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Evaluation of indicators for cyanobacterial risk in 108 temperate lakes using 23 years of environmental monitoring data

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Abstract

Background: Cyanobacterial blooms are of increasing concern for drinking water supply. In Sweden, a survey among drinking water producers showed that the sense of urgency was little. At 60% of the Swedish drinking water treatment plants, operators lacked monitoring strategies. To get a picture of the size of the problem the presence of cyanobacterial risk in 108 Swedish lakes was evaluated from 23 years of environmental monitoring data. The drivers and indicators for cyanobacterial growth were investigated by analyzing water quality in 9 lakes that have more frequent cyanobacteria bio-volume above the WHO drinking water alert level 1: 0.2 mm^3L^{-1}.

Results: The study shows that the most common species in those lakes are *Anabaena/Dolichospermum* and *Aphanizomenon* followed by *Microcystis*, *Woronichinia* and *Planktothrix,* which can produce a variety of toxins such as anatoxins, cylindrospermopsins, microcystins and saxitoxins, supported by literature study. Our results show that cyanobacterial risk in those problematic 9 lakes are mainly nutrients driven with possibly contribution of increased organic matter. By applying non-linear quantile regression with total phosphorus (TP) as an example, we demonstrated that certain drivers such as TP can be useful for cyanobacterial risk assessment and provide control measures by setting nutrients targets. We also evidenced that cyanobacterial peaks presented at low TN:TP ratio while not necessarily vice versa. We also further evaluated that chlorophyll-*a* and transparency might be suitable as indicators for cyanobacterial blooms in certain lakes, while for most of the lakes, their connection is low.

Conclusion: Nutrients are main drivers for higher cyanobacterial occurrence in the 9 lakes. We suggest TP concentrations should be investigated thoroughly to provide important knowledge which can be used to set nutrient targets to sustain safe drinking water supply and recreational services. The complexity of indicating cyanobacterial risk in a local condition was also highlighted in this study and future study is suggested. To classify different types of lake and identify their drivers and the similarities of species composition changes in those lakes will be future studied.

Keywords: Total phosphorus, Cyanobacteria, Cyanotoxins, Nonlinear quantile regression

Introduction

Globally, the frequency and intensity of cyanobacterial blooms in fresh water bodies are increasing due to eutrophication caused by anthropogenic nutrient enrichment and climatic induced changes [1, 2]. These consequently have a huge impact on the ecosystem [3], but they also have an impact on human activities. For example, fishing activities are negatively affected by clogging fishing-nets and drinking water treatment plants get operational problems by clogging raw water strainers and causing unpleasant odour and taste in the treated water [4]. Above all, public health concern regarding cyanobacteria is intensified, since some cyanotoxins produced by cyanobacteria cause severe and irreversible health

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effects [5–7]. The major exposure routes of cyanotoxins to humans are food, recreational swimming, and poorly treated drinking water.

In Sweden, half of the drinking water supply is based on surface water sources, which can be a problem, since harmful cyanobacterial blooms have been frequent. Specifically, there is a risk that existing water purifiers fail to remove the toxic cyanobacteria, particularly at small water treatment plants [8, 9]. Thus, it is of great importance for drinking water operators to develop strategies to cope with cyanobacterial risk. This is also highlighted for operators following Water Safety Plans (WSPs) in combination with Hazard Analysis and Critical Control Points (HACCP) [10] and emphasized by the Swedish Food Agency. Decision-making suggestions to counteract drinking water containing critical levels of cyanotoxins are provided, including a thorough understanding on how cyanobacteria blooms occur, what cyanotoxins are available, action limits for cyanotoxins in drinking water, to what extent the different drinking water preparation steps separate or inactivating cyanotoxins as well as sampling and analysis of cyanotoxins [11]. A challenge in this respect is the fact that many Swedish drinking water treatment plants (DWTPs) were built in the 1950ies of 1960ies, adapted to clearer water from the lakes during that time. As cyanobacterial blooms in freshwaters are a global issue, the knowledge can be used as inspirations for international comparison.

A survey was sent out to 98 DWTPs in 2016 by Swedish Food Agency in 2016 (Pekar, personal communication). 77 of the DWTPs (79%) participated. 62 of them completely lacked monitoring program or had any other type of surveillance for cyanobacteria and/or cyanotoxins. 3 of them performed ocular inspections for the presence of algal bloom or cyanobacteria in the surface water and/or at the raw water intake. 6 of them monitored the concentration of the cyanotoxin microcystin at the raw water intake and lastly, 6 of them were monitoring the presence of cyanobacteria and/or cyanotoxins occasionally. On indication of cyanobacteria in raw water, 3 of them followed up with analysis of microcystins also in the drinking water. Such indications were, most commonly, identification of potentially toxin producing cyanobacteria by microscope. The sense of urgency concerning problems with blooms was low.

An interesting source of data to investigate how common cyanobacterial blooms are in Swedish lakes is the list of so-called trend lakes in the environmental monitoring program managed by Swedish Agency for Marine and Water Management (SwAM) and operated by Swedish University of Agriculture Science (SLU) (Fig. 1). The lakes are reference lakes in terms of point sources and intensive different local land use, and also may be affected by large-scale airborne pollution and extensive land use [12]. Different toxins may be present in the waters. Previous investigation showed that most of the cyanobacterial blooms in the Swedish lakes produce a variety of toxins including anatoxins, cylindrospermopsins, microcystins and saxitoxins [13].

A general condition of cyanobacterial occurrence was investigated and 9 lakes that of high occurrence of cyanobacteria (i.e., median value > 0.2 $mm^3\ L^{-1}$) are specifically investigated about the drivers of cyanobacteria growth and indicating factors. As the bio-volume that is a above 0.2 $mm^3\ L^{-1}$ is of concern for drinking water supply, as *Drinking Water Alert Level 1* regulated by WHO, those lakes are of interest for future drinking water source investigation.

The objectives of this project are (1) to get a picture of the size of the problem in these 108 SwAM trend lakes utilizing the 23 years of environmental monitoring data, (2) to understand drivers behind high cyanobacteria abundance and their interactions in9 lakes of high incidence of cyanobacterial blooms, (3) to provide measures for indicating/predicating, monitoring, and controlling cyanobacteria risk.

