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Effects of nitrogen fertilizer on nitrogen use efficiency and yield of rice under different soil conditions

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Abstract Four rice cultivars were used to study the effects of nitrogen fertilizer on nitrogen use efficiency, yield and characteristics of nitrogen uptake under two soil conditions (sandy and clay soil) in soil culture pool. The results were as follows. First, yield of rice in sandy and clay soil was increased by nitrogen application, and that in clay soil was higher than that in sandy soil, but the effect of nitrogen on yield increment was greater in sandy soil than in clay soil. Second, nitrogen utilization of rice was different under different soil conditions. Nitrogen harvest index (NHI) and physiological Nitrogen use efficiency (PNUE) were higher in sandy soil than in clay soil. Apparent Nitrogen recovery efficiency (ANRE), partial factor productivity for applied Nitrogen (PPF), and soil Nitrogen dependent rate (SNDR) were higher in clay soil than in sandy soil. Agronomic Nitrogen use efficiency (ANUE) was varied in different cultivars under different soil conditions. Third, N harvest index, agronomic N use efficiency, physiological N use efficiency, partial factor productivity for applied N, and soil N dependent rate were decreased significantly with the increment of the amount of nitrogen applied under two soil conditions. In sandy soil, ANRE was increased with the increasing nitrogen application and reached the highest value at high nitrogen level. However, in clay soil, ANRE was increased with the increasing of nitrogen application at first, and reached the highest value at medium nitrogen level, then decreased dramatically at high nitrogen level. Fourth, N uptake rate for rice straw and for rice grain and total N uptake rate for rice were higher in sandy clay soil than in sandy soil, but the difference between them was relatively small. Fifth, under different soil conditions, there were significant genotypic differences in the effects of

applying nitrogen fertilizer on nitrogen use efficiency, yield, and characteristics of nitrogen uptake.

Keywords rice, soil condition, applying of nitrogen fertilizer, nitrogen use efficiency, effective yield increasing, characters of nitrogen uptake

1 Introduction

Nitrogen is the indispensable nutrient to rice production and its uptake is affected by a variety of characteristics, fertilizer application, soil conditions, and environmental factors. Rational application technique and nitrogen use efficiency for rice in the field had been studied by many scholars, which had a direct effect on high-yield and high-efficiency production of rice (Yang and Sun, 1992; Cui et al., 1998; Fu, 2001; Fu et al., 2000; Fu et al., 2003; Zhang and Wang, 2002; Yang et al., 2003; Zhang et al., 2003; Dai et al., 2003; Li et al., 1997; Liu et al., 2003; Sheehya et al., 1998; Wopereis-Pura et al., 2002; Khunthasuvon et al., 1998; Ohnishi et al., 1999; Fageria and Baligar, 2001; Berge et al., 1997a; Berge et al., 1997b). However, all of them were studied under the same soil conditions. Studies on the nitrogen use efficiency and yield under different soil conditions were still limited. In fact, the difference of soil condition consequentially results in the difference of nutrient uptake in rice under the same land tillage and management in the same region. The objective of this study was to investigate the variability of yield, nitrogen use efficiency, and characters of nitrogen uptake among rice cultivars under four nitrogen levels (zero, low, medium, and high) and two soil conditions (sandy and clay soil) in soil culture pool.

2 Materials and methods

2.1 Materials

Fengyouxiangzhan, Wuxiangjing 14, Wuyujing 3, and Huajing 2 were used as materials in the experiment. All the cultivars were widely cultivated in Jiangsu province, China.

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2.2 Experiment design

The experiment was conducted at the Agriculture College of Yangzhou University, Jiangsu province, China in 2003. The soils were sandy soil and clay soil. Some basic properties of soils are shown in Table 1. The experiment was conducted with a split plot design which took two soil conditions as main plots, four N rates (0, 150, 225, and 300 kg/hm²) as subplots and genotypes as sub-subplots with two replicates. The plot area was 6.25 m² (2.5 m long and 2.5 m wide). The sowing date was 13 May and transplanting date was 12 June. Transplanting density was 14.4 cm×26.0 cm. Fengyouxiangzhan single seedlings and double seedlings of the other cultivars were planted. N fertilizer was applied in two equal splits (basal and panicle initiation) at different times to the different genotypes. P (150 kg as P₂O₅) and K (75 kg as K₂O) were applied before transplanting and the other cultivation measures were followed according to common practices.

