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Agricultural non-point nitrogen pollution control function of different vegetation types in riparian wetlands: A case study in the Yellow River wetland in China

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Abstract

Riparian wetland is the major transition zone of matter, energy and information transfer between aquatic and terrestrial ecosystems and has important functions of water purification and non-point pollution control. Using the field experiment method and an isotope tracing technique, the agricultural non-point nitrogen pollution control function of different vegetation types in riparian wetland was studied in the Kouma Section of the Yellow River. The results showed that the retention of agricultural non-point nitrogen pollution by riparian wetland soil occurs mainly in top 0–10 cm layer. The amount of nitrogen retained by surface soils associated with three types of vegetation are 0.045 mg/g for *Phragmites communis Trin* Linn, 0.036 mg/g for *Scirpus triqueter* Linn, and 0.032 mg/g for *Typha angustifolia* Linn, which account for 59.21%, 56.25%, and 56.14% of the total nitrogen interception, respectively. Exogenous nitrogen in 0–10 cm soil layer changes more quickly than in other layers. One month after adding $K^{15}NO_3$ to the tested vegetation, nitrogen content was 77.78% for *P. communis Trin*, 68.75% for *T. angustifolia*, and 8.33% for *S. triqueter* in the surface soil. After three months, nitrogen content was 93.33% for *P. communis Trin*, 72.22% for *S. triqueter*, and 37.50% for *T. Angustifolia*. There are large differences among vegetation communities respecting to purification of agricultural non-point nitrogen pollution. The nitrogen uptake amount decreases in the sequence: new shoots of *P. communis Trin* (9.731 mg/g) > old *P. communis Trin* (4.939 mg/g) > *S. triqueter* (0.620 mg/g) > *T. angustifolia* (0.186 mg/g). Observations indicated that the presence of riparian wetlands as buffers on and adjacent to stream banks could be recommended to control agricultural non-point pollution.

Key words: riparian wetland; vegetation community; agricultural non-point source; nitrogen pollution

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Introduction

Riparian areas, defined as three-dimensional zones of direct interaction between terrestrial and aquatic ecosystems, constitute the interface between upland and river environments. Boundaries of riparian zones extend outward to the limits of flooding and upward into the canopy of streamside vegetation. The dimensions of the influence zone for a specific ecological process are determined by its unique spatial patterns and temporal dynamics (Gregory *et al*., 1991; Christopher and Jeffrey, 1997). Riparian wetland is an interface between aquatic and terrestrial ecosystems, and have remarkable boundary effects, rich biodiversity, and unique ecosystem structure, processes and functions. Stream riparian zones have a potential to regulate energy and material fluxes between terrestrial and aquatic ecosystems (Gregory *et al*., 1991; Naiman and Decamps, 1997; Christopher and Jeffrey, 1997).

The topographic location of riparian wetlands means that storm runoff and shallow ground water pass through the riparian zone before entering surface water (Casey and Klaine, 2001). The role of riparian zones in the removal of nitrates from subsurface flows contaminated by agriculture and other human activities has received particular attention (Gilliam, 1994; Hill, 1996; Casey and Klaine, 2001). Many studies have reported large declines in NO_3^- concentrations along shallow groundwater flow paths beneath riparian zones (Lowrance *et al*., 1984; Peterjohn and Correll, 1984; Haycock and Burt, 1993; Hill, 1996). Denitrification, the process by which bacteria reduce NO_3^- to N_2 gas in the absence of O_2, has been identified as the primary mechanism of NO_3^- removal in stream riparian zones (Cooper, 1990; Pinay *et al*., 1993; Verchot *et al*., 1997b; Martin *et al*., 1999; Hill *et al*., 2000; Schade *et al*., 2001). Purification effects of riparian wetland in a natural state on pollutants are unstable and are influenced by hydrology, climate, and extent of wetlands development (Arheimer and Wittgren, 2002). For this reason, the role of purification function in riparian wetland under natural state

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needs to be clarified (Kadlec, 2000; Guo *et al*., 2005).

