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Effects of available nitrogen and ammonium adsorption of plow layer on nitrogen uptake and yield of paddy rice (*Oryza sativa* L.)

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Abstract

Effects of available nitrogen (N) and ammonium adsorption of plow layer (PL) on N uptake and brown rice yield were investigated for seven soils. The experiment was conducted in a single paddy field under same conditions except for soils. Rice plants were grown in frames, which the seven different soils (four alluvial paddy soils and three andic paddy soils) were repacked. Not only a small percolation condition (i.e. original subsoil (OS) plot) but also an increased percolation condition was treated by the replacement of subsoil with sand (i.e. sandy subsoil (SS) plot). Percolation rate was lower in clayey smectitic (1-2 mm day^{-1}) than in sandy and andic (5-9 mm day^{-1}) soils in the SS plots. In the OS plots, percentage of exchangeable ammonium-N in total soil ammonium N was 89-96 % in all soils at 11 days after transplanting (DAT), and was higher in soils with the large ammonium adsorption of PL. Soil ammonium-N at 40 DAT (i.e. at active-tillering stage), N uptake at harvest and brown rice yield were explained by the available N of PL in the OS plots. It is considered that the difference of ammonium adsorption of PL did not strongly affect them, because of its small variation and the small percolation. In the SS plots, the soil ammonium-N at 40 DAT was explained by the ammonium adsorption and the available N of PL. It is considered that soil ammonium-N was much protected from leaching and denitrification in soils with the large ammonium adsorption of PL. However, the total N uptake and the brown rice yield were effectively explained by the available N of PL, and the ammonium adsorption of PL was not selected as an important parameter. It is considered that the ammonium adsorption of PL did not strongly affect the N uptake after maximum tillering stage. The ammonium adsorption of PL did not significantly related to recovery rate of fertilizer N both in the OS and SS plots because of the small variation in the ammonium adsorption of PL among soils.

INTRODUCTION

Yield of rice (*Oryza sativa* L.) is related to the amount of nitrogen (N) uptake until maturity (Wada, 1969). In the Tohoku district of Japan, 70 % of the total N uptake by rice plants comes from mineralized soil organic N (Shoji & Mae, 1984), especially from that in plow layers (PL) (Ando et al., 1990). Therefore, the amount of mineralization of soil organic N (available N) in PL profoundly affect the N uptake by rice plant. On the other hand, 30 % of the total N uptake by rice plant comes from fertilizer N. Recovery rate of fertilizer N with basal application was in the range from 18 % to 42 %. About 30 % of basal fertilizer N is immobilized in soils and about 40 % is diminished by denitrification and leaching (Shoji & Mae, 1984). Average of the recovery rate of topdressed fertilizer N was about 55 % (Shoji & Mae, 1984). From these studies, the recovery rate of the sum of basal and topdressed fertilizer N (5 g N m^{-2} and 2 g N m^{-2}, respectively) is estimated at between 30 and 46 %.

It is generally considered that ammonium adsorption in soil can affect the N uptake by rice plant. It is reported that the percentage of adsorbed ammonium in soils ranges from 85 to 95 % in paddy fields (Okajima & Imai, 1973; Toriyama & Ishida, 1987). The selectivity of ammonium is high in smectitic and low in allophanic soils (Okamura & Wada, 1984; Egashira et al., 1998). In a column experiment, leaching rate of ammonium was extremely less in smectitic soils than those in soils rich in allophane (Harada & Kutsuna, 1960). In a pot experiment, tillering of rice plants at early tillering stage was less in a smectitic soil than those in soils rich in other crystalline clay minerals. However, at the end of the tillering stage, the tiller number increased more rapidly and the yield of grain was higher in smectitic, than in the other soils (Harada et al., 1960). The recovery rate of basal fertilizer nitrogen was higher in a soil rich in smectite than in a soil rich in 2:1-2:1:1 intergraded minerals (Shoji et al., 1976). It is generally considered that N deficiency often occurs in coarse textured alluvial and andic paddy soils because of large amount of N leaching (Wakatsuki, 1998). These studies suggest that the ammonium adsorption by soil will influence the fertilizer N recovery and rice growth.

However, it is still questionable if the difference in the ammonium adsorption of soils affects the N uptake and the rice yield in the fields. The amount of fertilizer N applied in the column leaching experiment by Harada and Kutsuna (1960) was extremely greater than under condition of actual rice cultivation in fields. In a lysimeter experiment, which fertilizer N was applied at almost the same rate as for actual rice cultivation, the amount of N leaching was only 2 % of the applied fertilizer N (Maeda & Onikura, 1976). No relationship between the cation exchange capacity and the amount of N uptake by rice plants was observed among five paddy soils in Yamagata Prefecture (Tanaka et al., 1982).

The effects of the available N and the ammonium adsorption of PL on the N uptake and the grain yield of rice plants have not been comprehensively investigated in a field. In this study, we investigated if the ammonium adsorption of PL affects the N uptake and the yield of rice, together with the available N. In connection with ammonium-N in soils, an increased percolation promotes the ammonium-N leaching. It is also considered that oxygen supplied with percolating water promotes nitrification and denitrification. Therefore, it is hypothesized that the positive effects of the ammonium adsorption on the N uptake and the rice yield are clearly observed under the increased percolation condition. The effects of the ammonium adsorption were investigated also under a condition, where the percolation was increased and the rice plants depended N uptake only on the PL.