Materials and methods

Sampling

SwAM trend lakes is part of the freshwater programme within the Swedish National Environmental Monitoring Scheme. The sampling details are described by Swedish University of Agricultural Sciences [14]. A summary is given here. Phytoplankton was sampled yearly in August between 1995 and 2018 in 108 lakes across Sweden of varying sizes (Fig. 1), including 49 lakes < 0.5 km^2, 21 lakes > 0.5 to 1 km^2 and 38 lakes > 1 km^2. All qualitative samples were taken at the lake surface, using a landing net, in the centre of the lake to determine the composition of phytoplankton species and community. Total biomass and biomass of the different species were analysed in the quantitative samples which were collected using a 2 m tube sampler. Samples were collected in the photolytic zone between 0 and 5 m. In larger lakes (> 1 km^2), the sample was taken at the centre of the lake, while in smaller lakes (< 1 km^2), samples at five different locations were taken and then mixed to a composite sample. Surface water samples for water chemical analysis were collected using a Ruttner water sampler.

Biological and chemical analysis

The analysis of phytoplankton comprised 14 classes, with quantitative measures of bio-volume per water volume using Utermöhl technique [15]. The methods for species and subspecies identification are described elsewhere [16]. The data used in this study is hosted by the Swedish

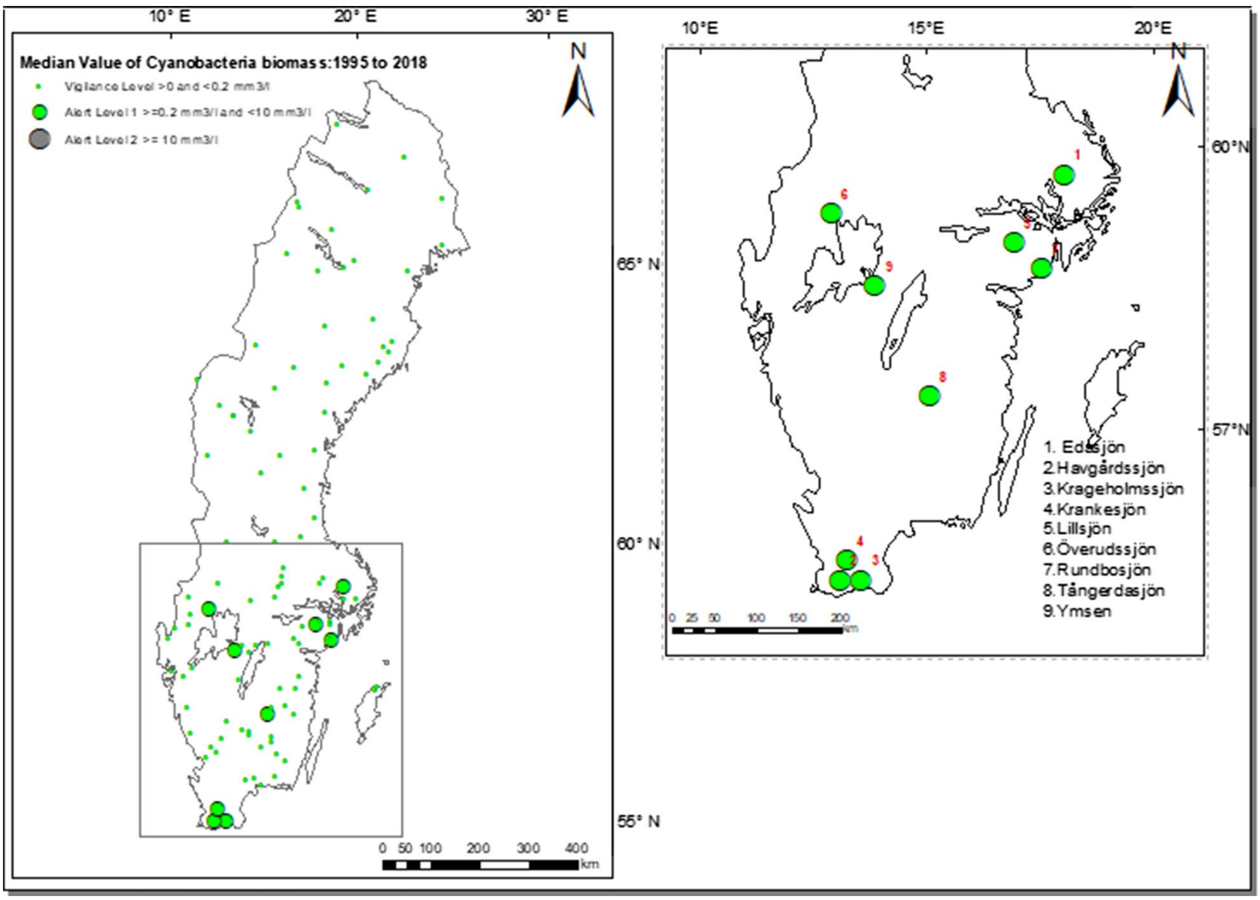

Fig. 1 Swedish Trend lakes under environmental monitoring program; 9 lakes are selected for further study with regards to cyanobacteria occurrence

University of Agricultural Sciences and available through open access (http://miljodata.slu.se/). Relevant parameters for this work are: Cyanobacteria biovolume, Chlorophyll-a, Transparency, Total Phosphorus, Total Nitrogen, Total Organic Content (TOC), pH, Fe, Si, Alkalinity/Acidity, and Conductivity. Analysis methods for chemical parameters including measurement uncertainty are presented in details elsewhere [17].

WHO guideline values

WHO [18–20] recommends 'a series of guideline values associated with incremental severity and probability of health effects'. WHO thresholds for cyanobacterial abundance in recreational waters and drinking waters were applied to identify cyanobacterial risk.

Drinking Water Alert Level 1

Cyanobacterial biomass as 2000 cells per ml or 0.2 $mm^3\ L^{-1}$ biovolume or 1 $\mu g\ L^{-1}$ chlorophyll-*a*. It requires an assessment of potential toxic cyanobacteria concentration and toxins and consultation with health authorities for ongoing assessment of the status of the bloom and of the suitability of treated water for human consumption. Weekly monitoring is suggested throughout the source water body.

