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Effects of common carp (*Cyprinus carpio*) on water quality in aquatic ecosystems dominated by submerged plants: a mesocosm study

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Abstract – Common carp (*Cyprinus carpio*) have been introduced into aquatic systems across the world, where their benthivorous feeding behavior has resulted in serious water quality problems. A 12-week mesocosm experiment was set up to test the hypotheses that common carp increase water column nutrient levels and decrease water clarity in aquatic ecosystems dominated by submerged plants. Further, we tested whether the effect of common carp on macrophytes depended on the species of plants. Relative to the controls, the presence of carp decreased water clarity by increasing total suspended solids (TSS) and light attenuation. However, levels of total nitrogen (TN) and total phosphorus (TP) in the water column were reduced. No significant change in phytoplankton biomass (measured as chlorophyll *a*) and the biomass of *Hydrilla verticillata* was observed between common carp treatment mesocosms and controls, but the common carp did reduce the biomass of the submerged macrophyte *Vallisneria denseserrulata*. We conclude that removal of common carp is likely to improve water clarity in aquatic ecosystems dominated by submerged plants primarily by decreasing TSS and that the effect of common carp on macrophytes is stronger for the meadow forming *Vallisneria* than for the canopy forming *Hydrilla*.

Keywords: common carp / submerged plants / aquatic ecosystem / water quality / water clarity

Résumé – Effets de la carpe commune (*Cyprinus carpio*) sur la qualité de l'eau dans les écosystèmes aquatiques dominés par les plantes submergées : une étude en mésocosme. La carpe commune (*Cyprinus carpio*) a été introduite dans les écosystèmes aquatiques du monde entier, où son comportement alimentaire benthivore a entraîné de graves problèmes de qualité de l'eau. Une expérience en mésocosme d'une durée de 12 semaines a été mise sur pied pour vérifier les hypothèses selon lesquelles la carpe commune augmente les niveaux de nutriments dans la colonne d'eau et diminue la clarté de l'eau dans les écosystèmes aquatiques dominés par des plantes submergées. De plus, nous avons vérifié si l'effet de la carpe commune sur les macrophytes dépendait de l'espèce des plantes. Par rapport aux témoins, la présence de carpes a réduit la clarté de l'eau en augmentant la quantité de solides en suspension (TSS) et l'atténuation de la lumière. Cependant, les niveaux d'azote total (TN) et de phosphore total (TP) dans la colonne d'eau ont été réduits. Aucun changement significatif de la biomasse du phytoplancton (mesurée en chlorophylle *a*) et de la biomasse de *Hydrilla verticillata* n'a été observé entre les mésocosmes expérimentaux avec carpe commune et les témoins, mais la carpe commune a réduit la biomasse du macrophyte immergé *Vallisneria*

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denseserrulata. Nous concluons que l'élimination de la carpe commune est susceptible d'améliorer la clarté de l'eau dans les écosystèmes aquatiques dominés par les plantes submergées, principalement en diminuant les MES, et que l'effet de la carpe commune sur les macrophytes est plus marqué chez *Vallisneria* qui forme des « prairies » que chez *Hydrilla* qui forme les couverts.

Mots clés : carpe commune / plantes submergées / écosystème aquatique / qualité de l'eau / clarté de l'eau

1 Introduction

The common carp, *Cyprinus carpio*, has been introduced into aquatic systems world-wide. Its broad environmental tolerances (Horoszewicz, 1973; Crivelli, 1981), high fecundity and long lifespan (Fischer *et al.*, 2013) combine to make common carp a highly invasive species (Roberts *et al.*, 1995). The wide distribution of common carp and the species' role as an ecosystem engineer makes common carp one of the more important species in freshwater systems (Parkos *et al.*, 2003; Semenchenko *et al.*, 2017) affecting water quality and submerged vegetation.