Table 1 Soil characteristics in the experiment

Soil type	Organic matter / g·kg ⁻¹	Total N / g·kg ⁻¹	Alkalihdro. N / mg·kg ⁻¹	Avail. P / mg·kg ⁻¹	Avail. K / mg·kg ⁻¹
Sandy soil	7.2	0.43	18.7	24.9	54.3
Clay soil	8.6	0.58	42.2	15.2	73.4

2.3 Indexes and mensuration methods

2.3.1 Basic characteristics of soil

Soil samples were collected before plowing to a depth of 0–20 cm and mixed. The characteristics of soil were described in Table 1.

2.3.2 Yield determination

Rice was harvested at maturing stage and yield of each plot was determined.

2.3.3 Nitrogen determination

Plant and grain nitrogen concentration was determined by the methods of micro-Kjeldahl digestion, distillation, and titration.

2.3.4 Definition of relative parameters

Nitrogen harvest index (NHI) = grain N uptake / total plant N uptake;

Apparent N recovery efficiency (ANRE) = (total plant N uptake with N application – total plant N uptake without N application) / N application × 100;

Agronomic N use efficiency (ANUE) = (grain yield with N application – grain yield without N application) / N application;

Physiological N-use efficiency (PNUE) = (grain yield with N application – grain yield without N application) / (total plant N uptake with N application – total plant N uptake without N application);

Partial factor productivity for applied N (PFP) = grain yield with N application / N application;

Soil N dependent rate (SNDR) = total plant N uptake without N application / total plant N uptake with N application.

2.4 Data analysis

All of the data were analyzed with Data Processing System and figured with Microsoft Excel 2000.

3 Results and analysis

3.1 Effect of N application on yield increase under different soil conditions

Grain yields with N application were significantly higher than those without N application under two soil conditions (Table 2). Significant variation in grain yield was also observed among treatments with N application. In this research, the effect of N application on yield increase was remarkable. With N application, grain yield was increased by 72.5% to 130.1% ranging from 3 508.5 to 9 303.0 kg/hm² in sandy soil, while it was increased by 64.6% to 104.4% ranging from 4185.0 to 9825.0 kg/hm² in clay soil. Thus, it can be seen that grain yield in clay soil was significantly higher than that in sandy soil, but the effect of N application on yield increase in sandy soil was significantly more than that in clay soil. It was demonstrated that soil basic fertility was important for rice yield increase and fertilizing soil was the precondition for high yield.

Response of the yield to the nitrogen fertilizer was varied among different cultivars under different soil conditions (Table 2). Under both soil conditions, yield of Wuxiangjing14 and Huajing2 was increased with increasing N application. The effect of yield increase still existed in the treatment with 300 kg/hm² N application. In sandy soil, yield of Fengyouxiangzhan and Wuyujing 3 was increased obviously with increasing N application and the effect of yield increase still existed in the treatment with 300 kg/hm² N application. But in clay soil, yield of Fengyouxiangzhan and Wuyujing 3 was increased obviously with increasing N application firstly and reached the maximum when N application was 225 kg/hm². Then it decreased when N application was 300 kg/hm². The effect of yield increase under 300 kg/hm² N applications was remarkably lower than that under 225 kg/hm² N applications. It indicated that the amount of N demand for the highest yield and the amount of N demand for the best economical benefit were different among rice cultivars under different soil conditions.

