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Nutrient removal in different overlying water layers and their variation in pore water of drainage ditches in Sanjiang Plain, Northeast China

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ABSTRACT

Agricultural drainage ditches which deliver excess water from poorly drained farmlands to ensure consistent agricultural production but also transport field pollutants, especially nitrogen (N) and phosphorus (P). Ditch management has been proposed to alleviate nutrient loads that are transported to receiving water. Experimental drainage ditches with *Phragmites australis* were used to examine the N and P mitigation capacity of drainage ditches at different plant growth stages and different initial concentrations as well as the mitigation capacity in different water layers by the intermittent strategy. This study also investigated nutrient variations in sediment pore water of drainage ditches under existing ditch management systems. Significant reductions were observed on the efficiencies of nitrate nitrogen (NO_3–N) and phosphate phosphorus (PO_4–P) with plant growth. The efficiencies of ammonia nitrogen (NH_4–N) remained the same at different growth stages. The rates of NH_4–N, NO_3–N and PO_4–P were higher under high initial concentrations. However, the efficiencies of these substances were higher under low initial concentrations. The values of the NH_4–N, NO_3–N, and PO_4–P efficiencies were 71.7–87.0%, 40.6–51.0%, and 52.8–78.3% in high water layers and 71.9–87.6%, 38.4–48.4%, and 52.6–77.2% in low water layers, respectively. Water quality stratification on NH_4–N and NO_3–N under high initial concentrations indicates that ditch plants, sediments, and soils are able to enhance nutrient mitigation. Low NH_4–N and PO_4–P concentrations in pore water show that ditch sediment adsorption plays a vital role in mitigating nutrients.

Keywords: Drainage ditch; Nitrogen; Phosphorus; Plant; Retention time; Water layer

1. Introduction

Agricultural drainage refers to discharging excess water from farmlands. It is employed to reclaim wetlands, improve public highways, reduce surface run-offs, prevent erosion, increase land value, increase crop yield, and reduce year-to-year yield variability [1–3]. As important integral components of hydrological facilities and landscape units in agriculture, drainage ditches convert diffuse flows from agricultural landscapes into concentrated flows and increase run-off coefficients in agriculture [2,4]. Moreover, drainage ditches serve as important temporary impounding reservoirs in flood-plains, which decrease peak flows and

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reduce the possibility of floods [5]. Drainage ditches also change the migration paths of surface run-offs and soil flows, hydraulic gradients in agricultural watersheds, and biogeochemical cycle paths of chemical elements, which affect soil properties and plant growth and development, as well as regional hydrological patterns, landscape patterns, and ecological environment [6–8]. Drainage ditches have the potential to act as major conduits in the export of nutrients, such as ammonia nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), and phosphate phosphorus (PO_4–P), from farmlands to receiving waters [9,10]. If no appropriate control measures are taken to deal with N and P in drainage ditches, these chemicals may pose a potential risk to adjacent receiving waters. Hence, agricultural ditch management plays an important role in improving downstream water quality and balancing production and precision conservation [11,12].

Food and fiber demands increase daily with global population growth [13]. Inorganic fertilizers are widely used in increasing yields for agricultural production, resulting in high loads of nutrients delivered from paddy fields to adjacent receiving waters [3,14]. Take the Sanjiang Plain, Northeast China as a case; the export loads of N and P from paddy fields were roughly 2.53 and 0.19 $t\,km^{-2}\,yr^{-1}$, respectively, most of which were lost through drainage ditches [15,16]. As a result, drainage water carries high nutrient loads from paddy fields in the Sanjiang Plain. In the Sanjiang Plain, common ditch management includes intercepting and accumulating drainage water in drainage ditches; returning drainage water to adjacent paddy fields if needed; making full use of surface water; recharging groundwater; and reducing groundwater use. However, ditch waters enriched with nutrients were potential pollution sources for receiving water under storm run-off. Hence, studying the mitigation capacities and variations of N and P in ditch water are necessary to intercept the mechanisms of these chemicals under existing ditch management conditions in the Sanjiang Plain.

Presently, the mitigation capacity of nutrients in drainage ditches is paid little attention at different plant growth stages. Water quality in different water layers may differ because of the varying distances of ditch sediments and sidewall soils, as well as plant absorption. However, studies on the nutrient mitigation capacity of drainage ditches in different water layers are ignored. The variation of nutrients is overlooked in the sediment pore water of drainage ditches, especially in the Sanjiang Plain. This paper aims to evaluate the mitigation capacity of NH_4–N, NO_3–N and PO_4–P in drainage ditches at different plant growth stages to interpret their mitigation efficiency in different water layers of drainage ditches and their variations in pore water with retention times at different growth stages. This study is a reasonable reference for the improvement of drainage management and environmental benefits in the Sanjiang Plain.

