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RESEARCH ARTICLE

Winter legumes in rice crop rotations reduces nitrogen loss, and improves rice yield and soil nitrogen supply

Yingliang Yu · Lihong Xue · Linzhang Yang

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Abstract Intensive irrigated rice-wheat crop systems have caused serious soil depletion and nitrogen loss in the Tai Lake region of China. A possible solution is the incorporation of legumes in rice because legumes are a source of nitrogen. There is actually little knowledge on the impact of legumes on rotation, soil fertility, and nitrogen loss. Therefore, we studied the effect of five rice-based rotations, including rice-wheat, rice-rape, rice-fallow, rice-bean, and rice-vetch, on soil nitrogen, rice yield, and runoff loss. A field experiment was conducted in the Tai Lake region from 2009 to 2012. Crop residues from rape, bean, and vetch were used to partially replace chemical fertilizer in rice. Results show that replacing 9.5–21.4 % of mineral nitrogen fertilizer by residues maintained rice yields of rice-rape, rice-bean, and rice-vetch rotations, compared to the rice-wheat reference. Moreover, using legumes as a winter crop in rice-bean and rice-vetch combinations increased rice grain yield over 5 %, and increased rice residue nitrogen content by 9.7–20.5 %. Nitrogen runoff decreased 30–60 % in rice-rape, rice-bean, and rice-vetch compared with rice-wheat. Soil mineral nitrogen and microbial biomass nitrogen content were also improved by application of leguminous residues.

Keywords Rice yield · Soil nitrogen supply capacity · Non-point pollution · Crop rotations · Legumes · Chemical nitrogen fertilizer reduction · Runoff nitrogen loss

1 Introduction

Nitrogen is one of the major limiting plant nutrients required by agricultural crops. For rice cropping, the soil should supply over 180 kg N hm^{-2} in an available form for each crop to meet the targeted grain yield requirement for the Tai Lake region (Qiao et al. 2012). Without additional nitrogen input, the soil nitrogen supply capacity could decline rapidly under continued cropping. Nitrogen fertilizer application is an indispensable way to meet crop demand and maintain the nitrogen balance in soil for sustainable production. Traditional organic materials (crop residue and manure) were used to maintain high yields in China for thousands of years. However, since chemical nitrogen fertilizers were introduced in the middle of the twentieth century, their consumption has continually and rapidly increased. As much as 300 kg N hm^{-2} was applied to one crop in the Tai Lake region, where annual double cropping is the main cultivation method (Cui et al. 2000). Excessive chemical nitrogen fertilizer may not only reduce the grain yields and result in economical losses (Qiao et al. 2012) but may also cause serious deterioration in soil properties and eutrophication from drainage (Vitousek et al. 2009). Inorganic nitrogen loss from agro-ecosystem runoff in China is estimated to reach over 1.74×10^9 kg per year (Duan et al. 2000), and it is an important contributor to water system pollution. To reduce the nitrogen runoff loss, a nutrient input source reduction technology was proposed by Yang et al. (2004). A sustainable cropping system should not only maintain crop production and soil nitrogen supply capacity but also reduce nitrogen runoff loss (Larkin 2008).

Previous research has confirmed that legumes within a cropping system could play an important role in maintaining soil fertility and sustaining crop production by increasing mineral nitrogen in root zone soil and by reducing weed populations and the incidence of root and leaf diseases in subsequent crops (Shafi et al. 2007; Mazzoncini et al. 2011). Including rapeseed in a crop rotation can stimulate biological activity in the soil (Larkin 2008). Organic matter applications from crop residues help in maintaining nutrients, crop yields, and soil structure. Soil organic matter is an essential component with key multifunctional roles related to many physical

Y. Yu · L. Xue (✉) · L. Yang
Institute of Agricultural Resources and Environment, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China
e-mail: lhxue@issas.ac.cn

and biological soil properties, which maintain soil nutrients and productivity, sustain high grain yields, ameliorate damaged soil structure, and prevent nutrient runoff and leaching losses (Douglas et al. 1998).

Rice is the dominant crop of the Tai Lake region and it is characterized by its high quality. Maintaining high quality soil fertility is essential for developing sustainable crop production systems. The main production season for this rice crop occurs from June to November. The second crop season goes from November to the following May (a supplemental production), which is flexible in terms of maintaining the soil nitrogen supply capacity. Wheat, rape, broad bean, and vetch are also common crops in this region. Fallowing in the winter after the rice harvest has also been common in recent years for economic reasons. Good management improves soil nitrogen fertility by means of crop rotations, promoting nitrogen fertility, increasing soil organic matter, and improving soil properties. The objectives of this study were to evaluate the effects of crop rotations on the rice yield, soil nitrogen supply capacity, and runoff loss with partial nitrogen replacement using crop residue applications rather than chemical nitrogen fertilizer.