Drinking Water Alert Level 2

Cyanobacterial biomass of 100,000 cells per ml or 10 $mm^3\ L^{-1}$ bio-volume or 50 $\mu g\ L^{-1}$ chlorophyll-*a* (with the presence of toxins confirmed by chemical or bioassay techniques). It describes an established and toxic bloom with high biomass and possibly also localised scums. Effective treatment is required, alternative drinking water source should be suggested and more extensive media releases of the emergency information, and even direct contact with consumers.

Thresholds for recreational waters

Three health alert categories: low ($<2\ mm^3\ L^{-1}$), moderate ($2\ mm^3\ L^{-1}$ to $10\ mm^3\ L^{-1}$) and high ($>10\ mm^3\ L^{-1}$). A high alert (or high probability of adverse health effects) is assigned when surface scums are present, where cell densities and toxin concentrations can be very high and severe health risks are possible. The 'low' and 'moderate' probabilities of adverse health effects are associated with less severe symptoms such as skin irritations and gastrointestinal illness.

The definition of bloom varies from different literatures and cases. Here we use the WHO drinking water alert level 1 as a threshold. There are 9 lakes which average cyanobacteria bio-volume above 0.2 mm^3L^{-1} during the observation period was evaluated further by terms of its common species and the magnitude of potential cyanotoxins that were relevant to drinking water production. One reference lake V. Rännöbodsjön which is a clean lake with low cyanobacteria presence was used for comparison.

Statistical analysis

The *Mann Kendall Trend Test (M–K test)* is used to analyse data collected over time for consistently increasing or decreasing trends (monotonic) in response values. It is a non-parametric test, which means that it works for all distributions. *Change point analyser* was used to check significant break point of a time series data [21]. *Principle component analysis (PCA)* was used to gain knowledge of the key water quality information and find out how significant the cyanobacterial condition in the selected 9 lakes plus a reference lake, in total 10 lakes, and which factors mostly relevant to its presence.

Quantile regression

Quantile regression aims to estimate either the conditional median or other quantiles of the response variable. The advantage of quantile regression is that its estimates are robust against outliners in the response measurements, facilitating a more comprehensive analysis of the relationship between variables [22]. Its application for example in ecology, has been proposed to discover more useful predictive relationship between variables, particularly in cases, where no relationship or only a weak relationship is expected. It has been successfully contributing to the understanding of the complexity of interactions between different factors leading to data with unequal variation of one variable for different ranges of another variable [23]. Its application is highlighted in a large European project to derive a quantitative understanding of total phosphorus on cyanobacterial abundance in over 800 European freshwater lakes and set nutrient targets to sustain recreational services and more [24]. In this project, quantile regression is used to study the situation of nutrients influence on cyanobacterial abundance in these SwAM trend lakes and set nutrient target to sustain both recreational and drinking water services and provide different levels of precaution for decision making.

Software R offers several packages that implement quantile regression, most notably quantreg by Roger et al. [25]. In this project non-linear quantile regression is used by applying Self-Starting Nls Logistic Model (SSlogis). SSlogis as selfStart model evaluates the logistic function and its gradient. It has initial attributes as initial estimates of the parameters Asym, Xmid and scal. The equation used is

$$\begin{aligned}&\mathrm{Log10}\left(\text{cyanobacteria bio - volume} + 1\right)\\&\quad = \mathrm{Asym}/\left(1 + \exp\left(\left(\mathrm{xmid} - \log10(\mathrm{TP})\right)/\mathrm{scal}\right)\right)\end{aligned} \quad (1)$$

where *Asym* a numeric parameter representing the asymptote (the carrying capacity).

Xmid a numeric parameter representing the TP value at the inflection point of the curve. The value of SSlogis will be Asym/2 at xmid (representing the time to fastest growth).
Scal a numeric scale parameter on the input axis (inverse of the slope of growth at xmid and represents the growth rate during the exponential phase (the smaller the scal value, the faster the growth rate).

Results

General status of cyanobacterial risk

The occurrence of cyanobacteria which of median value > 0.2 $mm^3\ L^{-1}$ was observed in in 9 lakes (8% of SwAM trend lakes) mainly located in south of Sweden (Fig. 1). Lillsön has the highest median value and more than 60% of the cases, cyanobacteria are dominating (> 50%). Krageholmssjön has the largest variance. All 108 lakes cyanobacterial bio-volume with minimum, maximum, and median refer to Additional file 1: Table S1. Land use and ecosystem statues of those 9 lakes are summarized in Additional file 1: Table S2, which indicates that those 9 lakes are categorized as having bad or unsatisfied ecosystem, high eutrophication statues and intensive land use.

Temporal distribution of cyanobacteria bio-volume of the targeted 9 lakes is plotted in Additional file 1: Fig. S1 which shows that most of these lakes varied much since 1995 with higher and more peaks of bio-volume before 2004 and slightly calmed down between 2004 and 2011 and increased variations and peaks after 2011. Mann–Kendall trend test shows that only Lillsjön shows significant variations of the average cyanobacteria bio-volume before 2003, 2003–2013 and after 2014 ($P < 0.03$).