2. Materials and methods

2.1. Site description

The experiment was organized at the comprehensive experimental field of the Sanjiang Mire Wetland Experimental Station (47°35′N, 133°31′E), Chinese Academy of Sciences, located in Tongjiang City, Heilongjiang Province, Northeast China. The mean annual precipitation is 550–600 mm (mainly in July, August, and September); the mean annual evaporation is 550–840 mm; and the mean annual temperature is 1.9°C. The frostless period is about 125 d. Farm soil was gleyed albic soil. There is 3–17 m of clay below ditch sediments with a low permeability coefficient of 0.0013–0.635 $cm\,d^{-1}$ in this area [17]. *Phragmites australis* and *Echinochloa crus-galli* are two dominant vegetations on ditch sidewalls and bottom in Sanjiang Plain. Most of the agricultural drainage water is intercepted and accumulated in field ditches and lateral ditches. Depth of water in lateral ditches is 30–100 cm during the plant growing season, when excess water from paddy fields is discharged.

2.2. Ditch and experimental design

Ditch sediment was a mix between farm silt soil and natural soil. Ditch sediment analysis indicated a pH of 5.6, cation-exchange capacity 23.7 $c\,mol\,kg^{-1}$, 42.41 $g\,kg^{-1}$ organic matter, and sand, 8.3%; silt, 18.7%; clay, 73.2%. Experimental drainage ditches were the width of 2.5 m, 20 m length, 0.8 m depth, and slope ''U'' design that is most common throughout Sanjiang Plain. *P. australis* was the main vegetable type within experimental drainage ditches. Drainage ditches were operated with the intermittent strategy, simulating farmland drainage. The artificial drainage water was prepared in a feed tank by dissolving ammonium nitrate and sodium dihydrogen phosphate in each ditch. Two kinds of inlet water were low N and P initial concentrations (I) and high N and P initial concentrations (II), respectively. Residence time was 120 h after reaching the setting water level. And water level of ditches was 45–55 cm. Perforated tubes of collecting water were set in experimental ditches. Centers of perforated parts of three sampling tubes were 17.5 cm apart from the surface of ditch sediment for collecting water samples from drainage ditches

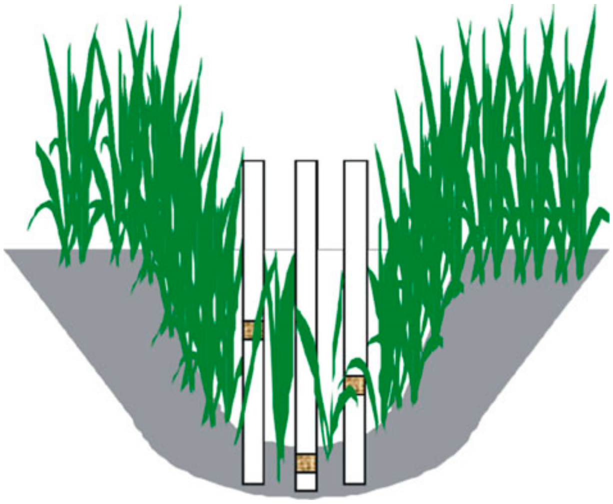

Fig. 1. Layouts and designs of experimental ditches.

(low water layers, LWL). Another three sampling tubes whose centers of perforated parts were 37.5 cm apart from the surface of ditch sediment were employed to collect water samples (high water layers, HWL). Moreover, centers of perforated parts of three tubes were 12.5 cm apart from the subsurface of ditch sediment in charge of collecting pore water (Fig. 1).

2.3. Water samples collection and analysis

Experiments were conducted from June to September in 2011. The plant communities were developed in the early period of experiments. Water samples were collected in the early, middle and late growing season of *P. australis*. We collected overlying water and pore water samples by perforated tubes and inverted siphon method. All of the samples were stored in an ice chest, transported to laboratory, filtered through 0.45 μm filters immediately, and then were analyzed.

