Acta Oecologica 81 (2017) 10–21

Contents lists available at ScienceDirect

Acta Oecologica

journal homepage: www.elsevier.com/locate/actoec

Taxa-specific eco-sensitivity in relation to phytoplankton bloom stability and ecologically relevant lake state

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ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form
13 April 2017
Accepted 18 April 2017
Available online 26 April 2017

Keywords:
Phytoplankton
Cyanobacteria
Microcystis-bloom
Sensitive and tolerant taxa
Water quality
Trophy

ABSTRACT

Phytoplankton (including plant-like, animal-like algae and Cyanobacteria) blooms have recently become a serious global threat to the sustenance of ecosystems, to human and animal health and to economy. This study focused on the composition and stability of blooms as well as their taxa-specific ecological sensitivity to the main causal factors (especially phosphorus and nitrogen) in degraded urban lakes. The analyzed lakes were assessed with respect to the trophic state as well as ecological status. Total phytoplankton biomass (ranging from 1.5 to 181.3 mg dm^{-3}) was typical of blooms of different intensity, which can appear during a whole growing season but are the most severe in early or late summer. Our results suggested that steady-state and non-steady-state bloom assemblages including mono-, bi- and multi-species or heterogeneous blooms may occur in urban lakes. The most intense blooms were formed by the genera of Cyanobacteria: *Microcystis*, *Limnothrix, Pseudanabaena*, *Planktothrix*, Bacillariophyta: *Cyclotella* and Dinophyta mainly *Ceratium* and *Peridinium*. Considering the sensitivity of phytoplankton assemblages, a new eco-sensitivity factor was proposed (E-SF), based on the concept of Phytoplankton Trophic Index composed of trophic scores of phytoplankton taxa along the eutrophication gradient. The E-SF values of 0.5, 1.3, 6.7 and 15.1 were recognized in lakes having a high, good, moderate or poor ecological status, respectively. For lake restoration, each type of bloom should be considered separately because of different sensitivities of taxa and relationships with environmental variables. Proper recognition of the taxa-specific response to abiotic (especially to N and P enrichment) and biotic factors could have significant implications for further water protection and management.

1. Introduction

An excessive growth of planktonic microorganisms belonging to phytoplankton, known as a planktonic blooms in Water Framework Directive (EC, 2000) or algal blooms (a more common term), is associated with an anthropogenically accelerated increase of eutrophication in many waters. While all blooms can be a nuisance to humans and animals, some may become harmful to their health, i.e. harmful algal bloom. The harmfulness of freshwater algal blooms is usually due to the cyanobacterial ability to produce toxins (Kobos et al., 2013) and this has become a serious problem to health and economy (Chorus and Bartram, 1999; Ibelings and Chorus, 2007; Zhang et al., 2009; Mankiewicz-Boczek et al., 2011). However, blooms of other phytoplankton groups, especially dinoflagellates (e.g. Hall et al., 2008; Matsumura-Tundisi et al., 2010; Silva et al., 2012), can also have adverse ecological effects. All type-specific blooms can occur more frequently in human-impacted lakes, and in urban rather than in non-urban water bodies. They develop in response to a combination of multiple factors, mainly temperature, nutrients, light availability, mixing regime and biological interactions (e.g. Becker et al., 2009; Grabowska and Mazur-Marzec, 2011; Beaulieu et al., 2013; Borics et al., 2015; Zębek, 2015). Therefore, lakes used for recreation or water supply need to be protected and treated as special-concern water bodies.

Worldwide, degraded lakes of all sizes are characterized by site-specific features and are at risk of blooms throughout a whole growing season. Such inland water bodies of special concern include also urban lakes under strong human impact (e.g. lakes treated as sewage receivers in the past), which are numerous in all

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http://dx.doi.org/10.1016/j.actao.2017.04.002
1146-609X/

Europe, including Poland. Because most recreationally attractive lakes can mitigate the urban climate, they are definitely 'worthy of the best care', as Naselli-Flores (2008) puts it. Detailed data on blooms in such urban lakes are still scarce. Recently, the intensity and thresholds of phytoplankton blooms have been just initially categorized in the context of an ecological status of urban lakes (Napiórkowska-Krzebietke and Dunalska, 2015), for instance the phytoplankton biomass of 2.6 mg dm^{-3} was recognized as the lowest bloom threshold for urban lakes. Furthermore, the maxima of 5 mg dm^{-3}, 8 mg dm^{-3}, 21 mg dm^{-3} and 100 mg dm^{-3} were proposed as bloom thresholds for the high/good, good/moderate, moderate/poor and poor/bad ecological status of degraded urban lakes. In comparison to cyanobacterial bloom intensity given for Central-Baltic LCB1 and LCB2 lakes (stratified and non-stratified lakes, respectively) bloom thresholds are lower, e.g. biomass of 2.0 mg dm^{-3} corresponds to the good/moderate threshold for cyanobacterial bloom intensity (Napiórkowska-Krzebietke, 2015), while the average values of 3.3, 9.9 and 22.4 mg dm^{-3} are characteristic for the moderate, poor and bad ecological status or ecological potential.