2 Materials and methods

2.1 Site description

This experiment was conducted from June 2009 to May 2012 at Longyan Village (31°31′N, 120°06′E), Hudai Town, Wuxi City, Jiangsu Province, China. The soil (0–20 cm) at the experimental site is gleyed-stagnant anthrosol developed from a lacustrine deposit. Its pH is 6.99, and it contains 1.75 g kg^{-1} total nitrogen, 188 mg kg^{-1} alkali-hydrolyzable nitrogen, 0.61 g kg^{-1} total phosphorus, 37.9 mg kg^{-1} Olsen phosphorus, 118 mg kg^{-1} available potassium and 32 g kg^{-1} soil organic matter. The experimental site is dominated by a northern subtropical humid climate with four distinct seasons and a mean annual temperature of 15.5 °C, and the average annual rainfall is 1,038.4 mm.

2.2 Experimental design and management

Based on the local practice, the crops designated as crop 2 were rotated with rice (crop 1) and consisted of wheat (*Triticum aestivum* L.), rape (*Brassica chinensis* L.), broad bean (*Vicia faba* L.), and vetch (*Astragalus sinicus* L.), or fallow (no crop). The treatment was comprised of five rotations, i.e., rice-wheat, rice-rape, rice-bean, rice-vetch, and rice-fallow. Field plots (15×8.5 m) were established in a random complete block design with three replicates (Fig. 1). The field plots were separated by 30-cm high banks.

The nitrogen fertilizer application rates for each crop were determined according to local recommended production practices. The nitrogen input included nitrogen from residues returned during the rice season, and added up to 210 kg hm^{-2} for all treatments. During the crop 2 season, rice straw was removed, 180 kg N hm^{-2} was applied to rice-wheat and rice-rape, 90 kg N hm^{-2} was added to the rice-bean treatment, and no nitrogen fertilizer was added to rice-vetch and rice-fallow. In the rice-rape, rice-bean, and rice-vetch treatments, rapeseed hulls, broad bean pods, and the entire vetch plant were returned to the rice field immediately after crop 2 was harvested. Crop residues were incorporated down to 20 cm using a rotavator. The total nitrogen returned to the rice field for rice-rape, rice-bean, and rice-vetch treatments averaged 20.6, 45.8, and 14.4 kg N hm^{-2} with total carbon/total nitrogen values of 16.44, 11.95, and 11.00, respectively. Phosphate (90 kg hm^{-2} super phosphate) and potassium (65 kg hm^{-2} potassium chloride) were thoroughly mixed into the soil with machinery at equal amounts for all crop rotations during each season, except for the winter fallow (no fertilizer application). Water from a tributary of the Tai Lake was used for irrigation when needed.

2.3 Sampling and measurements

2.3.1 Crop measurements

The crops were manually harvested at physiological maturity. The grain yield of crop 1 (rice) was determined by the whole plot as harvested in June. Then, grain and crop residues within 2 m^{2} were sampled for analysis. The whole plant, grain, and residue samples were oven dried at 70 °C to a constant mass, weighed, then ground into powder fine enough to pass a 0.149-mm sieve for total nitrogen and total carbon analyses (Flash EA 1112 series; Thermo Finnigan, Elk Grove Village, IL).

2.3.2 Soil measurement

Five soil cores (from 0–20 cm) were collected from each plot after the annual winter crop harvest. The five cores were then mixed to make one composite soil sample, in which half were passed through a 0.83-mm sieve to remove rocks and large organic debris, and then stored in plastic bags at 4 °C for mineral nitrogen, soil potential nitrification rate, soil microbial biomass nitrogen, and soil microbial biomass carbon analyses. The other half were oven dried at 105 °C to a constant mass, then ground to pass a 0.149-mm sieve for soil organic matter, total nitrogen, and total carbon analyses.