Water samples were analyzed for chemical oxygen demand (COD$_{Cr}$), dissolved oxygen (DO), pH, total nitrogen (TN), total phosphorus (TP), NH$_4$–N, NO$_3$–N, and PO$_4$–P. Potassium dichromate method was used to analyze COD$_{Cr}$. DO and pH of the samples were determined by DO electrode and Piccolo pH meter, respectively. TP was determined by using persulphate digestion method [18], and TN was tested with test-in-tube alkaline persulphate digestion method [19]. The remaining parameters were measured in accordance with the Standard Methods [20].

2.4. Statistical analysis

The SPSS 16.0 statistical packages were used in the statistical analysis, and all figures were drawn using the SigmaPlot 10.0 software. Comparison of the NH$_4$–N, NO$_3$–N, and PO$_4$–P removal rates and efficiencies in different water layers and plant growth stages was performed with one-way analysis of variance (ANOVA).

3. Results

3.1. N and P removal in HWL and LWL

Total N concentrations in NH$_4$–N and NO$_3$–N, and a small fraction of organic nitrogen or nitrite in overlying waters had close values at the same growth stage in either low or high initial concentrations. Total P concentrations with low organic P were similar at the same period (Table 1).

The NH$_4$–N removal rates and efficiencies in HWL and LWL of ditch waters are displayed in Fig. 2. Under low initial concentrations, NH$_4$–N removal rates decreased with the plant-growing season either in HWL or in LWL. NH$_4$–N removal rates were slightly lower in HWL than that in LWL in the early growing season. However, reduction in NH$_4$–N removal rates were only found in LWL under high initial concentration conditions NH$_4$–N removal rates in HWL were lower than that in LWL between the early and middle growing season. Compared when under low initial

Table 1

Mean initial concentrations ((±standard deviation) mg L^{-1}, excluding pH) in drainage ditches

Parameter	The early growing season		The mid-growing season		The late growing season	
	I	II	I	II	I	II
TN	13.55 ± 1.68	44.07 ± 1.46	14.29 ± 1.2	47.44 ± 2.57	13.86 ± 2.05	46.98 ± 2.03
TP	2.58 ± 0.28	13.56 ± 0.56	2.66 ± 0.46	12.94 ± 1.04	2.71 ± 0.37	13.87 ± 0.71
PO$_4$–P	2.00 ± 0.18	10.18 ± 0.26	2.18 ± 0.21	10.07 ± 0.69	2.33 ± 0.18	10.58 ± 0.23
NO$_3$–N	7.05 ± 0.31	19.92 ± 0.45	6.63 ± 0.45	22.12 ± 0.87	6.36 ± 0.92	22.14 ± 1.58
NH$_4$–N	5.01 ± 0.30	19.96 ± 0.16	5.68 ± 0.19	23.33 ± 0.70	5.45 ± 0.12	21.43 ± 0.87
COD$_{Cr}$	10.78 ± 2.87	10.25 ± 3.89	11.09 ± 2.68	12.03 ± 3.53	10.95 ± 3.12	11.03 ± 5.22
pH	7.11	6.98	7.01	6.56	6.86	6.81

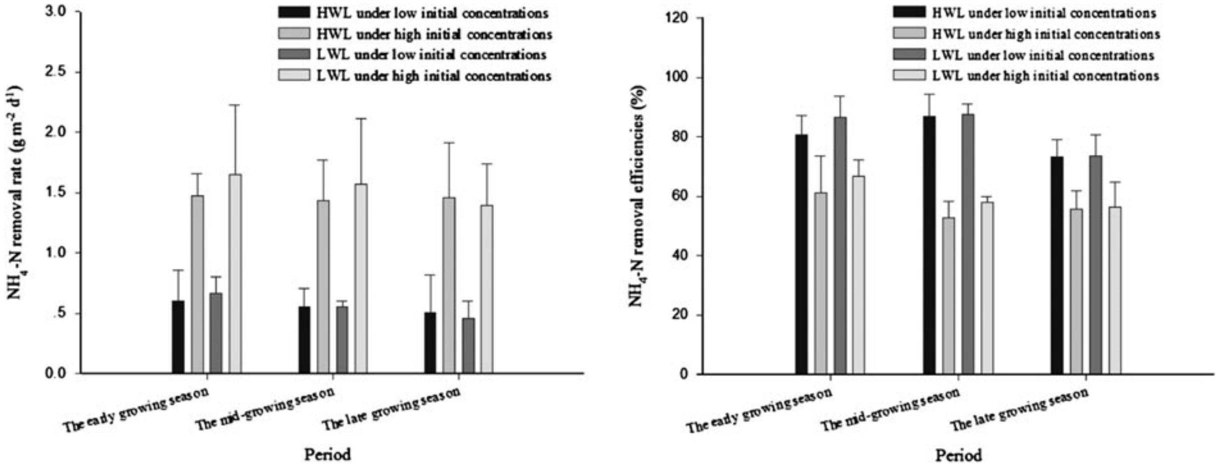

Fig. 2. Removal rates and efficiencies of NH_4–N in HWL and LWL of ditch water under different initial concentrations and different growing seasons.