Recently, the stable isotope technique has attracted much attention in modern ecological research. Stable N isotopes are used to examine the source, flow and fate of N in the ecosystem. There are two main approaches: the ^{15}N-enriched method using an artificially enriched source of ^{15}N, and the ^{15}N natural abundance ($\delta^{15}N$) method using natural ^{15}N differences between N sources and sinks. In most situations, the ^{15}N enriched method can be successfully applied to test hypotheses and to quantify N cycling through the landscape, regardless of background variability in $\delta^{15}N$ (Bedard-haughn *et al*., 2003). In this article, the Kouma Section in the Yellow River wetland was selected as the study area. Using the field experiment method and the ^{15}N enriched technique, the agricultural non-point nitrogen pollution control function of different types of vegetation in riparian wetlands was studied. The collection of a temporal and spatial array of samples within the wetland were performed during artificial runoff events, so that the plume of runoff water moving through the wetland could be traced and its attenuation determined.

1 Materials and methods

1.1 Study area and site description

The study area is located in the National Natural Protection Area in the Mengjin part of the Yellow River wetland. It is about 40 km downstream of the Xiaolangdi Reservoir, located at 34°47′–34°53′N and 112°29′–112°49′E, and with height above sea level ranging from 120 to 130 m. After the Xiaolangdi Reservoir was brought into service for flood control, a large area of the natural wetland was developed as farmland. The predominant plants with comparatively large areas included *Typha angustifolia* Linn, *Scirpus triqueter* Linn and *Phragmites communis Trin* Linn (Zhao *et al*., 2008).

1.2 Plot selection and experimental design

According to early monitoring results (Meng *et al*., 2008), there were large difference in the amount of N pollution generated as runoff among various landuse types, which indicats that vegetation communities have a huge influence on nitrogen interception. To simulate nitrogen interception of different community types according to the results of the vegetation investigation, three community types: *P. communis Trin*, *T. angustifolia*, and *S. triqueter* were selected as trial objects in a flat area. Four mobile runoff boards were fixed vertically to form a 25 m^2 area. Each board extended 30 cm above the ground and 20 cm underground (Fig. 1). $K^{15}NO_3$ was dissolved, loaded into the tank, and mixed before being pumped into the test plots. The flow rate was adjusted using a flow rotor. The $K^{15}NO_3$ concentrations and flow rates for each experiment are listed in Table 1. The ^{15}N abundance of $K^{15}NO_3$ (the Shanghai Chemical Industry Academy, China) was 10.25%.

The total nitrogen analysis methods used for soil, water and plants are the potassium-permanganate-reducing ferrum-modified Kjeldahl method, the Kjeldahl method, and the sulfuric-acid-catalyst mixtures-distillation method respectively (Lu, 1999). The relative N uptakes (N_R) in plants and soil were calculated by the following equation (Dahlman *et al*., 2002; Nordbakken *et al*., 2003):

$$N_R = (^{15}N_S - ^{15}N_C) \times (TN/0.1025) \qquad (1)$$

where, $^{15}N_S$ is at.% of ^{15}N of the respective sample; $^{15}N_C$ is the average at.% of the control sample; TN is the total ^{14}N + ^{15}N concentration (mg/g dry weight); the value 0.1025 corrects for the fraction of labeled ^{15}N in the N additions (10.25%). Control sample was collected before the nitrogen pre-dosing.

1.3 Sampling and pretreatment

To meet the requirements of statistical analysis, each result was obtained from three parallel random samples. Sampling times, types, and numbers are as described in Table 2.

1.3.1 Plant samples

Plant and soil samples were collected from plots to determine the fate of applied ^{15}N. The ^{15}N content of soil and plant were measured using a MAT-251 isotope ratio mass spectrometer (Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China). Plant samples were collected from three randomly selected 900 cm^2 subplots within each plot. Plant samples were dried at 70°C for 24 h, ground to pass a 50-μm sieve, and analyzed for total N and ^{15}N content.

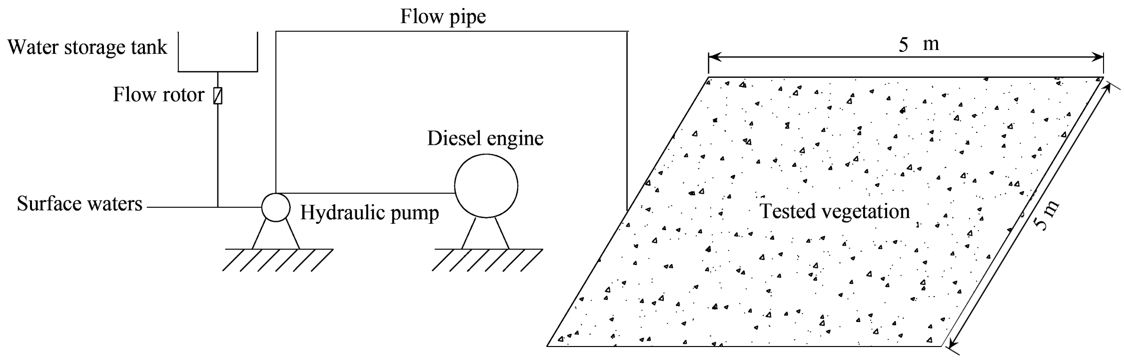

Fig. 1 Experimental apparatus.

