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ABSTRACT

Demands for water quality improvement and reduction of harmful algal blooms in Korean lakes and rivers due to eutrophication and climate change have been increasing. As an environmentally friendly measure to mitigate the eutrophication and phytoplankton growth, a full-scale artificial floating vegetation island (AFVI) was installed in Lake Paldang, a large on-river reservoir. This study investigated the detailed mechanisms for improving water quality and reducing the phytoplankton growth of the AFVI by comparing the biotic and abiotic environmental factors between the AFVI and the adjacent pelagic part of the lake. Much lower chlorophyll *a* concentration, much higher zooplankton biomass, especially large crustacean zooplankton, and a higher proportion of active bacteria in total bacteria in the AFVI indicate an effective reduction of phytoplankton growth and vigorous decomposition of organic matter. The major mechanisms for improving water quality of the AFVI are shown to be inhibition of phytoplankton growth by attenuating light and top-down control by zooplankton grazing. Active microbial decomposition of organic matters and nitrate reduction in the hypoxic rhizospheric zone also would be a major mechanism for improving water quality, even though it is difficult to quantify in the open water system.

Introduction

Eutrophication, due to anthropogenic influences, has been a major concern in freshwater rivers, lakes and reservoirs worldwide. As a prominent symptom of eutrophication, algal blooms, particularly toxin-producing harmful algal blooms, lead to water quality deterioration and serious problems in water use (Park et al. 2000; Gkelis et al. 2014). Recently, climate change, including warmer winters, extended dry periods and increased precipitation intensity are predicted to advance and extend the growing period of phytoplankton, increase outbreaks of harmful algal blooms and large watershed export of nutrients (Paerl and Otten 2013; Park et al. 2013). Therefore, a number of technologies and measures have been developed and adjusted to mitigate eutrophication and improve water quality, including bottom-up control through reduction of the limiting nutrient availability and top-down control through trophic cascade manipulation (Sosnovsky and Quiros 2009; Abell et al. 2010)

Artificial floating vegetation islands (AFVIs) and constructed wetlands have been increasingly used as ecological engineering technology for mitigation of eutrophication and improvement of water quality that is natural and benefits humans, whilst creating little secondary water pollution, compared with chemical and physical treatment of nutrients (Zhao et al. 2012; Keizer-Vlek et al. 2014). AFVIs are designed to float on the surface of the water with floats that provide buoyancy and are structured to stabilize the plants' roots and subterranean stems. Emergent macrophytes are planted on them which function in a similar way to natural floating mats.

As the largest drinking water source in Korea, Lake Paldang supplies drinking water for 20 million inhabitants of the metropolitan area of the capital Seoul (average intake quantity of water: 38.0 m^3/s). Kyungan River is one of the main inflow rivers of Lake Paldang. Anthropogenic pollution in the Kyungan River basin area, which is near the metropolitan area, has increased, resulting in diatom blooms and toxic cyanobacterial blooms in every spring and summer, respectively (Park et al. 2005). The algal bloom occurring in Kyungan River area of Lake Paldang could trigger off the spread of algal bloom in the confluence area of Lake Paldang. Furthermore, Kyungan River flows into the area near the intake sites of metropolitan drinking water supply facilities of Lake Paldang. Therefore, water quality improvement and algal control of Kyungan River area is critical for the management of Lake Paldang's water quality. As a part of water improvement management, an AFVI was installed in the Kyungan River area of Lake Paldang in 2000.

The treatment efficiency of the AFVI has been evaluated in pollution control, such as wastewater streams, stormwater runoff, acid mine drainage, and water supply reservoirs (Hubbard et al. 2004; Headley and Tanner 2006; Lynch et al. 2015). The treatment efficiency in a closed system can be easily quantified, but it is difficult to evaluate efficiency quantitatively in an open water environment, such as a river or large lake (Zhao et al. 2012). Therefore, the detailed interactions of physico-chemical and biological variables should be identified to evaluate the water quality improvement efficiency of AFVIs in the open water system. The objective of this study is to examine how biotic and abiotic variables interact to improve water quality within the AFVI's rhizosphere zone, by comparing the water quality between the within-island station of the AFVI and adjacent open water area as a control, and evaluate the mitigation of algal growth and water quality improvement effect of the full-scale AFVI installed in a large lake.

Methods

Sites description

Lake Paldang is located on the mid-downstream stretch of the Han River. North Han River, South Han River and Kyungan River converge ahead of Paldang Dam, forming Lake Paldang. Lake Paldang is a shallow reservoir (average water depth: 6.4 m) with a short hydraulic retention time (HRT; average annual HRT: 3–7 days).

The AFVI was installed in the embayment part of the Kyungan River area of Lake Paldang (Figure 1). The river width where the AFVI is placed is 450 m. The pelagic survey station (L station) is approximately 300 m apart from the AFVI. The average depth of the embayment part where the AFVI is placed is 2 m. The greatest depth of the pelagic part near the AFVI is 5.4 m (average 3.3 m).