MATERIALS AND METHODS

1. Soils

PL of four alluvial and three andic paddy soils from the Tohoku district of Japan were used (Table 1). Fujishima soil was used only in 2005, and the other soils were used in 2004 and 2005 without resampling. Clay content was determined by a pipette method. Clay mineralogical composition of clay fraction was identified by the X-ray diffraction (Rigaku Co. Ltd, Miniflex). Total contents of carbon and N were determined by a dry combustion method (Sumitomo chemical Co. Ltd., NC-80). The available N was evaluated by incubation using the fresh moist soils under a submerged condition at 30 °C for 4 weeks. The ammonium adsorption was estimated in a laboratory experiment. 10 g of the air-dry soils (<2 mm) was added with 20 mL of 25 mg N L^{-1} ammonium chloride (containing nitrapyrin at a concentration of 2 mg L^{-1} as nitrification suppressor) and was shaken for 24 h at 25 °C. The amount of added ammonium-N corresponded to 5 g N m^{-2} in the field. Ammonium chloride was used to avoid the effects of pH change or salt adsorption, which was expected to occur by the addition of ammonium carbonate or ammonium sulfate. After shaking, the concentration of ammonium-N in the filtered solution was determined by the indophenol blue photometric method (Scheiner, 1976). The decrease of ammonium-N in the solution was regarded as the ammonium adsorption rate by the soil. Therefore, the ammonium adsorption rate evaluates the sum of exchangeable form and fixed form into 2:1 type clay minerals. The available N and the ammonium adsorption of PL per square meter were calculated, using the weight of dry soil in the PL (0.15 m).

Table 1 Properties of the tested soils.

Soils		Clay content	Dominated clay minerals†	T-C	T-N	Available N‡		NH_4^+-N adsorption rate	Weight of dry soil in the plow layer (PL§)	Available N in PL		NH_4^+-N adsorption of PL‡
						2004	2005			2004	2005	
		(g kg^{-1})		(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(kg m^{-2})	(g m^{-2})	(g m^{-2})	(g m^{-2})
Alluvial	Tsuruoka	116	Sm, Int, KM	25.7	2.4	31.8	18.9	32.6	165	5.3	3.1	5.4
soils	Fujishima	264	Sm, Int, KM	37.8	3.3	-	60.5	41.0	126	-	7.6	5.2
	Kiyosato	411	Sm	39.3	4.0	65.4	33.0	44.7	125	8.2	4.1	5.6
	Ohgata	476	Sm, Int	41.6	4.3	60.2	46.7	47.2	118	7.1	5.5	5.6
Volcanic	Naruko	126	Sm, Vt, Int, Ch, KM	46.7	3.7	30.6	18.3	36.1	120	3.7	2.2	4.3
ash soils	Shikama	211	Sm, Int	68.8	5.2	26.6	21.8	38.0	113	3.0	2.5	4.3
	Mohka	341	Amor	106.6	8.1	20.8	17.2	38.4	106	2.2	1.8	4.1

† Abbreviations; Sm, smectite; Int, 2:1~2:1:1 intergraded minerals; KM, kaolin minerals; Vt, vermiculite; Ch, chlorite; Amor, amorphous minerals.

‡ Available N was evaluated by incubation under anaerobic condition at 30 °C for 4 weeks, using fresh moist soils before fertilization and puddling in each year.

§ The values were calculated using the weights of dry soil in the plow layers (0.15 m depth).

2. Replacement of PL by the soils and cultivation method

The field experiment was conducted at a paddy field in Field Science Center, Graduate School of Agricultural Science, Tohoku University, Miyagi Prefecture, the Tohoku district of Japan (38°44' N; 140°15' E). The paddy soil was Wet Andosol (Typic Melanudands) on terraced land. The depth of the PL was 0.15 m. The percolation rate was 3 mm day^{-1} at the most, because of the artificial subsoil compaction. In 2004 and 2005, plastic bottomless frames (0.076 m^2, 0.28 m×0.28 m×0.18 m height) were buried in the PL and soil in the frames was removed (i.e. original subsoil (OS) plot). In 2005, the effects of the ammonium adsorption of PL were investigated also in a condition, where the percolation was increased and rice did not elongate the roots to the subsoil. The subsoil (0.15-0.70 m in depth) was replaced with sand in a part of the field (7 m×1 m). The half-size frames (0.038 m^2, 0.28 m×0.14 m×0.18 m height), with fabric for root zone restriction attached on the bottom were buried in the plow layer (i.e. sandy subsoil (SS) plot). The fabric was made of polyester, and water can percolate through it (percolation rate was 10^{-4} cm s^{-1} in an upland condition, measured by the company). To evaluate the N uptake from the subsoil, additional circle frames (0.048 m^{-2}) with and without the fabric on the bottom were buried on the original subsoil. On May 12, 2004 and May 14, 2005, each PL was puddled with chemical fertilizers and rice straw. Each soil was filled in the frames to a depth of 0.15 m. Urea was incorporated into the PL at a rate of 5 g N m^{-2} as basal dressing and was topdressed at a rate of 2 g N m^{-2} at panicle initiation stage using ^{15}N labeled urea (3.05 atom %). Potassium chloride (7 g K_2O m^{-2}), calcium phosphate (7 g P_2O_5 m^{-2}) and rice straw (500 g dry matter m^{-2}) were also incorporated into the PL as the basal application. The plow layer of the field, which was applied with mixed fertilizer (7 g N m^{-2}; 10 g K_2O m^{-2}; 7 g P_2O_5 m^{-2}), was filled into the additional circle frames. Rice seedlings (cultivar: Hitomebore) at 7 leaf age were transplanted on May 14, 2004 and on May 17, 2005. Each hill was comprised of three seedlings. Two hills or one hill was transplanted in a frame in the OS plots or the SS plots. The rice plants were also grown around the frames. Planting density was 22.2 hills per m^2 in the vegetation community around the frames and 26.4 hills per m^2 in the frames. In the additional circle frame, two hills were transplanted, and the planting density was 41.7 hills per m^2. Midseason drainage was performed from July 8 to 12 in 2004 and from July 9 to 12 in 2005. Topdressing at the panicle initiation stage was applied on July 13, 2004 and on July 14, 2005. The rice plants above ground were harvested on September 18, 2004 and September 21, 2005.

