (e.g. temperature, oxygenation), biological productivity, and fluctuations of biodiversity, resulting from migration of organisms (eg. Funkey et al., 2014; Kahru and Elmgren, 2014; Majewska et al., 2017; Obolewski and Bąkowska, 2017). A less dynamic, in terms of hydrodynamics and hydrochemical parameters, including salinity, sediment composition, and organic matter content, is observed in intermittently open or closed (=limnetic/oligohaline) ecosystems (eg. Netto et al., 2012; Astel et al., 2016). Isolated freshwater lakes (=limnetic) are more uniform in terms of environmental conditions than other types of coastal ecosystems (Netto et al., 2012).

The change in environmental conditions resulted from natural or anthropogenic disturbance of hydrological connections between the sea and coastal reservoirs has been reported to influence the pattern of replacement among algae groups (Mazzei and Gaiser, 2018). High physico-chemical variability in open lagoons is commonly regarded be species-poor (Obolewski, 2009; Netto and Fonseca, 2017) because of physiological difficulties of hydrobionts to adapt to the varying mixtures of saltwater and freshwater (McLusky and Elliott, 2004). Although the shift in density or biomass patterns is theoretically sound, there is a lack of empirical evidence to support this hypothesis. So far, shifts in diversity patterns for coastal water bodies have been restricted to single lagoons and water column assemblages (Petersen et al., 2008; Viaroli et al., 2008; Netto and Fonseca, 2017). Typically, the composition of plankton of open lagoons consists of a number of estuarine residents and many temporary marine species (Abbate et al., 2017; Majewska et al., 2017).

The abundance of phytoplankton in intermittent lagoons may vary according to the current connectivity state due to the tolerance of organisms to salinity. After blocking hydrological connectivity (periodically or permanently), the lakes might become more homogeneous and dominated by freshwater species, typical of isolated coastal lakes (Lang-Yona et al., 2018). These observations suggest that the coastal system and inhabiting it pelagic organisms may respond gradually on the level of hydrological connectivity event, or may respond abruptly creating two alternative stable states.

The qualitative and quantitative structure of phytoplankton in coastal lakes can vary greatly, both in space and time, which makes it difficult to monitor with the use of conventional (microscopic) algological methods. A solution to this problem is the application of fluorescence measurements and continuous monitoring of chlorophyll *a* concentration (Lorenzen, 1966), without damage to biological material (Holm-Hansen et al., 1965; Yentsch and Yentsch, 1979). The use of spectral fluorescence, where repeated excitation and emission of waves is used to determine the taxonomic composition, has been classified as a good technique, as the measurements can be made continuously in a large number of samples (Yentsch and Yentsch, 1979; Richardson et al., 2010). This method may help to improve the knowledge on the spatial distribution patterns of biota along estuarine gradients and understanding of the underlying ecological processes (Abbate et al., 2017) and to develop tools for ecological quality assessments and mitigation strategies in coast lake management (eg. Ghezzo et al., 2011; Astel et al., 2016).

In this study we assessed to what extent the relatively small gradient of salinity of coastal ecosystems determines the biomass of phytoplankton communities. To estimate the factual contribution of the given algal community, we used in this study spectral fluorescence and Algae Online Analyser® (AOA). This technique allowed us to test that limnetic and oligohaline stable states represent reverse characteristics of ecological state of lakes, as well as to indicate the transitional phases between them: (1) limnetic-oligohaline with increasing salinity; and (2) oligohaline-limnetic with decreasing salinity, as integral parts of the adaptation cycle. Thus, we have verified the hypotheses that: (i) intrusion of sea water increases the distinctness of environmental conditions in coastal lakes; (ii) an increase in salinity declines phytoplankton abundance and biomass; (iii) structure of main phytoplankton groups is indicative of two opposing ecological states of the coastal water bodies (alternative stabile states) resulted from landward and seaward drifts of water differed by salinity levels; (iv) the transitional phase, when mixing of fresh and brackish waters takes place, allows for identification of limnetic/oligohaline habitats, specific for the inland coastal water bodies along the coastline of the Baltic Sea.

2. Materials and methods

2.1. Study area

Most of the lakes on the southern coasts of the Baltic Sea are large, shallow water bodies with a poorly developed shoreline and remarkable fluctuations of water level. All the water bodies are polymictic and hypertrophic (Astel et al., 2016). As they differ in morphometry, hydrological parameters, and salinity level (Fig. 1 and Table 1), ambiguous