Structure of artificial floating vegetation island

The AFVI consists of 16 floating units. Each floating unit (20 m × 8 m) comprises a stainless steel frame for supporting the floating unit, a float layer for buoyancy (made of compressed styrofoam) within the frame, a planting medium for growing the vegetation (made from junk fishnet and synthetic fibre), placed on the float layer. Floating units are connected and lined up in two parallel lines. Two lines of eight floating units are connected with each other through the wooden walkway for sampling operations.
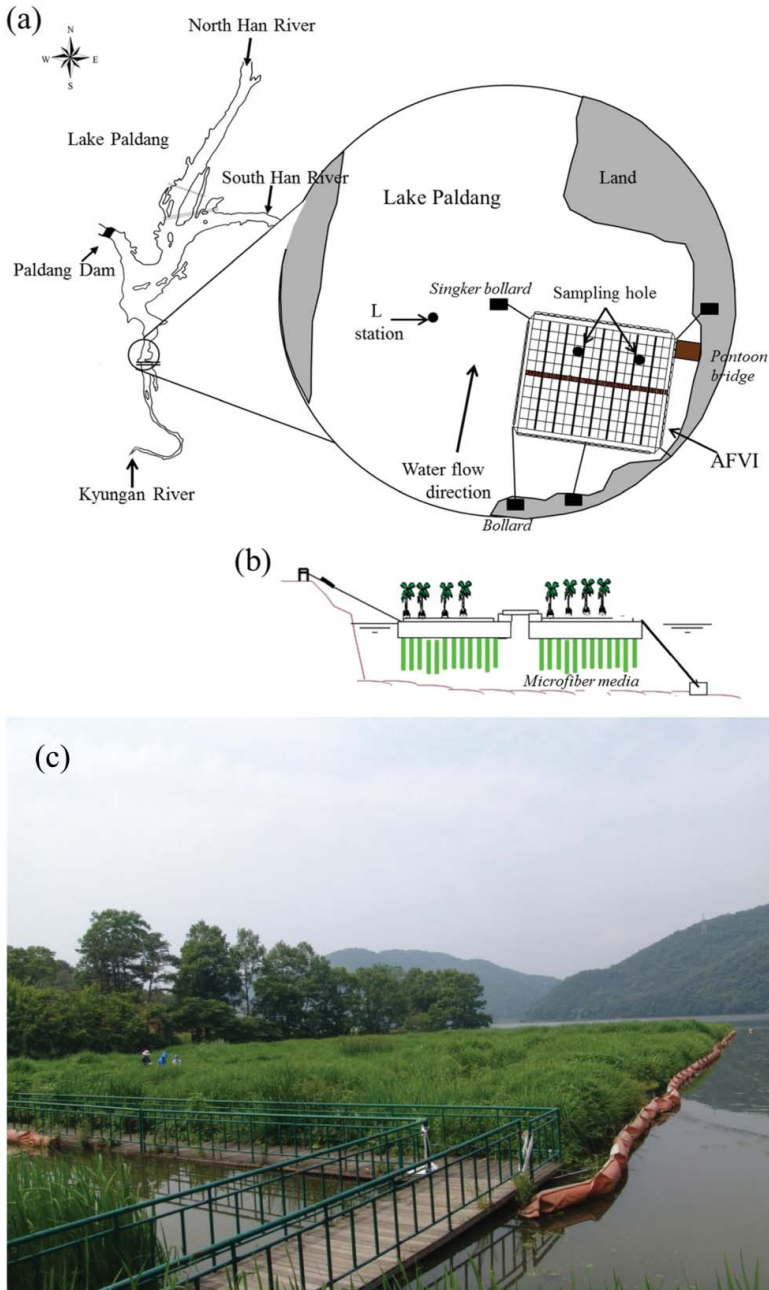
Figure 1. Aerial view of study site in Kyungan River area of Lake Paldang (a), lateral view of AFVI (b), and a photo of the AFVI (c).

The total area of AFVI is 2690 m^2, and the planted area is 2560 m^2. The AFVI has two sinker bollards and is connected by means of four bollards to the lakeside. *Phragmites australis* (*P. australis*) and *Phragmites japonica* (*P. japonica*), indigenous wetland plants of Lake Paldang, were planted with a density of 16 plants m^{-2} in the AFVI. The AFVI was initially installed with starter plants on a planting medium in the lake in 2000. *P. australis* and *P. japonica* started to grow in the spring, and reached about 1.8 m tall by late autumn. The macrophytes were cut, leaving approximately 15 cm shoots before leaf withering, and grew again next spring. We bored two cylindrical holes of 20 cm in

diameter, on the planting media and the float layer, to collect lake water underneath the AFVI. The two holes are approximately 32 m away from each other.

Sampling and analysis

Sampling for biotic and abiotic variables was performed at one- or two-week intervals from March to November, 2006, in two stations, the AFVI and adjacent pelagic part of the lake (L) (Figure 1). In the AFVI station, the water samples for chemical analysis were collected from two sampling holes and analyzed separately; water samples for bacteria, phytoplankton and zooplankton analysis from two holes were mixed and analyzed as one sample. In two stations, mixed water from the surface to 30 cm depth was collected (AFVI and L). Field measurements of water temperature (WT), dissolved oxygen (DO), pH and electric conductivity (EC) were performed using a calibrated multiparameter instrument (YSI 6600, YSI Inc.). Water samples for chemical analysis were stored in a cooler box and brought back to the laboratory immediately after collection. Samples for dissolved nutrients (total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), total dissolved nitrogen (TDN), nitrate nitrogen (NO_3^--N), ammonium nitrogen (NH_4^+-N) and dissolved organic carbon (DOC)) were filtered through glass-fibre filters (GF/F Whatman, acid rinsed and precombusted). Samples for total nitrogen (TN), TDN, total phosphorus (TP) and TDP were digested by the persulfate digestion method. Phosphorus samples were analyzed using the ascorbic acid method. NO_3^--N concentrations were determined by the ultraviolet spectrophotometric method. NH_4^+-N concentrations were determined by the phenate method. Water samples for suspended solids analysis were filtered through glass-fibre filters (pre-weighed), dried at 105 °C for two hours and weighed. Water samples for chlorophyll *a* (Chl *a*) concentration were filtered through glass-fibre filters, frozen and then analyzed using spectrophotometric determination (Eaton et al. 2005). The filtrate for DOC was dispensed into precombusted glass vials, sealed with acid-washed Teflon faced silicone septa, and the DOC concentrations were determined by high-temperature combustion analysis (Shimadzu TOC-VCTH). Filtered particulates were acidified with 12 N HCl, dried at 60 °C to remove inorganic carbon and used for the particulate carbon (PC) analysis with a CHN analyzer (Elemental, Vario EL) and interpreted as particulate organic carbon (POC).

The total number of bacteria (TB) was measured using the acridine orange direct count (AODC) method. The water samples for bacterial analysis were preserved with formaldehyde solution (final concentration 2%), filtered by black polycarbonate membrane filters (Millipore, pore size 0.2 μm, φ 25 mM) and stained with 2 mM of acridine orange ($C_{17}H_{20}C_{l3}N_3Zn$, Merck) solution. Then, the stained bacteria were counted using a fluorescent microscope (Olympus BX60, exciting filter: B, Lamp: Mercury lamp HBO 100W/2, OSRAM). The number of active (viable) bacteria (AB) was measured by the quantitative direct viable count (qDVC) method (Yokomaku et al. 2000). The number of active bacteria was determined by extracting the number of bacteria measured by the qDVC method from the number of total bacteria.

The water samples for phytoplankton analysis were preserved by adding Lugol's solution (final concentration 0.3%). Phytoplankton was classified into genus or species level under microscope (Komárek and Anagnostidis 1998; John et al. 2008), counted using Sedgwick-Rafter counting chamber and expressed phytoplankton cell density as cells per litre of water.