Common carp is benthivorous and forage by disturbing as much as the top 20 cm of lake sediment (Huser *et al.*, 2016). This activity exerts substantial effects on ecosystem structure and function (Kaemingk *et al.*, 2017), resuspending particulate matter and potentially releasing nutrients sequestered in the sediment into the water column. This resuspension of sediment by common carp is known to increase turbidity, although this is not always observed. Fletcher *et al.* (1985) found that the presence of carp did not increase water turbidity, whereas Chumchal *et al.* (2005) concluded turbidity increased along with chlorophyll *a* and total phosphorus (TP) levels in systems with common carp. Bajer and Sorensen (2015) implicated common carp reduced water clarity and damaged the macrophyte communities, but recorded no apparent effect on TP. Fischer *et al.* (2013) suggested that common carp reduced water clarity, increased nutrient concentrations and reduced macrophyte biomass. Additional nutrients excreted by the common carp (Roberts *et al.*, 1995) have been shown to stimulate phytoplankton growth (Fischer *et al.*, 2013).

Common carp can suppress submerged plants both indirectly by increasing light attenuation, and directly by uprooting plants during foraging and by consuming plants (King and Hunt, 1967; Crivelli, 1983). Analyses of common carp stomach contents have revealed plant tissues, seeds and detritus (Crivelli, 1981; Hinojosa-Garro and Zambrano, 2004). Bajer *et al.* (2009) demonstrated that common carp caused losses of vegetation over large areas for at least 4 years, damaging the ecological integrity of a shallow lake.

In addition, common carp can also affect the composition of submerged plant communities (Miller and Crowl, 2006) by feeding selectively on plants with higher food values. The experiment of Roberts *et al.* (1995) showed that common carp can exert a direct effect on *Vallisneria* sp. and *Chara jibrosa*, eliminating them from some systems, while no change was recorded in the abundances of *Juncus ingens*, *Schoenoplectus validus* or *Myriophyllum papillasum*. Miller and Crowl (2006) found that *Ceratophyllum demersum* and *Scirpus validus* were also significantly reduced by common carp, whereas *Potamogeton pectinatus* was unaffected. Common carp were also observed to consume more *Chara aspera* than other macrophytes, such as *Typha latifolia*, *C. demersum* and *S. validus* (Miller and Provenza, 2007).

Submerged plant communities play a central role in the ecological condition and sustainability of freshwater systems, and changes in the abundance and composition of such communities may have significant effects, not least on water quality. In shallow lakes, submerged plants play a key role in suppressing phytoplankton growth (Lemmens *et al.*, 2018) and improving and maintaining water clarity. Any impact of common carp activities is thus likely to be ecologically significant. Although the literature on the effects of common carp on aquatic ecosystems is extensive, more work is still needed to understand effects on water quality, especially in systems dominated by submerged plants. In addition, less is known about how common carp influence macrophytes with different morphology, such as meadow formers (biomass equally distributed over depth, *e.g. Vallisneria*), and canopy formers (biomass distributed mostly at the top of the plant, *e.g. Hydrilla*).

Here we present results from a mesocosm experiment conducted to evaluate the effects of common carp on water quality of nutrients, total suspended solid (TSS) concentrations, light intensity, and submerged plant biomass. We hypothesized that common carp would have a negative impact on water quality by increasing nutrient levels in the water column, decreasing water clarity and on submerged plants with the impact more stronger for *Vallisneria* than for *Hydrilla*. The results of this study may inform lake managers interested in reducing or removing benthivorous fish to improve water quality of aquatic ecosystem.

2 Materials and methods

2.1 Experimental mesocosm set up

The mesocosm experiments were carried out in seven tanks (diameter = 1.2 m, height = 1.2 m) containing sediment, water, and plants. Sediment was obtained from Ming Lake, a eutrophic shallow water body in Guangzhou City. The sediment was air-dried, powered, and sieved through a stainless sieve (mesh size, 0.5 mm) to remove coarse debris (Zhang *et al.*, 2016). The homogenized sediment was added as a 10 cm thick layer in each mesocosm (Zhang *et al.*, 2016). We planted 30 individuals each of two species of submerged macrophytes evenly in the mesocosm: the meadow forming *Vallisneria denseserrulata* and the canopy forming *Hydrilla verticillata.* All plants originated from Huizhou West Lake in Huizhou, Guangdong Province and cultivated in Jinan University for several years. The *V. denseserrulata* and *H. verticillata* were washed with distilled water to remove periphyton and debris before planting. Before planting, 10 plants of each species were randomly selected and washed through a 1 mm mesh sieve and oven-dried at 80 °C to constant weight to determine the dry weight of the plants. Each *V. denseserrulata* plant was 30 cm in length with dry weights of 0.73 ± 0.19 g. For *Hydrilla verticillata*, we used apical shoots separated from their mother plants, each 30 cm in length with dry weights of 0.04 ± 0.01 g (Zhang and Liu, 2011). The biomass of *V. denseserrulata* and *H. verticillata* in each mesocosm at the beginning of the experiment were therefore 21.8 ± 5.8 g and 1.3 ± 0.2 g respectively.

