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PRIMARY RESEARCH PAPER

Effects of common carp (*Cyprinus carpio*) on sediment mixing depth and mobile phosphorus mass in the active sediment layer of a shallow lake

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Abstract The common carp (*Cyprinus carpio*) is a globally distributed, benthivorous fish that is capable of substantially altering lake ecology. Although dozens of studies have demonstrated that it has the potential to negatively affect submersed vegetation and water quality, little attention has been paid to effects of carp on sediment mixing and sediment phosphorus (P) in lakes. This study examined carp effects on sediment mixing and mobile (mainly iron bound and pore water) sediment P in a shallow, Midwestern lake (Kohlman Lake, MN, USA) undergoing restoration with aluminum (Al) to reduce internal P loading. Using Al as a tracer, we determined that the sediment mixing depth was at least 2.5 times greater in areas with carp (13.0 ± 3.7 cm) than in areas from which carp had been excluded (5.0 ± 1.2 cm) using exclosures. Vertical sediment profiles of P mass suggested that the increase in sediment mixing depth caused by carp increased the amount of mobile P potentially available for release by 55–92%, depending on location within the lake. The increase in sediment mixing depth is likely to have a negative effect on the efficacy of management methods designed to reduce mobile sediment P availability in lakes.

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Introduction

The common carp (*Cyprinus carpio*, or carp) is a large benthivorous fish from Eurasia that has been widely introduced to other regions over the past century and is considered to be one of the world's most invasive organisms (Kulhanek et al., 2011; Sorensen & Bajer, 2011). Researchers have long recognized that carp can fundamentally modify the structure and function of aquatic ecosystems (Cahn, 1929). Lakes inhabited by dense populations (typically > 100 kg ha^{-1}) of carp are generally characterized by a lack of plants, low native diversity, and turbid, nutrient-rich water (Haas et al., 2007; Bajer et al., 2009; Kloskowski, 2011). Carp dig in the bottom sediment while searching for food with their mouths (Nikolsky, 1963; Meijer et al., 1990; Chumchal & Drenner, 2004), uprooting aquatic plants, re-suspending sediment, and increasing water turbidity (Crivelli, 1983; Breukelaar et al., 1994; Lougheed et al., 1998; Zambrano et al., 2001; Bajer et al., 2009). It has been suggested that carp play an important role in nitrogen and phosphorus (P) transport from sediment to the water column as a result of both physical sediment disturbance (i.e., bioturbation) as well as excretion (Lamarra, 1975; Breukelaar et al., 1994; Moss et al., 2002; Chumchal et al., 2005; Driver et al., 2005), but the relative roles of each have not been described in situ.

Although nutrient export from sediment to overlying waters has been suggested to be an important element of how carp alter ecosystems, this process has not been well documented. For example, debate exists about the magnitude of nutrient fluxes caused by carp foraging activity and whether these fluxes are primarily driven by excretion (Lamarra, 1975; Morgan & Hicks, 2013) and/or bioturbation (Driver et al., 2005). Although carp excretion rates have been estimated in experimental enclosures (Lamarra, 1975; Morgan & Hicks, 2013) and from bioenergetics models (Vanni et al., 2013), effects of bioturbation on nutrient availability are very poorly documented. Nutrient releases due to bioturbation are especially difficult to estimate because they are influenced by many factors including sediment properties, chemical milieu (i.e., P-binding, pH, oxygen), availability of mobile sediment P, water column mixing, and carp burrowing depth. The effects of wild carp on sediment mixing depth and potential P release have not been investigated in natural lakes. Of the studies available investigating changes to sediment, one study using aquaculture ponds with high-density sediment and low-carp biomass suggested mixing depth might be as low as 3 cm (Ritvo et al., 2004). In contrast, a laboratory study suggested that this depth could reach 15 cm in areas with soft sediments (Nikolsky, 1963). Due to a lack of clear information on carp sediment mixing in situ, estimates of this species' effects on sediment P availability are currently not available, complicating management of sediment and phosphorous in lakes.

This study determined the effect of carp on sediment mixing depth and associated changes in potential P availability in a shallow lake in Minnesota (USA) to which aluminum sulfate and buffered sodium aluminate (hereafter, alum) had been added as part of a restoration project to reduce internal P loading from the sediment. Alum treatment resulted in the formation and deposition of amorphous aluminum hydroxide ($Al(OH)_3$), a relatively inert mineral compound, that was used as a tracer to estimate carp sediment mixing depth inside and outside of carp exclosure devices. One hundred and fifty-two days after alum treatment, sediment was collected from areas within the lake where the carp had unobstructed access to sediment and from areas from which carp were excluded. Significant differences in sediment mixing depth were detected and sediment P content was then used to calculate changes in mass of potentially available P in the active sediment layer due to increased sediment mixing depth caused by carp bioturbation.

