Effects of Typical Plants on Nitrogen and Phosphorus Release Fluxes at Soil-Water Interface of Farmland in the Water-Level Fluctuation Zone of Danjiangkou Reservoir

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Abstract: The water-level fluctuation zone of reservoir is active in material migration and transformation. The release of nitrogen and phosphorus after soil flooding may cause eutrophication risk to reservoir water. Vegetation restoration is a common means of ecological restoration in water-level fluctuation zone of reservoirs, but there is still a lack of quantitative understanding of the inhibitory effect of vegetation on the release of nitrogen and phosphorus. Taking farmland soil in the water-level fluctuation zone of Danjiangkou Reservoir as the object, three typical plants (*Vetiveria zizanioides, Cynodon dactylon* and *Artemisia Lavandulaefolia*) were chosen to study the release of nitrogen and phosphorus in soil under waterlogging conditions and the effects of different plants on nutrient flux at the water-soil interface. The results showed that the three plants had good inhibition effect on soil nitrate release, and the average inhibition flux was 115 mg/m^2/d of *Vetiveria zizanioides*, 49 mg/m^2/d of *Artemisia Lavandulaefolia*, and 25 mg/m^2/d of *Cynodon dactylon*, respectively. The three plants had no obvious inhibition effect on the release of ammonium nitrogen and total phosphorus. The average inhibitory flux of ammonium nitrogen was 5.5 mg/m^2/d of *Vetiveria zizanioides*, 2.2 mg/m^2/d of *Cynodon dactylon* and 0.02 mg/m^2/d of *Artemisia Lavandulaefolia*. The average inhibitory flux of total phosphorus was 1.2 mg/m^2/d of *Vetiveria zizanioides*, 2.6 mg/m^2/d of *Cynodon dactylon* and 0.8 mg/m^2/d of *Artemisia Lavandulaefolia*. The results can provide reference for species selection in the ecological restoration of water-level fluctuation zone in Danjiangkou Reservoir.

1. Introduction

The water-level fluctuation zone (WFZ) of the reservoir is an active zone of material migration and transformation. When large amount of farmland or agricultural activities existing in the WFZ, the release of nitrogen and phosphorus generated after soil flooding may cause eutrophication risk to the reservoir water body[1]. Vegetation restoration is a common means of ecological restoration in the WFZ of reservoirs. Vegetation in the WFZ can play a good role in the interception of polluted runoff around the reservoir and the reduction of soil and water loss[2, 3]. However, there is still a lack of quantitative understanding on the inhibitory effect of vegetation on the release of nitrogen and phosphorus in the flooded soil in the WFZ.

Existing studies have carried out a lot of work on the inhibitory effect of aquatic plants on the release of pollutants from river and lake sediments[4, 5]. The growth of aquatic plants can absorb nutrients from water and sediment and reduce nitrogen and phosphorus concentration; Meanwhile, aquatic plants affect the process and flux of nitrogen and phosphorus release by changing the physicochemical environment at the water-sediment interface[6]. In addition, factors such as aquatic plant type and community structure can affect the removal efficiency of nitrogen and phosphorus[7]. However, soil properties are quite different from those of river and lake sediments. The water content of sediment of rivers and lakes is very high, generally between 83% and 95%, while the water content of soil is relatively low[8]. The sediment is dominated by fine particles with a particle size of less than 10 μm. However, there are many large particles in soil, and the particle size is generally greater than 100 μm[9]. In addition, the sediment has a longer mineralization time and the organic matter content is generally lower than that of soil. All of these may lead to the significant difference of plants growth environment and nutrients release processes between the submerged soil and the bottom mud of rivers and lakes. For example, high organic matter content tends to lead to an anaerobic environment, resulting in increased release of ammonium nitrogen and greater difficulty for plant roots to obtain oxygen[10]. At present, there are few studies on vegetation restoration of submerged soil, and the knowledge for nutrients release inhibitory ability of plants is also limited. Therefore, it is very necessary to study the effects of typical plants on nitrogen and phosphorus release fluxes at the soil-water interface.