Cyanobacterial species were analysed in samples with a biovolume > 0.2 $mm^3\ L^{-1}$ (424/ 2410 samples from 1995 to 2018) to investigate the most frequent taxa (Fig. 2a)

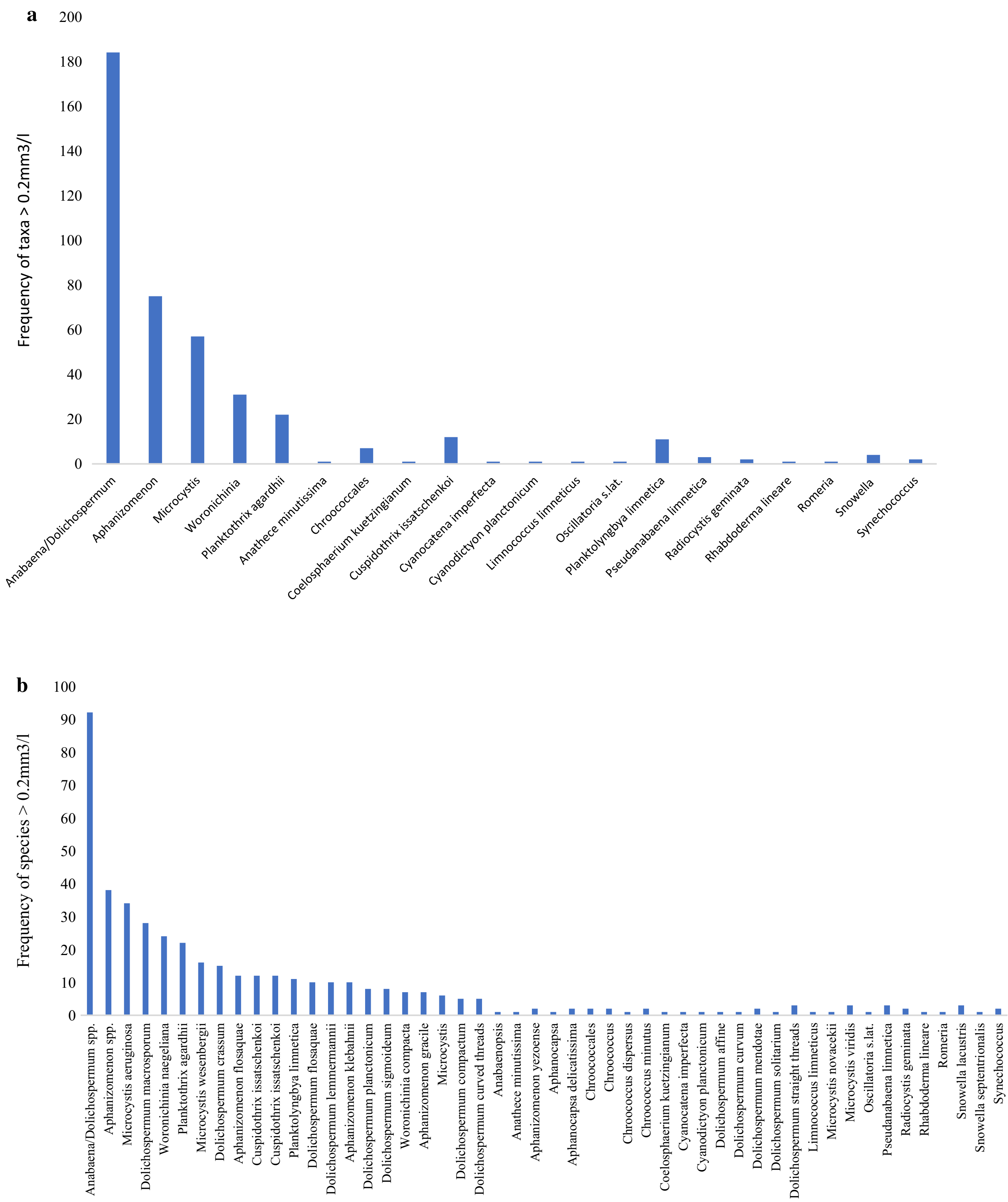

Fig. 2 Cyanobacteria biovolume in the Swedish trend lakes, exceeding 0.2 mm^3 L^{-1} (Drinking water alert level) divided into (**a**) dominating taxa and (**b**) dominating species

and species (Fig. 2b). *Anabaena* and *Aphanizomeno*n were the most frequent taxa, followed by *Microcystis* and *Woronichinia* and *Planktothrix agardhii.* Additional file 1: Table S3 summarizes literature study (Additional file 1: Table S4) of potential toxins produced by the most frequent cyanobacterial species. The species identified in Fig. 2b have the potential to produce several variants of anatoxins, cylindrospermopsins, microcystins and saxitoxins. As the most frequent cyanobacterial species comprise almost 90% of the occurrence, it indicates that cyanobacteria biovolume > 0.2 $mm^3\ L^{-1}$ in those lakes were potentially toxic.

Identification of drivers for cyanobacteria growth

The diversity of cyanobacteria species in the 9 lakes was illustrated in Fig. 3 with a reference Lake V. Rännöbodsjön which has a good status. Figure 3 shows that the more eutrophic the water is, the more diverse the cyanobacteria taxa are. Significant positive correlation ($P \leq 0.01$) between TP and the number of cyanobacterial taxa was found. The reference lake with the lowest level of phosphorus has only one species, while the lake with highest level of phosphorus, Krageholmssjön, has more than 7 taxa.

Investigation of primary water information and important factors were done by Pearson correlation and PCA analysis. Pearson correlation matrix in Additional file 1: Fig. S2 shows the correlations between cyanobacteria biovolume and other water quality parameters, where cyanobacterial biomass is positively (in order) correlated with TP, chlorophyll-a, TOC, alkalinity condition and TN; and strongly negatively correlated with transparency. This is also confirmed by PCA analysis in Additional file 1: Fig. S3; and variables that significantly correlated to each component are shown in Additional file 1: Table S5. The three main components represent 82% of original information. The first main component which accounts for 42% variance of original data reflects the prime information in those lakes are nutrients condition and total plankton biomass and they are positively connected, particularly in lakes surround by agriculture land. The second main component explains 27% of the variance of the original data and reflects the cyanobacterial condition, which is significantly positively connected to the total organic matter and Fe content, particularly in lakes surrounded by forestry lakes, and are negatively correlated with transparency, pH and conductivity. Thus, it might indicate that the increase of cyanobacteria would