Materials and methods

Kohlman Lake is a small (residence time 30 days), shallow polymictic lake (area 30 ha, mean depth 1.2 m, max depth 2.7 m) located in a suburban area in south-central Minnesota at the head end of a chain of urban lakes, USA (Fig. 1). Development within the watershed of this lake began in the mid-late 1880s, which has resulted in accumulation of P in the sediment that contributes to high levels of internal P loading. This lake was eutrophic at the time of alum treatment even though it had previously undergone a number of restoration measures to reduce external P inputs and improve water clarity and quality. The lake weakly stratifies and mixes numerous times during the growing season, resulting in periods of anoxia and internal sediment P release rates of up to 9.7 mg m^{-2} $days^{-1}$ that can contribute up to 25–30% or more of the total P load to the lake during the growing season. One of the final steps in the lake restoration plan was the application of alum to reduce the release of legacy P remaining in the sediment. The average population and biomass densities of carp in Kohlman Lake were estimated, using mark-recapture and catch per unit effort electro-fishing, to be approximately 50 individuals ha^{-1} and 180 kg ha^{-1}, respectively, at the time of this study (unpublished data). The

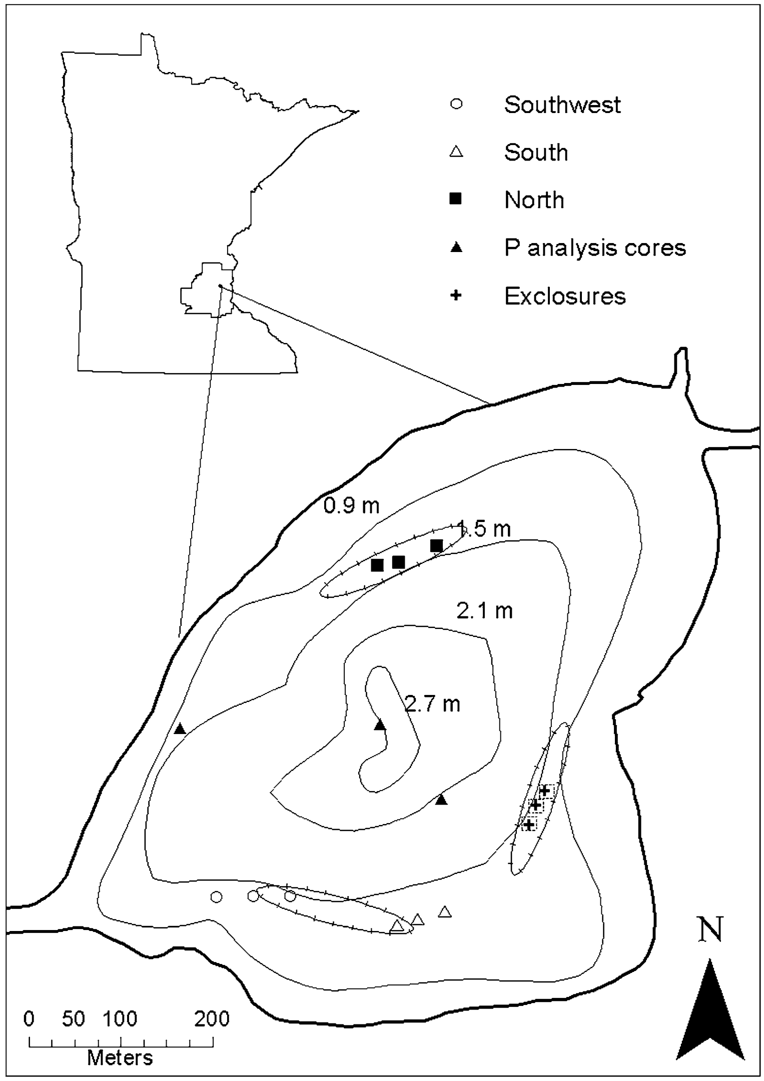

Fig. 1 Location of sediment cores collected within carp exclosures, and other areas within the lake (north, south, and southwest) exposed to carp. The *three hatched ovals* and *solid triangles* indicate areas where pre-treatment cores were collected for sediment P, density, and Al or sediment P by water depth

lake was also inhabited by several species of native fish, including bluegill (*Lepomis macrochirus*), black crappie (*Pomoxis nigromaculatus*), and largemouth bass (*Salmoides micropterus*), none of which forage in sediment. Radio-telemetry and electro-fishing surveys (Bajer et al., 2011) suggested that carp were relatively evenly distributed in the lake.