The water samples for zooplankton analysis were filtered through the plankton net of 60 μm mesh size. Concentrated zooplankton samples were preserved with formaldehyde solution (final concentration 5%). Zooplankton was classified into rotifers, cladocerans, and copepods to genus or species level (Kim 1988; Song 1989; Mizuno 1991; Cho 1993), counted using Sedgwick-Rafter counting chamber under microscope and zooplankton density expressed as total individuals per litre of water. The width and height lengths of all individual zooplanktons were measured and used to calculate the biomass of zooplankton. Zooplankton biomass was expressed as dried carbon weight per litre of water. The wet weight of rotifer was calculated using the formulas of Downing and Rigler (1984), and dry weight was calculated as 10% of wet weight (Pace and Orcutt 1981). The dry weight

of cladocera and copepods was calculated using length–dry weight relationship (Culver et al. 1985). The dried carbon weight was calculated by assumption of 48% dry weight (Andersen and Hessen 1991).

The height of *P. australis* and *P. japonica* was measured during the survey period. Ten stems of each species were selected and tagged, the length of the above-ground part measured at each water sampling.

Statistical analyses

On the assumption that the period in which the above-ground part of macrophytes has grown in the AFVI is the period when the AFVI functions as the vegetation island, the data of environmental variables from April, when macrophytes start to grow, to November, are used for the statistical analysis. The data of 12th of July, in which the water column was intensely disturbed by the inflow river water due to the monsoon heavy rain, were excluded from the data for the statistical analysis. To calculate mean value of each variable for the survey period, monthly mean was first calculated and mean value for 8 months (April to November) was calculated.

Since abiotic and biotic variables had different orders of unit of measurement, all variables data were standardized to z-scores for the statistical analysis such as Pearson correlation and redundancy analysis (RDA). Pearson correlations between environmental variables in each station were determined. Ordination was used to evaluate the relationships of environmental variables within the AFVI. The data were analyzed using RDA with CANOCO 4.5 (ter Braak and Sililauer 2012).

Results

Length growth of macrophytes

P. australis and *P. Japonica* started to grow at the beginning of April. They grew rapidly, showing a two-fold growth in just two weeks, and continued to grow to about 179 cm long by July 12, the maximum length until summer cut-off (Figure 2). The above-ground part of the macrophytes was harvested and taken out of the AFVI on July 21 leaving about 20 cm stems to maintain the nutrient uptake efficiency of the AFVI. Since the summer cut-off, macrophytes had continued to regrow
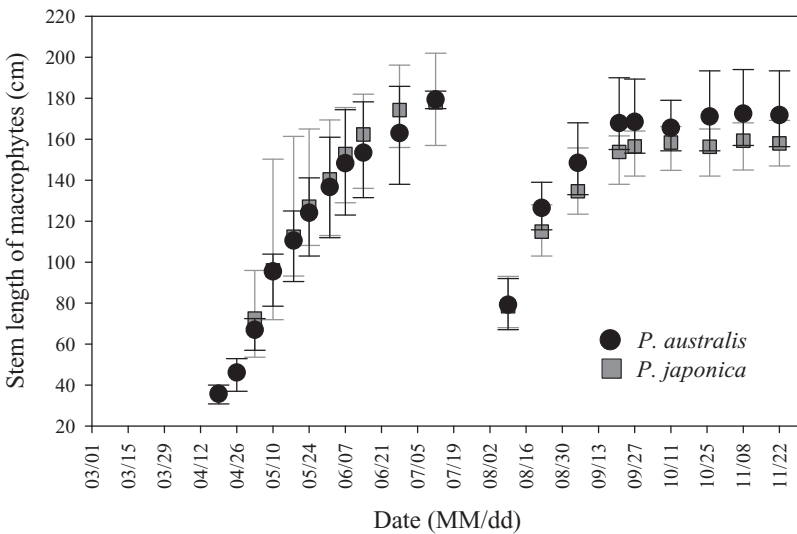
Figure 2. Temporal variation of stem length of *P. australis* (black circle, black error bar) and *P. japonica* (grey square, grey error bar) from April to November, 2006; error bar indicates the standard deviation.

quickly until the end of September. At the end of November, the above-ground part of the macro-phytes was harvested and taken out of the AFVI again (not shown in Figure 2).

### Differences in biotic and abiotic environmental variables

The mean values during survey period of pH, DO, TP, TDP, SRP, NO_3^--N, NH_4^+-N, SS, POC, Chl a, the proportion of AB in TB, phytoplankton cell density, zooplankton density and zooplankton biomass showed significant differences by survey stations (Table 1). Especially, the mean values of phosphorus, POC, phytoplankton and zooplankton density in the AFVI were markedly different from those of L station. The mean value of TP, TDP, SRP and POC in the AFVI was approximately twice as high value as that of L station, NH_4^+-N and the proportion of AB in TB of the AFVI was also higher than that of the L station. Zooplankton abundance and biomass was on average about 11 times and 20 times higher, respectively, in the AFVI than in the L station. On the other hand, the mean value of pH, DO and turbidity was higher in the L station compared to the AFVI. Nitrogen compounds were not significantly different except NH_4^+-N, and were also somewhat smaller in the AFVI compared to L station. The mean value of Chl a concentration, as an index of phytoplankton biomass in the AFVI was over 50% less, compared to L station and phytoplankton cell density was much less, indicating the effective reduction of phytoplankton growth by AFVI.

The temporal variations in abiotic and biotic variables, which were significantly different between two stations, are shown in Figure 3. TP and SRP showed similar temporal trends; the highest concentration at the end of August in the AFVI. L station showed relatively moderate temporal variations in concentrations of TP and SRP (Figure 3(e,f)). The proportion of TDP in TP is 17.0%–95.4% (average 39.7%) in the AFVI and 14.6%–80.2% (average 47.0%) in L, showing the higher proportion of dissolved phosphorus in the L station. The proportion of SRP in TDP in the AFVI and L is 45.2%–97.3% (average 77.4%) and 30.7%–99.6% (average 69.3%), respectively, showing the higher proportion of inorganic phosphorus in the AFVI.

Table 1. Average and standard deviation values of environmental variables for the survey period in two survey stations.