In this study, three typical plants, *Vetiveria zizanioides*, *Cynodon Dactylon* and *Artemisia lavandulaefolia*, were selected from Danjiangkou Reservoir, the water source of the South-to-North Water Diversion Middle Route Project (SNWDMRP), to carry out the experiment. The release of nitrogen and phosphorus from the submerged soil and the effects of different plants on nutrient flux at water-soil interface were studied. The study was intend to provide reference for species selection and ecological restoration in the WFZ of Danjiangkou Reservoir,

2. Materials and Methods

2.1. Study Area

Danjiangkou Reservoir is the water source of SNWDMRP (Figure 1). The dam of Danjiangkou Reservoir was raised from 162 m to 176.6 m in 2013, and the normal storage water level was increased from 157 m to 170 m. The flood area covered Danjiangkou City, Yunxian County of Hubei Province and Xichuan county of Henan Province. In Xichuan County, Henan Province, the WFZ has a gentle terrain, extensive farmland distribution, low vegetation coverage and large bare soil. Due to the influence of fertilizer application and crop residues, farmland soil has a higher nutrient storage, and the submerged farmland soil will face a greater risk of nutrient release.

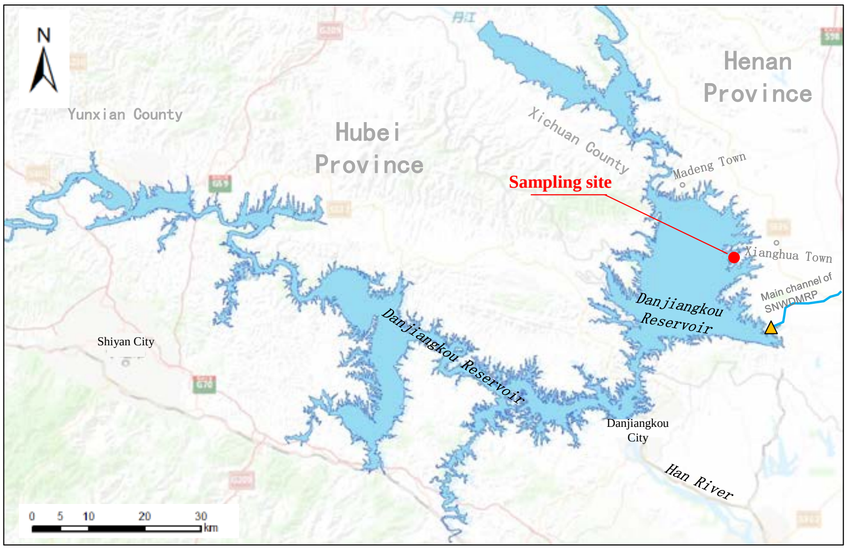

Figure 1: Location of the soil sampling site.

2.2. Experiment Plants and Soil

Vetiveria zizanioides is a perennial grass plant of gramineae, which has been used in landslide control[11] and heavy metal pollution remediation[12, 13]. *Vetiveria zizanioides* has developed roots, large aboveground biomass, and strong inundation and drought tolerance. *Vetiveria* *zizanioides* is suitable for soil growth in submerged farmland near the reservoir. *Cynodon dactylon* and *Artemisia lavandulaefolia* are common species in the reservoir banks of Danjiangkou Reservoir. As the dominant species in land greening and soil and water conservation, *Cynodon dactylon* has been widely used in various ecological restoration projects[14]. The plants used in the experiment were collected from the *Vetiveria zizanioides* planting base in Madeng Town of Xichuan County, which is located in the WFZ of Danjiangkou Reservoir. Meanwhile, wild *Artemisia lavandulaefolia* and *Cynodon dactylon* also grow a lot in this area, which is suitable for collection. In the process of plant collection, a small amount of soil root was retained. The biomass of *Vetiveria zizanioides* was large, so appropriate pruning could reduce water loss.

The farmland soil used in the experiment was collected from the WFZ of Xianghua Town. Xianghua Town is the township with the largest submerged area in Danjiangkou Reservoir area. The farmland in the submerged area is widely distributed, and wheat, corn and other cash crops have been planted for a long time. In the process of soil collection, typical farmland plots in the WFZ with an elevation of 160~170 m were selected to remove the surface vegetation and plant residues, and the soil within 15 cm of the surface was collected and put into a woven bag with a collection volume of about 0.5 m^3. The surface soil collected from the field and the plants were transported back to the laboratory together. The soil was filled in the experimental device and the plants were planted in the same day.

2.3. Experiment Design

The experiment was carried out in the laboratory, and the device used was a homemade plexiglass experimental tank. The size of the experimental tank was 150cm×40cm×40 cm, and the lower end was provided with a bracket and a water outlet with a valve (Figure.2). Soil was filled in the tank and plants were planted. The soil inundation was simulated through the flooding the experimental tank.

