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Effects of sediment resuspension on nutrient concentrations and algal biomass in reservoirs of the Central Plains

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Abstract

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Historically, lake and reservoir management has focused on controlling external nutrient loading. However, it is becoming increasingly clear that internal mechanisms, such as the episodic resuspension of benthic sediments, can also contribute to the processes of eutrophication. We conducted laboratory bioassay experiments to determine how resuspended sediments affected nutrient concentrations and algal biomass in four eutrophic reservoirs of the Central Plains. Surficial sediments and surface water were collected from each reservoir and returned to the laboratory where they were added to 1-L bioassay bottles at five turbidity concentrations (0, 50, 150, 250, and 500 NTUs). Sediments in the bioassay bottles were resuspended daily, and algal biomass (measured as relative fluorescence) was measured for 11–14 days. Resuspended sediments at the lowest experimental turbidity concentration, 50 NTUs, had highly significant effects on algal biomass in each of the sediment resuspension bioassays. Algal biomass appeared to increase following experimental sediment resuspension due to an increase in available nutrients and/or the establishment of algae (meroplankton) from the sediment. Overall, our results highlight the importance of considering internal mechanisms when developing reservoir management and restoration plans for these important ecosystems.

Key words: bioassay, Central Plains reservoirs, meroplankton, sediment resuspension

The resupsension of benthic sediments by wind-induced mixing (Schallenberg and Burns 2004) or recreational use (Anthony and Downing 2003) can have significant impacts on the ecology of lakes and reservoirs. In particular, nutrients that have accumulated in the sediment over time (Smith *et al.* 1999) can be recycled back into the water column during resupsension events (Sondergaard *et al.* 1992, Reddy *et al.* 1996, Hamilton and Mitchell 1997, Hansen *et al.* 1997). These pulses of nutrients from the sediment, mainly nitrogen (N) and phosphorus (P), can in turn stimulate algae production in nutrient limited systems (Ogilvie and Mitchell 1998, Schallenberg and Burns 2004). Resuspended sediments can also have direct effects on algal biomass if meroplankton, algae cells found at the sediment/water interface, become entrained in the water column following resuspension events (Carrick *et al.* 1993, Schelske *et al.* 1995, Schallenberg and Burns 2004).

A number of previous studies have focused on how sediment resuspension impacts the ecology of shallow lakes. Due to strong winds, typically large fetches, and the presence of shallow regions that are particularly vulnerable to wind induced mixing (*i.e.*, riverine zones), there is also a high potential for wind-induced mixing and sediment resuspension in both smaller/shallower and larger/deeper reservoirs of the Central Plains region of the United States. Little is known about how sediment resuspension affects these important ecosystems; therefore, we conducted laboratory bioassay experiments to: (1) determine how resuspended sediments impacted nitrogen and phosphorus concentrations (total and dissolved), and (2) determine if resuspended sediments served as a source of algae (meroplankton) during resuspension events.

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Methods

Study reservoirs

The effects of sediment resuspension were determined using experimental laboratory bioassay experiments with water collected from four eastern Kansas drinking water reservoirs (Fig. 1): Clinton Lake (CL), Gardner Lake (GL), Pomona Lake (PO), and Pony Creek Lake (PC). Clinton Lake and PO are relatively large federal reservoirs, while PC and GL are smaller city reservoirs (Table 1). Additional background and ecological information on GL and PC is provided in Dzialowski *et al.* (2005), and information on CL is provided in Wang *et al.* (1999).

Bioassay experiments were conducted between June and November 2005. For each reservoir, a 2 × 5 factorial design consisting of two types of reservoir water (nonfiltered and filtered to remove algae from the source reservoir water) and five sediment concentrations (0, 50, 150, 250, and 500 NTUs) was conducted in 30 1-L glass bioassay bottles. Each treatment was replicated in triplicate. A 20-L surface water sample and six sediment cores (10-cm diameter) were collected from the main basin of each reservoir. The reservoir water was initially filtered (200 µm) to remove most macrozooplankton. This coarsely filtered water (including background turbidity concentrations) was then added to 15 1-L bioassay bottles (nonfiltered, with algae). The remaining reservoir water was filtered (GF/F filter; pore size = 0.7 µm) to remove all algae and added to the remaining 15 bioassay bottles (filtered, without algae or background turbidity).