The experiment began on May 10, 2010, 5 days prior to alum addition, when we collected 10 sediment cores to determine background (pre-treatment) sediment aluminum (Al) concentrations in three cores and physical properties (density, organic matter, and P content) in all cores throughout the lake, including the future exclosure sites (Fig. 1). One of these cores was excluded from analysis because water depth was shallow (0.5 m) and the sediment consisted almost entirely of sand. Three additional cores were collected from shallow (1 m), moderately deep (2 m), and the deepest (2.7 m) areas of the lake to determine spatial variability of sediment P profiles by water column depth.

Alum was then applied from May 15 to 17, 2010 throughout the lake (approximately 39 g Al m^{-2}). A combination of aluminum sulfate and buffered sodium aluminate was used in this case to keep lake water pH within a range of 6–7 during treatment, thereby maximizing flocculation and precipitation of the newly formed $Al(OH)_3$. Immediately after application, three circular fish exclosures were installed in the lake (Fig. 1). Each exclosure had a diameter of 5 m and was constructed using plastic mesh (13-cm^2 mesh size). Plastic mesh was used to allow for wind action, water exchange, and fish removal from the exclosures using electro-fishing. PVC posts (5-cm diameter) were used as supports for the structure. Electro-fishing and video surveillance with underwater cameras were conducted in the exclosures by boat immediately after enclosure installation and approximately every 2 weeks thereafter to ensure that enclosures had no carp. No carp were detected in the exclosures during the experiment. Approximately, 5 months (152 days) after alum application (October 16, 2010), we collected sediment cores from inside of each exclosure and three additional areas (north, south, and southwest) in the lake ($N = 3$ for each location; Fig. 1) to determine if carp had an effect on sediment mixing depth. To address possible wind-mixing effects, effective fetch at each sampling location was calculated according to Håkanson & Jansson (1983).

A Willner gravity sediment-coring device (Uppsala, Sweden) was used to collect all sediment cores, which were sliced on-site (every 2 cm down to 14 cm and every 4 cm thereafter), and stored in opaque containers at 4°C until analysis that occurred within 1 week of collection. Sediment P fractions were determined using the sequential P extraction technique for wet sediment by Psenner et al. (1988) and modified by Hupfer et al. (1995). All fractions were determined but only mobile (total amounts of pore water, loosely sorbed, and reductant soluble) P and Al bound P (Al–P) are described herein. Soluble reactive P from sediment extracts was analyzed using the molybdate blue method (Murphy & Riley, 1962). By summing the mobile P (minus background) in sediment layers affected by carp bioturbation, we could thus calculate the additional amount of mobile P that may be released to the water column, depending on controlling physicochemical factors, via carp feeding activity. Total sediment Al was determined after digestion with 50% HNO_3 at 120°C using graphite furnace atomic absorption spectrometry at 309.5 nm. Background concentrations for Al were estimated by analyzing pre-treatment cores and deeper sediment layers unaffected by Al treatment in the post-treatment cores. Natural variability of Al in pre-treatment cores was used to determine excess Al attributable to treatment, which we defined as an Al concentration that exceeded two standard deviations of the mean background Al concentration (approximately 120% of the mean in this case). In addition, we also calculated and present results based on one standard deviation (110% of the background mean).

Water content was determined by freeze-drying sediment after storage at −70°C for 24 h, and sediment density was estimated according to Håkanson & Jansson (1983) after loss on ignition at 550°C for 2 h. Data used to determine average surface water quality parameters were downloaded from the Surface Water Environmental Data Access database (www.pca.state.mn.us/index.php/data). Means were determined using available growing season (May through September) data from the 10 years previous to alum treatment (Table 1) and 2 years post-alum treatment.