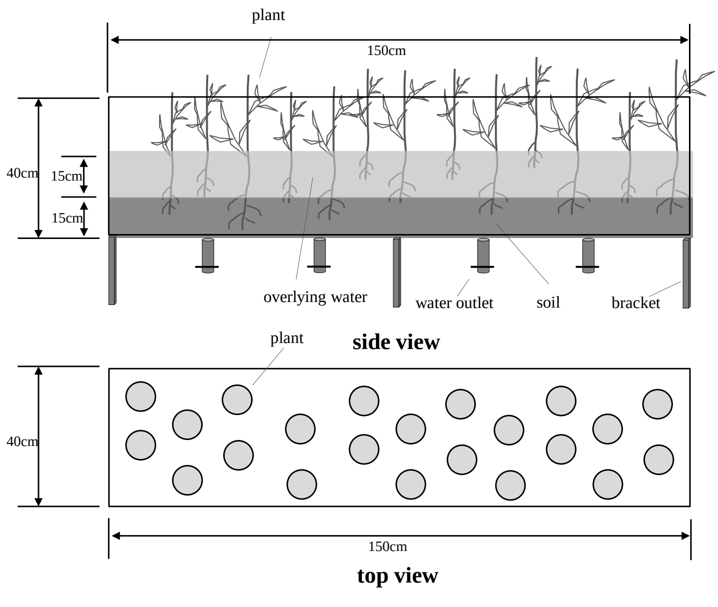

Figure 2: Experimental tank structure.

Four tanks were set up in the experiment. Each tank was filled with farmland soil with a thickness of about 15 cm. The contents of total nitrogen and total phosphorus in the soil of each experimental group were shown in Table 1. No plants were planted in tank 1, which was set as a control. *Vetiveria zizanioides* was planted in tank 2. As *Vetiveria zizanioides* collected in the field was fasciculated, it was separated in the laboratory transplantation process to form smaller plants containing 1 or 2 tillers with a height between 50 cm and 75 cm. Tank 3 planted *Artemisia lavandulaefolia*, plant height between 15 cm and 25 cm, evenly distributed in the experimental tank. Tank 4 was used to plant *Cynodon dactylon*, which were mainly stolons with a length of about 25 cm. In order to ensure the balance of planting density among the experimental tanks, the individual plant biomass scale and actual field growth density were taken into account and the number of *Vetiveria zizanioides*, *Cynodon dactylon* and *Artemisia Lavandulaefolia* transplants was set at 20, 24 and 50. All plants were evenly planted in the experimental tank. From the beginning of August 2015 to the beginning of October 2015, the plants under test were cultured. During the day, external sunlight was isolated and light was used to ensure consistent lighting conditions. At night, the light was turned off to maintain natural darkness. The light time is 7:00~18:00 every day, a total of 11 hours. The four experimental tanks were watered once every three days, and each experiment tank was watered about 5 L. After two months of culture, 19 *Vetiveria zizanioides* plants survived, with a survival rate of 95%. The survival rate of *Cynodon dactylon* and *Artemisia lavandulaefolia* were both 100%.

Table 1 Total nitrogen and total phosphorus contents in soil of each experimental tank.

Experimental tanks	**TN (g/kg)**
Vetiveria zizanioides	1.25
Cynodon dactylon	0.98
Artemisia Lavandulaefolia	1.28
Control	0.72

One day before the start of the flooding experiment, open the water outlet and drain the original water in the experiment tank. On October 7, the experimental tank was flooded to a depth of about 15 cm above the soil surface. Considering the good water quality of Danjiangkou Reservoir, distilled water was used as the experimental inundation water, and the total water consumption of each experimental tank was about 120 L. The flooding experiment was conducted from October 8, 2015 to November 4, 2015. After the start of the flooding experiment, the overlying water was sampled every two days with a volume of 250 mL, and the determination items included nitrate nitrogen, ammonium nitrogen and total phosphorus. Nitrate nitrogen was determined by ultraviolet spectrophotometry. Ammonium nitrogen was determined by Spectrophotometry with Nalkenes reagent. The total phosphorus was determined by potassium persulfate oxidation and molybdenum antimony resistance spectrophotometry. During the experiment, *Vetiveria zizanioides* grew well all the time, a large number of *Artemisia lavandulaefolia* died in the late experiment (after October 26), and part of the *Cynodon dactylon* died in the late experiment.