Table 2 Effect of nitrogen on rice yield under different soil conditions

Genotype	Nitrogen level / kg · hm ⁻²	Sandy soil		Clay soil		
		Yield / kg · hm ⁻²	Increased yield / %	Yield / kg · hm ⁻²	Increased yield / %	
Fengyouxiangzhan	0	4294.5	D d	5035.5	C d	
	150	7407.0	C c	8556.0	B c	69.9
	225	8448.0	B b	9385.5	A a	86.4
	300	8922.0	A a	9264.0	A b	84.0
Wuxiangjing 14	0	4053.0	C c	4806.0	D d	
	150	7285.5	B b	8055.0	C c	67.6
	225	8950.5	A a	9465.0	B b	96.9
	300	9303.0	A a	9825.0	A a	104.4
Wuyujing 3	0	3742.5	C d	4485.0	C d	
	150	6963.0	B c	7780.5	B c	73.5
	225	8080.5	A b	9042.0	A a	101.6
	300	8491.5	A a	8850.0	A b	97.3
Huanjing 2	0	3508.5	D d	4185.0	C d	
	150	6339.0	C c	6888.0	B c	64.6
	225	7605.0	B b	8295.0	A b	98.2
	300	8074.5	A a	8512.5	A a	103.4

Note: Values within a column followed by different letters were significantly different at 1% (capital letter) and 5% (small letter) levels, respectively.

Nitrogen fertilizer efficiency equations were developed according to the quadratic equation of one variable $y = b_0 + b_1x + b_2x^2$ (Table 3). A regression equation was used to evaluate the relative coefficient between y and the real yield Y , and significance test about the regression equation was also carried out. Results showed that they both reached the significant level. It indicated that the equation can reveal the relationship between N fertilizer and grain yield. According to Table 2, the rational amount of N application was varied in different soils. Through calculation by using the equation, tiptop yield in clay soil was higher than that in sandy soil for the four rice genotypes in our trial. However, the amount of N demand for the tiptop yield in sandy soil was higher than that in clay soil. These phenomena indicated that the lower the soil fertility, the more the amount of N application, and the higher the soil fertility, the fewer the amount of N fertility for the tiptop yields. Table 3 also showed that no matter what kind of soil, genotypic differences existed in the tiptop yield and amount of N demand for the tiptop yield. Therefore, the program of N application must be formulated based on soil conditions and cultivars in order to get the highest yield in rice production.

3.2 N use efficiency under different soil conditions

N use efficiency was measured through the minus method (Table 4). Results showed that all kinds of indexes for N use efficiency under different soil conditions were affected significantly by N application.

N harvest index was defined as the percent of grain N uptake to total plant N uptake. Under both two soil conditions, NHI of rice genotypes for experiment was decreased significantly with increasing N application. It indicated that the N ratio in straw enhanced with increasing N application and it led to rice plant uptake N excessively. This result was similar to that of Liu et al. (2003). N harvest index was compared under different soil conditions. Results showed that NHI of all rice genotypes was higher in sandy soil than that in clay soil except for Wuxiangjing 14 whose NHI was higher in clay soil than that in sandy soil.

Apparent N recovery efficiency was defined as the ratio that total plant N uptake with N application minus total plant N uptake without N application, then divided by N application. It was the primary index to describe the characteristics of N uptake and utilization in rice. Most

Table 3 Nitrogen fertilizer efficiency equation and amount of nitrogen application for tiptop yield in rice under different soil conditions

Soil type	Genotype	Nitrogen fertilizer efficiency equation	Tiptop yield / (kg · hm ⁻²)	Amount of nitrogen applied for tiptop yield / (kg · hm ⁻²)
Sandy soil	Fengyouxiangzhan	$y = -0.0369x^2 + 26.568x + 4288.9, r = 0.9998$	9071.1	360.0
	Wuxiangjing 14	$y = -0.0352x^2 + 28.539x + 4016.2, r = 0.9957$	9800.8	405.4
	Wuyujing 3	$y = -0.0399x^2 + 27.926x + 3733, r = 0.9996$	8619.4	349.9
	Huajing 2	$y = -0.0286x^2 + 24.047x + 3488.8, r = 0.9984$	8543.5	420.4
Clay soil	Fengyouxiangzhan	$y = -0.0645x^2 + 33.567x + 5026.7, r = 0.9996$	9393.9	260.2
	Wuxiangjing 14	$y = -0.0384x^2 + 28.574x + 4780.7, r = 0.9978$	10096.3	372.1
	Wuyujing 3	$y = -0.0567x^2 + 32.000x + 4451.6, r = 0.9956$	8966.6	282.2
	Huajing 2	$y = -0.0314x^2 + 24.287x + 4150.8, r = 0.9948$	8847.1	386.7

Note: Amount of nitrogen applied for tiptop yield was gained according to nitrogen fertilizer efficiency equation.