concentrations, NH_4–N removal rates are significantly higher in water under high concentrations either in HWL or in LWL ($p < 0.05$). The efficiencies of NH_4–N were higher in low initial concentrations than that in high initial concentrations ($p < 0.05$). However, no differences were found on the NH_4–N removal efficiencies between HWL and LWL in low or high initial concentrations ($p > 0.05$). The rates values of NH_4–N in HWL and LWL respectively ranged from 0.49 to $0.60\,g\,m^{-2}\,d^{-1}$ and 0.44 to $0.66\,g\,m^{-2}\,d^{-1}$ in the whole growing season under low initial concentrations, and the range of their efficiency values was 71.7% to 87.0% and 71.9% to 87.6% under the same condition, respectively. The ranges of NH_4–N removal rates and efficiencies were $1.44–1.47\,g\,m^{-2}\,d^{-1}$ and $1.40–1.65\,g\,m^{-2}\,d^{-1}$, and 52.9–61.3% and 56.4–66.6% in HWL and LWL during the whole experimental period under high initial concentrations.

No significant differences were found between the NO_3–N removal rates and different water layers under the low initial concentration conditions ($p > 0.05$). In general, the rates decreased with the growing season, and the NO_3–N removal efficiencies in HWL were slightly higher than that in LWL for the early and late growing season under low initial concentrations. Under the high initial concentrations, changes in NO_3–N removal rates were smaller in three periods, and the rates were higher in HWL than that in LWL; however, the NO_3–N removal efficiencies decreased from the early growing season to the late growing season. The efficiency values were 29.7–48.9% in HWL and 33.9–51.9% in LWL. The NO_3–N removal rates were significantly higher under high initial concentrations than that under low initial concentrations ($p < 0.05$). The NO_3–N removal rates were 2.1–4.1 times in HWL and 2.1–3.1 times in LWL under low initial concentrations. However, no significant differences were found on the NO_3–N removal efficiencies between low and high initial concentrations during the same period ($p > 0.05$) (Fig. 3).

As shown in Fig. 4, PO_4–P removal rates (0.15 to $0.23\,g\,m^{-2}\,d^{-1}$ in HWL and 0.13 to $0.22\,g\,m^{-2}\,d^{-1}$ in LWL) were lower under low initial concentrations than that under high initial concentrations during the same period ($p < 0.05$). The PO_4–P removal rates under high initial concentrations were 3.3 to 4.2 times in HWL and 3.7 to 4.6 times in LWL under low initial concentrations. Under low initial concentrations, the PO_4–P removal efficiencies also decreased from the early to late growing season. The values of the efficiencies decreased from 78.3% to 52.8% in HWL and from 77.2% to 52.6% in LWL. The PO_4–P removal efficiencies were slightly higher than that under high initial concentrations. The rates and efficiencies in different water layers did not differ under high low initial concentrations ($p > 0.05$). However, water quality stratification was observed in the mid-growing season and the late growing season in high initial concentrations.

3.4. N and P concentrations in pore water

Compared with overlying water, NH_4–N concentrations of pore water were lower during the same experimental period ($p < 0.001$). Under low initial concentrations, NH_4–N concentrations of pore water slightly decreased in the early growing season. However, the NH_4–N concentrations of pore water during the mid-growing season were higher than that during the early and late growing season. A significant reduction was observed for NH_4–N concentrations in the early growing season under high initial concentrations ($p < 0.05$). NH_4–N concentrations in pore water did not