2.4. Nitrogen and Phosphorus Release Flux and Inhibition Effect Calculation

In order to compare the inhibitory effects of different plants on the release of soil nutrients, the differential method was used to calculate the changes of nutrients. Differential calculation is an effective means of processing time series data[15], which can deduct the impact of nutrient concentration differences between experimental tanks. The effects of soil itself on nutrient release were compared between the plant planting group and the control group. Inhibition flux was used to represent the effect of plants on the release of soil nutrients, and inhibition flux was calculated according to formulas (1) to (3) :

$$F_{i\ inhibition} = \left(\Delta_{iplant} - \Delta_{icontrol}\right) \times V\ /\ S\ /\ T \tag{1}$$

$$\Delta_{iplant} = C_{iplant} - C_{i-1plant} \tag{2}$$

$$\Delta_{icontrol} = C_{icontrol} - C_{i-1control} \tag{3}$$

Where, $F_{i\ inhibition}$ is the inhibitory flux between sampling *i* and *i*-1 (minus sign means the plant inhibits the soil nutrient release, plus sign means the plant promotes the soil nutrient release), $mg/m^2/d$; V is overlying water volume, V=150cm×40cm×15cm=90L; S is the release area, $S=150cm\times40cm=0.6m^2$; T is the interval between two samples, T=2d; $\Delta_{i\ plant}$ is the change of nutrient concentration of water in the planted tanks between sampling *i* and *i*-1, mg/L; $C_{i\ plant}$ is the nutrient concentration of water in the planted tanks of sampling *i*, mg/L; $C_{i-1\ plant}$ is the nutrient concentration of water in the planted tanks of sampling *i-1*, mg/L. $\Delta_{i\ plant}$ is the change of nutrient concentration of water in the controlled tanks between sampling *i* and *i*-1, mg/L; $C_{i\ control}$ is the nutrient concentration of water in the controlled tank of sampling *i*, mg/L; $C_{i-1\ control}$ is the nutrient concentration of water in the controlled tank of sampling *i*-1, mg/L.

3. Results

3.1. Inhibition of Nitrate Nitrogen Release by Three Plants

The variation of nitrate nitrogen content in overlying water was shown in Figure 3. The initial concentration of nitrate nitrogen in each experimental tank showed great difference, among which the initial concentration of *Vetiveria zizanioides* tank was more than 8 mg/L, the initial concentration of *Cynodon dactylon* and *Artemisia Lavandulaefolia* tank was about 3 mg/L and 1 mg/L, respectively, while the initial concentration of the control tank was about 3 mg/L. The concentration of nitrate nitrogen in overlying water of *Vetiveria zizanioides*, *Cynodon dactylon* and *Artemisia Lavandulaefolia* tanks decreased significantly with the flooding experiment. The nitrate nitrogen in *Cynodon dactylon* tank was lower than 0.05 mg/L after 4 days of flooding (October 10). In the *Artemisia Lavandulaefolia* tank, it decreased to less than 0.05 mg/L after 10 days of inundation (October 18). In *Artemisia Lavandulaefolia* tank, nitrate increased slightly on the second day of inundation (October 10), but then decreased rapidly, and decreased to less than 0.05 mg/L on October 18 after 10 days of inundation. The change of nitrate in the control tank showed a small wavy change. Nitrate concentration increased slightly in the early stage of inundation, and increased from 3.2 mg/L to 4 mg/L on the 6th day of inundation (October 14). Then it slowly decreased to 3.4 mg/L on the 22nd day of inundation (October 30), and then began to rise again. From the analysis of nitrate inhibition flux of plants, *Vetiveria zizanioides* had the most obvious inhibition effect with an average inhibition amount of 115 mg/m^2/d, followed by *Artemisia Lavandulaefolia* with an average inhibition amount of 49 mg/m^2/d, and *Cynodon dactylon* had the weakest inhibition effect with an average inhibition amount of 25 mg/m^2/d.