3. Methods of field survey and chemical analysis

The percolation rate was measured in 2006, a year after the rice cultivation experiment. Plastic cylinders (diameter 0.07 m, height 0.33 m) with a small pore (diameter 0.01 m) were inserted to a depth of 0.20 m, and the PL inside the cylinders was removed. The seven soils were puddled with the chemical fertilizers at the rate of the basal fertilization in the cultivation experiment. The soils were packed in the cylinders to a depth of 0.15 m in the SS plot. The cylinders packed with Naruko soil were settled also in the OS plot. The small pores on the side were usually open so that ponding water level was same inside and outside the cylinders. The pores were closed with stoppers periodically, and the percolation rate was measured with a decrease of ponding water level after a day. The experiment was carried out with three replications.

The ammonium-N in the PL was measured at 3, 14, 35 and 48 days after transplanting (DAT) in 2004 and at 11 and 40 DAT in 2005. Soil samples were taken at two or four points in a frame to a depth of 0.12 m using a small cylinder (35 mL volume). The soil samples collected from the same frame were mixed and the soil samples of 30 g were centrifuged at 10,000 rpm for 20 minutes and the supernatant was obtained as soil solution. Exchangeable ammonium-N was extracted by shaking the precipitated soils for 2 hours with 2 M potassium chloride (KCl). The concentration of ammonium-N in the soil solution and the KCl extractant was determined by the indophenol blue photometric method (Scheiner, 1976). The amounts of ammonium-N per unit area (g N m^{-2}) in the soil solution (i.e. dissolved) and in the exchangeable form were calculated using the concentrations of ammonium-N and weight of dry soil in each frame.

The tiller number was measured periodically. After harvest, the shoots and half of the grains were dried in an oven at 70 °C for more than 72 hours and their dry weights were determined. The N content was determined by a dry combustion method (Sumitomo chemical Co. Ltd., NC-80). The ^{15}N atom percentages in the shoots and the grains were determined with a mass spectrometer (Finnigan MAT, DELTA plus). The N uptake from the fertilizer was determined using the ^{15}N ratio and the N concentration. The brown rice yield and the yield components were determined using the other half of the grains. The ripened grains and the poorly ripened grains were separated with sodium chloride solution with a density of 1.06. The thousand-grain weight and the brown rice yield were calculated to have a grain water content of 15 %.

4. Statistical Analysis

N supply from soil was largely different between the OS and SS plots, because of the percolation and the lack of root elongation to the subsoil. Therefore, statistical analysis was conducted separately in each plot. The experiment was carried out with triplicate randomized plots. Analysis of variance among soils was carried out using Tukey-Kramer's method. The effects of the available N and the ammonium adsorption of PL on the ammonium-N in PL at the tillering stage, the grain number, the brown rice yield and the N uptake in 2005 were investigated by multiple regression analysis (step-wise selection). In the step-wise selection, the available N and the ammonium adsorption of PL were selected as the parameters using p-value of 0.25. JMP 4.0.5. J (SAS Institute Inc.) was used for all analysis of variance and multiple regression analysis.

RESULTS AND DISCUSSION

1. Soil properties

Properties of the tested soils are shown in Table 1. The ammonium adsorption rate per the soil weight was larger in clayey smectitic soils (Ohgata and Kiyosato soils) than sandy soil (Tsuruoka soil). However, the difference of the ammonium adsorption of PL was not large among the alluvial soils, because the weight of dry soil in the PL was larger the in the sandy soil. The available N of PL was large in the alluvial soils. The available N of PL was larger in 2004 than in 2005; this is attributed to the positive effect of crushing and moderate drying during pretreatments in 2004.

2. Percolation rate in each soil

Table 2 shows the average percolation rate in each soil in 2006, a year after the cultivation experiment. The average percolation rate was only 1 mm day^{-1} in Naruko soil in the OS plots. On the other hand, it was 9 mm day^{-1} in Naruko soil in the SS plots. This difference was because of the subsoil modification. It is considered that the percolation rate was large also in 2005, because the difference between the OS and SS plots was clear even a year after the subsoil modifica-

Table 2 The average percolation rate in each soil during the irrigation season.

Subsoil replacement and plow layers.	pecoration rate (mm day^{-1})
Original subsoil (without subsoil replacement)	
Naruko	0.4 ± 0.0
Sandy subsoil (with subsoil replacement).	
Tsuruoka	5.2 ± 0.3
Fujishima	2.1 ± 0.2
Kiyosato	1.3 ± 0.2
Ohgata	2.3 ± 0.3
Naruko	8.7 ± 1.4
Shikama	7.8 ± 0.3
Mohka	8.6 ± 0.1
sand‡	39.9 ± 1.8

† Variation shows standard error (n=3).
‡ The sand is similar to that was used for subsoil replacement.