Prior to the experiment, the upper 3 cm of the sediment cores were combined individually for each reservoir. Sediment was then added to 1-L beakers of turbidity free water until the turbidity concentrations (measured with a laboratory turbidity meter) were equal to the four target concentrations of 50, 150, 250, and 500 NTUs. The amount of sediment needed to reach each target turbidity concentration was recorded, and sediment from the upper 3 cm of the cores was then added directly to the bioassay bottles at these concentrations to establish the sediment addition treatments and a control (no sediment).

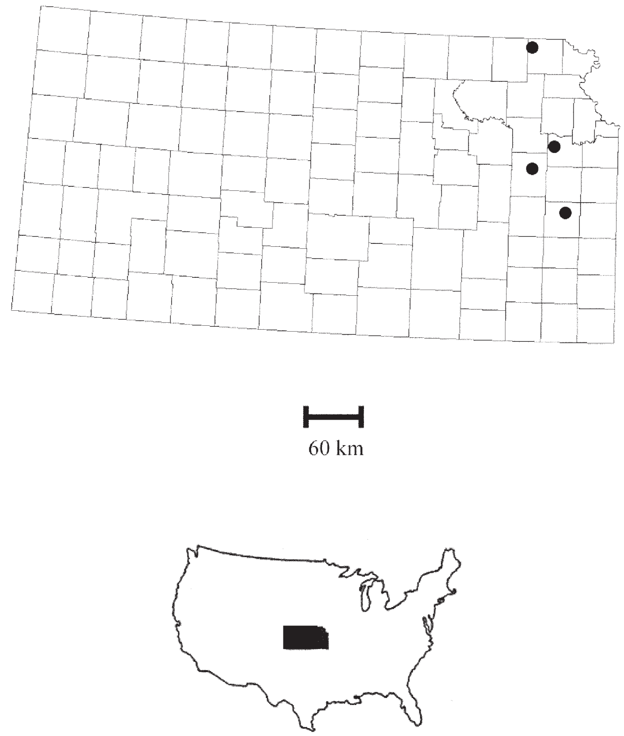

Figure 1.-Locations of the four study reservoirs in eastern Kansas.

The four turbidity concentrations (50, 150, 250, and 500) were selected to reflect concentrations that might realistically occur during resuspension events in Central Plains reservoirs. In general, background turbidity concentrations in the region tend to be high. Dzialowski *et al.* (2005) report that the mean turbidity concentration (based on depth profiles collected over two sampling dates at each reservoir) of 19 relatively small Central Plains reservoirs was 65 ± 86.5 (±S.D.) NTUs, with individual reservoir concentrations ranging between 7 and 398 NTUs. With respect to turbidity concentrations during actual resuspension events, we have observed elevated turbidity concentrations in excess of 200 NTUs in the shallow riverine zones of several larger reservoirs during strong

Table 1.-General reservoir and watershed characteristics of the four study reservoirs.

Reservoir	Watershed Area (km^2)	Surface Area (km^2)	Watershed:Surface Area Ratio	Maximum Depth (m)
Clinton	953	28	34:1	16.8
Gardner	13	0.28	46:1	11.6
Pomona	808	16	51:1	15.4
Pony Creek	17	0.73	23:1	10.3

wind events (Dzialowski *et al.*, unpubl. data). In at least one instance, we observed concentrations in excess of 500 NTUs in the riverine section of a large reservoir. Based on this information, we believe that the experimental concentrations of 50, 150, 250, and 500 NTUs realistically simulate the range of turbidity concentrations that are likely to occur, at least in the riverine zones of Central Plains reservoirs, during resuspension events.

After the experimental treatments were established, the bioassay bottles were incubated in a growth chamber at 20 °C, where they were exposed to roughly 200 $\mu E\ m^{-2}\ s^{-1}$ of light on a 12-hour light/dark cycle. *In vivo* fluorescence, which is often used as a surrogate for algal biomass in bioassay experiments (Elser *et al.* 1990), was measured daily using a Turner Model 10 Fluorometer. Each day, the sediment within the bottles was thoroughly mixed into suspension with an electronic stirrer, and fluorescence was recorded. Water samples were also collected at the beginning of each experiment (between day 1 and 3) for determinations of dissolved and total forms of nitrogen and phosphorus (Ebina *et al.* 1983, APHA 1995). Nutrient concentrations were measured just after the initiation of the bioassay experiments (between day 1 and 3) to minimize the amount of time that resident algae or meroplankton had for nutrient uptake. The bioassay experiments were conducted for 11–14 days.