Variables	AFVI	L
WT (°C)	20.1 ± 5.8	20.1 ± 6.0
pH	7.2 ± 0.4	8.1 ± 0.6
DO (mg L^{-1})	4.0 ± 3.0	11.3 ± 2.4
EC (μS cm^{-1})	260 ± 54	272 ± 41
Turbidity (NTU)	8.6 ± 3.2	10.7 ± 4.8
TP (mg L^{-1})	0.300 ± 0.097	0.128 ± 0.034
TDP (mg L^{-1})	0.117 ± 0.045	0.058 ± 0.021
SRP (mg L^{-1})	0.090 ± 0.032	0.041 ± 0.021
TN (mg L^{-1})	3.501 ± 0.959	3.527 ± 0.737
TDN (mg L^{-1})	2.282 ± 0.746	3.033 ± 0.840
NO_3^--N (mg L^{-1})	1.279 ± 0.762	1.927 ± 0.565
NH_4^+-N (mg L^{-1})	0.431 ± 0.145	0.254 ± 0.212
SS (mg L^{-1})	23.3 ± 7.0	14.1 ± 5.3
BOD$_5$ (mg L^{-1})	2.9 ± 0.9	2.5 ± 1.2
DOC (mg L^{-1})	2.7 ± 0.5	2.5 ± 0.6
POC (mg L^{-1})	5.6 ± 1.7	2.7 ± 1.4
Chl a (mg m^{-3})	23.6 ± 16.7	47.9 ± 35.3
TB (10^{6}cells mL^{-1})[*]	6.8 ± 3.2	6.9 ± 5.1
AB (10^6 cells mL^{-1})[*]	5.3 ± 2.7	4.2 ± 3.9
AB/TB (%)	79.2 ± 5.9	63.9 ± 7.2
Phytoplankton density (cells mL^{-1})[*]	2051 ± 13,577	6652 ± 24,550
Zooplankton density (Ind. L^{-1})[*]	8583 ± 10,561	730 ± 1739
Zooplankton biomass (mgC L^{-1})	18.2 ± 20.1	0.9 ± 0.8
Rotifer density (Ind. L^{-1})[*]	565 ± 6672	187 ± 1514
Copepoda density (Ind. L^{-1})[*]	1825 ± 6995	61 ± 221
Cladocera density (Ind. L^{-1})[*]	2640 ± 2845	180 ± 565

Average values of microbial variables with superscript * are geometric averages.
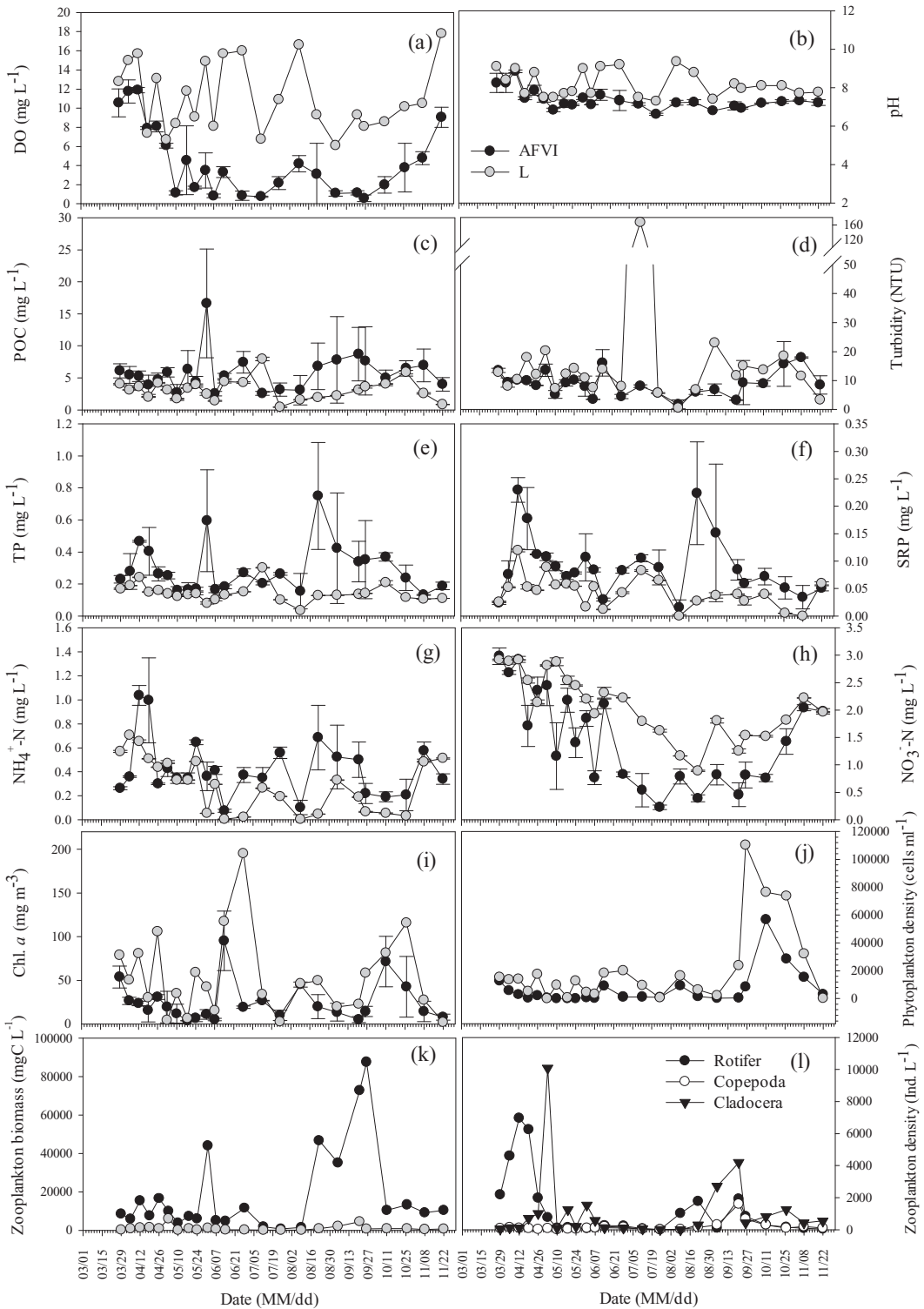
Figure 3. Temporal variation of DO (a), pH (b), POC (c), turbidity (d), TP (e), SRP (f), NH_4^+-N (g), NO_3^--N (h), chl a (i), phytoplankton density (j), zooplankton biomass (k) in two stations (black circle: AFVI, grey circle: L) and three zooplankton groups in the L station (l); error bar indicates the standard deviation.

L station showed decreasing trends in concentration of NO_3^--N (Figure 3(h)) before the rainy season, whereas the AFVI station showed fluctuations during the same period and very low concentrations in summer season. On the other hand, NH_4^+-N showed very low concentrations in the L station and relatively high concentrations in the AFVI during summer season. There were sharp reductions of NH_4^+-N concentrations in June and mid-August, late October in both stations, corresponding to the peaks of Chl a concentration, especially in the L station (Figure 3(g,i)). Similar reductions pattern of SRP also was shown.