Table 1 Parameters of field experiments

Plot	Roots distribution in soil	Pump flow rate (m^3/h)	Duration (h)	Gross water flow (m^3)	Gross $K^{15}NO_3$ (g)	Concentration of $K^{15}NO_3$ (mg/L)	Seeper depth on plots surface (cm)
P. communis Trin	more fibres, 0–10 cm	0.880	3.5	3.07	30	9.77	10
T. angustifolia	less fibres, > 20 cm	1.756	2.0	3.51	30	7.02	20
S. triqueter	less fibres, 10–20 cm	1.800	1.5	2.70	30	11.11	15

1.3.2 Soil samples

Three replicate soil cores were collected from all plots at 0–10, 10–20, and > 20 cm depths. Samples weighing approximately 1 kg were collected in each layer, loaded into different sacks, appropriately marked, and subjected to intensive mixing before total N analysis. Fresh and well-mixed soil sample 1.5 g were weighed before digestion.

1.4 Data processing

The Kolmogorov-Smirnov method was used to check the normality of each variable. If the variable did not follow a normal distribution, its distribution was normalized by transformation of the variables using Napierian logarithms. Analysis of variance was used to check the extent of deviation of the variables from a normal distribution or normalization. If normalization was not performed through logarithmic transformation, the variable differences were compared using distribution-free methods such as the Mann-Whitney U and Kruskal-Wallis Post Hoc tests. The confidence level of the entire data analysis was 95% except stated elsewhere. The SPSS software package (version 13.0) was used for data processing.

2 Results and analysis

2.1 Agricultural non-point nitrogen pollution interception in riparian wetland soil

Comparative results for LSD (least significant difference) analyzed by SPSS show that the ^{15}N percentages of three vegetation communities in the 0–10 cm soil layer showed a remarkable diversity during the experimental period, but this trend does not hold in the 10–20 cm and > 20 cm layers (Fig. 2).

The ^{15}N percentages of three tested soils after one day of $K^{15}NO_3$ addition are increased, and the retention of agriculture non-point N pollution by wetland soils occurs mainly in 0–10 cm layer. Retention amounts in descending order are: *P. communis Trin* (0.045 mg/g) > *S. triqueter* (0.036 mg/g) > *T. Angustifolia* (0.032 mg/g), which account for 59.21%, 56.25%, and 56.14% respectively of the total nitrogen interception. The greatest variation of exogenous nitrogen occurs in the 0–10 cm layer. The purification capability of the different communities for exogenous nitrogen captured in soil is different: one month later, *P. communis Trin* (77.78%) > *T. angustifolia* (68.75%) > *S. triqueter* (8.33%), and three months later, *P. communis Trin* (93.33%) > *S. triqueter* (72.22%) > *T. Angustifolia* (37.50%). The soil nitrogen interception of the different communities is presented in Table 3.

2.2 Effect of agricultural non-point nitrogen pollution on groundwater

The ^{15}N percentages in groundwater before $K^{15}NO_3$ addition, one day after, and one month after were compared (Fig. 3). The differences between the results of the "before" and "after" $K^{15}NO_3$ addition were not obvious, and it is also clear that groundwater was not affected by agricultural non-point pollution at this experimental concentration through detention by riparian wetland soil.

2.3 Differences in vegetation uptake of agricultural non-point nitrogen

As shown in Fig. 4, the ^{15}N percentages of three tested vegetations in different growing periods are obviously different. The test data show that purification capabilities for agriculture non-point pollution of the different vegetation communities are also different. The absorption for N of new shoots of *P. communis Trin* is the largest (9.731 mg/g), followed by older *P. communis Trin* (4.939 mg/g), *S. triqueter* (0.620 mg/g), and *T. angustifolia* (0.186 mg/g). After three months' infusion, the absorbed N was decreased by 90.48%, 62.52%, 58.84%, and 19.35% for *S. triqueter*, new shoots of *P. communis Trin*, old *P. communis Trin*, and *T. angustifolia*, respectively. The purification capabilities for agriculture non-point N pollution of the different vegetation communities are shown in Table 4.