The mesocosms were each filled to a depth of 1.0 m with rainwater (TN = 0.94 mg L^{-1}, TP = 0.01 mg L^{-1}) and allowed to equilibrate exposed to natural sunlight for seven weeks, after which nutrient concentrations of the water in the mesocoms were 0.63 ± 0.06 mg L^{-1} TN and 0.03 ± 0.01 mg L^{-1} TP.

Common carp bought from the market in Guangzhou City were habituated in 100 L tanks for two weeks before being introduced to the mesocosms. Two individuals (16.4 ± 1.5 cm in length and 63.8 ± 9.1 g in wet weight) were added to each of three mesocosms as common carp treatments. Another four mesocosms were maintained as no fish controls. The experiment ran for 12 weeks from June to September, 2017, during which time nitrogen (N) in the form of KNO_3 and phosphorus (P) as NaH_2PO_4 were added to each mesocosm at a rate of 1.5 mg N $L^{-1}wk^{-1}$ and 0.1 mg P L^{-1} wk^{-1}, respectively, to mimic external nutrient loading (Zhang *et al.*, 2014). Sampling took place biweekly, with nutrient addition taking place immediately after samples were taken (Zhang *et al.*, 2016). The mesocosms were exposed to natural environmental conditions throughout the experiment.

At the end of the experiment, submerged plants were harvested from each tank, separated according to species and washed with distilled water to remove sediment, debris and attachments. Finally, the plants were oven-dried at 80 °C to constant weight for about 24 h, and their dry biomasses recorded.

2.2 Sampling and analysis

Water samples (1 L) were collected from 30 cm below the surface in each mesocosm every two weeks for measurement of total nitrogen (TN), total phosphorus (TP), phytoplankton biomass as chlorophyll *a* (chl *a*), and total suspended solids (TSS). TN was determined by alkaline potassium persulfate UV spectrophotometry (APHA, 1998). TP was determined by ammonium molybdate UV spectrophotometry (APHA, 1998). Chl *a* was determined by acetone extraction UV spectrophotometry (Jespersen and Christolfersen, 1987). TSS was calculated by weighing filters dried at 108 °C for 2 h. Light intensity was measured biweekly between 10 a.m. and noon, before water sampling, using an underwater irradiance meter (ZDS-10W) at 1.0 meter below the surface of the water.

2.3 Statistical analyses

Repeated measures analyses of variance (RM-ANOVAs) were conducted to analyze differences of treatment effect in these indexes and with time as repeated factor of time effect. Independent sample *t*-test was used to analyze differences in levels of TN and TP, chl *a*, TSS, light intensity on each sampling occasion and to test for difference in macrophyte biomasses between carp treatments and controls at the end of the experiment. All data were analyzed using SPSS 18.0. All results are presented as mean ± 1 SD.

3 Results

3.1 Nutrients

Concentrations of NO_3^{-}-N (RM-ANOVAs, treatment effect, $F_{1,\ 10} = 64.0$, $p < 0.001$), TN ($F_{1,\ 10} = 42.8$, $p = 0.001$) and TP ($F_{1,\ 10} = 9.7$, $p = 0.026$), but not NH_4^{+}-N ($F_{1,\ 10} = 0.97$, $p = 0.370$) (Fig. 1) were lower in common carp treatments than in the controls. Concentrations of TN and TP varied significantly over time (RM-ANOVAs, time effect, $F_{5,\ 35} = 4.2$, $p = 0.006$ and $F_{5,\ 35} = 5.7$, $p = 0.001$, respectively). NO_3^{-}-N and TN were lower in the carp treatments than in the controls on each sampling occasion (*t*-test, $p < 0.05$), except on days 70 and 84 for TN. TP was lower in the carp treatment than in the controls on days 42 and 56 (*t*-test, $p < 0.05$).