The proportion of TDN and NO_3^--N in TN is 33.9%–88.0% (average 67.7%) and 6.9%–69.0% (average 36.3%) in the AFVI, 59.0%–99.1% (average 85.6%) and 32.5%–82.2% (average 55.6%) in the L station, showing lower proportion of dissolved nitrogen, especially nitrate, in the AFVI, whereas the proportion of NH_4^+-N in TN is 2.3%–31.3% (average 13.6%) in the AFVI and 0.1%–17.8% (average 7.1%) in the L station showing a higher proportion in the AFVI.

Chl a concentrations showed three peaks throughout the survey period in early Spring, just before the heavy rainfall, and October in both stations, showing much higher concentrations in the L station at the late two peaks. The phytoplankton cell density showed distinct differences between stations in June and September to October, and a much bigger difference in Autumn season when cyanobacteria dominated (Figure 3(j)).

From May onwards, there was comparatively little temporal variation in pH in the AFVI; by contrast, pH in the L station varied dramatically over the time, with the episodes of high pH corresponding to periods of high concentration of Chl a (Figure 3(b,i)). DO concentrations decreased consistently, reached a level below 3 mg L^{-1} in May, remaining in a hypoxic state until October in the AFVI. In contrast to the AFVI, DO concentrations never dropped below the hypoxic state throughout the survey period and showed very high concentrations corresponding to periods of high concentration of Chl a in the L station (Figure 3(a)).

There were moderate seasonal variations in turbidity in the AFVI, while unusually high turbidity coincided with heavy rain in July in the L (Figure 3(d)). POC concentrations in the AFVI were much higher in early June and August to September compared to the pelagic station (Figure 3(c)).

While there were three peaks in zooplankton density in April, June and September, there were two peaks in zooplankton biomass in the AFVI. In April, small rotifers increased sharply up to 30,395 Ind. L^{-1} following the increase in WT. *Brachionus calyciflorus* was the dominant species. From the end of April, Spring rotifers were succeeded by cladocera. Zooplankton density declined during the heavy rainfall period and recovered quickly again in August up to 38,365 Ind. L^{-1}, dominated by copepods (mainly nauplius, copepodid) (Figure 4(d)). In the L station, the zooplankton density was much lower than in the AFVI for almost all the survey period. In the L station, cladocera generally dominated throughout the survey period except April and August, when dominated by rotifers. Unlike the AFVI, copepods showed low abundance throughout the survey period except for a transient increase at the end of September (Figure 3(l)).

Detailed interaction of biotic and abiotic variables in the AFVI

To determine the mutual-effect mechanisms among biotic and abiotic environments in the survey stations, Pearson correlations were analyzed (Table 2). Chl a concentration, index of phytoplankton biomass, had significant negative correlation with only a concentration of NH_4^+-N ($p = 0.025$) in the AFVI. While no nutrients showed significant correlations with Chl a concentration in the L station, SS and POC showed positive correlations. POC showed strong positive correlation with copepoda biomass in the AFVI and with Chl a concentration in the L station, indicating different origins of POC in the AFVI and the L station. DO had a very strong correlation with TDN ($r = 0.861$, $p = 0.000$) and NO_3^--N ($p = 0.000$) in the AFVI, indicating the effect on the nitrogen metabolism. Within the zooplankton community, rotifers biomass had positive correlations with BOD_5 ($r = 0.533$, $p = 0.011$), DOC ($r = 0.421$, $p = 0.051$), and soluble nutrients such as TDP ($r = 0.453$, $p = 0.034$), SRP, TDN ($r = 0.729$, $p = 0.000$), NO_3^--N, NH_4^+-N in the AFVI. Similar positive
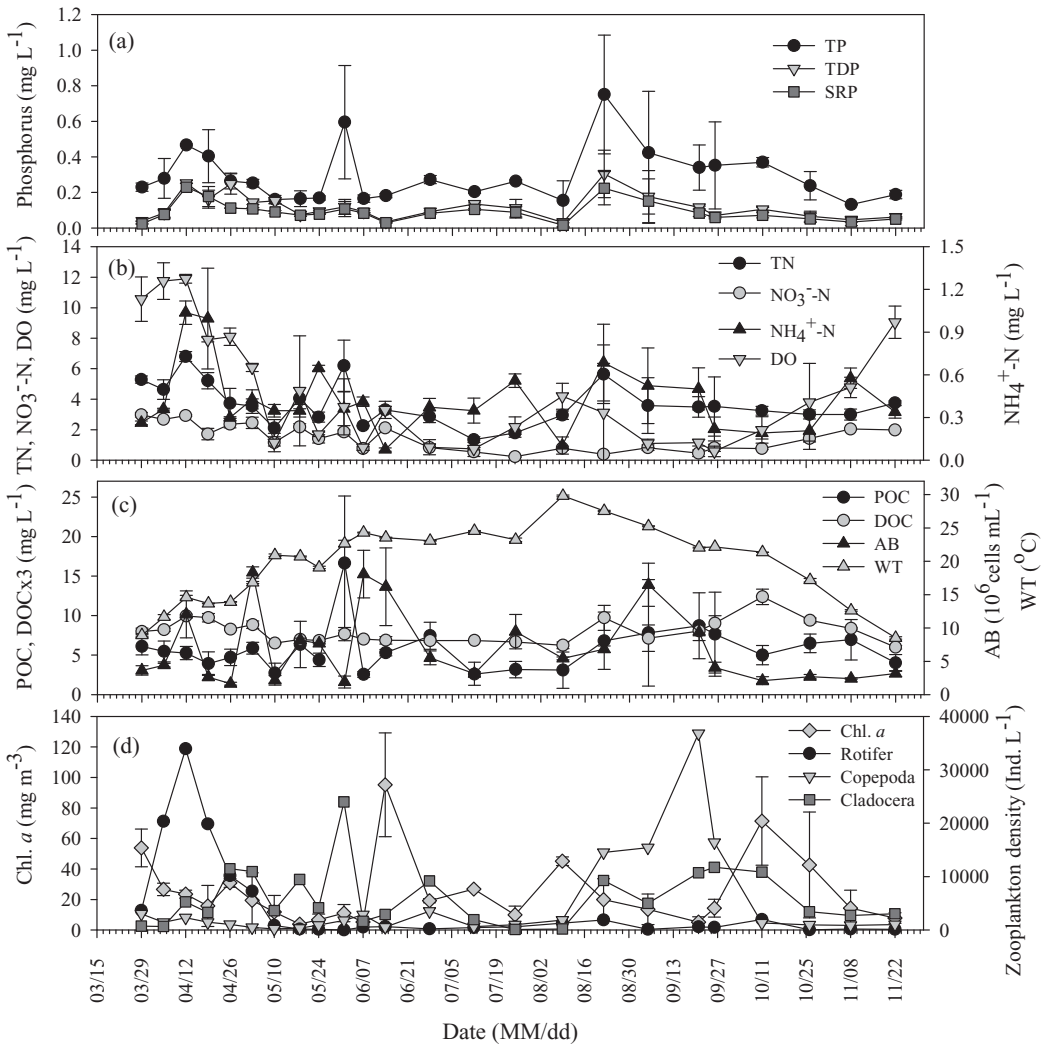
Figure 4. Temporal variation of concentration of phosphorus (a), nitrogen and DO (b), organic matters, AB and WT (c) and Chl *a* and zooplankton groups (d) in the AFVI; error bar indicates the standard deviation.