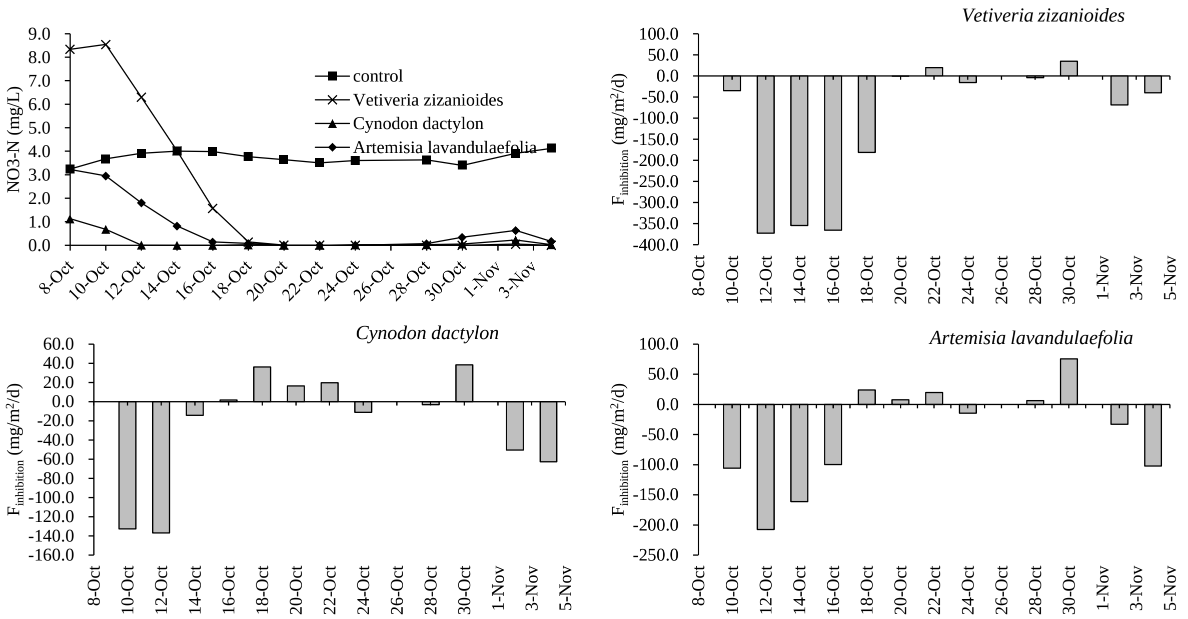

Figure 3: Effects of the plants on nitrate release flux.

3.2. Inhibitory Effect of Three Plants on Ammonium Nitrogen Release

The inhibitory effect of the three plants on the release of ammonium nitrogen was shown in Figure 4. The initial concentration of the three planted tanks were higher than that of the blank tank, and *Vetiveria zizanioides* tank was the highest (1.8 mg/L), followed by *Cynodon dactylon* tank (1.5 mg/L) and *Artemisia Lavandulaefolia* tank (1.4 mg/L). The control tank had the lowest initial concentration less than 1.3 mg/L. The ammonium nitrogen in each experimental tank showed a general downward trend, with an obvious fluctuation process. At the initial stage of flooding (from October 8 to October 16), the ammonium nitrogen in each experimental tank reached the first peak, with the highest value at about 2.1 mg/L. *Vetiveria zizanioides* tank reached the maximum value on the second day of flooding, and *Cynodon dactylon*, *Artemisia Lavandulaefolia* and control tank all reached the maximum value on the fourth day of flooding. In the middle stage of flooding (from

October 16 to October 24), the peak value of ammonium nitrogen in each experimental tank was 1.55 mg/L, and the peak value was higher in *Artemisia Lavandulaefolia* and *Cynodon dactylon* tank than that in *Vetiveria zizanioides* and control tank. At the late stage of flooding (From October 26 to November 4), the variation trend of ammonium nitrogen in each experimental tank was different. The *Cynodon dactylon* and *Artemisia Lavandulaefolia* showed peak values, while the *Vetiveria zizanioides* and control tank showed a decreasing trend. In general, the three plants did not show a sustained inhibitory effect on the release of ammonium nitrogen in soil. The average inhibitory amount of *Vetiveria zizanioides*, *Cynodon dactylon* and *Artemisia Lavandulaefolia* was 5.5 mg/m^2/d, 2.2 mg/m^2/d and 0.02 mg/m^2/d, respectively. The three plants even promoted the release of ammonium nitrogen in the initial stage of inundation. Although the inhibition effect of *Vetiveria zizanioides* appeared in the early stage, it gradually weakened in the middle and late period of submersion. The inhibitory effect of *Cynodon dactylon* and *Artemisia Lavandulaefolia* on the release of ammonium nitrogen was unstable, and the inhibitory amount fluctuated obviously.

