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Effects of vegetation on ammonium removal and nitrous oxide emissions from pilot-scale drainage ditches

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ABSTRACT

Recently, vegetated drainage ditches have been used as one of the best management practices for controlling the transport of agricultural pollutants. In this study, a pilot-scale field experiment within a 135-km^2 agricultural catchment was conducted to investigate the effectiveness of ditches vegetated with *Pontederia cordata* (Pontederia) and *Myriophyllum elatinoides* (Myriophyllum) and ditches without vegetation (Control) on ammonium (NH_4^+-N) removal and nitrous oxide (N_2O) emissions. Compared to the control treatment, the ditches with both plant species (*P. cordata* and *M. elatinoides*) increased NH_4^+-N removal rates by 50.8% and 71.4% and decreased N_2O emissions by 68.3% and 70.4% for NH_4^+-N loadings of 25 mg L^{-1} and 70 mg L^{-1}, respectively. The linear mixed-effect model revealed that effluent NH_4^+-N concentrations were significantly decreased by 2.54% and 2.10% for each increase of one unit on sediment NH_4^+-N sorption and plant TN accumulations ($p < 0.0001$). The dominant NH_4^+-N removal pathways in Myriophyllum ditch were plant uptake and microbial nitrification-denitrification. However, in Pontederia and control ditches, NH_4^+-N was mainly removed by sediment sorption. These findings may suggest that vegetated drainage ditches (e.g., *M. elatinoides*) are capable of removing NH_4^+-N from agricultural runoff and can additionally reduce N_2O emissions.

1. Introduction

China is one of the world's major rice producers, and rice cultivation consumes large quantities of N fertilizers. Ammonium (NH_4^+-N) is the dominant form of N in the flooded rice paddies and it can flow into the drainage ditches across the rice fields due to midseason drainage or rainfall runoff events. To effectively control N diffusion from agricultural regions, alternative ditch management strategies, e.g., riparian buffer vegetation, vegetated drainage ditches, flow control structures, sediment traps, and stream-bed denitrifying bioreactors, are typically implemented to decrease nutrient transport from various agricultural sources into downstream watersheds (Evans et al., 2007; Kröger et al., 2007; Elgood et al., 2010). Compared with other ditch alternatives, plant vegetation in drainage ditches is an easier practice for controlling agricultural non-point source pollution in rural areas. Previous studies have demonstrated that vegetated drainage ditches represent one of the best management practices (BMPs) (Madsen et al., 2001; Cooper et al., 2004; Bennett et al., 2005; Sharpley et al., 2007; Vallée et al., 2014).

In vegetated drainage ditches, the primary processes that contribute to NH_4^+-N removal from water include plant uptake, sediment sorption, and microbial nitrification and denitrification (Vymazal, 2007; Lu et al., 2009). During the NH_4^+-N removal process, only microbial nitrification-denitrification can result in a permanent removal of N by converting NH_4^+-N into gaseous products, e.g., nitrous oxide (N_2O) and nitrogen (N_2). However, N_2O is an undesirable greenhouse gas (Mosier et al., 1998; Park et al., 2000; Tallec et al., 2008). Moreover, it has also been reported that N_2O fluxes from agricultural drainage ditches are important in the total N_2O emissions at the agricultural landscape scale (Strock et al., 2007). Until recently, effective control measures for N_2O emissions have been scarcely established in agricultural drainage ditches, and only a few studies examined N_2O emissions in common drainage ditches (Reay et al., 2004). *Pontederia cordata* and *Myriophyllum*

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elatinoides are perennial emergent and floating plants that grow fast in shallow wetlands, especially in nutrient-rich water (Wang et al., 2014). These may contribute to NH_4^+-N removal and affect N_2O emissions in drainage ditches.

In this study, *P. cordata* and *M. elatinoides* were planted in pilot-scale-size ditches; the effectiveness of plant vegetation on NH_4^+-N removal and N_2O emissions was investigated under two NH_4^+-N loadings. It was hypothesized that plant vegetation in ditch systems can improve NH_4^+-N removal efficiencies and reduce N_2O emissions, compared to the non-vegetated ditch. The objective for this study was to test the hypothesis within the range of these data.

2. Materials and methods

2.1. Description of the study site

The experiment was conducted at the Changsha Research Station for Agricultural & Environmental Monitoring, Jinjing catchment, Changsha, Hunan Province, China (28°32′N, 113°19′E). The catchment is characterized by a subtropical monsoon climate. The annual air temperature ranges from 16.5 to 20.5 °C, with a mean value of 17.5 °C. The annual precipitation is between 1015–1660 mm (mean 1330 mm), with 50–60% of precipitation concentrated in March and April. The catchment has an area of 135 km^2, it is located in a typical agricultural region in subtropical central China. The main land-use types include tea fields, rice fields, and forests, which account for 2.4%, 26.5%, and 65.5% of the total catchment area, respectively. Approximately 460 kg N ha^{-1} year^{-1} of N fertilizers are typically applied in local agricultural systems. The soil in the catchment is a loam clay Ultisol (USDA soil taxonomy), which was developed from granite parental material.