Mineral nitrogen was extracted by KCl immediately after sampling. The potential nitrification rate was determined via the shaken slurry method. Soil microbial biomass nitrogen

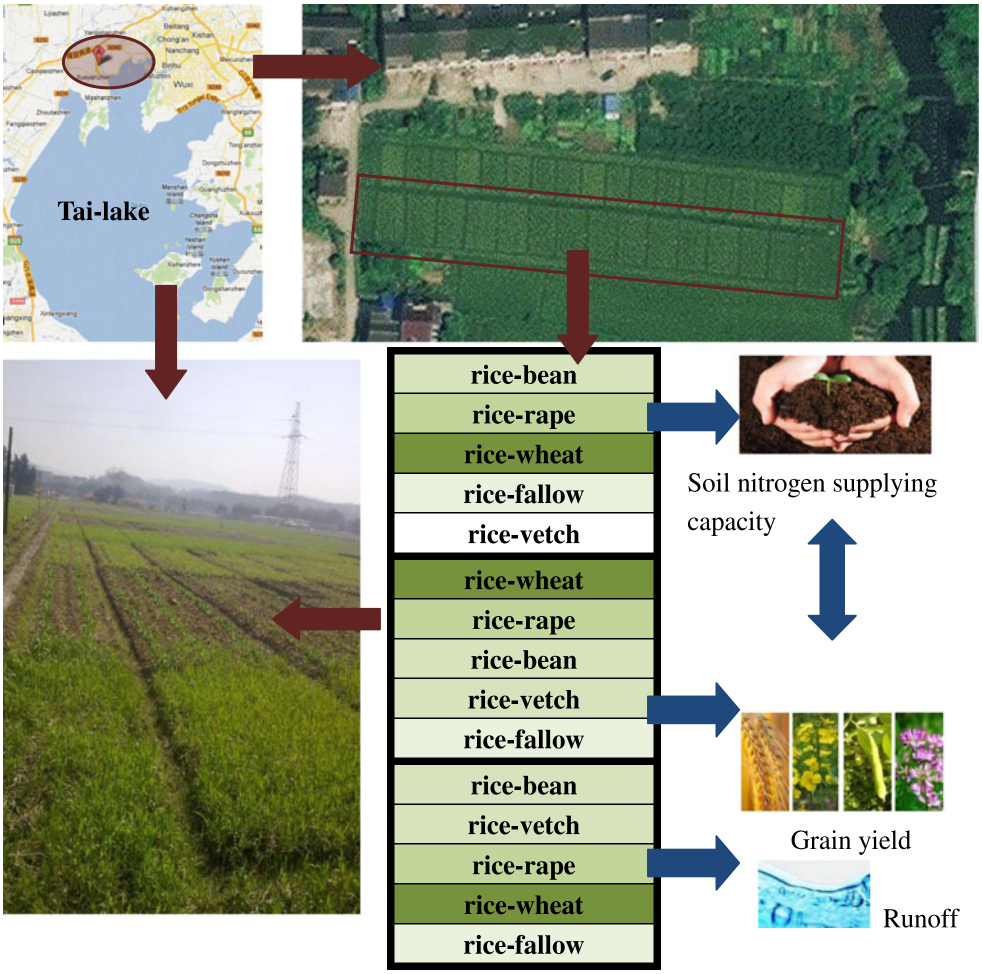

Fig. 1 Experiment design. The experiment ran from June 2009 to May 2012, and was comprised of five rotations, i.e., rice-wheat, rice-rape, rice-bean, rice-vetch, and rice-fallow. Crop residues from rape, bean, and vetch were returned to the rice fields to partially replace chemical fertilizer applications in rice. The total nitrogen input was the same for rice with 210 kg N hm^{-2} when the nitrogen was included in crop residues. During the winter season, the nitrogen input of rice-wheat, rice-rape, rice-bean, rice-vetch, and rice-fallow was 180, 180, 90, 0, and 0 kg N hm^{-2}, respectively. Phosphate (90 kg hm^{-2} super phosphate) and potassium (potassium chloride 65 kg hm^{-2}) were also the same for all crop rotations during each season

was determined using the chloroform fumigation extraction method. Nitrogen extracted from the methods described above was analyzed using an auto analyzer (Traacs 800, Bran+Luebbe, Hamburg). Soil microbial biomass carbon was estimated using the chloroform fumigation extraction method. Soil organic matter was determined by potassium dichromate method. Total nitrogen and total carbon were analyzed using an elemental analyzer (Flash EA 1112 series; Thermo Finnigan, Elk Grove Village, IL). The calculations were all based on the oven-dry (105 °C) weight of the soil samples.