Table 2 Time, types, and numbers of samples

Sampling date	Sample type	Number of samples	Remark
July 2007	Plant	9	^{15}N background abundance of samples
	Soil	27	(before $K^{15}NO_3$ addition)
	Groundwater	3	
July 2007	Plant	9	^{15}N abundance of soil and groundwater samples one
	Groundwater	3	day after water infusion
August 2007	Plant	9	^{15}N abundance of soil, plant and groundwater samples
	Soil	27	one month after water infusion
	Groundwater	3	
October 2007	Plant	9	^{15}N abundance of soil and plant samples three
	Soil	27	months after water infusion

Table 3 Nitrogen interception changes with vegetation communities, soil layers, and time

Community type	Soil layer (cm)	Nitrogen interception (mg/g)		
		One day after water infusion	One month after water infusion	Three months after water infusion
T. angustifolia	0–10	0.032 ± 0.011	0.010 ± 0.002	0.020 ± 0.002
	10–20	0.012 ± 0.002	0.013 ± 0.001	0.025 ± 0.003
	> 20	0.013 ± 0.003	0.011 ± 0.001	0.017 ± 0.003
S. triqueter	0–10	0.036 ± 0.008	0.033 ± 0.007	0.010 ± 0.001
	10–20	0.023 ± 0.003	0.023 ± 0.005	0.018 ± 0.001
	> 20	0.005 ± 0.001	0.006 ± 0.001	0.014 ± 0.002
P. communis Trin	0–10	0.045 ± 0.004	0.010 ± 0.001	0.003 ± 0.001
	10–20	0.007 ± 0.000	0.001 ± 0.000	0.011 ± 0.003
	> 20	0.024 ± 0.001	0.005 ± 0.002	0.003 ± 0.001

Table 4 Nitrogen absorption of different community types

Community type	Nitrogen uptake (mg/g)	
	One month after water infusion	Three months after water infusion
Young *P. communis Trin*	9.731 ± 0.299	3.647 ± 0.113
Old *P. communis Trin*	4.939 ± 0.722	2.033 ± 0.028
T. angustifolia	0.186 ± 0.007	0.150 ± 0.004
S. triqueter	0.620 ± 0.069	0.059 ± 0.001

3 Discussion

Riparian wetland has the ability to purify water by effective retention of N in surface water. It has been reported that riparian wetland vegetation can sequester 89% of the N from surface water which was 50 m away from a river (Wang, 2003). The major mechanisms of N retention in riparian wetland are soil retention, plant uptake, nitrification, denitrification, and microbial immobilization (Verchot *et al*., 1997a; Schade *et al*., 2001; Mariet *et al*., 2003; Revsbech *et al*., 2005; Hefting *et al*., 2005; Davis *et al*., 2006). Denitrification, the conversion of NO_3^- to N_2 gas, has been identified as an important mechanism for nitrate removal in riparian areas (Schipper *et al*., 1993; Hanson *et al*., 1994; Verchot *et al*., 1997b; Martin *et al*., 1999). These purification capabilities are affected by the types of vegetation covering the wetland (Hefting and de Klein, 1998; Matheson *et al*., 2002; Hefting *et al*., 2005; Hoffmann *et al*., 2006; Merrill and Benning, 2006), soil utilization types (Mander *et al*., 1995), hydrographic courses (Willems *et al*., 1997; Maître *et al*., 2003; Daniel and William, 2007; Hernandez and Mitsch, 2007), soil types (McKergow *et al*., 2003), oxidation-reduction potential of soil, physical features, temperature and nutrient content of soil (Sirivedhin and Gray, 2006).