Results

Prior to alum treatment, Kohlman Lake was characterized as eutrophic to hypereutrophic. Ten-year pre-alum treatment means (±SD) of total P (TP) and chlorophyll *a* (Chl *a*) were 82 (±13) and 29 (±11) ug l^{-1}, respectively, and water clarity, as measured by Secchi depth, was 1.1 (±0.3) m (Table 1). In the 2 years following treatment with alum, growing season means of epilimnetic TP decreased by 51%, resulting in a decrease in algal growth, measured as Chl *a*, of 69%. Secchi depth increased by 40% (Table 1) and did not appear to reach the bottom of the lake (max depth = 2.7 m) with the highest value being 2.4 m in the spring of 2011. The exclosures remained carp free throughout the experiment although electro-fishing surveys removed one adult and six juvenile largemouth bass. Predominant wind direction was from the southwest during the duration of the experiment.

Table 1 Growing season (May–September) mean total phosphorus (TP), chlorophyll *a* (Chl *a*), and Secchi depth from 10 years previous to (2000–2009) and the 2 years following (2011–2012) alum treatment

	Units	Pre	Post	% Change
TP	μg l^{-1}	82 (13)	40	-51
Chl *a*	μg l^{-1}	29 (11)	9.1	-69
Secchi depth	m	1.11 (0.3)	1.56	40

Percent change between both periods is given in the last column. Standard deviations are shown in parenthesis

Pre-treatment sediment conditions

The cores collected prior to alum treatment were similar across all locations and had elevated mobile P concentrations (the P fractions that contribute directly to internal P loading) near the sediment surface that declined to background concentrations with depth (Fig. 2). The mean, surficial (0–10 cm) concentration of mobile sediment P at experimental (both exclosure and non-exclosure) sites was similar and averaged from 0.17 to 0.18 ($\pm$0.02) mg g^{-1}, respectively, ranging from 0.15 to 0.20 mg g^{-1} (Table 2). Mobile P concentrations had greater variation in cores collected from shallow, mid-depth, and deeper areas of the lake (Fig. 2). The cumulative amount of mobile P mass increased in a linear manner with increasing sediment depth in these three cores and was substantially greater in deeper areas of the lake (Fig. 3). The cumulative amount of mobile P mass within the upper 16 cm of sediment was approximately two times higher than the amount of mobile P within the top 5 cm of sediment in the shallow area, and this ratio increased to nearly three-fold at the mid-depth and the deep sites in the lake.

Mean, surficial (uppermost 10 cm) sediment concentrations of Al before treatment ranged from 5.8 to 6.5 mg g^{-1} ($N = 3$), with a mean and standard deviation of 5.9 and 0.57 mg g^{-1}, respectively. Surficial sediment bulk density (wet) was also similar between experimental sites, averaging 1.13 ($\pm$0.01) g m^{-3} in the enclosures and non-enclosure areas and ranging from 1.12 to 1.14 g cm^{-3} within the individual cores (Table 2). Other physical properties in the sediment were also similar between exclosure and non-exclosure sites prior to treatment (Table 2). The effective fetch for all coring locations was short and similar (exclosures = 0.29 km, other locations = 0.34 km $\pm$ 0.11).

Post-treatment

The concentration of mobile sediment P decreased mainly due to conversion to Al–P, and both Al and Al–P were elevated in surficial sediment 152 days after addition of alum (Fig. 4). As expected, addition of alum resulted in a distinct layer of elevated Al in surficial sediment with peak concentrations ranging from 13 to 18 mg g^{-1} in the exclosures and from 7 to 11 mg g^{-1} in other areas of the lake outside of the exclosures (Online Resource 1). Mean values (mass) of added Al detected in the sediment from inside the enclosures and other sites outside the exclosures were 36 and 44 g Al m^{-2}, respectively, and seemingly reflected the quantity of Al applied during treatment (39 g m^{-2}). Even though the total mass of excess Al detected was similar among experimental areas, the depth penetration of Al into the sediment was substantially less within carp exclosures at the end of the experiment. Excess Al was found at an average sediment depth of approximately 5.0 ($\pm$1.2) cm within the exclosures, whereas it was detected more than 2.5 times deeper in the sediment (13 $\pm$ 3.7 cm) outside the exclosures (Fig. 5). If a less stringent, one standard deviation was used (i.e., 110% of background), the depth of excess Al penetration reached 16 cm outside