Table 4 N use efficiency for rice genotypes under different soil conditions

Genotype	Soil type	Nitrogen level / kg · hm ⁻²	NHI	ANRE / %	ANUE	PNUE	PFP	SNDR / %	
Fengyouxiangzhan	Sandy soil	0	0.889						
		150	0.856	39.7	20.8	52.2	49.4	39.0	
		225	0.819	41.8	18.5	44.2	37.5	28.9	
		300	0.706	44.8	15.4	34.4	29.7	22.1	
		Mean	0.817	42.1	18.2	43.6	38.9	30.0	
	Clay soil	0	0.872						
		150	0.851	44.1	23.5	53.3	57.0	46.1	
		225	0.723	52.0	19.3	37.2	41.7	32.6	
		300	0.697	43.8	14.1	32.1	30.9	30.0	
		Mean	0.785	46.6	19.0	40.9	43.2	36.2	
Wuxiangjing 14	Sandy soil	0	0.875						
		150	0.863	31.3	21.6	68.9	48.6	43.4	
		225	0.801	37.9	21.4	56.4	39.4	29.6	
		300	0.719	38.5	17.5	45.5	31.0	23.7	
		Mean	0.814	35.9	20.1	56.9	39.7	32.2	
	Clay soil	0	0.905						
		150	0.875	34.7	21.7	62.4	53.7	48.7	
		225	0.803	42.0	20.7	49.3	42.1	34.3	
		300	0.751	39.7	16.7	42.1	32.8	29.3	
		Mean	0.833	38.8	19.7	51.3	42.8	37.4	
Wuyujing 3	Sandy soil	0	0.917						
		150	0.907	36.5	21.5	58.8	46.4	42.7	
		225	0.897	37.5	19.3	51.4	35.9	32.6	
		300	0.802	38.3	15.8	41.3	28.3	26.2	
		Mean	0.881	37.4	18.9	50.5	36.9	33.8	
	Clay soil	0	0.915						
		150	0.908	40.2	22.0	54.7	51.9	47.9	
		225	0.881	46.1	20.3	44.0	40.2	34.8	
		300	0.794	40.9	14.6	35.6	29.5	31.1	
		Mean	0.878	39.6	18.9	48.0	38.4	35.6	
Huajing 2	Sandy soil	0	0.808						
		150	0.798	35.4	18.9	53.3	42.3	42.4	
		225	0.729	40.6	18.2	44.9	33.8	30.0	
		300	0.658	41.0	15.2	37.1	26.9	24.1	
		Mean	0.748	39.0	17.4	45.1	34.3	32.2	
	Clay soil	0	0.738						
		150	0.712	48.3	18.0	37.3	45.9	42.4	
		225	0.683	51.4	18.3	35.5	36.9	31.5	
		300	0.674	44.6	14.4	32.4	28.4	28.5	
		Mean	0.702	48.1	16.9	35.1	37.1	34.1	

researchers considered that this description accorded with the fact of rice production. In this research, ANRE was increased with increasing of N application in sandy soil while it was increased firstly and reach to the maximum under 225 kg/hm² N application, then declined significantly under 300 kg/hm² N application in clay soil. It indicated that it was not useful for improvement of ANRE with more or less N application. Compared ANRE under two soil conditions, it was higher in clay soil than that in sandy soil.

Agronomic N use efficiency was defined as the ratio of grain yield with N application minus grain yield without N application to N application and was used to describe the capability of yield increase per kilogram pure N. With increasing of N application, ANUE of all genotypes was both decreased significantly under two soil conditions. It indicated that no matter in what kind of soil, the capability of yield increase per kilogram pure N declined remarkably with increasing N application. Agronomic N use efficiency of

different genotypes was different under two soil conditions. Agronomic N use efficiency of Wuxiangjing 14 and Huajing 2 were higher in sandy soil than that in clay soil, while it was reverse in Fengyouxiangzhan and Wuyujing 3.