2.3.3 Runoff measurements

Before the experiment started, 15 30-L plastic buckets were buried beside each plot to collect runoff water from 2 m^2 of the plot through a piping system. Other runoff from the plot rest area flowed into the drainage ditch. An electromagnetic flow meter was equipped to measure the runoff volume at the drainage ditch outlet for the whole field. During rice season, the flood water was primarily maintained at a depth of 3–5 cm in the field and the height of the ridge was approximately 10 cm. Therefore, the hole for the runoff collection pipe was set at 10 cm above the soil surface. During the crop 2 season, small drainage ditches (20 cm in depth and 10 cm in width, usually spaced 1.5–2 m apart) were mechanically dug in the field to ensure the crop was not damaged by water-logging. Therefore, the hole for the runoff collection pipe was set at 20 cm below the soil surface. Thus, there were two holes in the runoff collection pipes, and the top hole was used to collect runoff during the rice season and the lower one was used to collect runoff during the crop 2 season. Meanwhile, the amount of rainfall was recorded daily by an automated rainfall collector (watch dog 2000, America). Water from the collection buckets was sampled after each rain, then immediately filtered and refrigerated at −5 °C for analysis. The rest of the water in the bucket was discharged to the drainage ditches. The empty buckets were washed with tap water and prepared for the next runoff collection. The runoff water volume was recorded by the flow meter at the outlet during the rice season, and calculated by the SCS-CN model (Mockus, 1972) depending on the rainfall during the crop 2 season. Runoff nitrogen was measured with an auto analyzer (Traacs 800, Bran+Luebbe, Hamburg).

2.4 Statistical analysis

The relative significance of different treatments was measured with an analysis of variance. Significant differences among the means were determined by Duncan's multiple range tests at the 5 % level. Data was analyzed using the SPSS 10.0 software package.

3 Results and discussion

3.1 Grain yield and nitrogen accumulation in crop 1 (rice season)

There was widespread concern about the crop productivity of continuous same crop rotation patterns over many years. We found that proper crop rotation coupled with crop residue return could stimulate both rice nitrogen accumulation and grain yield. As a consequence of nitrogen return from the crop residue, the chemical nitrogen fertilizer input during the rice season was reduced by 21.4 % for rice-bean and 9.5 % for rice-rape and rice-vetch. The rice grain yields of rice-bean and rice-vetch treatments, which involved a legume, were higher than those of other treatments, and increased by 5 % in 2010 and 10 % in 2011 when compared to the rice-wheat treatment (Fig. 2a). Rice grain yields responded to nitrogen accumulation in the plant for most treatments with a correlation coefficient of 0.588 (p <0.05). Incorporating organic amendments from crop residues increased the rice nitrogen accumulation by 9.7–20.5 % compared to those without residue return (rice-wheat and rice-fallow) in 2011 (Fig. 2b). Nitrogen accumulation in rice plants was greatest for the rice-rape treatment in both 2010 and 2011.

Shafi et al. (2007) found that applying fertilizer could substantially enhance the nitrogen accumulation in subsequent crops. The unexpected substantial carry over effect could be the reason for greater nitrogen accumulation in rice-rape and rice-bean treatments. The positive effect of legumes on the following rice crop included a higher rice grain yield, and chemical fertilizer application was reduced by 21.4 %(Fig. 2A). This finding was consistent with results from other investigators (Dalal et al. 2011; Zhu et al. 2012; Kim et al. 2012). Many studies verified that legumes fix substantial amount of atmospheric N_2, and the nodulated roots and residues can be potentially valuable sources for replenishing soil nitrogen pools (Mazzoncini et al. 2011; Zhu et al. 2012; Kim et al. 2012). Rice grain yields benefited from crop rotations, including legumes, and this improvement can even last for several years (Dawe et al. 2003; Mazzoncini et al. 2011; Zhu et al. 2012). A yield reduction was observed in rice-rape treatments, although the rice plant nitrogen accumulation was greatest when rapeseed hulls were incorporated for 2 years of crop rotations. Armstrong et al. (1996) reported a similar finding for the yield reduction of a rice-rape rotation, and attributed it to the high carbon/nitrogen ratio in rape residues.