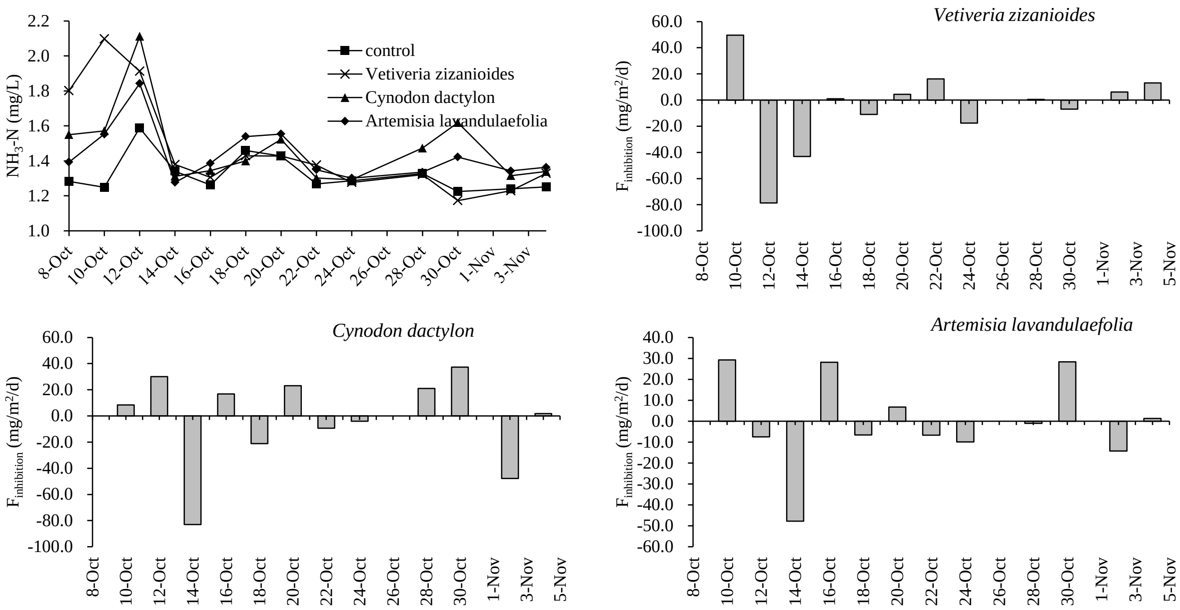

Figure 4: Effects of the plants on ammonium nitrogen release flux.

3.3. Inhibitory Effect of Three Plants on Total Phosphorus Release

Figure 5 showed that the initial concentration of total phosphorus in the *Cynodon dactylon* tank was over 0.3 mg/L, which was significantly higher than that in other tanks. The initial concentration of total phosphorus in *Vetiveria zizanioides*, *Artemisia Lavandulaefolia* and the control tank was about 0.1 mg/L. During the flooding, the total phosphorus in overlying water of each experimental tank increased first and then decreased, and the total phosphorus in *Cynodon dactylon* tank was always higher than that in the other experimental tanks. The maximum value was reached in each experimental tank after 6-10 days of flooding, of which the highest value was 0.65 mg/L in the *Cynodon dactylon* tank and about 0.3 mg/L in the other experimental tanks. The total phosphorus decreased rapidly after reaching the peak values, and decreased gradually with the extension of waterlogging time. The inhibition of total phosphorus release by the three plants fluctuated frequently, and the average inhibition was below 3 mg/m^2/d, indicating that the inhibition effect of the three plants on soil total phosphorus release was not obvious.