3.2 TSS and phytoplankton

Concentrations of TSS (Fig. 2) in the common carp treatment were higher than in the controls (RM-ANOVAs, treatment effect, $F_{1,\ 10} = 36.6$, $p = 0.002$), while levels of chl *a*, representing phytoplankton abundance, were not (RM-ANOVAs, treatment effect, $F_{1,\ 10} = 2.9$, $p = 0.152$), though this parameter was higher on day 28 (*t*-test, $p < 0.05$). Both TSS and chl *a* (Fig. 2) were seen to vary significantly over time (RM-ANOVAs, time effect, $F_{5,\ 35} = 9.6$, $p < 0.001$ and $F_{5,\ 35} = 8.7$, $p < 0.001$, respectively). TSS concentrations were higher in the common carp treatment than that in the controls on every sampling occasion except day 84 (*t*-test, $p < 0.05$).

3.3 Light intensity

The light intensity (Fig. 3) at 1.0 meter below the water surface of the common carp treatment was lower than in the controls (RM-ANOVAs, treatment effect, $F_{1,\ 8} = 18.1$, $p = 0.008$) and varied significantly over time (RM-ANOVAs, time effect, $F_{4,\ 24} = 41.7$, $p = 0.024$).

On each sampling occasion, light intensity was lower in the common carp treatment than in the controls (*t*-test, $p < 0.05$), except on day 84 ($p > 0.05$), indicating that the presence of fish increased light attenuation.

3.4 Biomass of submerged plants

At the beginning of the experiment, biomass of *H. verticillata* was 1.25 ± 0.24 g/mesocosm (Fig. 4). At the end of the experiment, the biomasses did not differ between common carp treatments (77 ± 45 g/ mesocosm) and the controls (60 ± 22 g/mesocosm) ($p > 0.05$). Biomasses of *V. denseserrulata* on the other hand were lower in the common carp treatments than in the controls (*t*-test, $p < 0.05$) at the end of the experiment. Their biomasses decreased from 21.8 ± 5.8 g/mesocosm at the beginning of the experiment to 1.7 ± 0.6 g/mesocosm at the end of the experiment in the controls, with an even greater loss in the common carp treatments.