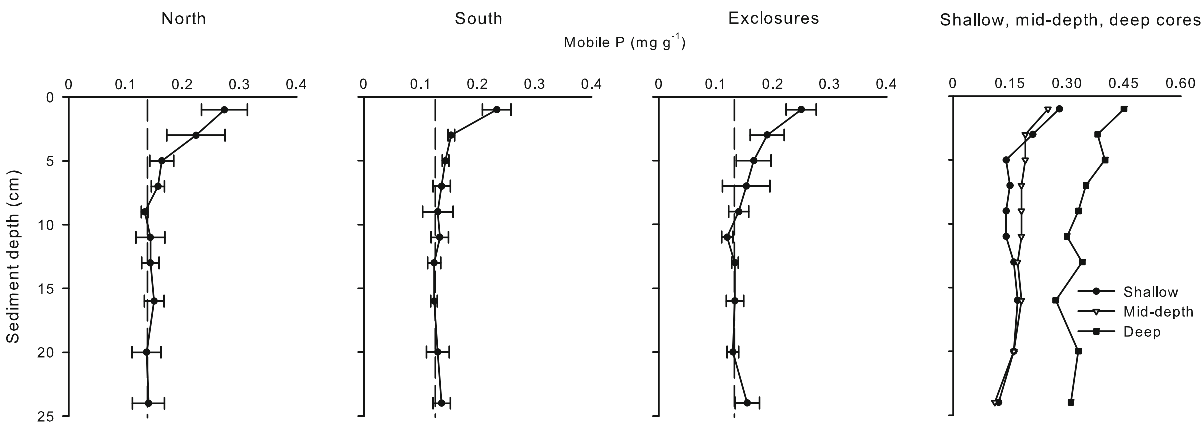

Fig. 2 Mean mobile P concentration in sediment collected at future exclosure locations and other areas within the lake exposed to carp activity (shown in Fig. 1) before alum treatment. *Dashed lines* represent estimated background concentrations for the exclosure and north and south sites

Table 2 Mean sediment density, water, dry substance and organic matter (LOI) content, and mobile phosphorus (P) concentration in the top 10 cm of lake sediment within and outside carp exclosures before alum treatment

	Units	Exclosures	Non-exclosure areas
Sediment density (wet)	g cm^{-3}	1.13 (0.005)	1.13 (0.003)
Water content	%	84.3 (0.7)	83.8 (0.4)
Mobile P	mg g^{-1}	0.18 (0.02)	0.17 (0.02)
Organic matter (LOI)	%	15 (0.004)	15 (0.001)
Dry substance	%	15.7 (0.7)	16.3 (0.1)

Standard deviations presented in brackets

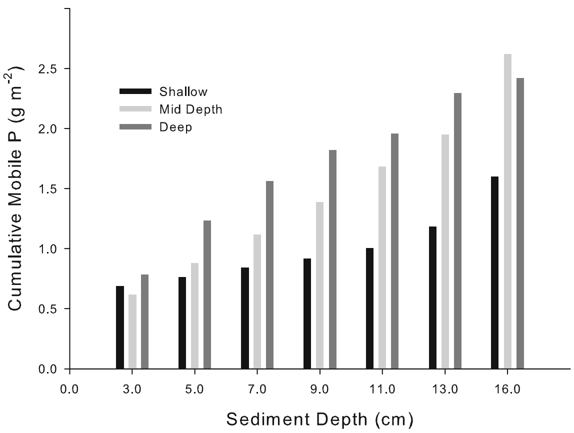

Fig. 3 The cumulative mass of mobile sediment P by sediment depth at three water column depths of 1 m (shallow), 2 m (mid-depth), and 2.7 m (deep) in Kohlman Lake prior to alum treatment

the exclosures, more than a threefold increase. This difference in mean mixing depth was statistically significant when comparing the exclosures and non-enclosure sites in both cases (Mann–Whitney rank sum test, $P < 0.01$). There was no significant difference when we compared only the three sites exposed to carp bioturbation (ANOVA, $P = 0.93$).

When the 2.5-fold increase in sediment mixing depth associated with carp (using the two standard deviation limit for excess Al) was taken into consideration, it was found that the total mobile sediment P pool potentially available for release increased by 55–92%, depending on location within the lake (Fig. 5). If the less stringent, one standard deviation was used to estimate excess Al and increased sediment mixing depth (16 cm, see Fig. 5), the amount of potentially available P caused by carp bioturbation was 109–198% greater than if carp were absent.