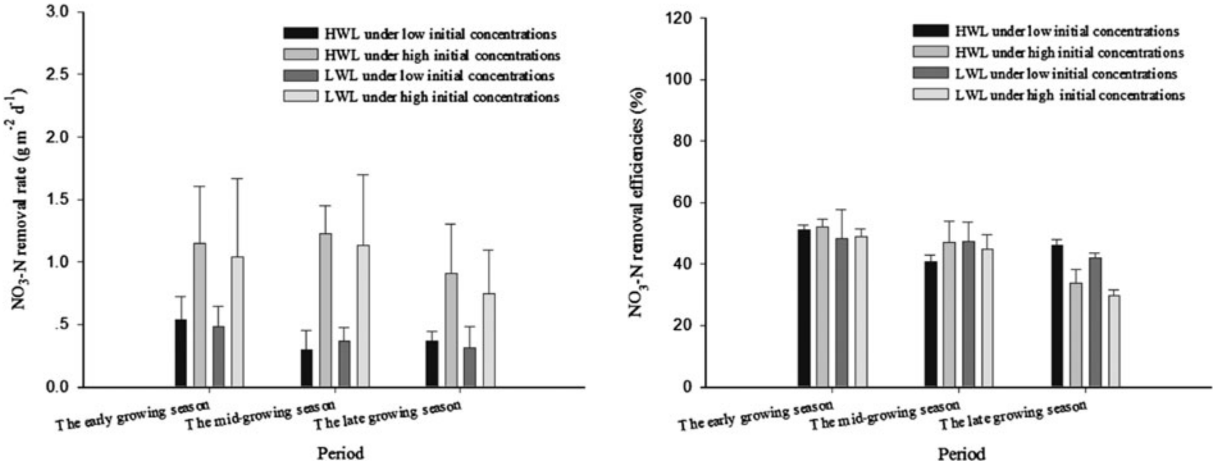

Fig. 3. Removal rates and efficiencies of NO_3–N in HWL and LWL of ditch water under different initial concentrations and different growing seasons.

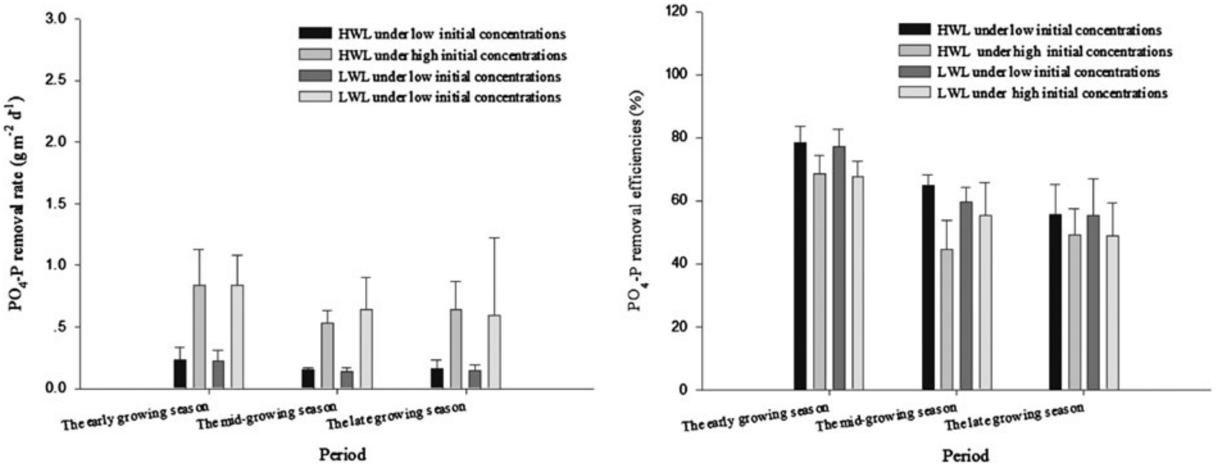

Fig. 4. Removal rates and efficiencies of PO_4–P in HWL and LWL of ditch water under different initial concentrations and different growing seasons.

show significant variations with retention time during the early and late growing season (Fig. 5).

NO_3–N concentrations in pore water are displayed in Fig. 6. NO_3–N concentrations in pore water fluctuated with retention time but had no significant variations at different growing seasons ($p > 0.05$). NO_3–N concentrations at different experimental periods did not differ either in low or high initial concentrations. Moreover, NO_3–N concentrations did not differ between low and high initial concentrations. In general, water quality of overlying water was only slightly affected by the NO_3–N concentrations of pore water. However, NO_3–N concentrations were higher than NH_4–N concentrations in pore water during the same period.