Physiological N use efficiency was defined as the ratio of yield increased with N application to total plant N uptake increased with N application and it reflected the use efficiency of N absorbed by rice plant. Under two soil conditions, PNUE of all genotypes was decreased significantly with increasing N application (Table 4). It showed that yield increased per kilogram N accumulated in rice plant was decreased with increasing N application and it obeyed the reward descending rule. Compared to PNUE under two soil conditions, it was higher in sandy soil than that in clay soil.

Partial factor productivity for applied N was defined as the ratio of grain yield with N application to N application and it reflected the marginal effect of N absorbed by rice plant from N fertilizer and soil. Partial factor productivity for applied

N was decreased significantly with increasing N application (Table 4) and it was higher in clay soil than that in sandy soil.

Soil N dependent rate was defined as the ratio of total plant N uptake without N application to total plant N uptake with N application and it reflected the contribution of soil N to plant N nutrition. Soil N dependent rate for all genotypes was decreased significantly with increasing N application (Table 4). It indicated that the reliance of rice growth on soil N was weakened while the reliance of rice growth on fertilizer N was strengthened with the increase of N application. The effect of fertilizer N on rice growth was increased remarkably. It demonstrated that the higher soil N

concentration, the more soil N supply, and the more the rice relied on soil N. On the contrary, the lower soil N concentration, the less soil N supply, and the less the rice relied on soil N. These fully indicated that the contribution of soil N nutrition to rice in the growth season was great. And it was important to improve soil fertility and maintain the high contribution of soil N to rice growth for high yield and high N use efficiency.

3.3 Characteristics of N absorbing in different soils

N accumulation at maturity in rice organs was shown in Figs. 1–3. Results indicated that N accumulation in straw,