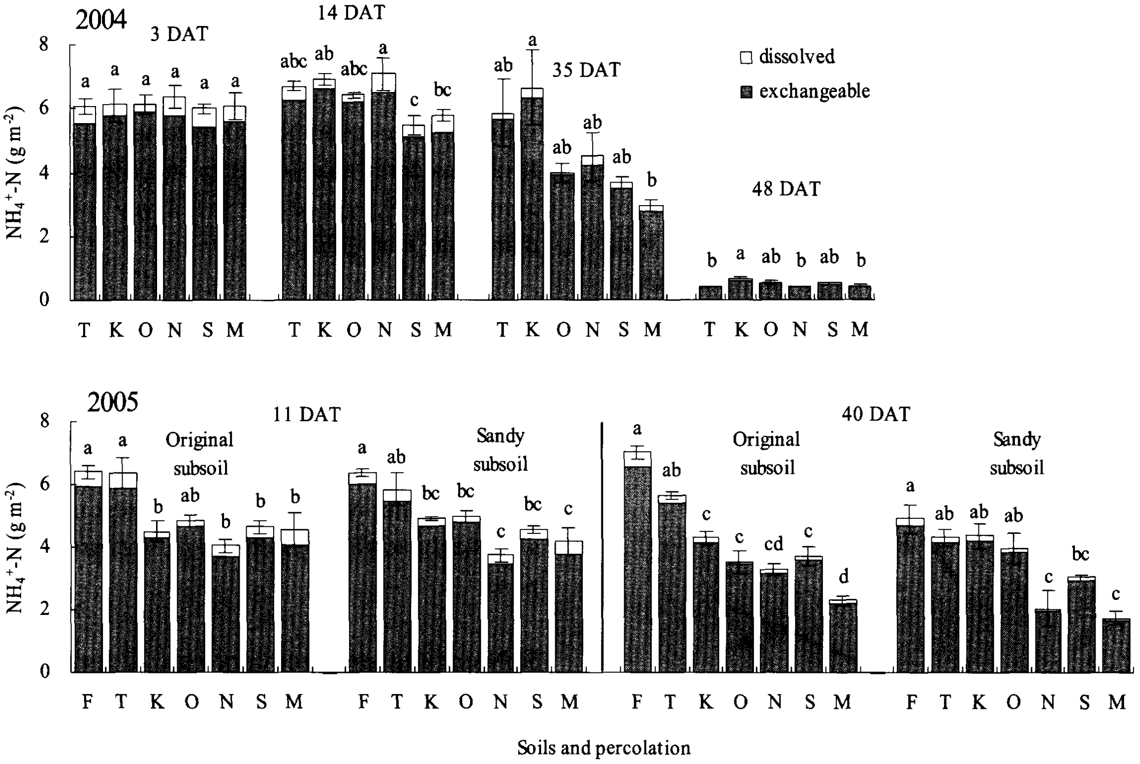

Fig. 1 The amounts of dissolved and exchangeable NH_4^+-N in the plow layers. Abbreviations: F, Fujishima; T, Tsuruoka; K, Kiyosato; O, Ohgata; N, Naruko; S, Shikama; M, Mohka. Error bars show standard error of total NH_4^+-N (n=3). Different letters show that means of total soil NH_4^+-N differ significantly ($p<0.05$, Tukey-Kramer's method).

tion. In the SS plots, the percolation rate was larger in the three andic soils than in the four alluvial soils. Among the alluvial soils, the percolation rate was small in Fujishima, Kiyosato and Ohgata soils (1-2 mm day^{-1}), which possessed large clay content. The percolation rate of sandy subsoil was 40 mm day^{-1}. Therefore, it is considered that the percolation rate (1-9 mm day^{-1}) approximately corresponded to those in ordinary paddy soils without artificial subsoil compaction in the Tohoku district of Japan.

3. Amount of ammonium-N in the PL.

The amounts of dissolved and exchangeable ammonium-N in the PL are shown in Figure 1. Total soil ammonium-N is defined as the sum of dissolved and exchangeable ammonium-N. Shoji et al. (1971) reported that ammonium-N from basal fertilizer (6-7 g m^{-2}) was only 15-38 % of total soil ammonium-N at 24-25 DAT, largely because of mineralization of soil organic N. Therefore, it is considered that total soil ammonium-N was derived from not only fertilizer N but also soil N in this study.

In the OS plots at 3 DAT in 2004, the percentage of exchangeable ammonium-N in total soil ammonium-N (defined as percentage of exchangeable ammonium-N) was no less than 90-96 %. We suggested that soil colloids could adsorb almost all of the added ammonium-N just after application of fertilizer, because the soil ammonium-N was much less than the negative charge of the soil. However, the percentage of exchangeable ammonium-N was slightly higher at, respectively, 96 % and 94 % in Ohgata and Kiyosato soils, clayey and smectitic, than those in the other soils. At 35 DAT, the total soil ammonium-N was 3.0 g m^{-2} and significantly smaller in Mohka soil than in the other soils. Until 48 DAT, the total soil ammonium-N rapidly decreased to 0.4-0.7 g m^{-2} in all soils. The rapid decrease was largely attributed to the uptake of fertilizer and soil N by rice plants.