3.2 Nitrogen runoff loss

Precipitation conditions resulted in a runoff pattern depicted in Fig. 3. There were 21 total runoff incidents from Jun 2009 to May 2012, with 10 in the first year, 4 in the second year, and 7 in the third year. Runoff during the crop 1 (rice) season occurred 2–3 times, including drainage at the mid-tillering stage to promote panicle initiation. During the crop 1 (rice) season, runoff was not common because of the presence of a ridge. Runoff occurs only when continuous rainfall exceeded 100 mm and the water depth in the plots was higher than 10 cm, which was not a high frequency event in the Tai Lake region (Tian et al. 2011). The total nitrogen concentration in runoff was less than 3 mg L^{-1} during the crop 1 season, and the differences between treatments were not significant

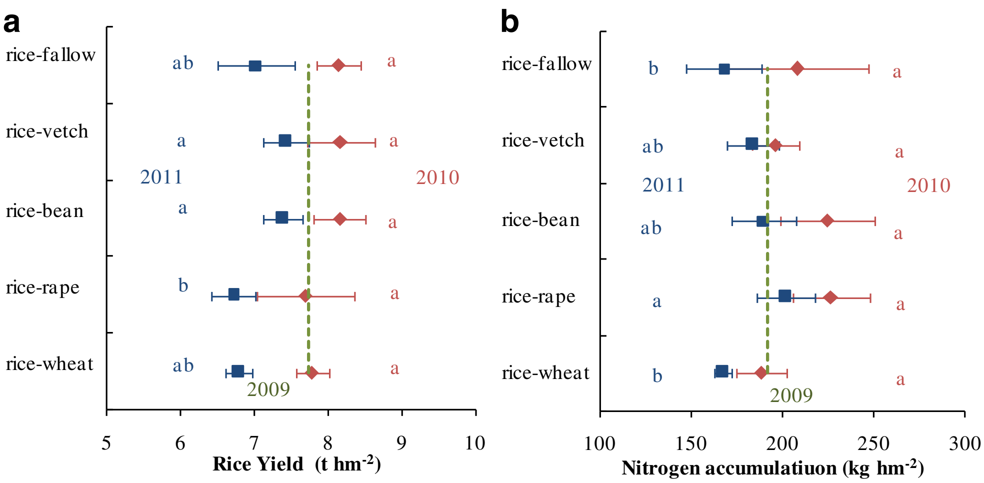

Fig. 2 Grain yield (**a**) and plant nitrogen accumulation in rice (**b**) for 3 years. Crop rotations involving legumes such as rice-bean and rice-vetch treatments increased plant nitrogen accumulation and grain yield by over 5 % with reduced nitrogen fertilizer inputs when compared with the traditional rice-wheat rotation