PO_4–P was consistently analyzed in pore water of drainage ditches, and was found to be generally low (less than $0.6\,\mathrm{mg\,L^{-1}}$). No significant differences were found for PO_4–P concentrations under low initial concentrations. PO_4–P concentrations slightly fluctuated in the range of 0.08–$0.23\,\mathrm{mg\,L^{-1}}$ with retention time. PO_4–P concentrations under high initial concentrations were slightly higher than that under low initial concentrations during the same period. After 48 h, PO_4–P concentrations were higher in the mid-growing season than that in the early and late growing season (Fig. 7). Compared with NH_4–N and NO_3–N concentrations, PO_4–P concentrations in pore water were lower at different growth stages.

4. Discussion

In an aqueous environment, alternative mechanisms for NH_4–N, NO_3–N and PO_4–P removal would do the following: microbial biomass immobilization, ditch sediment and soil adsorption, and plant and

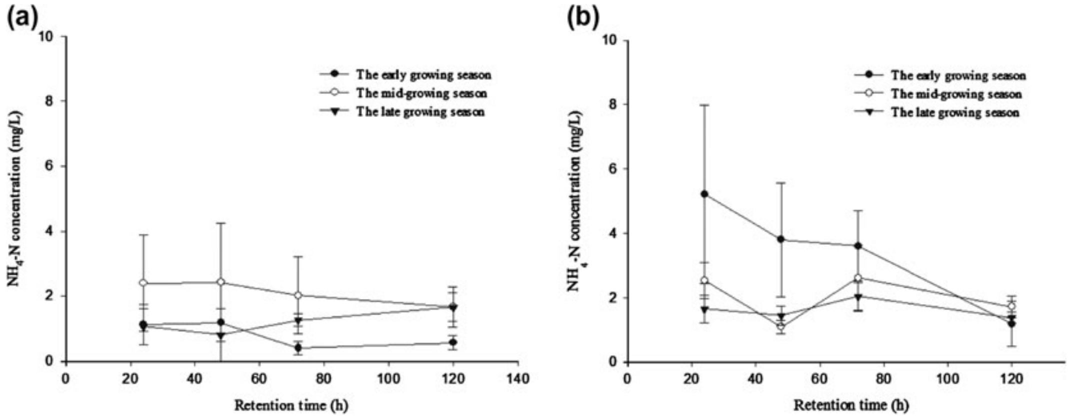

Fig. 5. NH_4–N concentrations in pore water with retention times at different growing seasons; a and b indicate under low and high initial concentrations, respectively.

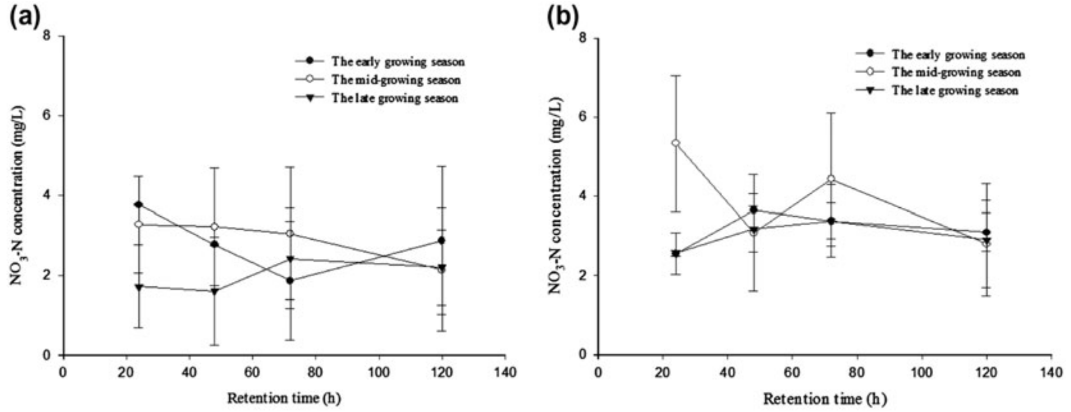

Fig. 6. NO_3–N concentrations in pore water with retention times at different growing seasons; a and b indicated under low and high initial concentrations, respectively.