Repeated measure analysis of variance (RM-ANOVA) was used to determine if sediment resuspension had significant effects on nutrient concentrations and algal biomass. Greenhouse-Geiser corrections were used to account for potential violations of the assumptions of sphericity (von Ende 2001). The RM-ANOVA provides a number of comparisons both within and between treatments; however, for the purposes of this research we focused on several specific comparisons. First, the results from the nonfiltered bioassay experiments (resident algae in tact) were used to determine how resident algal communities responded to resuspension events, presumably through nutrient additions. Second, the results from the filtered bioassay experiments (resident algae were initially removed) were used to determine if meroplankton became established within the water column following resuspension events. Tukey's Honestly Significant Differences (HSD) ($P = 0.05$) was used to determine which individual treatments were different when significant treatment differences were identified.

Two-way ANOVA was used to determine significant effects of the reservoir water (filtered and nonfiltered) and sediment addition (0, 50, 150, 250, and 500 NTUs) treatments on concentrations of total and dissolved nutrients. When necessary, nutrient data was log transformed to help meet the assumptions of normality. As with RM-ANOVA, Tukey's HSD ($P < 0.05$) was used to identify specific treatment differences.

Results and discussion

Our results strongly suggest that the episodic resuspension of benthic sediments can have significant effects on the ecology of Central Plains reservoirs. Algal biomass increased following sediment resuspension in the bioassay experiments for each of the four reservoirs (significant sediment [S] effect, $P < 0.001$ for each reservoir; Fig. 2). Specifically, algal biomass was significantly greater in all four sediment addition treatments than in the control treatments for each reservoir except at the highest sediment concentrations in PO (250 and 500 NTUs; see discussion of potential sediment induced light limitation below).

Sediment resuspension likely affected algal biomass through a combination of two mechanisms. Large concentrations of N and P, which can release resident algae from nutrient limitation, are often cycled back into the water column during or following resuspension events (Hamilton and Mitchell 1997, Ogilvie and Mitchell 1998, Schallenberg and Burns 2004). In the current study, sediment resuspension resulted in highly significant increases in both total N and P in the bioassay experiments from each reservoir (significant sediment [S] effect, $P < 0.001$, for each reservoir; Fig. 3). Total nutrient concentrations increased successively with increasing sediment additions in most of the bioassay experiments (Fig. 3). Previous research suggests that Central Plains reservoirs are often nutrient limited. Dzialowski *et al.* (2005) conducted bioassay experiments with water collected from 19 reservoirs (including GL and PC) and found that resident algae were nutrient limited in the majority of reservoirs. This was particularly true in GL and PC, in which algae were co-limited by N and P in experiments conducted during two seasons. The observed increases in algal biomass and total nutrient concentrations in the current experiment (Fig. 2 and 3), combined with the high incidence of nutrient limitation observed in the bioassay experiments of Dzialowski *et al.* (2005), strongly suggest that increases in nutrients following resuspension will help to release resident algae from nutrient limitation in at least some Central Plains reservoirs.

The effects of sediment resuspension on dissolved nutrient concentrations are generally more variable and complex than the effects of sediment resuspension on total nutrient concentrations (Sondergaard *et al.* 1992, Ogilvie and Mitchell 1998, Schallenberg and Burns 2004). We found that dissolved nutrients decreased, increased, or did not change in the sediment addition treatments relative to the controls (Fig. 4 and 5). The release of dissolved nutrients from the sediment is influenced by a number of factors, including the equilibrium of nutrients in the water and sediment, pH, adsorption-desorption, and the time since the last resuspension event (Sondergaard *et al.* 1992, Ogilvie and Mitchell 1998, Koski-Vähälä and Hartikainen 2001, Schallenberg and Burns 2004). Therefore, more detailed measurements