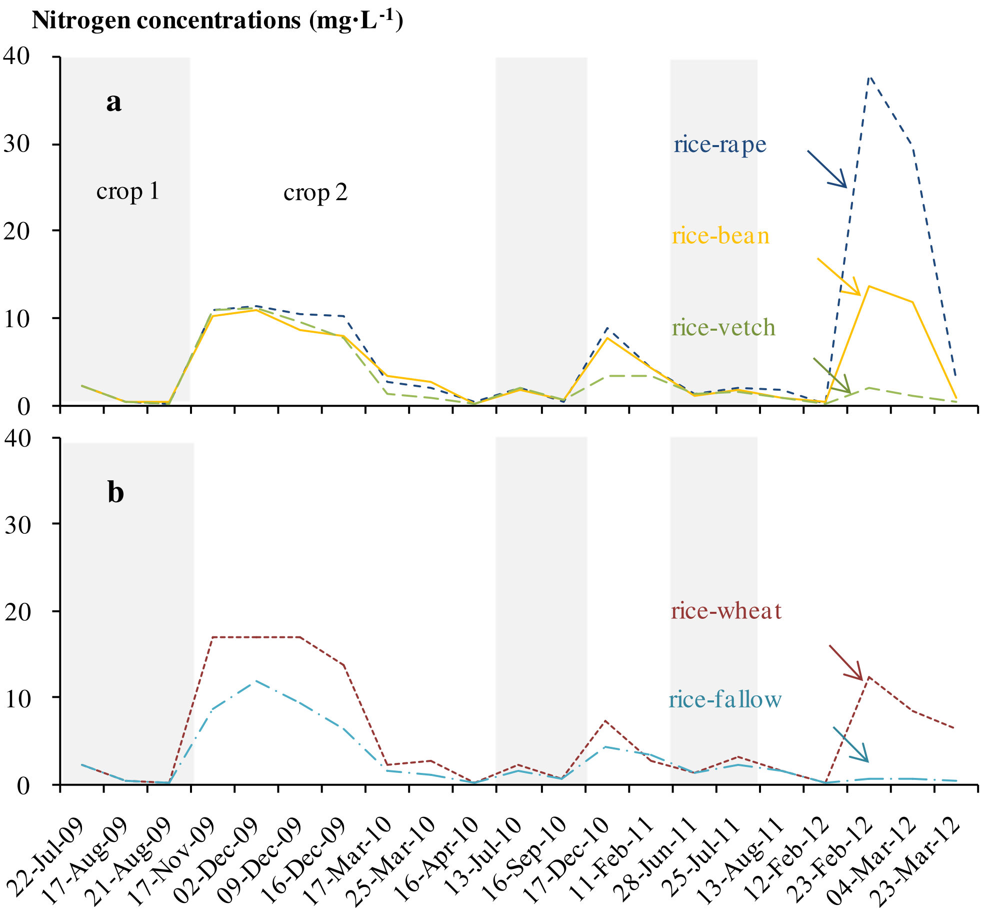

Fig. 3 Nitrogen concentrations from runoff, which occurred 21 times in 3 years. During the rice season, runoff happened 2–3 times and the nitrogen concentration in the runoff was less than 3 mg L^{-1} without significant differences among the five treatments. However, the runoff frequency during the crop 2 season was higher than that of the crop 1 season because the field dried out. The nitrogen concentration in the runoff would be much higher following winter rainfall or shortly after fertilization

(Figs. 3, 4). Thus, the annual nitrogen loss from runoff during the crop 1 season was relatively stable among different treatments and varied from 4–5 kg hm^{-2} (Fig. 4).

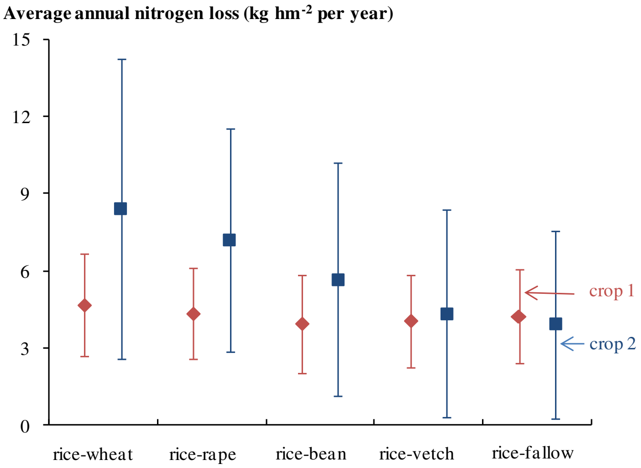

Fig. 4 Average annual nitrogen loss from runoff over 3 years. The annual nitrogen loss during the rice season was relatively stable among treatments and years, and averaged 4–5 kg hm^{-2} per year. However, it was highly variable among the years and treatments during the crop 2 season, with the average value ranging from 3.93 kg hm^{-2} per year in rice-fallow to 8.46 kg hm^{-2} per year in rice-wheat. Reducing the nitrogen input in crop 2 helped decrease nitrogen runoff loss

However, during the crop 2 season from November to the following April, the field dried and deep ditches of approximately 15 to 20 cm were dug for drainage to support normal growth for crop 2. Hence, runoff occurred easily when the soil water content was saturated and it was driven by rainfall and snowmelt events. As Fig. 3 shows, the relatively intensive runoff from Nov to Dec 2009 was a result of snowmelt. Consequently, the frequency and volume of runoff from crop 2 were likely to be higher than that of crop 1. In addition, soil nitrogen content remains at a relatively high level for a long time after fertilization because of slow plant growth at low winter temperatures. The nitrogen concentration in the runoff would be much higher once runoff had happened. The nitrogen concentration in crop 2 widely ranged from 0.16 to 37.80 mg L^{-1}. More than 10 mg L^{-1} nitrogen concentration in runoff was observed from Nov to Dec 2009 and Feb 2012 just a few days after nitrogen fertilization. Nitrogen concentrations in the runoff of fertilized treatments such as rice-wheat, rice-rape, and rice-bean increased 30–60 % relative to the no fertilizer treatments (rice-vetch and rice-fallow).

There was no clear relationship between the runoff volume and nitrogen concentration with time and the amount of rainfall, but high runoff nitrogen loss is usually accompanied by a high nitrogen concentration in the runoff. The runoff loss

Table 1 Concentrations of organic matter (SOM), mineral nitrogen (MN), potential nitrification rate (PNR), total nitrogen (TN), total carbon (TC), soil microbial biomass nitrogen (SMBN) and carbon (SMBC) in soil after crop 2 harvest