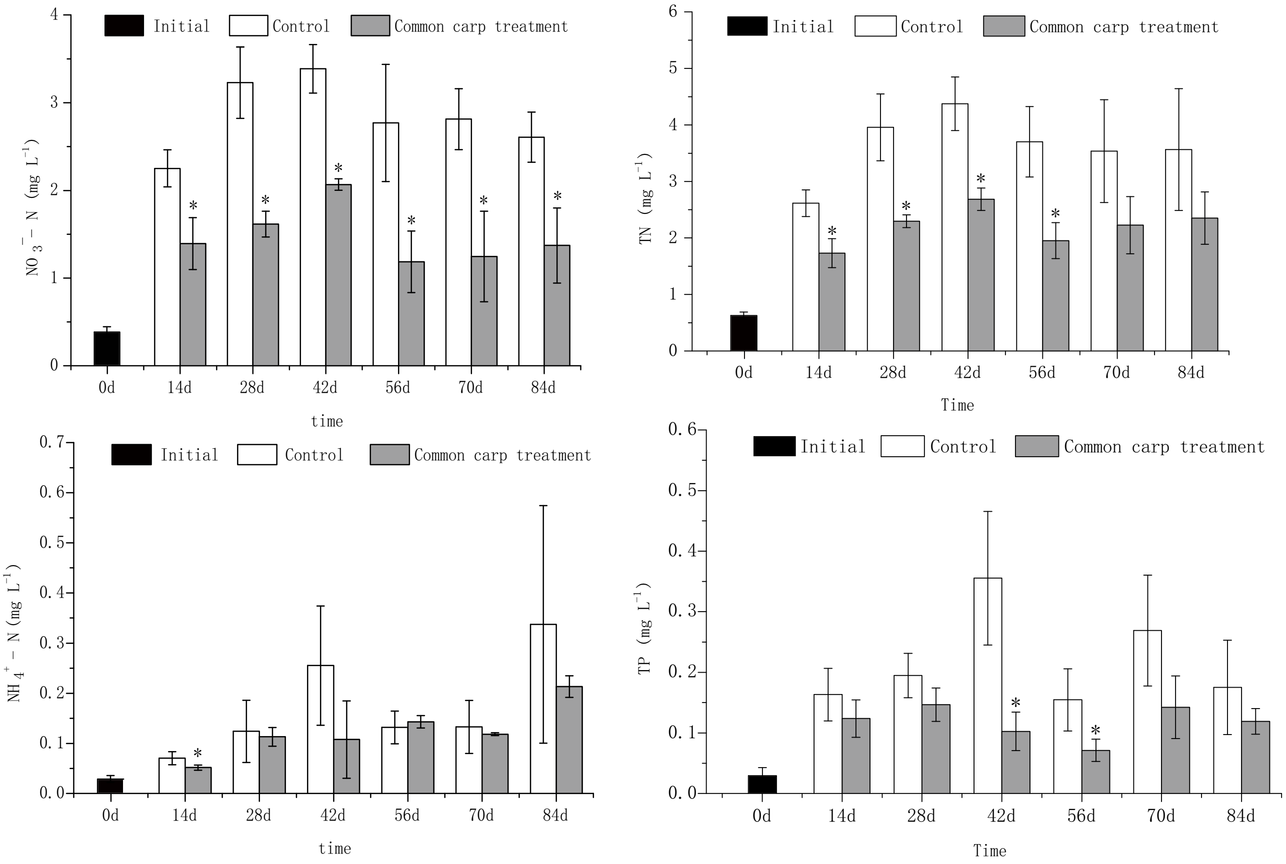

Fig. 1. Nitrogen and phosphorus in different treatments over time. Asterisks indicate significant differences between common carp treatments and the controls ($p < 0.05$). Bars indicate ±1 SD.

4 Discussion

We found that the presence of common carp was associated with increased TSS concentration and light attenuation. Although we could find no significant relationship between fish presence and increased phytoplankton chl *a*, we did find that the presence of fish appears to reduce the biomass of *V. denseserrulata.* Contrary to our hypothesis, we found no evidence that common carp increase levels of TN and TP, but we did find an association between fish and declining water clarity.

Bioturbation by benthivorous fish can cause resuspension of sedimented materials (Cline *et al.*, 1994) and increase levels of TSS in the water column (Lougheed *et al.*, 1998; Parkos *et al.*, 2003). This disturbance effect explains the reduced availability of light observed at the sediment surface in the common carp treatments.

Increased light attenuation may have a negative effect on submerged plant growth (Badiou and Goldsborough, 2015), especially for *V. denseserrulata.* This species produces a basal rosette of leaves, but does not form a canopy. The plant therefore depends more on light being available near the sediment for growth and survival. In this study, biomasses of *V. denseserrulata* in the common carp (total dry weight = 0.40 ± 0.69 g) were lower than in the controls (total dry weight = 1.70 ± 0.61 g). However, the degree to which this reduced biomass was caused directly by the grazing of fish or indirectly by light limitation linked to fish bioturbation cannot be determined from this study. Elsewhere, common carp have had a negative impact on submerged plants biomass (King and Hunt, 1967; Badiou and Goldsborough, 2015).

The apparent lack of a significant effect of common carp on the biomass of *H. verticillata* is consistent with previous work showing that different plant species vary in their susceptibility to the effects of common carp (Zambrano and Hinojosa, 1999). Roberts *et al.* (1995) reported that common carp can directly consume *Vallisneria*, preferring it to *H. verticillata*. Also, *H. verticillata* has high rates of reproduction and growth (Shearer *et al.*, 2007), which might compensate for any grazing losses. In addition, more biomass of *H. verticillata* is in a dense canopy distributed near the surface of water and thus less impacted by reduced light condition induced by carp activities. Therefore, the response of an aquatic ecosystem to common carp may be different depending on the dominant submerged plant species present. An aquatic ecosystem that is dominated by *H. verticillata* would be less sensitive to common carp than one dominated by *V. denseserrulata*.