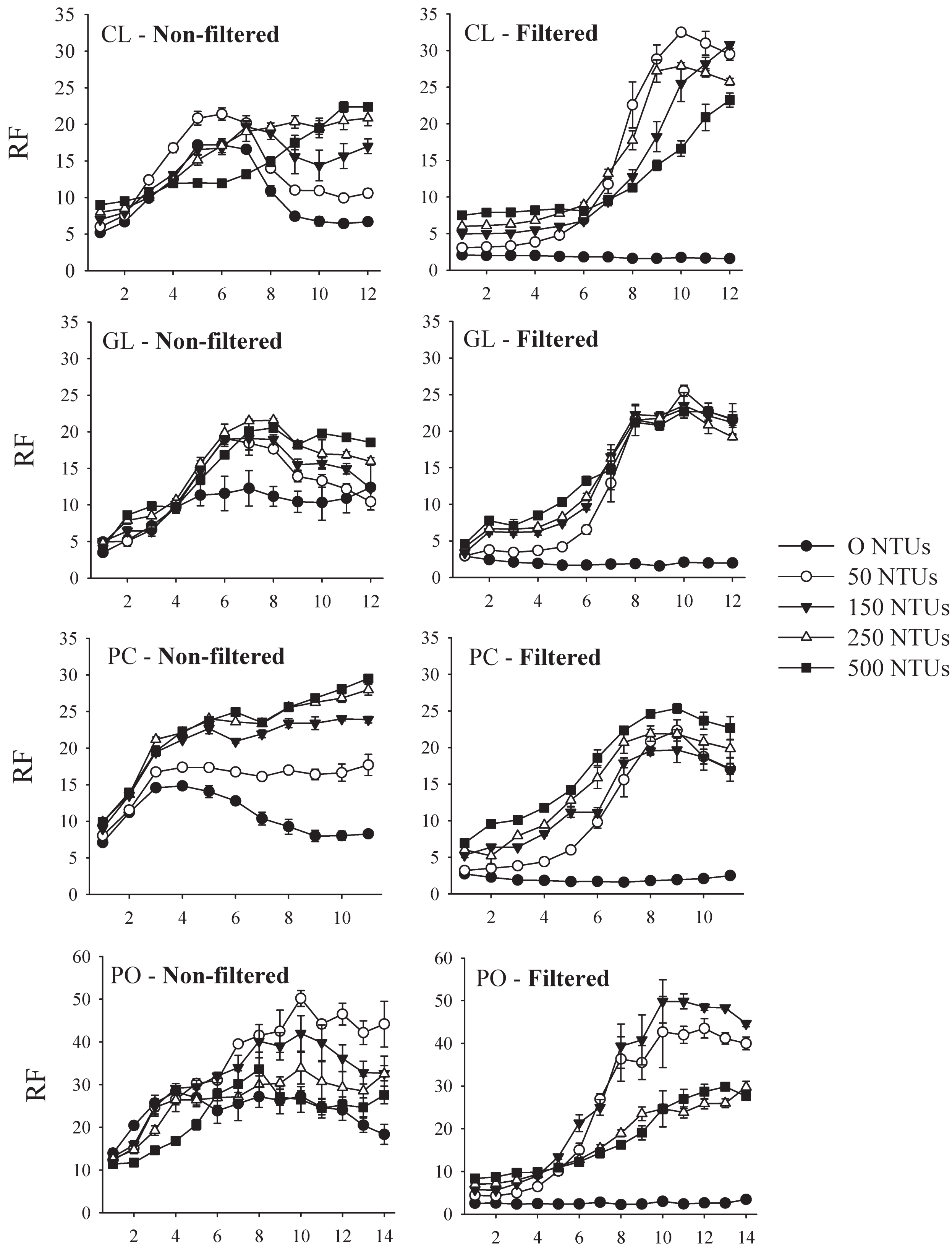

Figure 2.-Relative fluorescence (RF) values from each bioassay experiment. Data are presented for both nonfiltered (with algae) and filtered (without algae) reservoir water. Note differences in the relative fluorescence scale between graphs.

