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Land use patterns, ecoregion, and microcystin relationships in U.S. lakes and reservoirs: A preliminary evaluation

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ABSTRACT

A statistically significant association was found between the concentration of total microcystin, a common class of cyanotoxins, in surface waters of lakes and reservoirs in the continental U.S. with watershed land use using data from 1156 water bodies sampled between May and October 2007 as part of the USEPA National Lakes Assessment. Nearly two thirds (65.8%) of the samples with microcystin concentrations $\geq$1.0 μg/L (n = 126) were limited to three nutrient and water quality-based ecoregions (Corn Belt and Northern Great Plains, Mostly Glaciated Dairy Region, South Central Cultivated Great Plains) in watersheds with strong agricultural influence. canonical correlation analysis (CCA) indicated that both microcystin concentrations and cyanobacteria abundance were positively correlated with total nitrogen, dissolved organic carbon, and temperature; correlations with total phosphorus and water clarity were not as strong. This study supports a number of regional lake studies that suggest that land use practices are related to cyanobacteria abundance, and extends the potential impacts of agricultural land use in watersheds to include the production of cyanotoxins in lakes.

1. Introduction

Excessive inputs of both nitrogen and phosphorus to aquatic ecosystems are a global concern (Conley et al., 2009; Paerl, 2009; Abell et al., 2010). The potential for increased eutrophication of lakes and reservoirs (hereinafter, lakes) to result in higher incidences of harmful cyanobacteria blooms is recognized (Heisler et al., 2008; Paerl and Huisman, 2008; O'Neil et al., 2012). Land use changes, particularly increased nutrient loading associated with agricultural and urban development, are likely major drivers of degraded water quality in lakes and often result in modified and/or simplified aquatic food webs (Carpenter et al., 2011; Martinuzzi et al., 2013). Temperature is also recognized as a primary structuring factor for the compositional, seasonal, and physiological status of cyanobacteria communities in lakes. Warmer conditions typical of summer favor cyanobacteria in planktonic environments because they can maximize growth rates and exploit buoyancy regulation in a stratified water column (Paerl and Paul, 2012; Carey et al., 2012). In addition to increased nitrogen and phosphorus inputs, the concentrations of dissolved organic carbon (DOC) in lakes have been increasing worldwide (Evans et al., 2005) and may reflect the increased importance of autochthonous carbon in higher productivity plankton environments. The expected impacts of climate change on lakes (e.g., drought and extended stratification) would intensify these competitive adaptations and potentially disproportionately favor toxigenic cyanobacteria (Paerl and Otten, 2013).

Eutrophication of lakes and the associated compositional shifts in phytoplankton communities to increased dominance by cyanobacteria is well documented, but the relationship between watershed land use and microcystin concentrations in lakes remains poorly described. Microcystins are cyclic nonribosomal peptides produced by cyanobacteria which exhibit potent hepatotoxic properties. We used a database consisting of phytoplankton and microcystin analyses from samples collected during the growing season from 1156 lakes located within the 48 contiguous U.S. during the 2007 National Lakes Assessment (USEPA, 2009) to determine whether total microcystin concentrations, a common class of cyanotoxins, and the total abundance of cyanobacteria displayed any relationship to ecoregion, individual watershed land

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use, nutrient concentrations, water temperature, water clarity and DOC. To date, no systematic attempt has been made to relate watershed land use characteristics to microcystin concentrations over such a large geographical area. A recent analysis of this same database indicated that total nitrogen and temperature explained more variance in estimated cyanobacteria biomass than other water quality variables (Beaulieu et al., 2013). Given that a number of regional studies suggest that water column nutrient concentrations and/or phytoplankton community composition are influenced by watershed land use practices (Karatayev et al., 2005; Bremigan et al., 2008; Vanni et al., 2010; Beaver et al., 2012; Katsiapi et al., 2012; Paul et al., 2012; Beaver et al., 2013), we hypothesized that patterns in watershed land use should likewise be related to microcystin concentrations.

2. Methods

2.1. National Lakes Assessment study sites

1156 lakes selected from the USGS/EPA National Hydrography Dataset (NHDPlus) (see Simley and Carswell, 2009) were comprehensively sampled throughout the continental United States in 2007 (USEPA, 2009). Each lake was sampled for water quality, biological condition, habitat conditions, and recreational suitability. Lakes were selected without bias using probability-based selections and constituted a statistically valid representation of lakes in similar regions (USEPA, 2009). Both man-made and natural lakes greater than 4 hectares in size (excluding the Great Lakes) were included as well as some lakes sampled during the National Eutrophication Survey conducted in the 1970s (USEPA, 1975). Our study constitutes the first nationwide assessment of microcystin concentrations in U.S. lakes.