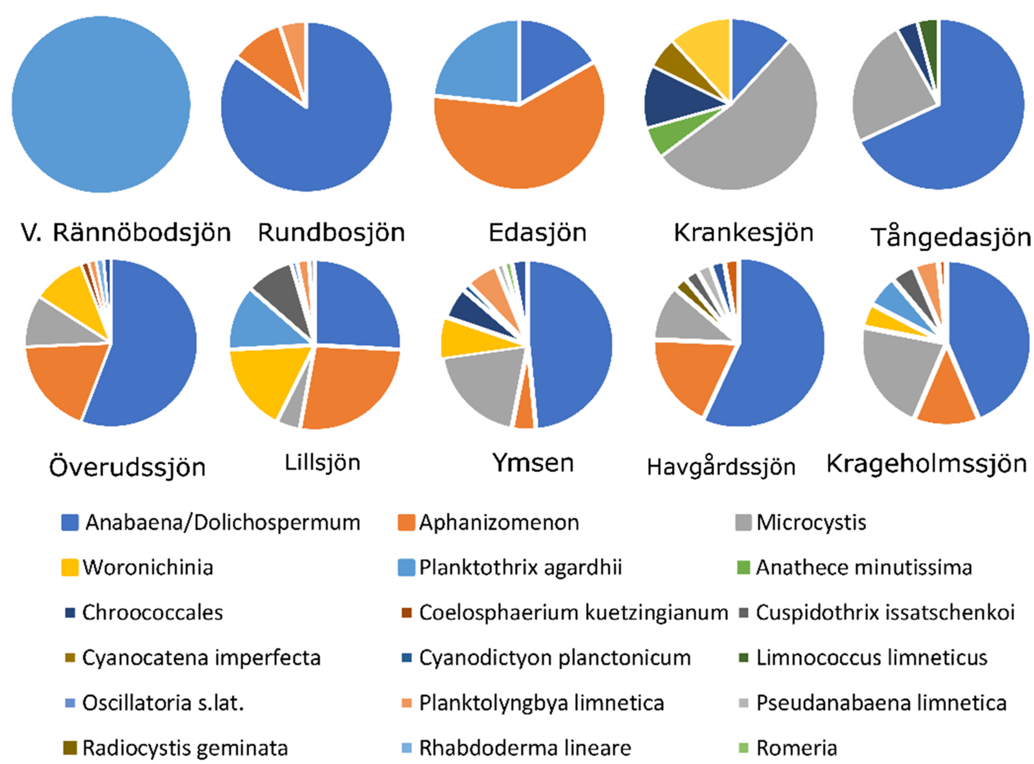

Fig. 3 The diversity of species in all selected 9 lakes and one reference lake V. Rännöbodsjön. Diversity of cyanobacteria species increases with eutrophication status; eutrophication statues is increasing from left to the right, from the first line to the second line

increase together with TOC and Fe in water, causing water deterioration.

Water quality in a lake is largely influenced by land use in the surrounding. Additional file 1: Fig. S3 illustrates clearly that lakes surrounded by more forest form a distinct cluster on the top left, and lakes that are surrounded by more agricultural land, are clustered in the bottom right. Forestry lakes are closer to high cyanobacterial biomass and cyanobacteria dominating situation, total organic matter and Fe. Lakes surrounded by agriculture land are closer to nutrient condition. Besides, two lakes are very distinct from others, one is a lake with mixed land use (Ymsen), located in-between the two clusters and a reference lake (V. Rännöbodsjön) of good water quality is located far from all others.

In these 9 focused lakes, TN:TP also demonstrates a significant negative correlation ($P<5.881\text{e}{-}07$), all occurrences above the *Drinking Water Alert Level 2*: cyanobacterial bio-volume of 10 mm^3L^{-1} bio-volume is under the value of 40 (Additional file 1: Fig. S4).

Evaluation indicators for cyanobacterial presence

As nutrients have been identified as the main drivers for those lakes that of higher cyanobacterial risk, therefore, nutrients condition can be investigated as indicating factors for cyanobacterial risk for all 108 lakes. Here we demonstrate an example of how total phosphorus can be applied as an indicator for cyanobacterial presence.

Quantile regression was successfully applied to demonstrate cyanobacterial risk in terms of total phosphorus condition for 800 European lakes [24]. We would like to check how it is used for all 108 lakes by applying quantile regression. Quantile regression curves (0.05–0.99) using a fitted 3-parameter sigmoid nonlinear model are displayed in Fig. 4. All quantiles, including lower quantile (0.05), show significant relationship between

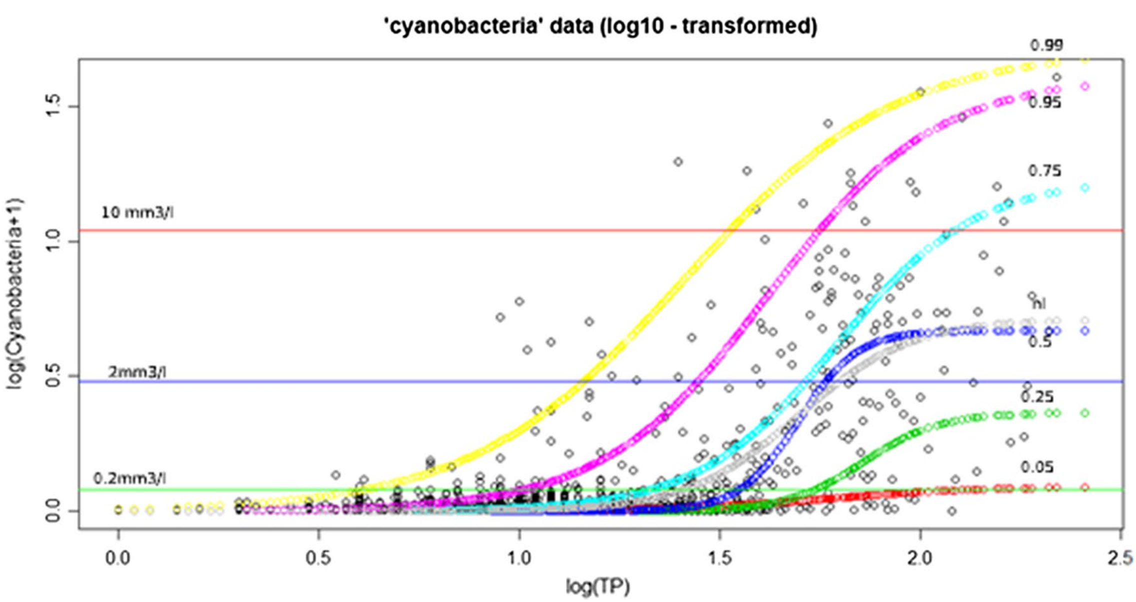

Fig. 4 Scatter plot for log10 (cyanobacteria + 1) and log10(TP) (Total phosphorus) for Swedish trend lakes ($n=108$, 1995 to 2018). Quantile regression curves (0.05–0.99) using a fitted 3-parameter sigmoid nonlinear model are displayed. nls = nonlinear least square regression fit to mean of data. Thresholds relating to approximate WHO (1999) alert level 1 and 2 for drinking water are indicated together with thresholds relating to approximate low and medium health risk thresholds for recreational water