correlations were also shown in the L station except NO_3^--N. Copepoda biomass showed significant positive correlations with TP, TN, SS and POC indicating major contribution to particulate materials in the AFVI.

Temporal variations of nutrients, organic matters and biotic variables in the AFVI were shown in Figure 4. The periods of zooplankton showing high density, regardless of zooplankton group, coincide with the periods of high concentrations of TP, TN and POC. Inorganic nutrients such as SRP and NH_4^+-N also increased at the same periods. Active bacteria increased at the same or just after peak periods of zooplankton.

Chl *a* concentrations fluctuated inversely to zooplankton density; that is, when zooplankton density increased in April, late May and August, Chl *a* concentrations decreased, and when zooplankton density decreased, Chl *a* concentrations increased showing grazing effect of zooplankton to phytoplankton within the AFVI. Chl *a* concentration also increased just after the summer cut-off of macrophytes. As Chl *a* concentrations increased, the concentration of SRP and NH_4^+-N, which are known to be readily taken up for phytoplankton growth, decreased. Given the negative correlation

Table 2. Pearson correlation coefficients between environmental variables in two stations ($n = 22$).

Variables	TP		SRP		TN		NO₃⁻-N		POC		Chl a		ROT-B		COP-B	
Stations	AFVI	L	AFVI	L	AFVI	L	AFVI	L	AFVI	L	AFVI	L	AFVI	L	AFVI	L
SRP	0.757**	0.596**	1	1	0.673**	0.640**	0.069	0.531*	0.097	−0.141	−0.269	−0.211	0.607**	0.497*	0.294	0.237
TN	0.735**	0.481*	0.673**	0.640**	1	1	0.465*	0.554**	0.485*	0.014	−0.051	0.007	0.619**	0.598**	0.570**	−0.186
NO₃⁻-N	−0.163	0.408	0.069	0.531*	0.465*	0.554**	1	1	0.055	0.181	0.108	0.032	0.598**	0.390	0.020	0.025
NH₄⁺-N	0.407	0.430*	0.783**	0.629**	0.492*	0.555**	0.137	0.671**	−0.049	−0.167	−0.478**	−0.368	0.633**	0.546**	−0.006	0.085
SS	0.644**	0.435*	0.192	−0.071	0.613**	0.031	0.143	0.316	0.833**	0.754**	0.173	0.493*	0.086	0.275	0.798**	0.264
POC	0.542**	0.455*	0.097	−0.141	0.485*	0.014	0.055	0.181	1	1	−0.133	0.716**	−0.141	0.018	0.837**	0.067
Chl a	−0.071	0.312	−0.269	−0.211	−0.051	0.007	0.108	0.032	−0.133	0.716**	1	1	0.001	0.053	−0.129	−0.329
WT	0.227	−0.430*	−0.015	−0.376	−0.217	−0.435*	−0.714**	−0.580**	0.129	−0.087	0.153	0.107	−0.452*	−0.421	0.146	−0.009
pH	0.180	0.043	0.349	−0.258	0.664**	0.083	0.768**	−0.156	0.049	0.335	0.248	0.655**	0.798**	0.207	0.072	−0.281
DO	0.049	−0.058	0.277	−0.058	0.579**	0.322	0.801**	0.107	−0.141	0.036	0.039	0.364	0.744**	0.112	−0.091	−0.417
Phytoplankton	−0.035	0.201	−0.299	−0.364	−0.150	−0.321	−0.118	−0.315	−0.054	0.535*	0.620**	0.363	−0.119	−0.161	−0.069	−0.110
ROT-B	0.243	0.592**	0.607**	0.497*	0.619**	0.598**	0.598**	0.390	−0.141	0.018	0.001	0.053	1	1	−0.119	−0.132
CLA-B	0.309	0.035	0.044	−0.074	0.035	−0.353	−0.444*	−0.384	0.322	0.023	−0.223	−0.163	−0.206	−0.102	0.260	0.468*
COP-B	0.698**	0.007	0.294	0.237	0.570**	−0.186	0.020	0.025	0.837**	0.067	−0.129	−0.329	−0.119	−0.132	1	1

* and ** indicate $p < 0.05$ and $p < 0.01$, respectively.
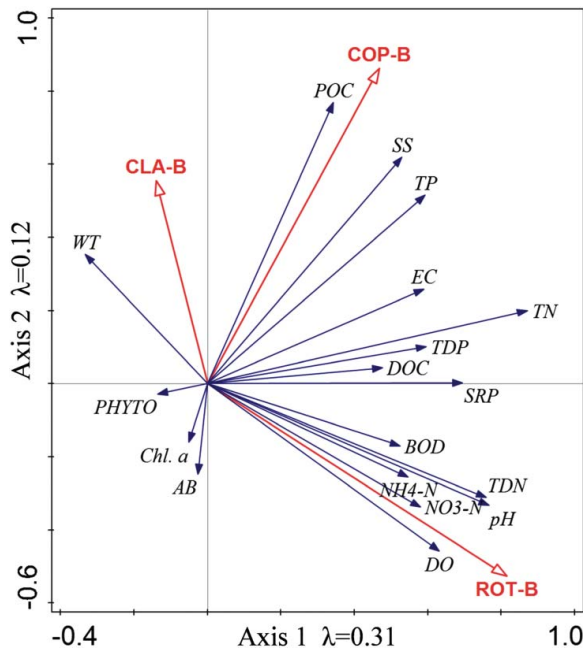
Figure 5. Ordination graph of environmental variables and three zooplankton groups against redundancy analysis axes 1 and 2. See Methods section for the abbreviations of variables.

of Chl *a* concentrations and NH_4^+-N, phytoplankton uptake seems to be the main reduction metabolism of NH_4^+-N in the AFVI.