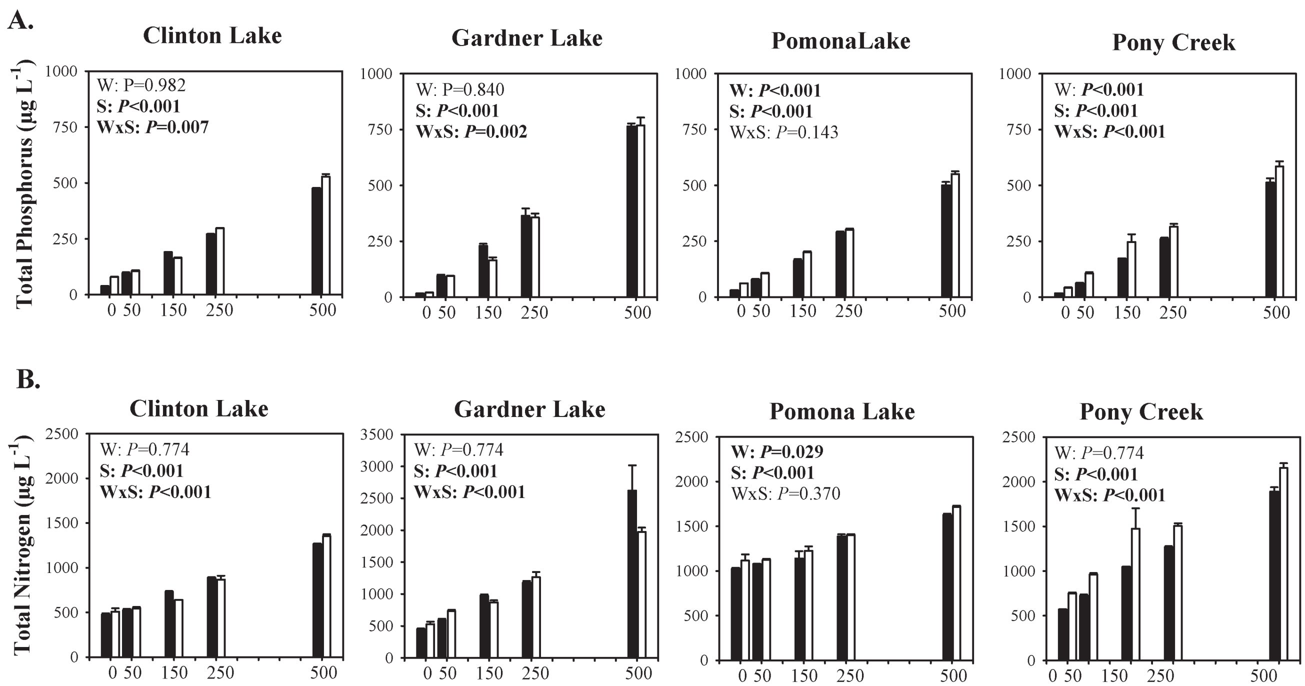

Figure 3.-Total phosphorus (A) and total nitrogen (B) concentrations measured at the beginning (day 1–3) of each bioassay experiment. Data are presented for both filtered (black) and nonfiltered (white) treatments. Statistics for the reservoir water (W; filtered and nonfiltered) and sediment (S; 0, 50, 150, 250, and 500 NTUs) treatments were determined with two-way ANOVA.

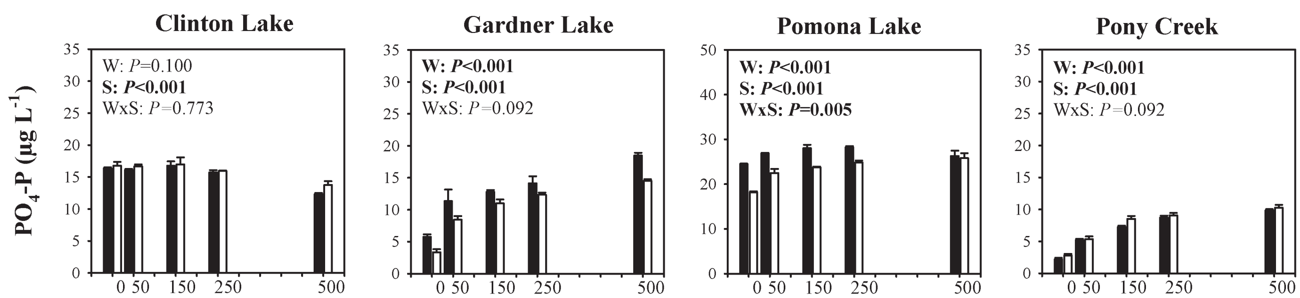

Figure 4.-Dissolved phosphorus (PO_4-P) concentrations measured at the beginning (day 1–3) of each bioassay experiment. Data are presented for both filtered (black) and nonfiltered (white) treatments. Statistics for the reservoir water (W; filtered and nonfiltered) and sediment (S; 0, 50, 150, 250, and 500 NTUs) treatments were determined with two-way ANOVA. Note differences in scale between graphs.

of nutrient concentrations in the water and sediment as well as the physical-chemical characteristics of the sediment (*i.e.*, moisture content, pH, density) will help determine under what conditions dissolved nutrients are released during resuspension events in Central Plains reservoirs. Furthermore, determining Equilibrium Phosphorus Concentrations (EPC; Koski-Vähälä and Hartikainen 2001), the concentration where P is neither released nor taken up by the sediment, in combination with the environmental factors mentioned above, will help determine under what specific conditions dissolved P is released.

