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Controlling cyanobacterial blooms by managing nutrient ratio and limitation in a large hyper-eutrophic lake: Lake Taihu, China

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ABSTRACT

Excessive nitrogen (N) and phosphorus (P) loading of aquatic ecosystems is a leading cause of eutrophication and harmful algal blooms worldwide, and reducing nutrient levels in water has been a primary management objective. To provide a rational protection strategy and predict future trends of eutrophication in eutrophic lakes, we need to understand the relationships between nutrient ratios and nutrient limitations. We conducted a set of outdoor bioassays at the shore of Lake Taihu. It showed that N only additions induced phytoplankton growth but adding only P did not. Combined N plus P additions promoted higher phytoplankton biomass than N only additions, which suggested that both N and P were deficient for maximum phytoplankton growth in this lake (TN:TP = 18.9). When nutrients are present at less than 7.75–13.95 mg/L TN and 0.41–0.74 mg/L TP, the deficiency of either N or P or both limits the growth of phytoplankton. N limitation then takes place when the TN:TP ratio is less than 21.5–24.7 (TDN:TDP was 34.2–44.3), and P limitation occurs above this. Therefore, according to this ratio, controlling N when N limitation exists and controlling P when P deficiency is present will prevent algal blooms effectively in the short term. But for the long term, a persistent dual nutrient (N and P) management strategy is necessary.

Introduction

Nitrogen (N) and phosphorus (P) are essential elements for the synthesis of nucleic acids, ATP and proteins, which are necessary for cell division and growth (Conley et al., 2009). The cycles of the key macronutrients N and P have been massively altered by anthropogenic activities (Canfield et al., 2010; Elser et al., 2007). N and P over-enrichment accelerates eutrophication in aquatic ecosystems and has promoted harmful algal blooms worldwide (Conley et al., 2009; Paerl et al., 2011a; Schindler and Hecky, 2009). Some of our largest aquatic ecosystems are now experiencing severe cyanobacterial blooms (Paerl et al., 2011a). The strongest stimulation of algal productivity is usually observed when N and P enrichment occurs simultaneously (Elser et al., 2007; Lewis and

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Wurtsbaugh, 2008; Paerl et al., 2008). These results suggest that there is a need to reduce both N and P inputs to prevent further eutrophication and harmful algal bloom expansion (Paerl and Otten, 2013; Paerl and Paul, 2012; Xu et al., 2010).

Nutrient control strategies strongly rely on nutrient limitation studies. The TN:TP ratio has been widely proposed as a means to identify whether phytoplankton is N or P limited (Healey and Hendzel, 1980; Hecky et al., 1993; Smith, 2006; Verburg et al., 2013). Previous studies to predict which nutrient is limiting have often applied the hypothesis that there is an optimal ratio of N and P supply rates that promotes maximum rates of primary production (Redfield, 1958; Schanz and Juon, 1983). The most commonly cited ratio is the Redfield ratio, which states that marine algal cells contain N and P in a 16:1 (atomic) ratio on average (Redfield, 1958). Thus, assuming that nutrient concentrations in the water reflect supply rates and according to Liebig's law of the minimum (Liebig, 1842), algae should be limited by N if the water N:P ratio is lower than 16 on an atomic basis (TN:TP of 7.2). In contrast, they should be limited by P if the ratio is above that.

However, shifts from N to P limitation have often been found to occur at ratios different from the Redfield ratio in many field observations (Bergström, 2010; Elser et al., 2009; Guildford and Hecky, 2000; Morris and Lewis, 1988). In both lakes and oceans, N limitation was apparent at TN:TP < 9 whereas P limitation consistently occurred when TN:TP > 22.6, and either N or P could become deficient for ratios in the range 9 < TN:TP < 22.5 (Guildford and Hecky, 2000). In 106 oligotrophic lakes across Europe and North America, 72% of the variation in the response of algae to nutrient-enrichment assays revealed that phytoplankton growth shifted from N limitation at DIN:TP mass ratios <1.5 to P limitation at DIN:TP mass ratios >3.4 (Bergström, 2010). Schanz and Juon (1983) have reported N limitation of stream microphytobenthos at atomic N:P ratios <10 and P limitation at N:P ratios >20. Moreover, the N:P ratio also failed to predict the nutrient-limiting status in some cases (Francoeur et al., 1999; Wang et al., 2008).