The taxa forming blooms are generally well known, but data on the stability of bloom assemblages and taxa-specific ecological sensitivity to the factors controlling trophy are still limited. Worldwide, health-threatening blooms formed by some Cyanobacteria species are becoming a serious problem (Kobos et al., 2013). The World Health Organization (WHO; Chorus and Bartram, 1999) defines the risk thresholds, i.e. alert levels or probability of adverse health effects, and implicates some association with the cyanotoxin hazard in recreational waters. For the upper 0–4 m of the pelagic water column, low (2 mg dm^{-3}) and moderate (10 mg dm^{-3}) risk thresholds were designed (Chorus and Bartram, 1999), with a probable microcystin content of 2–4 μg dm^{-3} (up to 10 μg dm^{-3}) and 20 μg dm^{-3} (up to 50 μg dm^{-3}), respectively. The range of risk thresholds can be extended to high (20 mg dm^{-3}) and very high (40 mg dm^{-3}), as given by Napiórkowska-Krzebietke et al. (2015), and then, the potential toxin risk can significantly increase, which has been demonstrated for an urban *Microcystis*-dominated lake with a theoretically predicted concentration of microcystins up to *ca* 450 μg dm^{-3}. Therefore, the sustenance of ecosystems in degraded urban lakes that are recreationally attractive or perform strategic functions in water supply has been recently recognized as a great research challenge worldwide.

The aim of this study was to determine the composition and stability of phytoplankton communities in human-impacted urban lakes during summer blooms, including taxa-specific ecological sensitivity to the main eutrophication factors. The research focused on multiple approaches to describing bloom events, i.e. existing (e.g. recently proposed bloom intensity and thresholds) and newly proposed ones. The new approaches concern bloom classification and eco-sensitivity factor based on selected criteria of steady-state theory, national phytoplankton indices and functional classification, all in accordance with the Water Framework Directive imposing mandatory ecological status assessment.

2. Materials and methods

2.1. Study area

The nine moderately human-impacted lakes selected for this study lie within the administrative boundaries of four towns: Kartuzy, Skępe, Kościerzyna and Susz (with populations ranging from *ca* 4000 to 24,000). They can be identified as urban lakes, situated in north-eastern Poland (Western Europe Unit) (Fig. 1, Table 1), in glacial deposits within the basin of the Vistula River, which drains waters to the Baltic Sea. All these water bodies, except for Suskie Lake (lack of natural surface inflows, but outflow to River Liwa), are flow-through lakes with various retention time. According to the common intercalibration types, all the lakes meet typology requirements stipulated in the European Water Framework Directive (European Commission, 2000) for Natural Water Bodies (NWBs), namely two lakes are stratified, (LCB1), and seven lakes are non-stratified (LCB2) (Commission Decision, 2013/480/EU). For several decades, since the 1950s until the most recent years, these lakes were strongly exposed to many different (point, nonpoint or diffused) sources of pollution (Mazur-Marzec et al., 2008; Dunalska et al., 2015; unpublished data of the Department of Water Protection Engineering, UWM in Olsztyn). According to Dunalska et al. (2015), the Kartuzy lakes received huge external loads of phosphorus and nitrogen, i.e. 17.2–976.7 kg P y^{-1} and 202.6–5186.5 kg N y^{-1} in 2012–2013. They used to serve as both recreational waters and sewage receivers. Now, they are important recreational lakes used primarily for fishing, bathing and water sports. The catchments of these lakes comprise diverse landscapes, including developed urban agglomeration, villages, farmlands and forests. Higher values of the Ohle's index (ratio of catchment area to lake area, Bajkiewicz-Grabowska, 2010) implicate a stronger effect of a basin on a lake, and the values of the Ohle's index for the lakes studied (12.7–689.2; Table 1) indicated an increasing effect in the following order: Karczemne < Suskie < Klasztorne Duże < Mielenko < Klasztorne Małe < Skępskie Wielkie < Skępskie Małe<Święte < Wierzysko < Skępskie Małe.

2.2. Phytoplankton and environmental variables

The standard qualitative and quantitative analyses of pelagic phytoplankton were carried out in all the nine lakes, for one growing season (from April to November) in each lake, between 2011 and 2014. Phytoplankton was sampled from the deepest site in each lake (representative site in the pelagial zone) according to European standards (Kelly, 2004; Mischke et al., 2012), i.e. from the euphotic zone during spring and autumn turnover and from the epilimnion during summer in stratified lakes, and from the whole depth throughout an entire season in non-stratified lakes. Phytoplankton blooms were studied in detail on samples collected in early (late June) and late (late August/early September) summer, which is the recommended period and sampling frequency in summer phytoplankton research according to the national phytoplankton-based method of ecological status assessment (June–September, 2 samplings; Phillips et al., 2014). Individual phytoplankton samples were collected at every 1-m depth and then integrated for further analyses. Both quantitative and qualitative analyses of phytoplankton were conducted based on CEN standards (EN 14996, EN 15204, PN-EN 15204:2006; DIN EN, 2015; Napiórkowska-Krzebietke and Kobos 2016), deemed suitable for phytoplankton monitoring according to the European Water Framework Directive. Parallel to phytoplankton sampling, water temperature, dissolved oxygen (DO) concentration (YSI 6600-m, U.S.) and Secchi disk depth (SDD) were measured. Additional samples were taken for chemical analysis including chlorophyll *a*, total suspended solids, total carbon and total and mineral forms of nitrogen and phosphorus, and analyzed according to standard methods (PN-EN ISO 6878:2006p.7; PN-EN 25663:2001; PN-ISO 10260:2002).

2.3. Phytoplankton bloom classification according to ecological and trophic relevant state of lakes

The phytoplankton-based ecological status of the lakes was assessed with the positive intercalibrated national method, i.e.