To understand the interaction of biotic and abiotic variables in the rhizospheric zone of the AFVI, the relationships of biotic and abiotic variables in the AFVI during survey periods were analyzed by RDA (Figure 5). The constrained three RDA axes ordinations accounted for 45.3% of total variance. The first axis represented 30.7% of variance and the second axis represented 12.2% of variance. Small-size zooplankton, rotifer biomass (ROT-B), was separated from large-size zooplankton, copepod (COP-B) and cladocera biomass (CLA-B), by the first axis. Similar to the result of Pearson correlation (Table 2), rotifer biomass was closely related to BOD_5, TDN, NH_4^+-N, NO_3^--N and DO. Copepoda biomass was closely related to particulated matters such as POC, SS and TP. Phytoplankton (PHYTO) and Chl *a* concentrations showed the opposite direction to large-size cladocera and copepod biomass. DO and NO_3^--N showed close relationship.

Discussion

The detailed interactions of biotic and abiotic environmental factors in the rhizospheric zone of the AFVI are summarized in Figure 6. The primary differences in physical environment between the AFVI and pelagic part of the lake are the flow rate, shading from the sunlight and underwater structure. Structural complexity containing floating frames, vegetation media and macrophytes of the AFVI shields the water surface from wind, reduce the water flow, turbulence and aeration, and restrict mixing within the AFVI (Frodge et al. 1990). As a result, the AFVI was more stagnant than the adjacent open water. Moreover, extensive covers of emergent plants on the AFVI also caused severe underwater light attenuation, inhibiting the photosynthesis of phytoplankton and finally resulting in the reduction of phytoplankton cell density and oxygen supply to the water column. The roots and hanging media of the AVFI, suspended in the water column, can adsorb suspended solids and dissolved nutrients; they form a habitat for microorganisms forming the biofilm along the roots and synthetic media. Combinations of these microorganisms and roots themselves
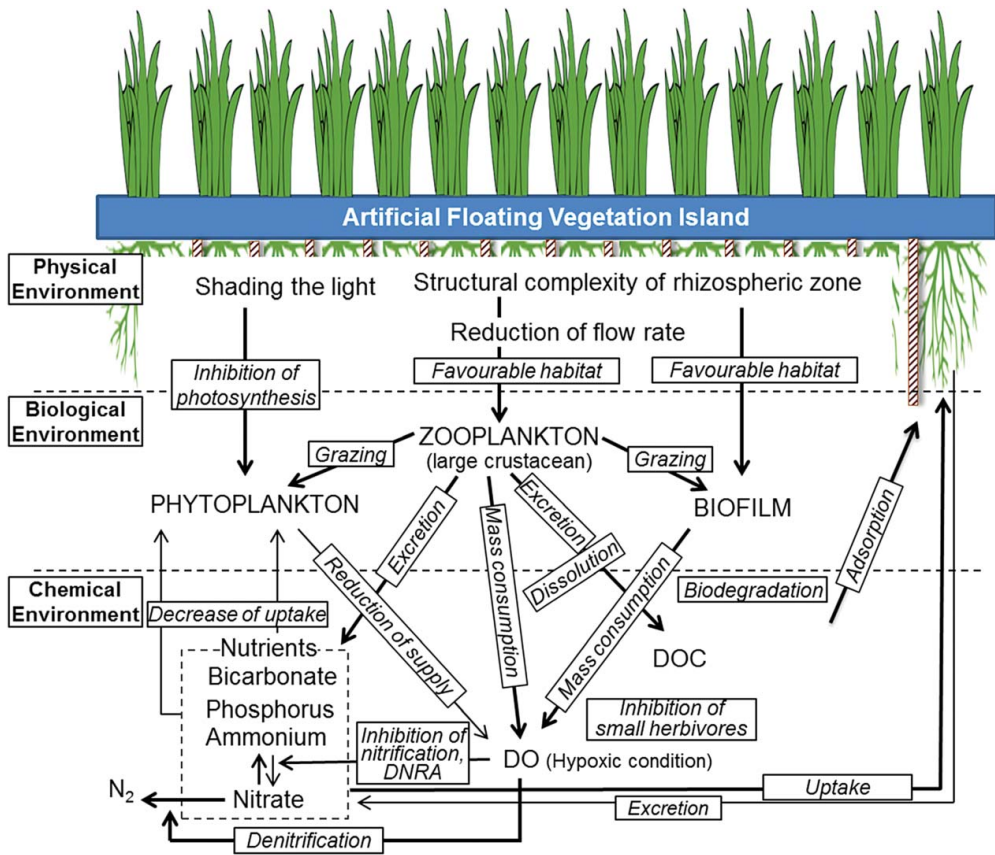
Figure 6. Schematic diagram of detailed interactions of biotic and abiotic environmental factors in the rhizospheric zone of the AFVI; bold arrows indicate major interactions.

metabolize suspended and nutrient pollution by degrading the organic matter and absorbing the nutrients (Bachand and Horne 2000). Previous studies reported that nitrogen and phosphorus concentrations within a floating island were consistently higher than adjacent lake water, possibly because the macrophytes and supported aquatic organisms liberate dissolved nutrients from decomposing organic matters (Sasser et al. 1991). The roots of macrophytes in the AFVI can also excrete nutrients in the water column. The plant uptake and translocation of nutrients dominates over excretion for the rapid growth period (Sasser et al. 1991). During the survey period, the aboveground part of the macrophytes had continued to grow until the end of September including summer cut-off and regrowth, indicating uptake of nutrients predominated over excretion in the AFVI throughout the survey period.

The proportion of active bacterial count in the total number of bacteria (60.4%–89.0%, average77.3%) in the AFVI is higher than in the open water of Lake Paldang and other lakes of the Han River system, such as Lake Paro (32.0%–44.3%) and Lake Uiam (32.7%–39.0%) as well (Suck et al. 2001). The higher proportion of AB in TB in the AFVI seems to be supported by a higher accumulation of organic matter and abundant predators in the rhizospheric zone of the AFVI. Aquatic microorganisms, such as bacteria and zooplanktons, are known to shorten the generation time to increase population size rather than individual growth, called r-selection strategy in the presence of predators (Kim et al. 1995). Therefore, it seems that in the AFVI, where zooplankton density was much higher than in the pelagic part of the lake, the proportion of AB in TB was higher than in the L station. Even though there is no significant difference of total bacterial count between stations, the

relatively higher active bacterial count and higher proportion of AB in TB in the AFVI indicate the more vigorous decomposition and dissolution of organic matters would have occurred in the rhizospheric zone of the AFVI; this could be one explanation for the higher concentration of inorganic nutrients such as SRP and NH_4^+-N in the AFVI.