Contrary to our hypotheses, concentrations of TN and TP were lower in mesocosms containing common carp than in the controls. However, most other studies have shown an increase in nutrients with common carp (Breukelaar *et al.*, 1994; Chumchal *et al.*, 2005). There are a couple of explanations for our results. There is a positive relationship between nutrient uptake by the leaves of macrophytes and water velocity,

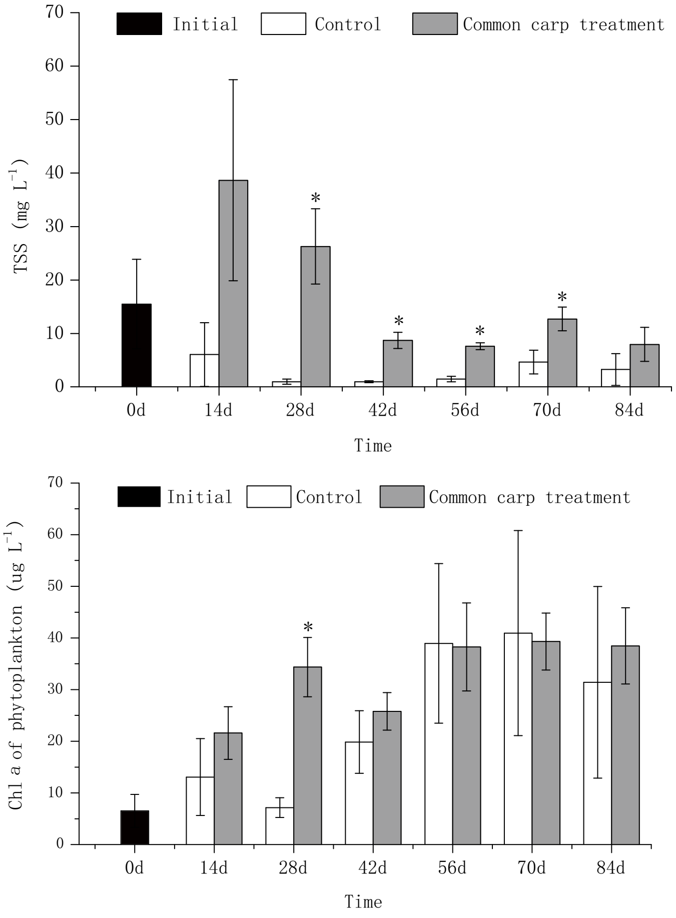

Fig. 2. TSS and chl *a* of phytoplankton in different treatments over time. Asterisks indicate significant differences between the common carp treatment and the controls ($p < 0.05$). Bars indicate ±1 SD.

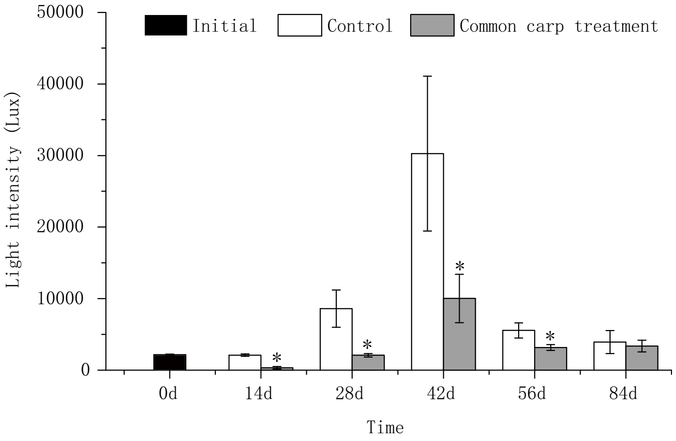

Fig. 3. Light intensity in different treatments over time. Asterisks indicate significant differences between the common carp treatments and the controls ($p < 0.05$). Bars indicate ±1 SD.