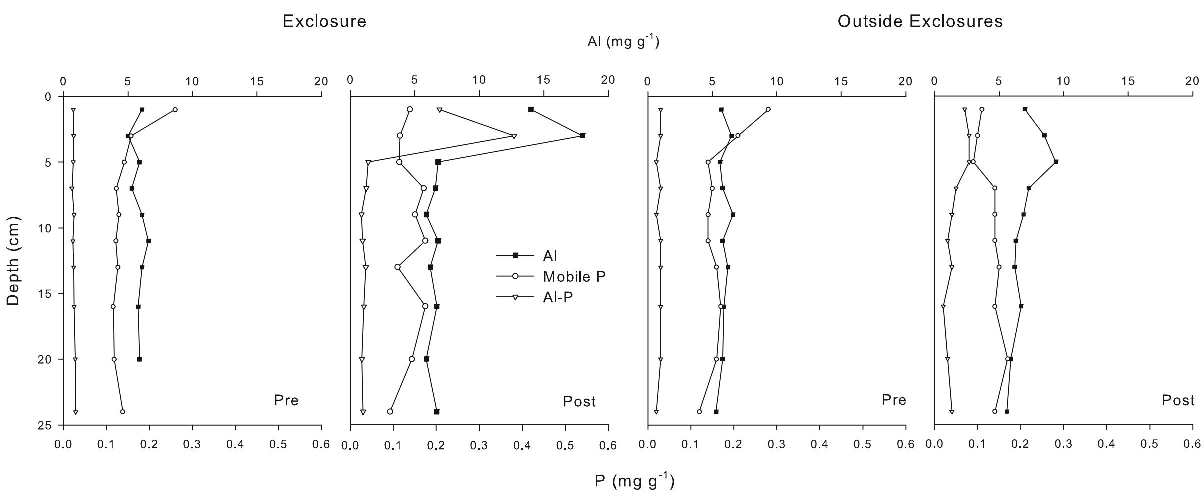

Fig. 4 Sediment concentrations of Al, mobile P, and Al–P within one carp exclosure and just outside the exclosure area immediately before alum application (pre) and 152 days after alum application (post) in Kohlman Lake

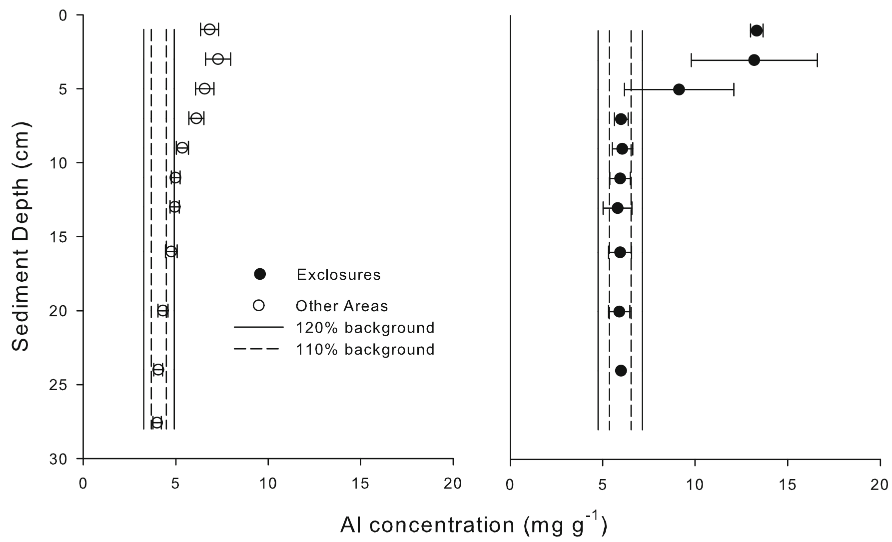

Fig. 5 Mean Al concentrations (with standard error bars) in sediment at exclosure and non-exclosure sites. *Vertical dashed* and *solid lines* represent 110% (one standard deviation) and 120% (two standard deviations) of background, respectively

Discussion

The addition of alum to Kohlman Lake to reduce internal sediment P release provided an opportunity to test the effect of common carp on sediment mixing and the potential availability of sediment P in shallow lakes. Significant differences in depth penetration of added Al were detected when comparing sediment from areas with and without carp. It was reasonable to use Al concentrations in the sediment as a tracer for sediment mixing depth due to the inert nature of the $Al(OH)_3$, which forms in water with circum-neutral pH (Stumm & Morgan, 1996). Numerous studies show that Al added from treatment is stabile and can be detected many decades after treatment in both shallow and deep lakes (Rydin et al., 2000; Lewandowski et al., 2003; Huser et al., 2011; Huser, 2012). The results presented herein are the first measurements of the likely influence of free-ranging adult carp on sediment mixing and changes to sediment P potentially available for release in a shallow lake using definitive biochemical techniques after alum treatment.