Table 1 Correlation matrix of quantile estimates and phosphorus concentrations

Pearson's product-moment correlation	Quantiles					
	0.05	**0.25**	**0.5**	**0.75**	**0.95**	**0.99**
Correlation with TP concentration	0.81	0.63	0.68	0.77	0.87	0.96
P value	2.2e−16	2.2e−16	2.2e−16	2.2e−16	2.2e−16	2.2e−16

cyanobacteria biomass and TP (Table 1). This relationship differs from Carvalho and his colleagues' study [24], in which a significant relationship was only present in higher quantiles (0.25 and above). Figure 4 shows that the higher the quantile, the earlier the take-off of cyanobacteria response to TP. For example, the 95th quantile and 75th quantile have a take-off of cyanobacteria response at a threshold around 10 μg L^{-1}, while for the 50th and 25th quantile, cyanobacteria start to response at TP around 30 μg L^{-1}. All quantiles have a flattening of response at a threshold about 100 μg L^{-1}. It means that the increase of TP after this point have low impact on additional cyanobacteria growth.

Evaluation transparency and chlorophyll-a as indicator for cyanobacterial presence

Transparency and chlorophyll-a are listed as important factors for assessing the potential presence of cyanobacterial biomass in water among other indicators such as total phosphorus, water residence time, temperature and pH [20, 26, 27]. If transparency is low (less than 1–2 m) and accompanied by a blue and green water colour, high cyanobacterial biomass is likely to occur. A chlorophyll-*a* concentration of 1 μg L^{-1} in raw water triggers Alert Level 1 in WHO management system for cyanobacterial blooms in the perspective of drinking water [19]. Taste and odour problems begin occurring once chlorophyll-*a* values reach 10 μg L^{-1} [28].

A general overview of transparency and chlorophyll-*a* concentration with cyanobacterial biomass in the 9 lakes are presented in boxplot (Additional file 1: Fig. S5 and S6) with drinking water alert levels and health thresholds. In general, when transparency decreases, it is likely to trigger higher alert levels and health thresholds; and the more chlorophyll-*a* content in water, the more likely higher cyanobacterial biomass present. In the selected 9 lakes, an average transparency as 1.2 m and chlorophyll-*a* median value as of 32 μg L^{-1} correspond in general to their high cyanobacteria occurrence. From specific lake study, high correlation between transparency and cyanobacterial risk are only found in Lillsjön (−0.75, $P<0.01$) and Ymsen (−0.70, $P<0.01$). A high correlation between chlorophyll-*a* and cyanobacterial risk are only found in Krankesjön (0.85, $P<0.01$) and Tångerdasjön (0.79, $P<0.01$).

Significant indicators for the variance of cyanobacterial biomass might be different in different lakes, for example, Iron and pH for Edasjön, conductivity for Krageholmssjön and pH condition for Rundbosjön.

Discussion

Drivers behind cyanobacterial risk

From our study, all those 9 lakes that of potential concern for possible drinking water supply share similarities with high eutrophication statues and intensive land use. They are also categorized as having bad or unsatisfied ecosystem status mainly due to high eutrophication, highly influenced by urbanization, agriculture and historically exposed for not well treated wastewater [29]. Those higher cyanobacteria bio-volume in those lakes are mainly nutrients driven. Our results also confirmed previous studies that low ratio of TN:TP might trigger cyanobacteria dominating situations. This is also confirmation of past study that nutrients' ratio affect cyanobacteria composition [30].

Our results emphasize that besides nutrients which are essential condition for cyanobacterial growth, the organic matter has high correlation with the cyanobacteria abundance particularly in eutrophic forestry lakes. PCA analysis results showed that there is a clear difference between agricultural lakes and forestry lakes; the former is more eutrophic, and the latter is browner (more organic matter). The increase of iron bond TOC in eutrophic forestry lakes might trigger even more intensive cyanobacterial blooms. It brings worries under future climate scenarios that the increase of brownification (increase of organic matter in water), particularly in the northern hemisphere [31] together with the increase of temperature might trigger more intensive cyanobacterial blooms [32].

Cyanobacterial blooms are triggered by various environmental conditions. They are rather a consequence of a combined effect. While certain parameters could be considered as prime indicator for cyanobacterial risk assessment.

Cyanobacterial risk management

The results analysis of all lakes using TP as a tool for demonstrating cyanobacterial risk. The results can contribute to compare with other studies worldwide and at the same time serve a local lake a possible method for a controlling measure for maximizing drinking water safety and minimizing health risks. Because TP is likely more controllable than TN in practice even though both are drivers in cyanobacteria formation.

Phosphorus control is the key to control cyanobacterial blooms and consequent health risk, which has been highlighted in many research projects [30, 33, 34] and used in practice at for example Lake Erie [35] and Vombsjön, South Sweden [36]. It is important to understand more fully the response of cyanobacterial abundance in relation to nutrient pressures [37]. Our study verified the advantage of using quantile regression for a quantitative study of the cyanobacteria response of TP in a Swedish context.

The algorithm and calculations in the results would facilitate water operators for decision making regarding to TP targets in the case of those 9 lakes are considered as drinking water sources.

As we noticed that from a drinking water point of view, under 10% exceedance rate, TP target would be reduced less than 15 μg L^{-1}, and for recreational purpose, under 10% exceedance rate, TP target for low health risk is 35 μg L^{-1} which is higher than Carvalho and his colleagues' study [24], which is 20 μgL^{-1}. In a Swedish drinking water context, this is of special importance as many water treatment plants are applying artificial ground water recharge. To prevent cyanobacteria regrowth in the artificial recharge ponds, pretreatment of reducing nutrients condition is a key to protect following treatment process [36].