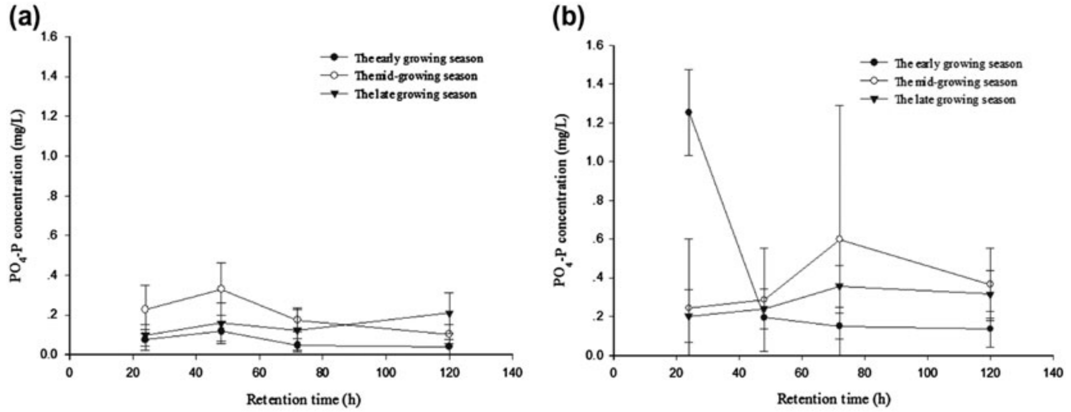

Fig. 7. PO_4–P concentrations in pore water with retention times at different growing seasons; a and b indicated under low and high initial concentrations, respectively.

algae uptake. Among these processes, the retention time of ditch water plays a key role. Increasing the retention time of ditch water is useful for microbial transformation, plant and algae uptake, sediment/soil adsorption and sedimentation processes, as well as increases chemical residence time [21–24]. All of these processes are useful for N and P removal.

4.1. Effect of ditch plants

Plants within drainage ditches can not only remove N and P by direct uptake but also strengthen the friction and roughness of ditches, reduce water velocity and suspended sediments from overlying water, as well as increase water depth, sedimentation rate, and the hydraulic retention time to provide a suitable environment for microbial growth [25,26]. NH_4–N and NO_3–N are the main forms of plant uptake [27], thus high rates of NH_4–N and NO_3–N are found in drainage ditches. However, the direct uptake of the hydrophytes from overlying water was small. Hydrophytes with large root systems absorb nutrients primarily from the sediments [28]. Overlying water in LWL is closer to ditch bottoms and sidewalls than that in HWL. NH_4–N and PO_4–P in LWL are easily adsorbed by ditch soils, plants, and microbials. As a result, NH_4–N removal rates in LWL are higher than that in HWL. This phenomenon is highlighted under high initial concentrations. Hence, the stratification of NH_4–N and PO_4–P removal rates appeared. Moreover, *P. australis* aboveground are based mainly on nitrogen metabolism in the early growing season, which is the lifetime maximum period for nitrogen- and phosphorus-absorbing plants. Dominated by carbon and nitrogen metabolism, aboveground plants still absorbed nitrogen and phosphorus in the mid-growing season; however, aboveground plants based mainly on carbon metabolism stopped growing, and nutrients were only absorbed by underground part of plants in the late growing season [29,30]. Thus, nutrient rates and efficiencies were different between three periods. Meanwhile, ditch sediments adsorbed some NH_4–N and PO_4–P during the diffusion process of N and P from overlying water to sediment pore water. As a result, a concentration gradient was formed between overlying water and pore water.

Plants within ditches can transport oxygen through their leaves and stem structures into rhizomes. The appearance of aerobic, anoxic, and anaerobic zones around plant roots enhanced ammonia oxidation into nitrite followed by further oxidation of nitrite to nitrate [31,32]. Hence, oxidation–reduction potential in LWL may be higher than that in HWL because of the oxygen functions of plant. As a result, the stratification of NH_4–H and NO_3–N was displayed in ditch water. Simultaneously, the NO_3–N removal rates in HWL were higher than that in LWL.

The rhizomes of *P. australis* absorbs cation (e.g. NH_4^+) and releases hydrogen ions (H^+) [33]. Meanwhile, carbon dioxide (CO_2) released by microbial metabolism in ditch sediments could decrease the pH of pore water. However, CO_2 diffusion from pore water and overlying water to the atmosphere could lead to increase pH value. Thus, plant and microbial activities affect the pH values of pore water (5.8–6.2). In non-alkaline aqueous environment, the precipitation reactions of PO_4–P, $Al^{3+}$and Fe^{3+} are promoted in ditch sediments [34]. Meanwhile, the wide gradients of NH_4–N, NO_3–N, and PO_4–P concentrations are formed between overlying water and sediment pore water before being promoted to downward transport. Hence, hydrophytes can promote the down diffusion of NH_4-N, NO_3–N, and PO_4–P, as well as can enhance the ditch sediment adsorption and plant uptake of N and P leading to low NH_4–N and PO_4–P concentrations in pore water. Higher NO_3–N concentrations were observed in pore water because of sediment electronegativity and the slow adsorption of plants. Furthermore, PO_4–P diffusion velocity may be faster with higher temperature and light intensity in the early growing season, resulting non-existent water-quality stratification in the period.