Also at 11 DAT in 2005 in the OS plots, the percentage of exchangeable ammonium-N ranged from 90 % to 96 % in all soils. Figure 2 shows the significant linear relationship between the ammonium adsorption of PL estimated by a laboratory experiment and the percentage of exchangeable ammonium-N in the field. We suggested that the ammonium adsorption of PL determined by the incubation experiment was effective in estimating existing forms in the paddy fields after fertilizer application. At 40 DAT in the OS plots, the total soil ammonium-N was high in Fujishima soil with 7.0 g m^{-2} and was the smallest in Mohka soil with 2.3 g m^{-2}.

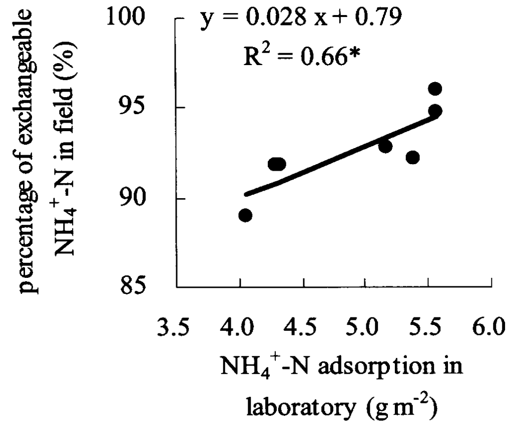

Fig.2 The relationship between the ammonium adsorption of plow layer (g m^{-2}) in a laboratory experiment and the percentage of exchangeable NH_4^+-N in total soil NH_4^+-N (%) in a field at 11 DAT in the original subsoil plot in 2005. * means the relationship is significant ($p<0.05$).

At 11 DAT, the dissolved ammonium-N in the SS plots was less than that in the OS plots, in Tsuruoka, Fujishima, Naruko, Shikama and Mohka soils. We considered that the percolation increased leaching and denitrification of ammonium-N. However, the differences were the least in Ohgata and Kiyosato soil rich in smectitic clay, probably because of the large ammonium adsorption of PL and the small percolation. At 40 DAT, the total soil ammonium-N was less in the SS plots than the OS plots in Tsuruoka, Fujishima, Naruko, Shikama and Mohka soils. On the other hand, there was almost no difference in the total soil ammonium-N in Ohgata and Kiyosato soils. It is considered that leaching and denitrification of ammonium-N were less in the clayey smectitic soils than in the other soils.

4. Tiller number change of rice

The tiller number change was shown in Figure 3. In the OS plots, the tiller number was the highest in Kiyosato soils in 2004 and Fujishima soils in 2005, and was the lowest in Mohka soil. Also in the SS plots in 2005, the tiller number was the highest in Fujishima soil and the lowest in Mohka soil, similarly to the OS plots.

5. N uptake and recovery rate of fertilizer N

Figure 4 shows the N uptake by the rice plants from soil and fertilizer, and the recovery rate of fertilizer N at the harvest. Both in the OS and SS plots, the N uptake from soil largely attributed to the total N uptake. The total N uptake was closely related to the N uptake from soil (R^2=0.99 in 2004; R^2=0.99 in 2005 in the OS plots; R^2=0.97 in the SS plots).

In the OS plots, the total N uptake was the largest in Kiyosato soil with 12.6 g m^{-2} in 2004 and Fujishima soil with 15.1 g m^{-2} in 2005, and was small in Mohka soil. The recovery rate of fertilizer N ranged from 28 % to 33 %, and the difference among every soil was