In addition to indirectly influencing algae through nutrient additions, resuspended sediments can also have direct effects on algal biomass if they transport meroplankton, dormant algal cells within the sediment, into the water column (Carrick *et al.* 1993, Schelske *et al.* 1995). The results from the filtered bioassay experiments allowed us to determine if meroplankton were able to establish from the resuspended sediments because resident algal communities were initially filtered from the source water. Algal biomass did not increase in any of the control treatments during the bioassay experiments (Fig. 2); however, increases in algal biomass were highly significant in all of the sediment addition treatments relative to controls in each of the filtered bioassay experiments (Tukey's, $P < 0.05$ for all sediment treatments vs. control treatments; Fig. 2). As such, the results from the

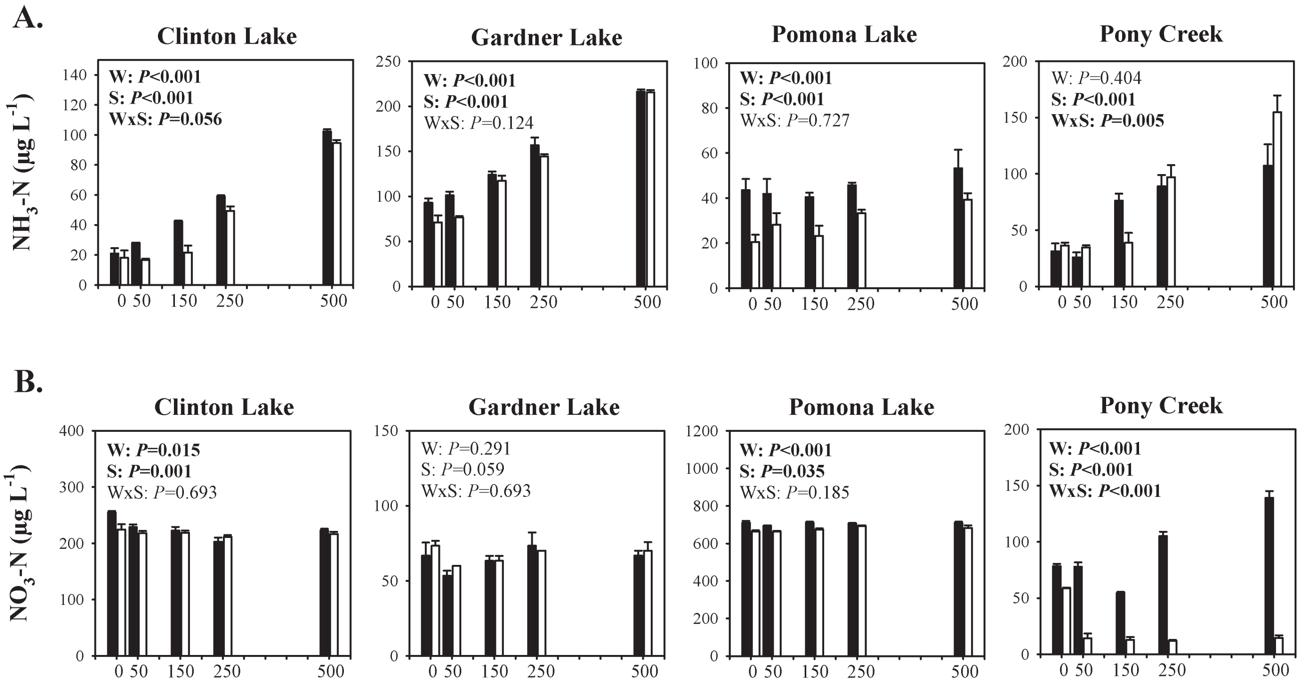

Figure 5.-Dissolved nitrogen (A. NH_3-N; B. NO_3-N) concentrations measured at the beginning (day 1–3) of each bioassay experiment. Data are presented for both filtered (black) and nonfiltered (white) treatments. Statistics for the reservoir water (W; filtered and nonfiltered) and sediment (S; 0, 50, 150, 250, and 500 NTUs) treatments were determined with two-way ANOVA. Note differences in scale between graphs.

filtered bioassay experiments suggest that meroplankton from the sediment were able to establish following resuspension events in the absence of resident algal communities. Carrick *et al.* (1993) similarly showed that algal biomass doubled in response to the resuspension of meroplankton during wind-induced turbulence in a hypereutrophic shallow lake.