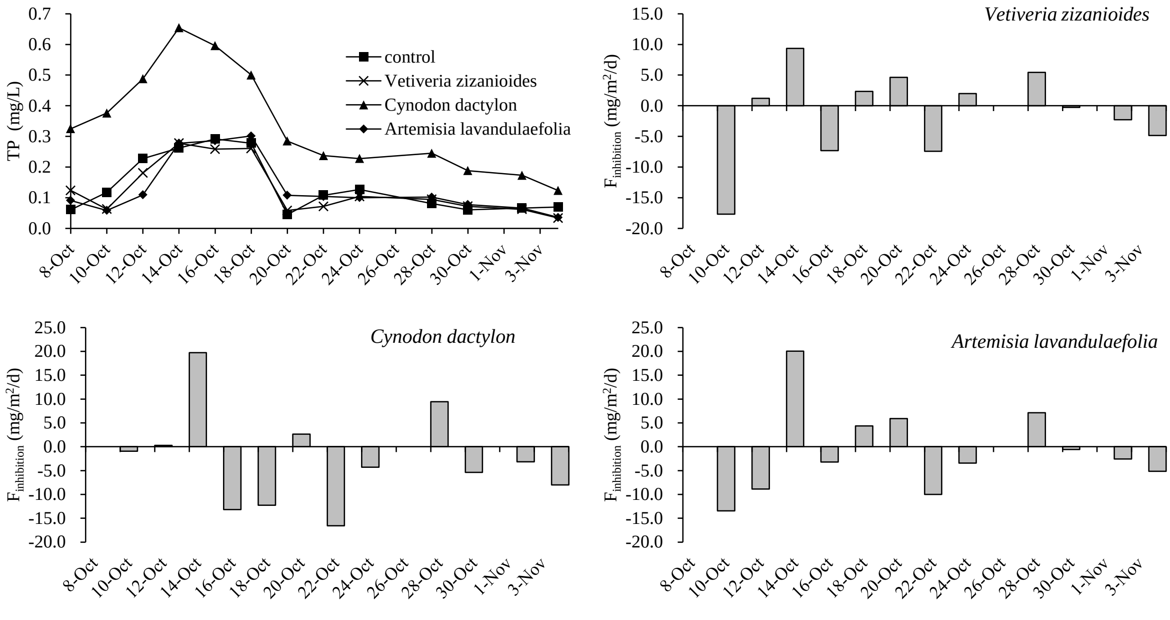

Figure 5: Effects of the plants on total phosphorus release flux.

4. Discussion

The results showed that during flooding, the plants had significant inhibitory effect on the release of nitrate nitrogen in soil, and *Vetiveria zizanioides* had the strongest inhibition effect, followed by *Artemisia Lavandulaefolia* and *Cynodon dactylon*. The inhibition effect on the release of ammonium nitrogen and total phosphorus was not obvious. Studies have shown that the effects of plant roots can alter the soil physicochemical environment and soil microorganisms, which may change the migration and transformation process of soil nitrogen and phosphorus[16]. For example, plant roots can increase the dissolved oxygen in soil and improve nitrification rate, thus inhibiting the release of ammonium nitrogen[10]. Organic matter secreted by plant rhizosphere can promote denitrification, thus reducing nitrate nitrogen release[17]. The formation of humus from plant residues can change the adsorption capacity of soil particles and affect the migration and release process of nitrogen and phosphorus[18].

4.1. Effects of Plants on Initial Concentration of Nitrogen and Phosphorus

The difference of initial nutrient concentration between planted tanks and the contronl tank may be caused by the nitrification, ammonification and physical adsorption by plant roots before waterlogging. *Vetiveria zizanioides* has developed root system and strong capacity withstanding water flooding. The root aerenchyma of *Vetiveria zizanioides* can produce strong oxygen-secreting effect[18, 19], and improve the partial pressure of oxygen in the rhizosphere. The increase of oxygen can improve the nitrification rate[10], resulting in more nitrate nitrogen accumulation and higher initial concentration of nitrate nitrogen. However, *Cynodon dactylon* is not a typical hygrophytic plant, the size of root aerated tissue is small, and the oxygen consumed by the exudates and organic residues in the rhizosphere is far more than the oxygen secreted by the root, which inhibits the nitrification process. Therefore, the initial nitrate concentration of *Cynodon dactylon* was lower than that of the control tank.

The mechanism plant roots affecting the initial concentration of ammonium nitrogen may be more complicated than that of nitrate nitrogen. Besides nitrification, plant roots can also promote soil ammonification process[20, 21] and strengthen the adsorption of ammonium nitrogen by soil particles. Acording to the experimental results, the promotion effect of plant roots to ammonium nitrogen release (including improve ammonification rate and reduce the soil adsorption) may be significant, leading to higher ammonium nitrogen in planted tanks than that in control tank. *Vetiveria zizanioides* has a larger root structure than other plants, which may change the ammoniation process and soil adsorption more dramatically, so the initial ammonium nitrogen concentration is the highest.