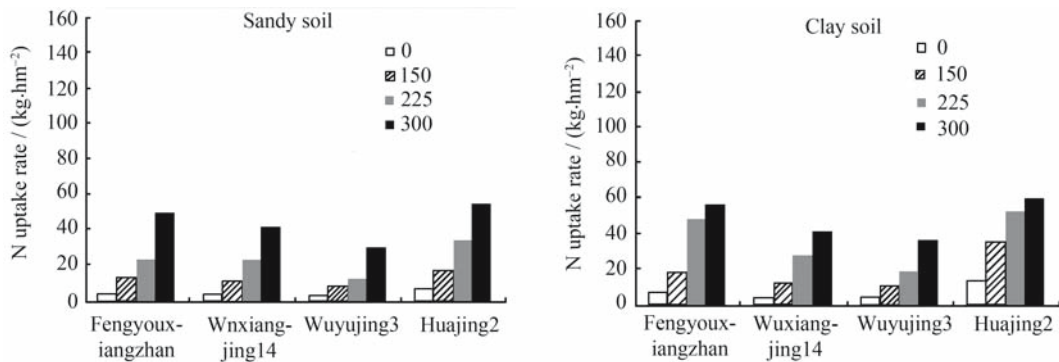


Fig. 1 N uptake rate for rice straw under different soils

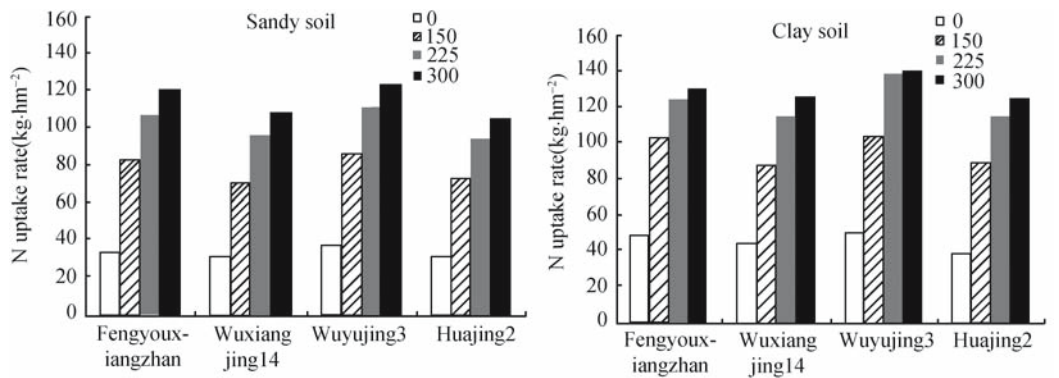


Fig. 2 N uptake rate for rice grain under different soils

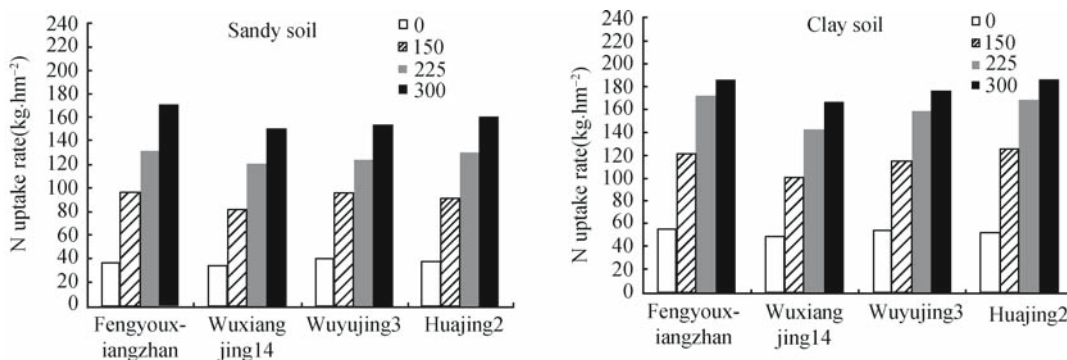
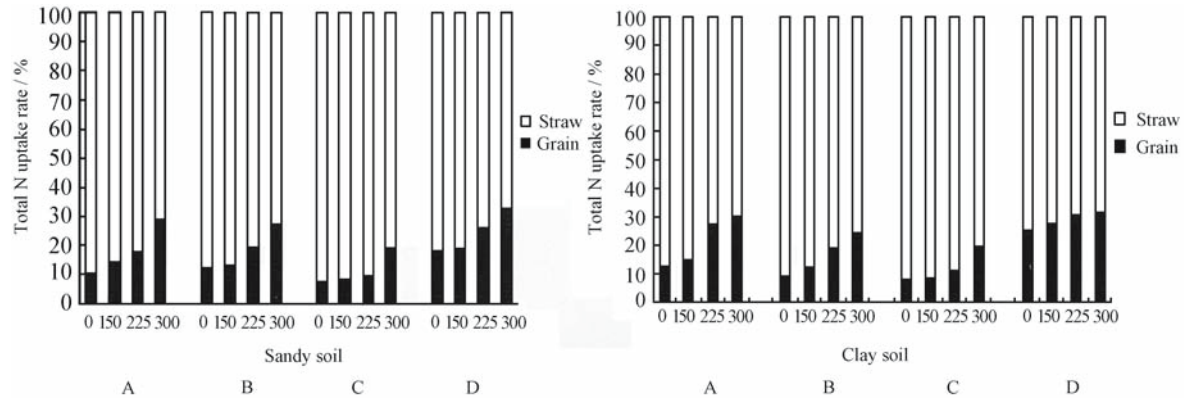


Fig. 3 Total N uptake rate for rice under different soils



A: Fengyouxiangzhan; B: Wuxiangjing 14; C: Wuyunjing 3; D: Huajing 2
Fig. 4 Distribution of N uptake in rice plant under different soils