Compared to Carvalho and his colleagues' study [24], the application even suits low quantiles models. The difference between the two studies is on one hand likely due to different sampling procedure and local environmental conditions such as temperature variations, sun radiation and salinity, etc. and on the other hand, in Swedish lakes which in a colder climate, low temperature could be a limiting condition and the increase of TP in oligotrophic possibly drive cyanobacteria growth.

From a practical management point of view, quantile responses Fig. 4 can be used to predict the bloom capacity at present temperature regimes. For example, in Table 2, the 95th quantile (i.e., 5% exceeding rate) is used to estimate the potential maximum capacity of cyanobacteria in response to the increase of TP. In the table, the results show that the capacity for cyanobacteria growth increases with increasing TP, until TP concentrations > 150 μg L^{-1}; 5% of samples would exceed drinking water alert level 1 at TP of 10 μg L^{-1}; and exceed low health risk threshold for recreational water at TP of 27 μg L^{-1} and exceed drinking water alert level 2 and medium risk threshold at TP of 53 μg L^{-1}.

This analysis method can also contribute to setting local nutrients targets in relation to alert levels for drinking water and health risk for recreational water. For example, by applying quantiles algorithms with quantiles > 0.5 in Table 3, nutrients targets are calculated in relation to alert levels for drinking water and health risk thresholds. The results in Table 4 demonstrates that at a TP of about 14 μg L^{-1}, 10% of samples exceeded the WHO drinking water alert level 1, if TP increases to 35 μg L^{-1}, the percentage of exceedance will be 50%. Similarly, 10% of water samples would surpass low health risk for recreational water (2 mm^3 L^{-1}), at TP level of 35 μg L^{-1}, at a level of around 60 μgL^{-1}, the percentage of exceedance will be 50%. In the same way, it shows at a TP concentration level of 72 μg L^{-1}, 10% of samples would surpass the drinking water alert level 2 and medium health risk.

Table 3 Parameter estimates derived using nonlinear quantile regression for 108 Swedish trend lakes together with the estimates for nonlinear mean response

Model	Asym	mid	Scal
0.05	0.09 ± 0.04	1.77 ± 0.15	0.19 ± 0.02
0.25	0.36 ± 0.15 *	1.86 ± 0.12	0.09 ± 0.03
0.5	0.67 ± 0.09	1.70 ± 0.04	0.07 ± 0.01
Mean (Non-linear)	0.71 ± 0.03	1.70 ± 0.02	0.14 ± 0.01
0.75	1.23 ± 0.19	1.79 ± 0.06	0.17 ± 0.01
0.95	1.61 ± 0.23	1.62 ± 0.09	0.21 ± 0.02
0.99	1.71 ± 0.22	1.41 ± 0.11	0.26 ± 0.04

The rest $P < 0.01$, * $p < 0.05$

By applying results from Table 4 to our selected 9 lakes, of which all median value of TP above 33 μg L^{-1}, that least 40% exceedance rate above the drinking water alert level 1 and 10% exceedance rate above the low health threshold. Lake Krageholmssjön with the highest median value of TP, around 129 μg L^{-1}, it is more than 20% likely to above the medium health risk and drinking water alert level 2. TP target for low health risk in SwAM trend lakes allow 10% exceedance is 35 μgL^{-1}.

Our study also included other indicators evaluation that might be interesting to further study for a local assessment of cyanobacterial risk. Here we only looked in to driving factors' point of view and provide insights for controlling measures. The most applied approach is monitoring chlorophyll-a content or cyanobacteria pigment.

Challenges and opportunities of cyanobacterial risk monitoring and predicting

No clear trend of cyanobacteria occurrence and the diversity of toxic species have added complexity of managing cyanobacterial issue in eutrophic waters. The likelyhood of increase of co-occureance of multi-toxin

Table 2. 95% quantile fitted values showing the changing cyanobacterial biovolume (mm^3 L^{-1}) with change in total phosphorous (μg L^{-1})

Total Phosphorus (μg L^{-1})	0	10	27	53	100	150	200	250	300	500
Cyanobacteria capacity (95%) (mm^3 L^{-1})	0	0.2	2	10	25	32	35	36	37	38

The fitted quantile reaches an asymptote at 38 mm^3 L^{-1} of cyanobacteria biovolume

Table 4 Total phosphorus (TP) concentrations for a given likelihood (quantile) of being below low and medium risk World Health Organisation (WHO 1999) threshold levels for cyanobacteria volume

Quantile		50th	60th	70th	80th	90th	95th	98th
%Exceeded		50%	40%	30%	20%	10%	5%	2%
Drinking water alert 1 0.2 mm^3 L^{-1}	TP μgL^{-1}	35.34	30.31	23.90	19.39	13.42	10.25	5.87
Low health risk 2 mm^3 L^{-1}	TP μgL^{-1}	57.88	56.15	53.58	48.69	35.44	27.84	19.33
Drinking water alert 2/Medium health risk 10 mm^3 L^{-1}	TP μgL^{-1}				117.30	72.15	56.11	43.99

TP concentrations are obtained from the fitted quantile regression models

producing species with increase of eutrophication were also observed in a large scale Finnish lakes' study [38].

Even though, above quantile regression has demonstrated its advantage and usefulness to indicate cyanobacterial risk over single factor such as transparency or chlorophyll-*a,* we still need to keep in mind that various environmental factors are influencing cyanobacteria abundance such as temperature, wind, land use, DO, salinity, and pH, lake geometry, species competition, grazers as well as their various surviving strategies [39].

Other studies have also shown poor correlation between chlorophyll-*a* and bio-volume of cyanobacteria; rather phycocyanin could be recommended as an early warning signal [40] and direct measurement of specific chlorophyll-*a* in cyanobacteria cells by their specific fluorescence spectra became popular such as application of Algae Online Analyzer (AOA) fluorometer [41]. Such fluorometer can simultaneously distinguishes four different phytoplankton groups by their specific fluorescence spectra and thus allows for real-time in-situ chlorophyll-*a* measurements per algal group. At the end, other elements also showed their importance in relation to cyanobacterial biomass formation. Individual lake investigation and deeper understanding of the individual lakes is crucial for setting indicators or building cyanobacterial risk assessment.