2.2. Sample collection

The study lakes were sampled between May and October 2007 using the protocol developed by the USEPA (USEPA, 2007). Most lakes were sampled near the deepest point which usually was the mid lake area. Samples for total nitrogen (TN) and total phosphorus (TP) analyses were collected from an integrated photic zone sample down to 2 times the Secchi depth or 2 meters, whichever was shallower and were analyzed in accordance with USEPA (2007). Although the vertical temperature profile was usually collected from the deepest part of each lake, for the purposes of this study the mean water column temperature of the top 5 m was used. Approximately ten percent of the lakes were sampled twice during the study period and mean values were used for analyses.

Phytoplankton and microcystin samples were collected from integrated water samples from the euphotic zone of each lake. Phytoplankton samples were preserved with Lugol's iodine and shipped to EcoAnalysts (Moscow, Idaho) for microscopic examination. Microcystin samples were shipped on ice to the USGS Organic Geochemistry Research Laboratory in Lawrence, Kansas.

2.3. Laboratory analyses

A single laboratory determined TP (detection limit 4.0 μg/L), TN (detection limit 20 μg/L), and DOC (detection limit 0.2 mg/L) concentrations (USEPA, 2009). Phytoplankton samples were analyzed with compound microscopes using pre-concentrated samples prepared in Utermöhl sedimentation chambers that had been allowed to sit for a minimum of eight hours. Taxonomists were responsible for the lowest possible taxonomic identification and enumeration of 300 natural algal units and included cell tallies. Although cell densities were determined for all phytoplankton identified, for the purposes of this study only total cyanobacteria abundance was considered. Cyanobacteria cell densities were reduced to taxonomic order (Chroococcales, Nostocales, and Oscillatoriales – see Beaulieu et al., 2013) and summed within each sample prior to statistical analyses. Total microcystin concentrations were determined using the Abraxis Microcystins/Nodularins enzyme-linked immunosorbent assay (detection limit 0.1 μg/L; -ADDA specific) after three freeze-thaw cycles to lyse cyanobacteria cells (USEPA, 2007; Graham et al., 2010).

2.4. Percent land use determination

We assigned watershed land use to 10 categories (Developed, Barren Land, Deciduous Forest, Evergreen Forest, Mixed Forest, Shrub/Scrub, Grassland/Herbaceous, Pasture/Hay, Cultivated Crops, Wetlands). Watersheds were delineated and were grouped into two categories, on-network and isolated lakes. On-network lakes were lake/pond features that are located on the NHDPlus network flowlines (i.e., NHDPlus stream network); whereas isolated lakes were lake/pond features that were lake points in NHDPlus, but not located on the network flowlines (see Simley and Carswell, 2009). For all on-network lake basins, delineations began at the lake outlet as represented by the NHDPlus stream network. The reachcode and measure of the stream network line that represented each lake's outlet was determined and used by the NHDPlus Basin Delineation Tool to derive the drainage basin shapefile. For all isolated lakes, delineations were made using the Watershed Tool, located within Spatial Analyst package of ArcGIS (ESRI, 2011). The input to the Watershed Tool was a rasterized NHDPlus lake polygon and the NHDPlus flow direction grid, and resulted in a basin that was converted into a polygon shapefile. Once the shapefiles were created from the two delineation processes, the NLCS 2001 v1 dataset was applied to each basin shapefile to come up with land use percentages.

2.5. Statistical analyses

A canonical correlation analysis (CCA) was performed using the Canonical Analysis of Principal Coordinates (CAP) function of the PERMANOVA+ add-on in PRIMER 6 (Clarke & Gorley, 2006) between untransformed percentage land use and log-transformed water quality variables. A data matrix was prepared detailing the percentage of each type of land use in the watersheds of the 1156 lakes. A Bray–Curtis resemblance matrix was computed from the percentage land use data matrix prior to analyses. A data matrix was also prepared using five environmental variables including TN (μg/L), TP (μg/L), DOC (mg/L), water temperature (°C), and Secchi depth (m). For CAP analysis, the percentage land use resemblance matrix was analyzed against the sample-matched and log-transformed environmental matrix. Subsequent to the CCA analysis, concentrations of microcystin and cyanobacteria abundance were superimposed over the CCA plot. Additional details on the statistical methodology are provided in Beaver et al. (2012, 2013). Mann–Whitney tests were performed in order to determine significant differences between water quality variables using GraphPad Prism 6.04 software (GraphPad, 2014).

3. Results and discussion

126 samples from the 1156 lakes used in this study (10.9%) contained $\geq$1.0 μg/L of microcystin (Fig. 1). A comparison of mean land use in the high ($\geq$1.0 μg/L) and the low (<1.0 μg/L) microcystin lakes indicated that the mean percentage land use of $\geq$1.0 μg/L and <1.0 μg/L microcystin lakes differed primarily on the proportion of land devoted to agricultural (grassland/herbaceous, pasture/hay, cultivated crops) and forested land uses (Table 1). The mean percentage land use for $\geq$1.0 μg/L microcystin