grain and plant was remarkably affected by N application. N accumulation in grain was increased remarkably with increasing of N application at first because grain yield increased quickly, then slowed down because grain yield increased slowly or even decreased (Fig. 2). By contrast, N accumulation in straw was increased gradually because of the quickly increasing of straw yield (Fig. 1). Total N accumulation in rice plant also showed the trend of fast increasing at first and then slowed down (Fig. 3). Genotypic differences were also existed among the rice cultivars under two soil conditions. N accumulation in straw was highest for Huajing 2 and it was the lowest for Wuyunjing 3 under the both soil conditions. And the mean value of Huajing 2 was higher than that of Wuyunjing 3 by 109.7% and 133.1% in sandy soil and in clay soil, respectively. N accumulation in grain was the highest in Wuyunjing 3 while it was the lowest in Huajing 2. The mean value of Wuyunjing 3 was higher than that of Huajing 2 by 17.8% and 18.2% under two soil conditions, respectively. Total N accumulation in rice plant was the highest for Fengyouxiangzhan and the lowest for Wuxiangjing 14. The mean value of Fengyouxiangzhan was higher than that of Wuxiangjing 14 by 12.6% and 16.7% under two soil conditions, respectively. N accumulation in straw, N accumulation in grain, and the total N accumulation in rice plant were all higher in clay soil than that in sandy soil for the rice genotypes in this research.

N distribution in grain was higher than that in straw for all treatments in this research. The concentration in straw was increased significantly while it declined in grain with increasing N application under the two soil conditions. It indicated that N application can improve N translation from nutrition organs to grain, but more N was left in nutrition organs because of the decreasing N translation rate and led to an excessive uptake of N by rice plant, and decreases in NHI and nitrogen use efficiency. Differences of N distribution for four rice genotypes were not significant under the two soil conditions.

4 Discussion

The effect of soil condition on rice yield and N absorption and utilization existed in rice production. Because of the restrictions from the experiment conditions, few complete comparisons between characteristics of N absorption and utilization under different soil conditions were done although it was important for rice production. According to the relationship between soil conditions and rice production, adjustment of N practice aiming at improving the potential of soil production could increase N use efficiency and increase rice grain yield. In this experiment, the effect of yield increase was varied under different soil conditions. Rice yield under the tested soil conditions was both increased with the increasing N application, but the yield in clay soil was higher than that in sandy soil, the effect of yield increase was higher in sandy soil than that in clay soil. The difference of the effect of yield increase may be related to the basic soil fertility. It also demonstrated that improving and maintaining high soil fertility is the basis of rice production for high yield and high N use efficiency.

N use efficiency was varied under different soil conditions. In this experiment, NHI and PNUE were higher in sandy soil than those in clay soil while ANRE, PFP, and SNDR were higher in clay soil than those in sandy soil. Agronomic N use efficiency was varied under two soil conditions among different rice genotypes. These were different from former research results because of soil fertility was lower in sandy soil than that in clay soil. With increasing N application, NHI, ANUE, PNUE, PFP, and SNDR were decreased significantly under the tested soil conditions. Apparent N recovery efficiency was increased with increasing of N application in sandy soil while it was increased at first and reaches to the maximum under 225 kg/hm² N application and then decreased significantly with 300 kg/hm² N application. It indicated that the ability of N supply of clay soil was stronger than that of sandy soil. Clay soil was found to supply more N than sand soil, so the

dependence of soil N was higher in clay soil than in sand soil, and the dependence of N fertilizer was lower in clay soil than in sandy soil. Therefore, effect of N fertilizer on yield increase was more obvious in sandy soil than that in clay soil. In order to make full use of the effect of fertilizer N on yield increase and increase grain yield and N use efficiency, we should control N application in clay soil and stabilize N application in sandy soil on condition that the soil is fertile for rice production.

Results in this research also showed that the response of different rice cultivars to N application was not the same. Significant genetic differences existed among effect of yield increase with N application, N use efficiency, N accumulation, and distribution in rice under different soil conditions. Rational N application, as an important factor affecting rice yield and quality mostly, has always been the important aspect in rice research. However, in the recent practices of rice production, genetic differences in rice N nutrition are always neglected when applying N fertilizers, inevitably making N application and demand unbalanced, reducing the production efficiency, and wasting resources. Therefore, studies on the differences in N nutrition originated from rice genotypes are urgent for the purpose of proper fertilization, reduction of resource wasting and protection of the environment.