		Rice-wheat	Rice-rape	Rice-bean	Rice-vetch	Rice-fallow
2010						
	SOM (%)	2.24b	2.79a	2.35b	3.07a	2.07b
	MN (mg kg^{-1})	9.11a	7.52a	10.63a	10.25a	8.65a
	TN (g kg^{-1})	1.77a	1.84a	1.89a	1.86a	1.75a
2011						
	SOM (%)	2.93b	3.59a	3.22ab	3.28ab	2.95b
	MN (mg kg^{-1})	9.82ab	9.63ab	10.95a	5.93bc	5.64c
	TN (g kg^{-1})	1.71a	1.83a	1.75a	1.87a	1.74a
2012						
	SOM (%)	2.68ab	3.37a	3.28a	3.15ab	2.47b
	MN (mg kg^{-1})	8.53b	8.18b	14.81a	13.12ab	10.51ab
	PNR (mg kg^{-1} per day)	2.36c	4.77a	4.82a	4.18b	4.01b
	TN (g kg^{-1})	1.74b	1.99a	1.87ab	1.93ab	1.78ab
	TC (g kg^{-1})	15.57c	19.40a	16.60bc	18.30ab	17.43abc
	TC/TN	8.92ab	9.74a	9.37a	9.49a	9.81a
	SMBN (mg kg^{-1})	81.99ab	75.42b	115.06a	100.91a	76.85ab
	SMBC (mg kg^{-1})	711.3ab	657.1b	815.9a	823.8a	771.1ab
	SMBC/SMBN	8.68ab	8.71ab	7.09b	8.16ab	10.03a

Different letters in the same row mean there is a significant difference at the 0.05 level (Duncan's test)

during the crop 2 season was highly variable among the treatments, from 3.93 kg hm^{-2} per year in rice-fallow to 8.46 kg hm^{-2} per year in rice-wheat. In total, the average annual runoff nitrogen loss was highest in rice-wheat (13.15 kg hm^{-2} per year), then followed by rice-rape (11.59 kg hm^{-2} per year) and rice-bean (9.66 kg hm^{-2} per year), and rice-vetch and rice-fallow had the lowest runoff and fewest differences between two treatments (Fig. 4). It was shown that reducing nitrogen input to crop 2 such as rice-bean, rice-vetch, and rice-fallow treatments helped decrease nitrogen loss during runoff, confirming that legume plants had a positive impact on runoff reduction (Douglas et al. 1998). It also suggested that fertilizer nitrogen loss from runoff was limited when fertilizers were applied at suitable rates under proper crop rotations.

3.3 Soil nitrogen fertility and microbial biomass

Soil organic matter, total nitrogen, mineral nitrogen, and potential nitrification rates had similar patterns as those noted in an evaluation index for soil nitrogen fertility (Table 1). The soil nitrogen supply capacity was the major factor contributing to grain yield and crop sustainability. The improvement in soil organic matter, total nitrogen, and mineral nitrogen contributed to incremental grain yield (Mazzoncini et al. 2011); although it may be argued that soil biological activity could contribute to increased grain yields (Larkin 2008).

In this experiment, crop residue return treatments such as rice-rape, rice-vetch, and rice-bean had balanced soil organic matter contents after 3 years of cropping. Nevertheless, soil organic matter decreased by 16.2 % for rice-wheat treatment and 22.8 % for rice-fallow treatment compared to the initial value of 3.2 % in 2009 after 3 years of cropping without crop residue applications (Table 1). Soil organic matter depletion, which has happened in most South Asian countries under intensive rice-based crop rotation (Dawe et al. 2003), was demonstrated to be the major factor in determining yield or nitrogen accumulation reduction.

Soil nitrogen dynamics were directly and closely related to soil organic matter, which was positively correlated with total nitrogen(r=0.758, p <0.01). Total nitrogen had a slight increase over the initial 1.75 g kg^{-1} with crop residue return treatments, but was not statistically significant at the 0.05 level (Table 1). Although other studies (Bi et al. 2009; Dalal et al. 2011) found that plant residues could increase the soil nitrogen content, the changes in total nitrogen were long-term processes and hard to verify with a 3-year experiment.