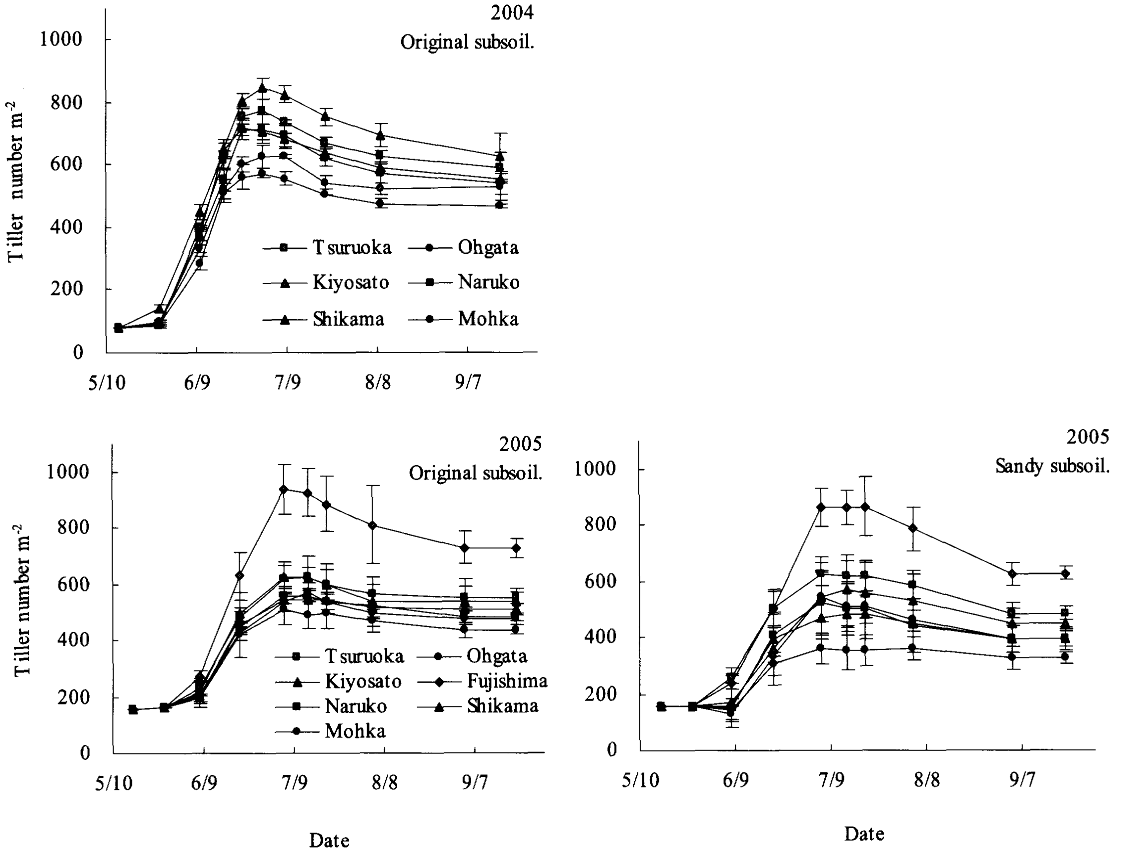

Fig. 3 The change of tiller number. Error bars show standard error (n=3).

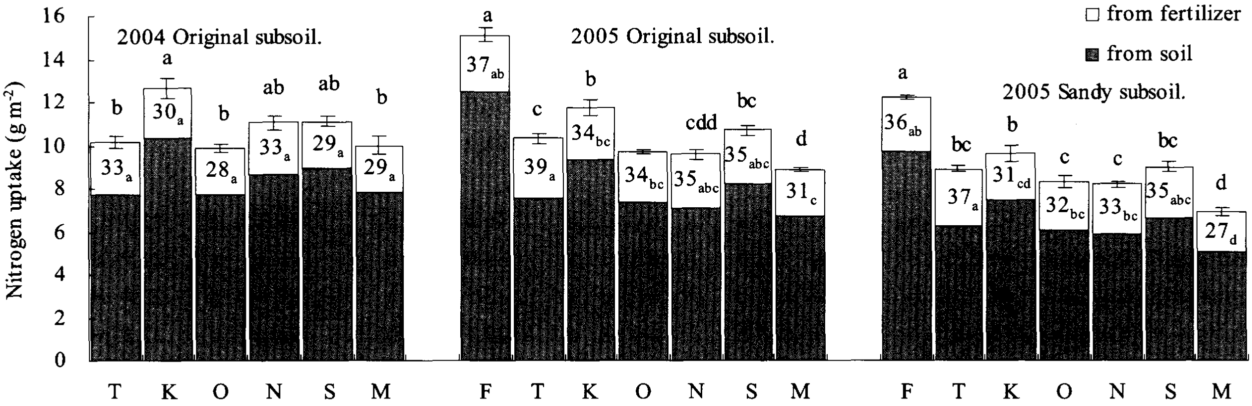

Fig. 4 The Nitrogen uptake and the recovery rate of fertilizer nitrogen at the harvest. Numbers in the figure shows the recovery rates of fertilizer nitrogen (%). Abbreviations: F, Fujishima; T, Tsuruoka; K, Kiyosato; O, Ohgata; N, Naruko; S, Shikama; M, Mohka. Error bars show standard errors of the total nitrogen uptake (n=3). Different letters show that total nitrogen uptakes and the recovery rates differ significantly between soils in each year and percolation plot ($p<0.05$, Tukey-Kramer's method).

not significant in 2004. The recovery rate of fertilizer N was the highest in Tsuruoka soil with 39 % and the lowest in Mohka soil with 31 % in 2005. The recovery rate approximated to 30-46 % calculated from previous studies (Shoji & Mae, 1984). The N uptake was smaller in the SS plots than in the OS plots. According to the additional cultivation experiment using the circle frames, the difference of the N uptake was 2 g m^{-2} between the plots with and without the fabric (data is not shown). Therefore, the smallness of N uptake in the SS plots was largely due to the lack of N uptake from subsoil. The total N uptake was the largest in Fujishima soil with 12.2 g m^{-2} and the smallest in Mohka soil with 6.9 g m^{-2} in 2005. The recovery rate was larger in Tsuruoka soil than in Kiyosato and Ohgata soil, and was not significantly related to the ammonium adsorption of PL. This was probably due to the small variation in the ammonium adsorption of PL among soils.

6. Brown rice yield and yield components

Table 3 shows the brown rice yield and the yield components. In the OS plots, the brown rice yield was significantly large in Kiyosato soil (799 g m^{-2}) in 2004 and in Fujishima soil (950 g m^{-2}) in 2005, and small in Mohka soil (614 g m^{-2} in 2004; 531 g m^{-2} in 2005). In the SS plots in 2005, the brown rice yield was also the highest in Fujishima soil (791 g m^{-2}) and the lowest in Mohka soil (396 g m^{-2}). The brown rice yield was significantly related to the total N uptake (R^2= 0.63 and R^2=0.93 in 2004 and 2005 in the OS plots; R^2=0.85 in the SS plots in 2005).