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References

- Berge H F M, Qinghua S, Zhiming Z, Rao K S, Riethoven J J M, Xuhua Z (1997b). Numerical optimization of nitrogen application to rice. Part II: Field evaluations. *Field Crops Research*, 51: 29–42
- Berge H F M, Thiyagarajan T M, Qinghua S, Wopereis M C S, Drenth H, Jansen M J W (1997a). Numerical optimization of nitrogen application to rice. Part I: Description of MANAGE-N. *Field Crops Research*, 51: 29–42
- Cui Y T, Cheng X, Han C R, Li R G (1998). Rice nitrogen utilization efficiency and nitrogen leaching amount in Taihu Lake watershed of south Jiangsu Province. *Journal of China Agricultural University*, 3(5): 51–54 (in Chinese)
- Dai P A, Nie J, Zheng S X, Xiao J (2003). Efficiency of nutrient utilization of controlled-release nitrogen fertilizer for rice at different soil fertility levels. *Chinese Journal of Soil Science*, 34(2): 115–119 (in Chinese)
- Fageria N K, Baligar V C (2001). Lowland rice response to nitrogen fertilization. *Commun Soil Sci Plant Anal*, 32(9, 10): 1405–1429
- Fu J R (2001). Effects of controlled release fertilizer on rice yield and N recovery. *Plant Nutrition and Fertilizer Science*, 7(2): 145–152 (in Chinese)
- Fu Q L, Chen Y X, Yu J Y (2003). Study on satisfactory amount of nitrogen fertilizer applied on rice in the middle area of Zhejiang Province. *Acta Pedologica Sinica*, 40(5): 787–790 (in Chinese)
- Fu Q L, Yu J Y, Chen Y X (2000). Effect of nitrogen applications on dry matter and nitrogen partitioning in rice and nitrogen fertilizer requirements for rice production. *Journal of Zhejiang University*, 26(4): 399–403 (in Chinese)
- Khunthasuvon S, Rajastasereekul S, Hanviriyapant P, Romyen P, Fukai S, Basnayake J, Skulkhu E (1998). Lowland rice improvement in northern and northeast Thailand I. Effects of fertiliser application and irrigation. *Field Crops Research*, 59: 99–108
- Li W B, Wu L S, Liao H Q (1997). Application and crop recovery of N-fertilizer in high-yielding paddy field of Taihu region. *Acta Pedologica Sinica*, 34(1): 67–73 (in Chinese)
- Liu L J, Sang D Z, Liu C L, Wang Z Q, Yang J C, Zhu Q S (2003). Effects of real-time and site-specific nitrogen managements on rice yield and nitrogen use efficiency. *Scientia Agricultura Sinica*, 36(12): 1456–1461 (in Chinese)
- Ohnishi M, Horie T, Homma K, Supapoj N, Takano H, Yamamoto S (1999). Nitrogen management and cultivar effects on rice yield and nitrogen use efficiency in Northeast Thailand. *Field Crops Research*, 1999, 64: 109–120
- Sheehya J E, Dionora M J, Mitchell P L, Peng S, Cassman K G, Lemaire G, Williams R L (1998). Critical nitrogen concentrations: Implications for high-yielding rice (*Oryza sativa* L) cultivars in the tropics. *Field Crops Research*, 59: 31–41
- Wopereis-Pura M M, Watanabe H, Moreira J, Wopereis M C S (2002). Effect of late nitrogen application on rice yield, grain quality and profitability in the Senegal River valley. *European Journal of Agronomy*, 17: 191–198
- Yang J P, Jiang N, Chen J (2003). Dynamic simulation of nitrogen application level effects on rice yield and optimization analysis of fertilizer sup-my in paddy field. *Chinese Journal of Applied Ecology*, 14(10): 1654–1660 (in Chinese)
- Yang X E, Sun S (1992). Varietal difference of rice plants in response to N and its mechanisms. *Acta Pedologica Sinica*, 9(1): 73–79 (in Chinese)
- Zhang H C, Wang X Q, Dai Q G., Huo Z Y, Xu K (2003). Effects of N-application rate on yield, quality and characters of nitrogen uptake of hybrid rice variety Liangyoupeijiu. *Scientia Agricultura Sinica*, 36(7): 800–806 (in Chinese)
- Zhang Q C, Wang G H (2002). Optimal nitrogen application for direct-seeding early rice. *Chinese J Rice Sci*, 16(4): 346–350 (in Chinese)