In all three plots, artificial runoff water entering the riparian wetland infiltrated into the subsurface and dispersed both vertically and laterally. As shown in this and other studies (Li and Vitt, 1997; Aldous, 2002; Heijmans *et al*., 2002; Nordbakken *et al*., 2003), the downward movement of ^{15}N is restricted to the upper part of the riparian wetland soil profile. In this study, it was found that after $K^{15}NO_3$ addition, the ^{15}N amount in the 0–10 cm soil layer was obviously greater than in the 10–20 cm and > 20 cm soil layers in riparian wetland (Table 3). The explanation appears to be that the surface soil takes up deposited N and thereby functions as a filter, which is the same with the study results by Nordbakken *et al*. (2003). Furthermore, the study by Casey and Klaine (2001) (using Br as tracer) indicated that the majority of runoff remained in the shallow subsurface and did not disperse beyond 1.2 m below ground surface.

Nutrient absorption depends mainly on the fibres. The fibres of *P. communis Trin* were found mainly in the 0–10 cm layer of the soil. This is why *P. communis Trin* has the most significant N uptake capability. Furthermore, it was found that N interception in the 10–20 cm soil layer in *P. communis Trin* polt was the lowest of all plots. The reason is that this soil in the *P. communis Trin* plot was composed mainly of silver sand, which restricted the N interception ability of the soil. The fibres of *T. angustifolia* were found less in the soil, and its N purification in the surface soil layer mainly occurred due to the denitrification. *S. triqueter*, with its short height, was located mainly in the bottomland portion of the wetland. During the experimental period, the Xiaolangdi Reservoir in the Yellow River carried out a flow-sediment regulation project in July, resulting in a huge impact on the 0–10 cm layer of the *Scirpus triqueter* plot area, which influenced the N uptake of *S. triqueter*. This was the reason for the significant difference between the N uptake at the later time and three months before. The riparian wetland was highly effective in preventing nutrients in storm runoff from entering downstream waters, suggesting that the mechanisms of nutrient retention can function without constant exposure to NO_3^-.

Another factor contributed to attenuation was the ability of runoff to seep into the subsurface and move through the organic wetland soil. This allowed for intimate contact between runoff water, microbial communities, and the root zone in the wetland. High level of denitrification expected in the wetland soils given the high organic-matter content and continuously saturated conditions. The subsurface movement of water in the wetland would also enhance the ability of denitrifying populations to interact with storm runoff. Previous study indicated that denitrification can be substantial in riparian wetland systems receiving pulsed NO_3^- inputs (Casey *et al*., 2001). The denitrification capabilities of soil in this area need further study. The attenuation mechanisms may have been short-circuited in these events by hydrological overloading in the wetland. If flow into the wetland exceeded the infiltration rate of the soils, overland flow would be resulted, which would limit the contact between nutrient-rich runoff water and wetland soils.