The brown rice yield was strongly related to the grain number (R^2=0.87 and R^2=0.99 in 2004 and 2005 in the OS plots; R^2=0.98 in 2005 in the SS plots), because variations in the percentage of ripened grains and the thousand-grain weight were not so great among all soils (88-95 % and 21.4-23.0 g m^{-2}). In the OS plots, the panicle number was significantly small in Mohka soil in 2004, and was significantly large in Fujishima soil in 2005. There was no significant difference in the grain number per ear between soils in 2004 and 2005. In the SS plots in 2005, the panicle number was significantly large in Fujishima soil and small in Mohka soil. As shown in Figure 5, the amount of total soil ammonium-N in the PL at 40 DAT in 2005 were significantly correlated with the grain number, which related most strongly to the brown rice yield. The total soil ammonium-N in PL at 35 or 40 DAT was also significantly related to the maximum tiller and the panicle number both in the OS and SS plots. Tanaka et al. (1982) found a rela-

Table 3 The brown rice yield and yield components.

Year and subsoil	soils	Brown rice yield (g m^{-2})	Panicle number (m^{-2})	Number of grains per ear	Number of grains (× 10^3 m^{-2})	Percentage of ripened grains (%)	Thousand-grain weight (g)
2004 Original subsoil	Tsuruoka	649 ±36 b	591 ±36 a	56 ±4 a	33.1 ±1.3 b	88 ±4 a	22.4 ±0.2 ab
	Kiyosato	799 ±20 a	626 ±29 a	62 ±2 a	38.6 ±1.2 a	93 ±2 a	22.2 ±0.2 b
	Ohgata	691 ±13 b	529 ±23 a	64 ±2 a	33.6 ±0.3 b	91 ±2 a	22.6 ±0.1 ab
	Naruko	687 ±27 b	538 ±16 a	59 ±2 a	31.7 ±1.1 bc	94 ±2 a	22.9 ±0.0 a
	Shikama	660 ±1 b	555 ± 8 a	56 ±1 a	30.7 ±0.1 bc	93 ±2 a	22.9 ±0.1 ab
	Mohka	614 ±8 b	467 ± 4 b	61 ±1 a	28.2 ±0.3 c	94 ±1 a	23.0 ±0.1 a
2005 Original subsoil	Fujishima	950 ±10 a	727 ±33 a	64 ±3 a	46.4 ±0.3 a	94 ±0 a	21.7 ±0.0 a
	Tsuruoka	668 ±27 b	551 ±22 b	62 ±1 a	34.0 ±1.0 b	91 ±1 a	21.7 ±0.1 a
	Kiyosato	687 ±22 b	538 ±46 b	61 ±3 a	32.5 ±1.3 b	95 ±1 a	22.4 ±0.3 a
	Ohgata	652 ±15 b	476 ±23 b	68 ±3 a	32.1 ±0.6 b	92 ±0 a	22.1 ±0.2 a
	Naruko	580 ±17 c	480 ±12 b	60 ±1 a	28.7 ±0.3 cd	91 ±2 a	22.1 ±0.1 a
	Shikama	646 ±2 b	507 ±23 b	62 ±3 a	31.5 ±0.2 bc	93 ±1 a	22.0 ±0.2 a
	Mohka	531 ±7 d	436 ±15 b	59 ±1 a	25.9 ±0.3 d	94 ±1 a	21.9 ±0.1 a
2005 Sandy subsoil	Fujishima	791 ±17 a	626 ±23 a	63 ±1 a	39.4 ±1.1 a	93 ±1 a	21.6 ±0.1 a
	Tsuruoka	635 ±33 b	485 ±23 b	65 ±2 a	31.4 ±0.6 ab	94 ±1 a	21.4 ±0.3 a
	Kiyosato	600 ±17 bc	458 ±32 bc	64 ±7 a	29.1 ±0.8 b	95 ±1 a	21.8 ±0.3 a
	Ohgata	598 ±44 bc	397 ±31 bc	74 ±3 a	29.4 ±1.4 b	94 ±0 a	21.4 ±0.1 a
	Naruko	492 ±34 cd	357 ±13 bc	73 ±4 a	26.1 ±0.4 b	93 ±0 a	21.7 ±0.5 a
	Shikama	549 ±24 bc	397 ±26 bc	66 ±2 a	26.1 ±0.9 bc	94 ±1 a	22.3 ±0.2 a
	Mohka	396 ±14 d	326 ±23 c	60 ±2 a	19.6 ±0.6 c	92 ±1 a	22.0 ±0.1 a

† Variation shows standard error (n=3).

‡ Means with different letters differ significantly among soils in each year and subsoil plot ($p<0.05$, Tukey-Kramer's method).

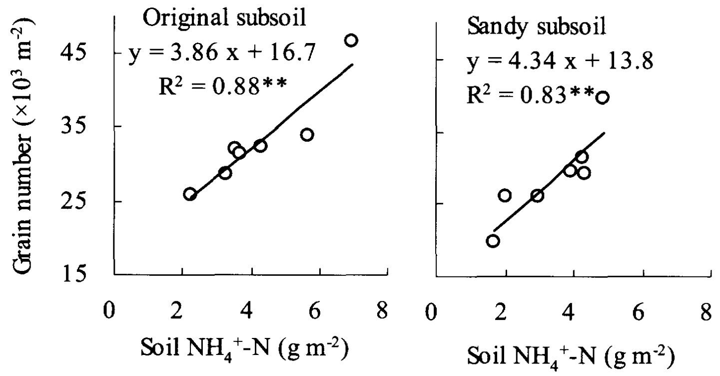

Fig. 5 The relationship between the amount of total soil NH_4^+-N in the plow layer at 40 DAT and grain number in 2005. ** means the relationship is significant ($p<0.01$).

tionship between ammonium-N in PL on June 10 and 20 and panicle number in Yamagata Prefecture, the Tohoku district of Japan. They considered that ammonium-N in the PL on June 10 showed the amount of N that could be absorbed by rice plant during the tillering stage.