Algal biomass responded differently to sediment resuspension in the filtered and nonfiltered bioassays (significant water [W] effect, $P < 0.001$, for each reservoir; Fig. 2). Determining if the algae established in the filtered bioassays were similar to the resident species originally in the unfiltered source water is not possible; however, previous research does indicate that environmental conditions can help determine which species are able to establish from the sediment following resuspension events (Nalewajko and Murphy 1998). Therefore, sediment resuspension might be an important factor facilitating blooms of nuisance algal species such as cyanobacteria in Central Plains reservoirs (Faithfull and Burns 2006). If cyanobacteria become entrained in the water column during resuspension events, they may have a greater probability of establishing under N-limiting conditions because of their ability to fix atmospheric nitrogen (Van Baalane 1987). Verspagen *et al.* (2005) reported that recruitment of cyanobacteria from the sediment accounted for up to 50% of the summer blooms in a eutrophic lake. The timing of resuspension events in combination with current water quality conditions may be particularly important in determining how resuspended sediments affect algal species composition in reservoirs of the Central Plains.

Several studies have shown the difficulty in separating the relative effects of resuspended nutrients and meroplankton on algal biomass following resuspension events. Schallenberg and Burns (2004) reported that resuspended sediments rarely released algal communities from nutrient limitation in a meso-trophic lake. Instead, resuspended sediments more often contributed meroplankton to the water column leading to direct increases in algal biomass. However, Ogilvie and Mitchell (1998) found that resuspended sediments released algal communities from nitrogen limitation in at least some of their New Zealand study lakes. While determining which processes had a greater impact in our study is difficult, both processes are likely important in Central Plains reservoirs. Factors such as competition with resident algal communities, available nutrients, and environmental conditions will help to determine which process has a greater relative impact during a particular resuspension event.

Only results for PO suggest that the highest turbidity concentrations had negative effects on algal biomass (Fig. 2). Specifically, algal biomass in the 250 and 500 NTU treatments did not increase relative to the control treatment in the nonfiltered bioassay, and while algal biomass did increase in these two treatments relative to the control treatment in the filtered bioassay, it did not increase to the levels observed in the 50 and 150 NTU treatments (Fig. 2). Therefore, algae may have experienced light limitation at elevated turbidity concentrations in PO (Hellestrom 1991, Scheffer 1998). Schallenberg and Burns (2004) reported that algae experienced light limitation at similarly high turbidity concentrations (>200 NTUs). Light limitation was possibly not observed in the bioassay experiments from the other three reservoirs due to shifts in species composition to taxa that perform well at low light conditions at high turbidity levels (Padisak *et al.* 1990). However, our experiments were not designed to explicitly test the hypothesis that resuspension events affected light conditions because the simulated resuspension events occurred daily, and were therefore not continuous. Additional studies are needed to assess how the duration of individual sediment resuspension events impact algal biomass for extended periods of time (Ogilvie and Mitchell 1998).

Conclusions

Our results have important implications for the long-term management of reservoirs in the Central Plains. Resuspended sediments (at concentrations as low as 50 NTUs) had highly significant impacts on nutrient concentrations and algal biomass. The effects of sediment resuspension should be particularly important in the shallower riverine zones of reservoirs, which are particularly vulnerable to wind-induced mixing. The effects of sediment resuspension on algal biomass likely resulted from the release of nutrients during sediment resuspension and/or the release of meroplankton that were able to establish in the water column. Regardless of the mechanisms, our results highlight the importance of considering internal mechanism such as sediment resuspension in long-term management goals and restoration efforts for these important ecosystems. As external nutrient loads are reduced, nutrient concentrations and algal biomass will possibly continue to increase for some period of time as nutrients and/or meroplankton are cycled back up into the water during resuspension events.

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