2.2. Construction of the simulated drainage ditches

The simulated drainage ditch systems were constructed in 2011. The system contained a water tank, water flow meters, flumes, and 20 ditches. The water tank (100 m^3) was used as a water source for the simulated experiment and supplied clean water from a nearby reservoir. The physicochemical characteristics of the clean water were: 0.2 mg L^{-1} NH_4^+-N, 0.4 mg L^{-1} NO_3^--N, 0.8 mg L^{-1} TN, 0.03 mg L^{-1} TP, and a pH value of 7.2. The water tank was connected to 20 stainless steel flumes through a set of polyvinyl chloride (PVC) pipes to deliver water into the simulated drainage ditches. The flume was 2.0 m long, 0.1 m wide, and 0.1 m deep and was installed in the water inlet of each ditch. Additionally, a water-regulating valve and a water meter (LXS-E-095-DN25, Amico, Shanghai, China) with a 0.1-L measurement accuracy were placed in front of each flume to adjust the current velocity. A wave-shaped configuration on the effluent side of each flume was used to provide well-distributed water inflow to the ditches. The 20 ditches, which were 16.0 m long, 2.0 m wide, and 0.55 m deep (Fig. 1), were constructed in a rice field and separated by stainless steel plates. 3840 kg of paddy soil was added to each ditch to produce a substrate layer of approximately 20 cm in depth. Throughout the experiment, water depth was maintained at 15 cm by two L-shaped discharge tubes. The discharge tubes were installed at the outlet of each ditch to collect the effluents. Additionally, during the experiment, the effluents from the simulated drainage ditches were continuously discharged into the adjacent wetlands for further purification.

2.3. Experimental operation

To eliminate edge effects, 18 ditches in the middle of the ditch system were used to conduct the experiments. In early March 2013, *P. cordata* and *M. elatinoides* with a uniform shoot height of 0.2 m were collected from a local wetland, which were respectively planted in 6 ditch cells with plant cover density of 36 plants m^{-2} (1152 plants per ditch cell). After plant vegetation, they grew in clean water for 5 weeks. In the middle of May, the biomass of *P. cordata* and *M. elatinoides* had developed into 4800 g fresh weight per m^{-2} and 4300 g fresh weight per m^{-2}, respectively. To compare the vegetated treatments (Pontederia: ditches vegetated with *P. cordata*; Myriophyllum: ditches vegetated with *M. elatinoides*), the non-vegetated treatment (Control: non-vegetated ditches) was used in the remaining 6 ditches. All of the ditches for the three treatments were randomly arranged.

The five years' monitoring data suggested that the base flow rate of natural drainage ditches ranged from 3.3 to 8.8 m^3 d^{-1}. Therefore, the flow rate was set to 4.5 m^3 d^{-1} in the simulated drainage ditches. Ammonium sulfate (95% purity, Wugang, Wuhan, China) was used to provide NH_4^+-N in this study. Artificial wastewater was prepared as follows. Clean water was pumped into the water tank via two submersible pumps (QDX10-14-0.75, Langqi, Shanghai, China), and then $(NH_4)_2SO_4$ was added to the water and mixed in the water tank. In the study, the experiments were conducted twice on sunny and cloudy days from May 12 to June 28, 2013. In the first experiment, artificial wastewater containing 25 mg L^{-1} NH_4^+-N was transported to Pontederia, Myriophyllum, and control ditches from May 12 to 21. Then an NH_4^+-N loading of 70 mg L^{-1} was used in the same way as the NH_4^+-N loading of 25 mg L^{-1} from May 22 to June 2. When the effluent for each ditch was stable, five days were selected to test each NH_4^+-N loading with simultaneous water, sediment, plant and gas sampling and analysis. To verify the experimental results, each NH_4^+-N loading test was repeated again from June 3 to 28.

2.4. Water, plant, and sediment sampling and analysis

Water samples were collected on days 1, 3, and 5 from the sampling sites located at 0, 2, 4, 8, 12, and 16 m in each ditch. The water samples were immediately returned to the laboratory for analysis within 24 h. NH_4^+-N and NO_3^--N were filtered through 0.45-μm membranes; the concentrations were measured using an automatic flow injection analyzer (Fia-star 5000, Foss Tecator, Sweden). TN was measured using the alkaline potassium persulfate oxidation method, with oxidized NO_3^--N also analyzed via the flow injection analyzer. The water pH was determined in situ using a portable multi-parameter meter (SG68-ELK-ISM, Mettler-Toledo, Switzerland).

On days 1, 3, and 5, *P. cordata* and *M. elatinoides* were sampled from the simulated ditches. The fresh biomass of all plant samples was first weighed. Then the plant tissues were dried at 105 °C for 30 min and oven-dried at 70 °C until constant weight was obtained. The dried plant tissues were ground into power and filtered using a 1 mm sieve. After digestion in a H_2SO_4- H_2O_2 solution, the TN contents in plant tissues were measured via the automatic flow injection analyzer (Fia-star 5000, Foss Tecator, Sweden).

Three replicate sediment samples of each treatment were obtained from the top 0–10 cm of sediment. The sediment water content was gravimetrically measured by drying the fresh sediment at 105 °C for 48 h. NH_4^+-N and NO_3^--N in the sediment samples were extracted using 2 M KCl solution. The suspensions were first filtered with qualitative filter papers and subsequently used to analyze the NH_4^+-N and NO_3^--N contents using an automatic flow injection analyzer (Fia-star 5000, Foss Tecator, Sweden). Sediment TN content was determined using the semi-micro Kjeldahl digestion method, and transformed NH_4^+-N was measured via the automatic flow injection system. The sediment organic carbon (SOC) was measured using the dichromate oxidation method. The sediment pH was determined using a pH meter in suspension with a 2.5:1 mass ratio of distilled water to sediment.