7. Regression analysis to determine soil properties related to rice yield

In 2004, a multiple regression could not be applied because the available N and the ammonium adsorption of PL were significantly related to each other among the six soils. Table 4 shows results of regression analysis between the available N and the ammonium adsorption of PL and the soil ammonium-N at tillering stage (40 DAT), the grain number, the brown rice yield and the N uptake among the seven soils including Fujishima soil in the OS and SS plots in 2005. In the OS plots, the total soil ammonium-N at the tillering stage, the grain number, the brown rice yield and the N uptake at the harvest were effectively explained by the available N of PL. The ammonium adsorption of PL was not selected as an important parameter. It is reasonable that the ammonium adsorption of PL did not strongly affect the N uptake in the OS plots because leaching and denitrification of ammonium-N were not strongly promoted by percolation even in soils with the small ammonium adsorption of PL. The equation of the N uptake has a large intercept value (7.79 g m^{-2}) and shows that the contribution of the available N of PL to the N uptake was about 44 % at most (in Fujishima soil). The coefficient of determination in the equation of the N uptake was not large (R^2=0.58). The large intercept value and the small coefficient of determination were probably because of (1) the fertilizer N uptake (2.2-2.7 g m^{-2}), (2) uptake of N mineralized from the subsoil, (3) uptake of N fixed by bacteria from air and (4) added N interaction, for which uptake of soil N increased by application of readily available N fertil-

Table 4 Equations of the most effective regression by stepwise selection and their coefficients of determination (R^2).

	regression	$R^{2\dagger}$
Original subsoil.		
Y, Soil NH_4^+-N in tillering stage.	Y= 0.55×(available N) +2.14	0.43
Y, Grain number	Y= 2.75×(available N) +22.5	0.73*
Y, Brown rice yield	Y= 57.1×(available N) +455	0.76*
Y, Nitrogen uptake at harvest	Y= 0.80×(available N) +7.79	0.58*
Sandy subsoil.		
Y, Soil NH_4^+-N in tillering stage.	Y= 1.13×(NH_4^+-N ad.) + 0.23×(available N) - 3.02	0.78*
Y, Grain number	Y= 2.53×(available N) +19.0	0.77*
Y, Brown rice yield	Y= 51.6×(available N) +383	0.72*
Y, Nitrogen uptake at harvest	Y= 0.64×(available N) +6.52	0.60*

† * means the regression was significant ($p<0.05$).

izer (Jenkinson et al., 1985). It is also considered that the available N of PL (evaluated by the anaerobic incubation using fresh moist soils in 30 °C for only 4 week) did not show certainly the amount of N mineralization during rice growing season.

In the SS plots, it was hypothesized that the effects of the ammonium adsorption of PL on the N uptake and the brown rice yield were clearly observed, because the percolation promoted leaching and the rice plants depended their N uptake on PL. The soil ammonium-N at the tillering stage was more effectively explained by multiple regression using the available N of PL and the ammonium adsorption of PL than by simple regression with each parameter. We consider that the ammonium adsorption of PL affected the soil ammonium-N at the tillering stage in the SS plots, because greater amount of ammonium-N was retained against leaching and denitrification in soils with the large ammonium adsorption of PL (ex. Kiyosato and Ohgata soils) than in the other soils, as shown in Figure 1. However, the grain number was efficiently explained by the available N of PL in the SS plots, and the ammonium adsorption of PL was not selected as an important parameter, although the ammonium-N at tillering stage was significantly correlated to the grain number (Figure 5). The brown rice yield and the N uptake were also effectively explained, not by the ammonium adsorption of PL, but by the available N of PL. The grain number is closely correlated to the N uptake until panicle heading (Wada, 1969). The N uptake until panicle heading would be affected not only by the soil ammonium-N at the tillering stage but also the mineralization of soil organic N after the tillering stage and the recovery rate of fertilizer N topdressed at panicle initiation stage. After maximum tillering stage, the amount of soil ammonium-N is extremely small because of rapid uptake by rice plants (Shoji & Mae, 1984); leaching loss of N is also considered to be extremely small. Therefore, we considered that the effects of the ammonium adsorption of PL did not significantly relate to the N uptake until the panicle heading stage. The lack of significant relationship between the ammonium adsorption of PL and the N uptake or the brown rice yield was because the total N uptake of rice can be greatly affected by mineralization of soil organic N after the tillering stage and the difference of ammonium adsorption of PL were small among the soils used in this study. However, the ammonium adsorption of PL affected the total soil ammonium-N at tillering stage, which correlated with the grain number. Therefore, it is considered that the ammonium adsorption of PL contributed to the large intercept value and the small coefficient of determination, especially in the SS plots. The ammonium adsorption of PL may affect the brown rice yield and the N uptake in sandy soils rich in kaolin minerals, in which percolation is extremely large and the ammonium adsorption of PL is very small.

Based on the above results in the field cultivation experiment using the seven soils (the available N of PL was 1.8-7.6 g m^{-2}; the ammonium adsorption of PL was 4.1-5.6 g m^{-2}), we concluded that the available N of PL significantly affected the N uptake and the brown rice yield. The effects of the ammonium adsorption of PL on the N uptake and the brown rice yield were not clearly observed by multiple regression analysis not only in the small percolation condition but also in the increased percolation condition by subsoil replacement with sand (average percolation rate 1-9 mm day^{-1}).

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