Moreover, SRP and NH_4^+-N are known as the nutrients which are primarily consumed by phytoplankton proliferation, suggesting less nutrient uptake by phytoplankton in the AFVI, where phytoplankton cell density was lower than in the pelagic part of lake, whereas, the sharp reductions of SRP and NH_4^+-N concentrations in the L station corresponded to the peaks of Chl a concentration, suggesting the reduction of SRP and NH_4^+-N in the L station was mainly caused by the consumption by phytoplankton. This would also be the one reason for the higher nutrient concentrations in the AFVI.

However, unlike TDP and SRP, TDN and NO_3^--N concentrations do not show a big difference between stations, or even show lower concentrations in the AFVI. This probably resulted from differences of DO concentrations between stations. In aquatic systems, DO concentrations are influenced by primary production, respiration, physical structure and hydrologic regime. The oxygen dynamics are particularly important to biotic and chemical environment when oxygen concentrations drop below hypoxic state and generally have a negative impact on aquatic organisms as well as nutrients cycling (Harrison et al. 2005; Goodwin et al. 2008). The microorganisms in the rhizospheric zone can facilitate the conversion of NH_4^+ to NO_3^- in aerobic conditions. However, in the AFVI, DO concentrations showed hypoxic state from May to October, in which nitrification is impossible; rather NO_3^--N could be expelled as nitrogen gas by denitrification or reduced to NH_4^+-N by dissimilatory nitrate reduction (DNRA) (Jahangir et al. 2017). NO_3^--N concentrations showed a decreasing trend as DO concentrations declined, showing low concentrations, less than 1 mg L^{-1} from late June when DO showed an anoxic state in the AFVI. In this period, NH_4^+-N concentrations fluctuated inversely to NO_3^--N concentration.

Macrophytes are likely to provide a daytime refuge for zooplankton against fish predation (van Onsem et al. 2010). The AFVI also showed much higher density and carbon biomass of zooplankton than the adjacent lake water (L station) indicating a role of effective habitat for zooplankton. The shading by vegetation mat and the roots and hanging media of the AVFI suspended in the water column would obstruct the foraging activity of fish, providing refuge for zooplankton. The more stagnant environment within the AFVI is also likely to play a role in high zooplankton abundance, especially large crustacean zooplankton which prefer a stagnant environment (Obertegger et al. 2007; van Onsem et al. 2010).

Abundant zooplankton development could variously affect physico-chemical and biological water quality. Zooplankton can supply DOC, inorganic nitrogen and phosphorus, in widely varying ratios, to microbial heterotrophs and primary producers via feeding and excretion (Frost et al. 2004). The significant correlations between zooplankton, especially rotifer carbon biomass and BOD_5 ($r = 0.533$, $p = 0.011$) and soluble nutrients support the evidence that the excretion of soluble, biodegradable compounds from zooplankton is another source of higher nutrient concentrations in the AFVI, together with active bacterial decomposition of organic matters. In addition, the peak periods of AB corresponded with the peak period, or just after the peak period, of zooplankton, indicating the detritus and excreted DOC from abundant zooplankton biomass promote the bacterial growth.

Top-down effect of zooplankton seems to occur in the AFVI. Even though zooplankton density or carbon biomass did not reveal significant correlation with Chl a concentrations or phytoplankton density, the temporal variations of zooplankton and Chl a concentrations show the opposite trend, that is, when zooplankton biomass increases, Chl a concentration decreases inversely (in April and from the end of August to the end of September), or vice versa (mid-June and October). Therefore, top-down effect of zooplankton also plays a role in the lower density of phytoplankton in the AFVI than in the pelagic water (L station), together with the shading effect of the AFVI (Figure 6).

The negative effects of hypoxia on zooplankton abundance and distribution have been previously acknowledged. According to Fontanarrosa et al. (2010), periodical or permanent shading, associated with anoxic conditions, impaired the success of small herbivores. Large herbivores were negatively affected only under persistent shade and anoxia. Our results are similar to those of Fontanarrosa et al. (2010). The only positive correlation of rotifers among zooplankton groups with oxygen concentrations in the AFVI supports this finding. Cladocera and copepods showed abundant biomass under the hypoxic condition in May, September and October, indicating the oxygen availability seemed to play a minor role compared with favourable environment, such as stagnant water flow and lower predation pressure.

In a small-scale closed system (pond), AFVIs could reduce phytoplankton growth through sequestration of nutrients competitively (Jones et al. 2017). However, in an open water system like a large lake where nutrients are supplied continuously from inflow water, reduction of phytoplankton growth through sequestration of nutrients by AFVIs would be limited. Likewise, the higher concentration of dissolved nutrients such as SRP and NH_4^+-N in the rhizospheric zone of the AFVI would have only a minor effect on the stimulation of the algal growth of adjacent water column. Instead, the physical inhibition like shading and integrated biotic and abiotic interaction within the rhizospheric zone of the AFVI including zooplankton grazing, microbial degradation, and nitrate reduction would work effectively for mitigation of phytoplankton growth and water quality improvement (Figure 6). In addition, cutting off and removing the above ground part of macrophytes twice a year from the AFVI of this study resulted in the removal of 17.6 gN m^{-2} $year^{-1}$ of nitrogen and 1.3 gP m^{-2} $year^{-1}$ of phosphorus from the lake water through the AFVI (Choi et al. 2007).

Conclusion

The water quality improvement mechanism of the full-scale AFVI which was installed in a large Korean lake was investigated through comparing the biotic and abiotic environmental factors between the AFVI and adjacent pelagic part of the lake. As summarized in Figure 6, in addition to basic removal of nutrients from plant uptake and harvesting the plants, the major mechanisms for improving water quality of AFVIs are shown to be inhibition of phytoplankton growth by attenuating light, top-down control by zooplankton grazing, and active decomposition of organic matters in the rhizospheric zone. The cycling of matters in the rhizospheric zone, such as respiration of abundant zooplankton and biofilm microorganisms, active microbial decomposition of organic matters and nitrate reduction, also would be the major mechanism for improving water quality, even though it is difficult to quantify in the open water system.

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Disclosure statement

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Hae-Kyung Park is a senior researcher who had worked on limnological and ecological researches of lakes and rivers including this study in the Han River Environment Research Centre. She moved to the Nakdong River Environment Research Centre in 2013, and has been working on the harmful cyanobacterial blooms in the river.

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