There was a significant difference in the mineral nitrogen content after 3 years of adding residues to the soil. Highly significant relationships between mineral nitrogen and nitrogen accumulation in plants from non-nitrogen fertilizer plots showed that mineral nitrogen was a valid relative measurement of soil nitrogen supply capacity. The crop type was the most important factor influencing mineral nitrogen in soil. It was also influenced by chemical fertilizer input and residue return. Our experiment indicated that mineral nitrogen was 54 % higher in treatments with legume residue application even though chemical fertilizer inputs were reduced (Table 1). It was suggested that returned legume residue increased the soil mineral nitrogen, which agreed with results reported by

Dalal et al. (2011) and Mazzoncini et al. (2011). The increased mineral nitrogen was attributed to nitrate-sparing by the legume and the mineralization of nitrogen-rich residues. Nitrogen in the vetch biomass was mineralized very soon after being incorporated into the soil. Crop residues from three plants had different nitrogen and carbon contents. It was unsurprising that rice-rape treatments had lower mineral nitrogen than rice-bean and rice-vetch treatments with legume crops because of its higher carbon/nitrogen ratio (Armstrong et al. 1996). Carbon/nitrogen ratios in different crop residues resulted in a nitrogen form change, which influenced nitrogen dynamic processes in the soil. The carbon/nitrogen ratio of rapeseed hulls (16.44) was significantly higher than that in broad bean (11.95) and vetch (11.00). It was also much higher than the carbon/nitrogen ratio in soil (8.9–9.9). Adding residues with higher carbon/nitrogen ratios resulted in nitrogen immobilization in the soil because of high energy from microbes that could consequently decrease the grain yield in subsequent crops in the short term (Kumar and Goh 1999). In contrast, adding residues with low carbon/nitrogen ratios increased the nitrogen released from the residues.

Soil microbial biomass carbon and nitrogen were also significantly higher for rice-bean and rice-vetch treatments influenced by legume residue applications. Zhu et al. (2012) also found that soil microbial biomass nitrogen was improved by the introduction of vetch as winter cover crops in double rice system in southern China. However, the soil microbial biomass carbon/nitrogen ratio of rice-bean treatment was the lowest (Table 1). The total carbon and nitrogen in rice-wheat treatments were significantly lower than other treatments; however, no significant difference was found in the ratio of carbon/nitrogen among the treatments (Table 1). It was inferred that soil microbial biomass carbon and nitrogen determined the transformations of nitrogen, influenced the dynamics of soil organic matter, and strongly impacted micro-environmental changes by residual nitrogen.

The potential nitrification rate resulted from the conversion of ammonium to nitrate, which was used to predict the soil nitrification ability needed for plant growth. Soil carbon content added by residue return was not simply related to the potential nitrification rate, but by a more complex relationship. In this study, the potential nitrification rate had significant positive relations with the soil organic matter, total carbon and nitrogen, and residual carbon. A possible explanation for soil organic matter improvement and its relationship to the potential nitrification rate is to consider that most NH_4^+-N used for nitrification is derived from ammoniating organic matter, and organic matter could promote the reproduction of autotrophic and heterotrophic nitrifiers (Fan et al. 2005). The plants for different crop rotations also affected the nitrification rate. The potential nitrification rates for rice-rape and rice-bean treatments were doubled in comparison to the rice-wheat treatment. The lowest potential nitrification rate for the rice-wheat treatment was likely explained by a strong and long-term inhibition effect from root exudates and no residual return. Wheatley et al. (1990) reported that nitrification rates were significantly reduced by a variety of plants, when compared to the fallow. This experiment showed that the rice-fallow treatment had a higher potential nitrification rate than rice-wheat. The potential nitrification rate of rice-rape treatments did not decline with lower residual nitrogen when compared to rice-bean and rice-vetch treatments in response to the weak and short-term inhibition effects of rape root exudates.

4 Conclusions

Crop rotations are able to influence grain yields and soil nitrogen transformation significantly if incorporated crop residues are returned along with chemical fertilizer nitrogen application. Crop residue return maintained rice grain yields with a reduced chemical fertilizer nitrogen input. Crop rotations involving legumes increased the grain yield by over 5 %. The grain yield responded to nitrogen accumulation in plants, especially with residue return. Rotation treatments with lower nitrogen input in crop 2 helped decrease the nitrogen runoff loss during the winter–spring season. Residue return was also beneficial for runoff reduction during the rice season because of the decreased chemical nitrogen rate. The additional crop residues prevented soil organic matter from depletion and effectively improved the contents of mineral nitrogen, total nitrogen, and the potential nitrification rate of soils. Additional crop residues with a very low carbon/nitrogen ratio promoted the release of nitrogen. Returning legume residues positively influenced both nitrogen transformation and the microenvironment, which reduced nitrogen runoff loss, improved the nitrogen supply capacity, and enhanced crop production with a lower chemical fertilizer nitrogen input. Implementing legume crop rotation may be a feasible method and an important way to reduce chemical fertilizer application while also stabilizing grain yields by improving the soil nitrogen supply capacity, facilitating a healthy agro-ecosystem.

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