The initial concentration of phosphorus was affected by soil redox conditions. Under reduction conditions, Fe^{3+} was converted to Fe^{2+}. The insoluble phosphate bound with iron was dissolved, and some phosphorus combined with iron was released. In this study, the ventilation capacity of *Cynodon dactylon* was the weakest, and the oxygen consumption of rhizosphere itself might cause the soil to be in reductive condition, resulting in the amount of accumulated active phosphorus significantly higher than that of other planted tanks.

4.2. Effects of Plants on Nitrogen and Phosphorus Release

During the flooding, plant roots play an important driving role in the change of nitrate nitrogen. As the diffuse of dissolved oxygen decreased, and the oxygen consumption increased, the soil in each experimental tank gradually changed to the reduction state. Therefore, the rhizosphere denitrification may be the main driving force for the decline of nitrate nitrogen. The denitrifying bacteria in the rhizosphere was more active than other regions because the plant root exudates and residues can provide sufficient carbon source supply[17]. Denitrification occurred in the rhizosphere of the three plants, so nitrate nitrogen decreased significantly. *Vetiveria zizanioides* had the most developed root system. Therefore, the decrease rate of nitrate nitrogen in *Vetiveria zizanioides* tank was the fastest. In the control tank, nitrate nitrogen remained at a high level all the time, probably because the soil lacked plant roots and could not provide sufficient supply of organic matter, which limited the denitrification precess and the consuming of nitrate nitrogen.

The fluctuation of ammonium nitrogen may be the result of the organic nitrogen decomposition. Organic nitrogen in soil can be roughly divided into two types: easy to degrade and difficult to degrade. In the early stage of flooding, the easily degradable organic nitrogen in soil rapidly ammoniated, and the concentration of ammonium nitrogen in water increased rapidly. With the extension of waterlogging time, part of the refractory organic nitrogen began to ammoniate decomposition, and ammonia nitrogen appeared a second peak. In the late period of flooding, a large number of *Artemisia Lavandulaefolia* and *Cynodon dactylon* died, and the organic residues enhanced ammoniation. Therefore, there was a third peak of ammonia nitrogen in the planted tanks of *Artemisia Lavandulaefolia* and *Cynodon dactylon*, but not in the control tank and *Vetiveria zizanioides*.

The plant effect on phosphorus concentration was not significant, and the soil adsorption process might be the dominant factor. Under the condition of flooding, the soil reducibility was enhanced. The minerals containing ferric iron may be dissolved under the reduced condition and the phosphorus absorbed and stored by ferric hydroxide was released. Therefore, the total phosphorus concentration of each experimental tank showed an increasing trend in the early stage of flooding. Long-term flooding may lead to an increase in pH. When the pH exceeded 7, ferrous iron and ferric iron can combine to form amorphous Fe^{3+}-Fe^{2+} mixed hydroxide with larger surface area and more phosphorus adsorption sites than iron hydroxide, which can enhance the soil ability to absorb phosphorus. Therefore, the phosphorus concentration of each experimental tank decreased in the late period of flooding.

5. Conclusion

In this paper, the inhibition effect of nitrogen and phosphorus release of three kinds of plants was experimentally studied, and the nitrogen and phosphorus release fluxes of soil in water-fluctuation zone planted with different plants were calculated. The three plants showed significant inhibition effect on the release of nitrate in soil. The inhibition flux of *Vetiveria zizanioides* was the largest (average 115 $mg/m^2/d$), followed by *Artemisia Lavandulaefolia* (average 49 $mg/m^2/d$) and *Cynodon dactylon* (average 25 $mg/m^2/d$). However, the three plants showed no significant effect on the release of ammonium nitrogen and phosphorus. The average ammonium nitrogen release inhibition flux of *Vetiveria zizanioides*, *Cynodon dactylon* and *Artemisia Lavandulaefolia* was only 5.5 $mg/m^2/d$, 2.2 $mg/m^2/d$ and 0.02 $mg/m^2/d$ respectively. The average phosphorus release inhibition flux was less than 3 mg/m^2/d for the three plants. What is obtained in this study is the released flux under experimental conditions, which may be different from the actual released flux under field conditions. The next step is to optimize the setting of test conditions and strengthen the field monitoring study, so as to provide a more accurate basis for the comparison of plant inhibition effect.

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