Preliminary analysis of the groundwater samples

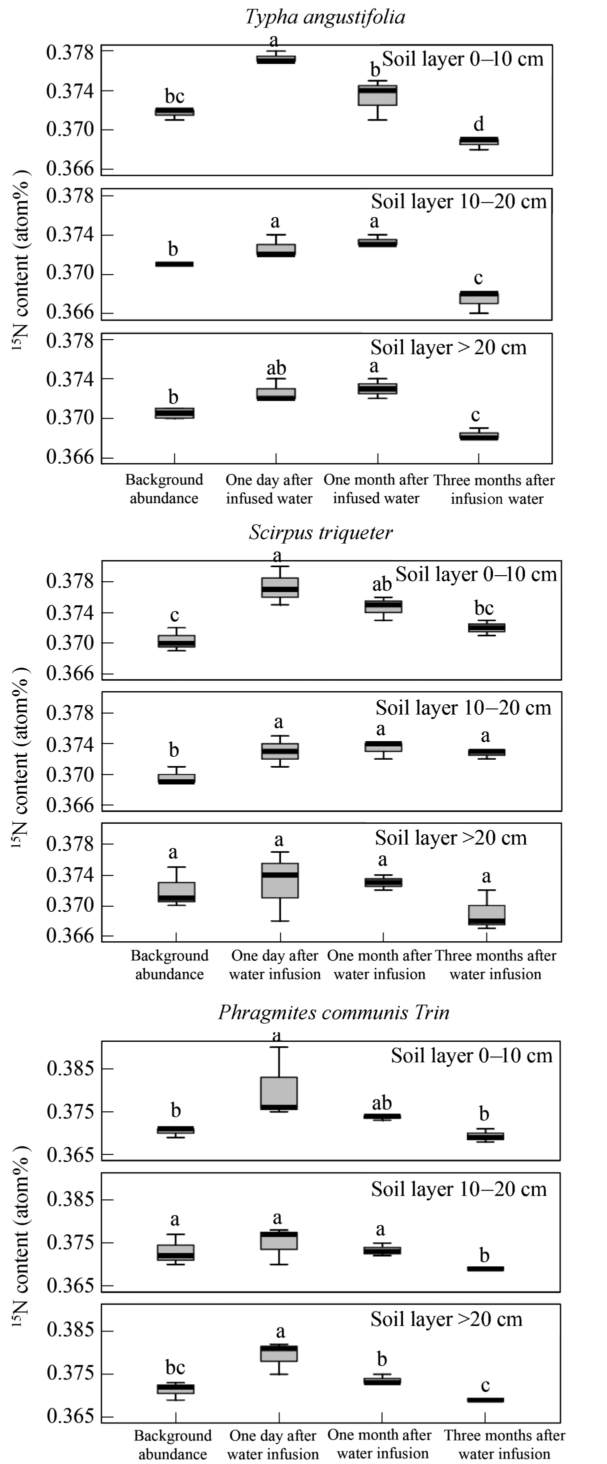

Fig. 2 Variation of soil ^{15}N content at different time. Values in the same soil layer followed by the same letter are not significantly different at $p < 0.05$.

indicated that ^{15}N was not present in groundwater in the interim between artificial runoff events (Fig. 3). These data confirmed that NO_3^- from infiltrated storm runoff was not being stored in groundwater between events. These observations also suggested that the riparian wetland was receiving input predominantly in pulses during storm events and not through continuous groundwater transport.

Elevated levels of ^{15}N in all N-exposed plants across three community types showed that the plants absorbed the

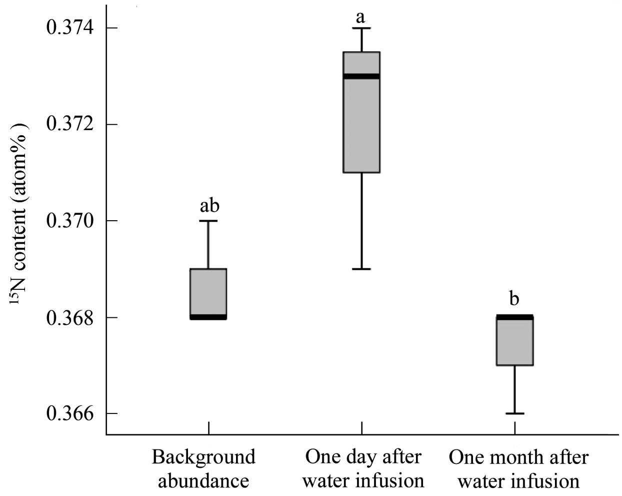

Fig. 3 Groundwater ^{15}N content at different time. Values in the same soil layer followed by the same letter are not significantly different at $p < 0.05$.

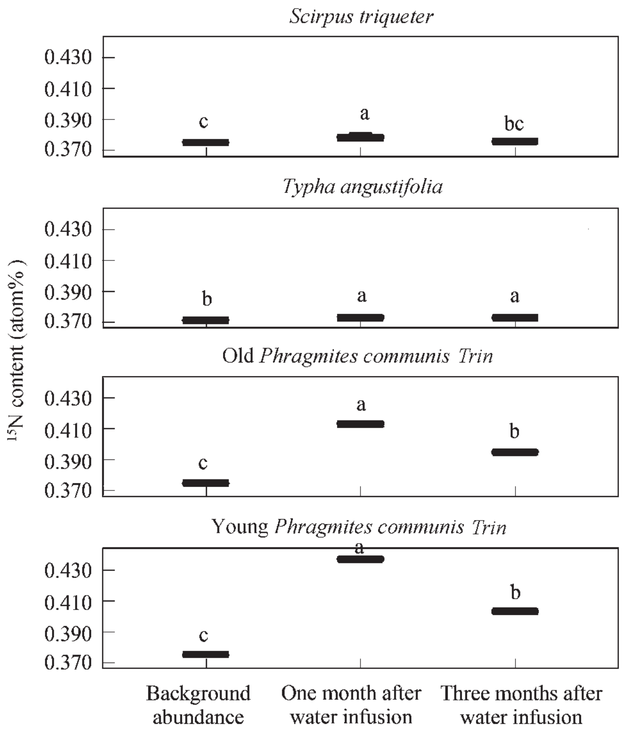

Fig. 4 ^{15}N content of plant samples at different time. Values in the same soil layer followed by the same letter are not significantly different at $p < 0.05$.