Carp burrowing and sediment mixing depth

Although the effects of benthivorous fish on sediment mixing depth and P availability have been relatively poorly documented to date, this study clearly shows that free-ranging carp can dig deeply in lake sediment. In laboratory settings, carp have been shown to be the deepest burrowing species among European minnows (Nikolsky, 1963). Even relatively small (<30 cm) individuals have been shown to be able to dig up to 15 cm into the sediment. Others studies have shown that mixing depth in systems inhabited by carp and bream (*Abramis brama*) can be as high as 12 cm (Alikunhi, 1966), with bream appearing to be even stronger sediment burrowers than carp. Ritvo et al. (2004) found that carp burrow only 3–5 cm into the sediment of aquaculture ponds; however, the bulk density of sediment in the ponds was very high and not typical of sediment found in shallow, productive lakes (Håkanson & Jansson, 1983). Unfortunately, very little information is available from previous carp studies about physical sediment properties or the amount of potentially available P in sediment.

Size and density of carp are likely to affect sediment mixing depth caused by foraging (Zambrano et al., 2001). The size (mean weight 3.4 kg) and biomass (180 kg ha^{-1}) of carp in Kohlman Lake were similar to other studies where significant habitat alteration occurred, resulting in changes to suspended sediment, nutrients, and plant communities (Zambrano & Hinojosa, 1999; Williams et al., 2002; Haas et al., 2007; Bajer et al., 2009). Although wind and wave action can affect sediment mixing in lakes, carp was likely the primary driver of increased sediment mixing depth in this study. Effective fetch for all coring locations was similar (exclosures = 0.29 km, other locations = 0.34 km + 0.11) and short (<0.5 km), meaning that the study areas were not likely to be substantially affected by wind and wave action (Håkanson & Jansson, 1983). The predominant wind direction was from the southwest, thus the north site and the exclosures were likely to have the longest fetch, whereas the south and southwest sites had the shortest. Considering that there was no significant difference in mixing depth between the north, south, and southwest sites, it seems that wind played little role in the different mixing depths detected between the exclosures and non-exclosure areas. In addition, substantial wind-driven sediment disturbance would be more likely to redistribute the low-density $Al(OH)_3$ floc to deeper areas of the lake (Huser et al., 2011). The fact that we found uniform and similar amounts of Al in Kohlman Lake sediment (36–44 g Al m^{-2}) compared to the applied dose (39 g Al m^{-2}) 5 months after treatment lends support to low wind-driven sediment disturbance or mixing.

Benthic invertebrates are also known to increase the active layer of sediment (Adámek & Maršálek, 2012), in some cases by up to 10 cm in low-density sediment (Andersson et al., 1988). High biomass densities of carp, however, can suppress macroinvertebrate abundance by up to 70% through feeding (Miller & Crowl, 2006). Thus, the differences in sediment mixing depth between the exclosures and other lake areas are likely conservative due to the potential for greater benthic invertebrate abundance inside the exclosures. It should also be noted that there was a brief period while the lake was being treated (2 days) before the exclosures were installed when carp might have affected mixing depth. The results presented herein are thus conservative.

Changes in mobile P mass related to sediment mixing depth

When applying the increase in mixing depth caused by carp bioturbation to the mass of mobile P present in Kohlman Lake sediment, the amount of mobile P potentially available for release increased by 55% (shallow areas) to 92% (deeper areas approximately 2.0–2.7 m) based on the more stringent two standard deviation method used to estimate excess sediment Al from alum treatment. Because the mobile P pool, along with physicochemical conditions at the sediment–water interface, contributes directly to internal P loading (Pilgrim et al., 2007), the increase in mobile P mass exposed to the water column due to carp burrowing may have a substantial long-term impact on nutrient availability in the lake after Al treatment. These are the first empirical, lake-wide measurements of sediment P availability due to carp bioturbation and they support studies showing significant effects of carp on TP concentration in lake water e.g., (Breukelaar et al., 1994; Angeler et al., 2002; Parkos et al., 2003; Schrage & Downing, 2004; Chumchal et al., 2005; Akhurst et al., 2012; Fischer et al., 2013). Other studies, however, have found only subtle or no relationship between carp and changes in water column nutrients (e.g., Roberts et al., 1995; Egertson & Downing, 2004; Matsuzaki et al., 2007; Roozen et al., 2007; Bajer & Sorensen, 2015). These inconsistencies may be due to a number of factors including fish age/size (Driver et al., 2005), sediment composition (Ritvo et al., 2004), and food availability (Zambrano et al., 2001). For example, high densities of carp may limit overall food availability (Zambrano et al., 2001), leading to increased energy spent searching for food that will likely contribute to increased sediment disturbance and mixing. While theoretical calculations suggest that carp bioturbation may be a major process affecting P availability in lakes, especially those with low density, organic rich sediments, whole-lake carp biomass removals are needed to better quantify this process (Bajer & Sorensen, 2015).