4.2. Effect of drying and wetting

Drying and wetting frequently took place in drainage ditches of the Sanjiang Plain. In fact, the intermittent inflow of water simulated the drying and wetting process. The drying and wetting process promotes soil aggregate stability rather than the destruction of soil aggregate structures [35]. Soil aggregate stability is beneficial for the transport of nutrients, water, and air to ditch plants [36]. Meanwhile, the swelling and shrinkage of ditch sediments easily took place under drying and wetting conditions, and affected the distribution of sediment pore space; cracking during shrinkage process accelerated the overlying water to filter down [37,38], which affected migration and transfer of N and P in overlying water and pore water. Furthermore, the diffusion of NH_4–N, NO_3–N, and PO_4–P in overlying water was enhanced into deeper sediment layers. Microbial structures and the quantity and validity of microbial substrates in ditch sediments were changed in the drying and wetting process [39–42]. Simultaneously, the release of sediment organic substrates, which provided energy for microbial activities, was accelerated in the drying and wetting process [43–46]. Dry and wet drainage ditches favor the growth of *P. australis* [47]. Under drying conditions, *P. australis* roots utilize atmospheric oxygen, enhancing root system activities. As a result, *P. australis* absorbed N and P from ditch sediments, and the good condition of sediments absorbing NH_4–N and PO_4–P was prepared. Ditch water promotes *P. australis* growth under intermittent water. However, the water demand of *P. australis* was different at different growth stages [47], affecting N and P rates and efficiencies. Air temperature was significantly different at different growth stages. Ditch water temperature also differed for three periods, leading to the possible occurrence of water quality stratification.

4.3. Initial concentration effect

The driving force of NH_4–N, NO_3–N, and PO_4–P diffusion between overlying water and pore water were enhanced by high initial concentrations [48,49]. The diffusion of NH_4–N, NO_3–N, and PO_4–P into ditch sediments and sidewall soil was also accelerated by high initial concentrations. The manners in which ditch sediment and soil absorbed NH_4–N and PO_4–P mainly included chemiadsorption and ion-exchange adsorption [48]. Higher NH_4–N and PO_4–P concentrations corresponded to higher amounts of exchangeable ammonium ions. The difference of NH_4–N and PO_4–P concentration was greater between water and ditch sediment, thus promoting the transport of NH_4–N and PO_4–P into ditch sediments and pore waters in deeper sediments and soil layers, respectively. The equilibrium adsorption capacity under low initial NH_4–N and PO_4–P concentrations was less than the sediment-saturated adsorption capacity. However, adsorption energy and adsorption sites may limit the sediment adsorption of NH_4–N and PO_4–P under high initial concentrations [50–52]. As a result, N and P efficiencies were lower in high initial concentrations than that in low initial concentrations.

5. Conclusions

These results showed that water quality stratification, nutrient removal rates, and nutrient removal efficiencies in overlying water are affected by plant growth stage, drying and wetting, and initial nutrient concentrations. NH_4–N, NO_3–N, and PO_4–P had higher removal efficiencies under low initial concentrations. However, the removal rates of NH_4–N, NO_3–N, and PO_4–P were higher under high inlet concentration. In general, nutrient rates and efficiencies were higher in the early growing season. Meanwhile, N and P concentrations in pore water were affected by nutrient concentrations in overlying water. Low permeability coefficient decreased the potential risk of ground water pollution by ditch water infiltration. Ditch plants may improve the appearance of water quality stratification and nutrient removal. Hence, retention time should appropriately be increased under high inlet concentrations; macroohytes should be implanted in drainage ditches for increasing nutrient removal, especially in the bottoms of drainage ditches. As direct conduits between farmland and downstream receiving water, drainage ditches have mitigation capacities for N and P in local agricultural management systems. Therefore, the improvement of existing drainage ditch management is perfect for rural environments as well as an important area of water quality concern.

Acknowledgments

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