added N. The isotopic data showed N uptake of 0.186–9.731 mg/g among plants 1 month after water infusion and 0.059–3.647 mg/g after 3 months water infusion. Different plants access different nitrogen sources when they grow. NO_3^- assimilation was shown to be oxygen-dependent, whereas NH_4^+ assimilation was little affected by O_2 deprivation in some plants (Lena *et al*., 2002). This also reflects the increased energy requirement of NO_3^- reduction as opposed to NH_4^+ assimilation. Preferential uptake of NH_4^+ is a common phenomenon in plants. At the same time, because the roots of different plants are distributed in different soil layers, these plants take up the

N retained in soil differently. Variations in the ^{15}N content of different plants may be caused by different species using different N sources (Schulze *et al*., 1994; Michelsen *et al*., 1998; Nordbakken *et al*., 2003). For vascular plants, different rooting patterns allow plants to exploit different parts of the soil horizon (Table 1). For example, *P. communis Trin* has most of its finer roots positioned less than 10 cm beneath the surface, whereas the fine roots of *T. angustifolia* penetrate to depths below 10 cm. As for the retention ability for N of soil in riparian wetland, exogenous N generated by agricultural non-point pollution was retained mainly in the 0–10 cm soil layer during the whole storm simulation process (Table 3), which was the main reason that the amount of ^{15}N in *P. communis Trin* tissue was obviously different from the natural abundance and the reason that the ^{15}N amount in *S. triqueter* and *T. angustifolia* was less than that in *P. communis Trin*. The old-tissue ^{15}N concentrations of *P. communis Trin* were 0.969–1.008 mg N/g, whereas total N concentrations in newly formed tissue were as high as 1.320–1.600 mg N/g. This implies that the dominant part of the N required for making new tissue might have been provided by the added N.

The ^{15}N amount in vegetation increased after one-month growth for three types of plants, implying that roots directly contacted with recently deposited N represent the main absorbing surfaces. Even though the effect of N fertilization on total N content is not straightforward, the effects of ^{15}N supply are more evident. However, the amounts of ^{15}N uptake differ among the three plants. The shallow-rooted *P. communis Trin*, which has absorbing surfaces almost in direct contact with deposited N, take up more ^{15}N than vascular plants with deeper roots. The uptake of supplied ^{15}N decreases as root depth increases, such as *T. angustifolia*.

4 Conclusions

(1) Retention of agricultural non-point nitrogen pollution by riparian wetland soil occurs mainly in the top 0–10 cm soil layer. The amount of nitrogen retained by surface soils is 0.045 mg/g for *P. communis Trin*, 0.036 mg/g for *S. triqueter*, and 0.032 mg/g for *T. angustifolia*, accounting for 59.21%, 56.25%, and 56.14% respectively of the total nitrogen interception.

(2) Exogenous nitrogen content in the top 0–10 cm soil layer changes faster than in other layers. After 1 month, nitrogen content in the top layer is 77.78% for *P. communis Trin*, 68.75% for *T. angustifolia*, and 8.33% for *S. triqueter*. After 3 months, nitrogen content is 93.33% for *P. communis Trin*, 72.22% for *S. triqueter*, and 37.50% for *T. angustifolia*. The results indicate that the absorption by *T. angustifolia* of agricultural non-point nitrogen in riparian wetlands soil is mainly occured in the first month, but that the time span of absorption by *P. communis Trin* and *S. triqueter* is longer.

(3) There is a large difference among different vegetation communities in their ability to purify agricultural non-point nitrogen pollution. The absorption capacity of new shoots of *P. communis Trin* was the best (9.731 mg/g); the second is old *P. communis Trin* (4.939 mg/g), the third is *S. triqueter* (0.620 mg/g), and the last is *T. angustifolia* (0.186 mg/g). With the addition of vegetation biomass, the change of nitrogen content in vegetation organism is as follows: *S. triqueter* (90.48%) > new shoots of *P. communis Trin* (62.52%) > old *P. communis Trin* (58.84%) > *T. angustifolia* (19.35%). The results indicate that riparian wetlands as buffers on and adjacent to stream banks are recommended to control agricultural non-point pollution.

Acknowledgments

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