Lake management concerns

Increased sediment mixing and mobile P mass in the active sediment layer caused by carp bioturbation are likely to have implications for most management methods designed to reduce internal P loading in lakes. Although the alum applied to Kohlman Lake was successful at reducing mobile sediment P concentration via conversion to Al–P in surficial sediment in the short term, the increased sediment mixing depth caused by carp may reduce the longevity of treatment. The main reason for this is that the Al dose added to the lake was based on the mass of mobile P in the upper 6–10 cm of sediment (a slight over-estimate of sediment mixing without carp of 5 cm). This would have been adequate to bind mobile P in the active sediment layer if there had not been carp in the lake, but with carp the active layer of sediment is at least 2.5 times higher, leading to an increase of mobile sediment P (potentially available for release) of at least 55% in the active layer. Because this increase was not accounted for in dosing calculations, the positive water quality effects from treatment may last less than the estimated 15-year longevity. The additional mobile P may eventually overwhelm the Al added to the sediment, resulting in a return of elevated internal P loading in the lake. Thus, internal P loading management methods (e.g., Al addition, dredging, etc.) may need to be altered in order to achieve desired effectiveness in lakes with moderate to high densities of carp.

The release rate of mobile P from sediment might not change substantially when carp are present even though the total amount of P potentially available for release will increase due to the increase in the active sediment layer, which is a key issue. This is because sediment P release rate is largely a function of average mobile P mass by depth under anoxic conditions (Pilgrim et al., 2007), and not the total amount of mobile P mass in the active layer. We show a clear increase in the sediment active layer caused by carp (from 5 to between 13.5 and 16 cm), resulting in an increase of the total mass of P (g m^{-2}) in the active layer that is potentially available for release, depending on in-lake conditions. The average mass of mobile P by depth (g m^{-2} cm^{-1}, data not shown) throughout the upper 16 cm is generally constant, however, meaning that the sediment P release rate may not be affected by an increase in mixing depth. This may be another reason why some studies show small or even non-significant changes to water column TP when carp are present (Roberts et al., 1995; Egertson & Downing, 2004; Matsuzaki et al., 2007; Roozen et al., 2007; Bajer & Sorensen, 2015). If, however, bioturbation results in migration of mobile P from deeper layers towards the surficial sediment, increasing the average mass in the upper sediment layers, the internal P loading rate might be expected to increase. A distinction should be made, however, between P released from inorganic compounds (e.g., loosely bound P and Fe–P) and release of P contained in organic matter. Carp bioturbation has the potential to increase the total amount available for release from both sediment P forms due to the increase in mixing depth, but more research is needed to elucidate the relationship between increased sediment mixing, oxygen availability, and mineralization of organic matter in deeper sediment layers and how these factors contribute to the release of sediment P (from both organic and inorganic P forms) to the water column in the presence of carp.

One possible benefit from carp bioturbation, which also deserves further investigation, is an apparent increase in the short-term binding effectiveness between Al and P in the presence of carp. The ratio of Al to Al–P in Kohlman Lake sediment averaged approximately 30 just 5 months after treatment, whereas an average Al:Al–P ratio of 87 was found in nearby Lake Calhoun sediment after 15 months (Huser & Pilgrim, 2014) even though Al doses to both lakes were similar (39 and 42 g Al m^{-2}, respectively). The lower Al:Al–P ratio detected in Kohlman Lake indicates carp mixing may increase the potential for contact between sediment P and the added Al, potentially increasing the effectiveness of treatment by decreasing the reduction in binding efficiency that can occur when Al is allowed to age (crystalize) in the absence of P (de Vicente et al., 2008). Other factors that should eventually be addressed with respect to carp effects on sediment P availability and Al treatment efficacy are sediment biogeochemistry, including pH and oxygen availability, and both mixing and thermocline effects. In sum, this study sheds new light not only on the complexity of properly dosing Al treatments, but also on the significant role that carp have on sediment mixing and potential sediment P availability in lakes.

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