To provide a rational strategy and predict future trends of eutrophication in eutrophic lakes, we need to understand the relationships between nutrient ratio, absolute nutrient concentration and nutrient limitation.

Lake Taihu, a large, shallow and hyper-eutrophic lake in China, has suffered annual cyanobacterial blooms from May to October and has changed from bloom-free to bloom-plagued conditions over the past 3 decades (Chen et al., 2003b; Paerl et al., 2011b). Approximately 40 million people live in cities and towns within the Taihu watershed. The lake is a key drinking water source for the local human population (estimated to be about 10 million), with tourism, fisheries, and shipping being additional important economic functions. Ironically, it is also a repository for waste from urban centers and nearby agricultural and industrial segments of the rapidly growing local economy (Qin et al., 2007).

Anthropogenic activities are likely to accelerate nutrient loading to Lake Taihu. Here, we analyzed the results of field experiments to evaluate the responses of phytoplankton biomass to manipulations of N and P availability in Lake Taihu water using a set of outdoor bioassays. Our goals were to examine the effects of individual and combined N and P additions on phytoplankton growth and determine the relationship between nutrient ratio and nutrient limitation in Lake Taihu, using a nutrient addition bioassay incubated under natural light and temperature conditions during the bloom period.

1. Materials and methods

1.1. Bioassay

A set of bioassays was conducted from 10 to 28 September, 2012 (Ma et al., 2014). Lake water samples were incubated under natural light and temperature conditions at the Taihu Laboratory for Lake Ecosystem Research (TLLER), located on the shore of Lake Taihu, near Wuxi, China. We prepared 48 white plastic buckets (maximum volume of 35 L) and then pumped 30 L water from the lake into each bucket. N and P were added as $NaNO_3$ and KH_2PO_4 respectively as three treatments (N only, P only and N plus P). The added nutrient concentrations of treatments were 2, 4, 8, 16 and 32 times relative to the control (lake water with no additions) concentrations (Table 1). Each treatment was performed in triplicate. The pH, dissolved oxygen (DO), dissolved oxygen saturation (DO%), and electrical conductivity (EC) were measured in each bucket between 8:00 and 9:00 on days 0, 3, 6, 9, 12, 15, and 18 by a Yellow Springs Instruments (YSI) 6600 multi-sensor sonde (YSI Incorporated, Brannum Lane, Ohio, USA). We sampled 0.5 L water from each bucket in order to determine the chlorophyll *a* (Chl-*a*) concentration and total phytoplankton biovolume. Weather conditions and air temperature were recorded every day. Each bucket was stirred before sampling and twice daily at 7:00 and 19:00. Chl-*a* concentrations were determined spectrophotometrically after extraction in 90% hot ethanol (Pápista et al., 2002). Phytoplankton samples were preserved with Lugol's iodine solution (2% final concentration) and sedimented in a plastic bottle for 48 hr. Cell density was measured with a Sedgwick–Rafter counting chamber under magnification of 200×–400×. Algal biovolumes were calculated from cell numbers and cell size measurements. Conversion to biomass was calculated by assuming that 1 mm^3 of volume was equivalent to 1 mg of fresh weight biomass (Chen et al., 2003a).

1.2. Statistical analysis

Data are presented as means ± SD. Significant differences between control and treated samples were determined by analysis of variance with the Tukey post-hoc test. Statistical analyses were conducted with SPSS 17.0 (IBM, Armonk, State of New York, USA).

The growth rate (μ) under each set of treatment conditions was calculated according to the modified exponential growth equation,

$$\mu = \frac{\ln(X_2/X_1)}{T_2 - T_1}$$

where, X_1 (mg/L) is the concentration of Chl-*a* on day 0 (T_1), and X_2 (mg/L) is the concentration of Chl-*a* on day 18 (T_2).

2. Results

2.1. Environmental factors

The weather conditions were cloudy (days 0–2, day 4, day 11, days 17–18), rainy (day 3 and day 12) and sunny (days 5–10, days 13–16). Air temperature ranged from 16 to 28°C. Water temperature ranged from 18.8 to 22.5°C. The pH, dissolved oxygen (DO) concentration, dissolved oxygen saturation (DO%), and electrical conductivity (EC) in N plus P additions were greater than those observed in either N or P additions or controls (Table 2).