The WHO thresholds adopted in this study (WHO [18–20]) are not the only targets that exist. For example, in Finland, DWTPs are recommended to increase monitoring actions and preparedness when the biomass exceeds 0.1 mm^3 L^{-1} in incoming raw water [42]. When the biomass exceeds 1 mm^3 L^{-1}, DWTPs are recommended to take action such as to change the abstraction point or depth, identify species of cyanobacteria or potential cyanotoxins, perform a health risk assessment and inform the municipal health protection authority [42]. While Australia set at a total bio-volume equivalent of 4 mm^3 L^{-1} as health alert levels, although skin irritations have been observed at densities as low as 0.4 mm^3 L^{-1} [43].

A suggestion to local water operators is that to study your lake individually and find a proper indicator or a combination of indicators that fit your situation for better monitoring cyanobacteria abundance. Set a routine to check total phosphorous, cyanobacteria abundance, composition and cyanotoxin content and trace their variations. Advanced treatment might be introduced, or alternative water resources should be investigated.

Limitations and further study

Among SwAM trend lakes, only 8% lakes displayed problematic cyanobacteria abundance mainly between 1995 and 2018. The percentage cannot be extrapolated and cannot be applied to source waters for drinking water supply, since the selection criteria for trend lakes and source water for drinking water production are different. Trend lakes were selected with the purpose of tracing environmental changes amongst other, climate change, and the majority of them are located in rural areas. Source waters for drinking water production are often located close to cities and in general more impacted by anthropogenic activities than many of the Swedish trend lakes.

There is no clear trend of cyanobacteria abundance in those lakes during the monitoring period, partly due to data limitation. As sampling was done once per year in August, implying that trend lakes blooming at other times would not appear as a blooming lake in this study. In Sweden the main bloom period for cyanobacteria starts in May and continues through August, even into the middle of November. For example, *Aphanizomenon* was abundant also in November and *Planktothrix agardhii* has been identified in considerable volumes during winter in some lakes [44]. The value of long- term monitoring program has also been questioned and summarized by Lovett and others [45]. For a better understanding of the cyanobacterial abundance in SwAM trend lakes, particularly in those highlighted 9 lakes, sample frequency should be increased, at least to cover the bloom season.

Even though we have above limitations, our results demonstrated certain benefits from a national monitoring program. Further study would focus on a general framework development of categorizing different lakes and study deeper of the driving factors and limiting condition for cyanobacteria' presence. It is also interesting to investigate the similarities of cyanobacteria species composition in those problematic 9 lakes and their changes through time and how that change along with environmental conditions would be give more insights for understanding the cyanobacteria dynamics in those lakes.

Conclusion

Cyanobacterial blooms are of increasing concern, not least when using water for bathe or water supply. Our study presented a general picture of the size of the cyanobacterial risk in 108 Swedish trend lakes. The national environmental monitoring data was used for this study. The most common taxa discovered were *Anabaena/Dolichospermum* and *Aphanizomenon* followed by *Microcystis*, *Woronichinia* and *Planktothrix*. Those species might produce a variety of toxins such as anatoxins, cylindrospermopsins, microcystins and saxitoxins. Our study also found the more eutrophic the lake, the more likely multispecies dominate. In eutrophic forestry lakes, cyanobacterial biovolume tends to increase with the increase of organic matter. We further evaluated that chlorophyll-*a* and transparency might be suitable as indicators for cyanobacterial blooms in certain lakes, while for most of the lakes, their connection is low. Applying non-linear quantile regression is highlighted as an example for cyanobacterial risk assessment and provide control measures by setting nutrients targets. Our results conclude that if using TP as a controlling measure for preventing cyanobacteria' growth, allowing 10% exceedance, for WHO drinking water alert level 1, TP should be targeted lower than 15 μg L^{-1}; for recreational purpose, TP target for low health risk is 35 μg L^{-1}. This might particularly be interesting for artificial ground water retention ponds management. We suggest TP concentrations should be investigated thoroughly to provide important knowledge which can be used to set nutrient targets to sustain safe drinking water supply and recreational services. Individual lake study is necessary to find a proper or a combination of indicators that fit local situation for better indicating cyanobacteria abundance. Driving factors and limiting condition for cyanobacteria' presence in different categories of lakes can be future investigated as well as the similarities of species composition along with time and water quality condition.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-021-00483-1.

Additional file 1: Figure S1. Temporal distribution of cyanobacteria in the focused 9 lakes. **Figure S2.** Correlation matrix between all water factors concerned. **Figure S3.** PCA biplot which graphically demonstrates the first and second main components to represent 67% of the water quality information. **Figure S4.** Cyanobacteria Bio-volume and its connection to TN: TP. High amount corresponds to low ratio. **Figure S5.** Boxplot result of transparency and cyanobacteria with the drinking water alert level and health risk levels for recreational water. **Figure S6.** Boxplot of Chlorophyll-a and Cyanobacterial biomass. **Table S1**. Cyanobacterial biomass general condition in 108 trend lakes from 1995 to 2018 with their min. max and median values. 9 lakes are selected for further analysis due to their high level of biomass. **Table S2**. A summary of status in the selected 9 lakes.**Table S3**. Potential toxin production for the most frequently cyanobacterial species in the Swedish trend lakes between 1995 -2018. Only species above 0.2mm3L-1 were considered. This table is based on a literature study. **Table S4**. Linking toxins to cyanobacteria species.

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Authors' contributions

JL is the main contributor for data collection and data analysis, and manuscript writing. KMP contributes to the supervision. HP was the main contributor for species dynamics analysis and project coordinating for survey study and project design. DJ was the main contributor for the cyanotoxin literature study. All authors read and approved the final manuscript.

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Availability of data and materials

Open-source data: https://miljodata.slu.se/MVM/Search.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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