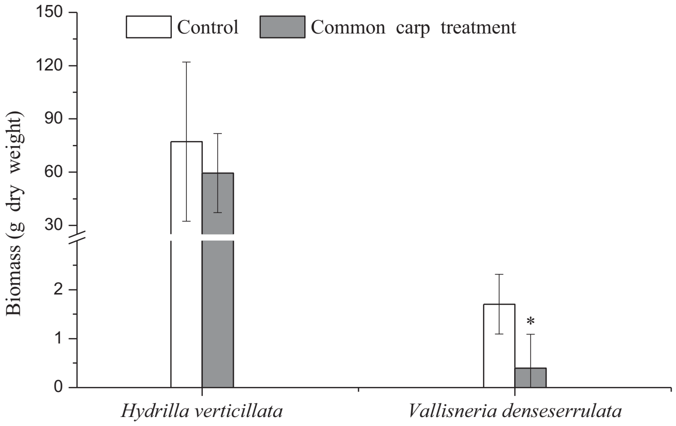

Fig. 4. Submerged plant biomass in different treatments. Asterisk indicates a significant difference between the common carp treatment and the controls ($p < 0.05$). Bars indicate ±1 SD.

resulting from reduced thickness of the boundary layer around leaves in disturbed water (Westlake, 1967; Wheeler, 1980; Madsen and Søndergaard, 1983). The swimming of common carp may enhance nutrient uptake by leaves of submerged plants, thereby contributing to decreased nutrient concentrations in the water. In addition, phosphate and dissolved nitrogen in the water can also adsorb to the resuspended sediment particles caused by the fish bioturbation and with these dimentation of these particles carrying it to the bottom. Another explanation is associated with the high plant abundance in our experiments. While foraging activities by common carp can enhance the release of nutrients from sediment, the effect is likely to be mitigated when macrophytes are abundant due to their role in enhancing sedimentation (Qin and Threlkeld, 1990; Cline *et al.*, 1994). Additionally, activities by carp may increase the water exchange between deeper layer and surface layer which may increase oxygen concentrations at the sediment-water interface and thus decreased the sediment P release by oxidizing the surficial sediments. Whether denitrification is a possible mechanism causing nitrogen loss in our experiments is unknown as we did not measure dissolved oxygen in the surficial sediment. Finally, common carp may also consume some particles suspended in water column, further helping to reduce nutrient levels (Boers *et al.*, 1991; Roberts *et al.*, 1995). Note that in this experiment we added nutrients to mimic external nutrient loading. The concentrations of TN and TP might have increased due to the bioturbation of the fish if no nutrients were added during the experiment simulating a system without external loading. However, a system without nutrient additions may not reflect a real lake.

The effect of common carp on phytoplankton is more variable. Previous studies have demonstrated that common carp have positive effects on the growth and biomass of phytoplankton (Breukelaar *et al.*, 1994; Roberts *et al.*, 1995). However, Fischer *et al.* (2013) was not able to observe any increase in chl *a* in treatments with common carp present and Lougheed *et al.* (1998) found no significant correlation between chl *a* concentration and common carp biomass. Likewise in this study, we found no significant difference in chl *a* between common carp treatment and controls, possibly because of the high abundance of macrophytes (density = 61.5 gm^{-2}) limiting phytoplankton growth in both treatments.

In conclusion, in ecosystems dominated by submerged plants, common carp can negatively impact water clarity by increasing TSS concentration which increase light attenuation in the water column. However, contrary to our expectations, common carp presence reduced the concentrations of TN and TP and had no significant impact on phytoplankton biomass (chlorophyll *a*). The fish can also reduce the biomass of *V. natans* but not *H. verticillata*, which has important implications for plant management. By planting carp-resistant or carp-tolerant plants we can minimize their impact because decline of submerged plants can markedly alter many aspects of aquatic ecosystem. Our findings indicate that the removal of common carp would be a useful practice for managers to protect and maintain water clarity in well-vegetated aquatic ecosystems.

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