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Can animal manure and liming increase the availability of phosphorus to the plant in acid Andosol?

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INTRODUCTION

Phosphorus (P) is one of the major essential nutrients for plant growth, since it is involved in cellular energy transfer, respiration, and photosynthesis. P is also a structural component of the nucleic acids of genes and chromosomes, and of many coenzymes, phosphoproteins and phospholipids (Ozanne, 1980). Nevertheless, P is one of the problems in the soil fertility, particularly in acid soil. First, the total P level of the soils is low; second, the P compounds commonly found in the soils are mostly unavailable for plant uptake, often because they are highly insoluble; and third, when soluble sources of P, such as those in fertilizers and manures, are added to soils, they are fixed by aluminum (Al) and/or iron (Fe) in the soil and in time form highly insoluble compounds (Brady and Weil, 2002a), turning the nutrient unavailable for the plant.

Application of lime to acid soil can stimulate crop growth by eliminating the toxicities (particularly Al, Fe and manganese (Mn) toxicity) and by increasing the availability of certain plant nutrients (Adams, 1984). The supply of P to plants is largely controlled by adsorption-desorption reactions, which regulate the concentration of P in the soil solution. These reactions may be influenced by lime-induced increases in pH and calcium (Ca). An increase in pH will change two key factors that underpin the adsorption reactions, the speciation of phosphate and the electrostatic potential of the adsorbing surfaces. When pH is increased, the proportion of the divalent phosphate ion (HPO_4^{2-}), the P species considered to be adsorbed (Barrow, 1984), is also increased. This change in phosphate speciation promotes adsorption, but, at the same time, surface electrostatic potential becomes more negative as pH increases and thus less attractive to phosphate ions.

It is generally recognized that application of P with animal manure can increase the availability of this nutrient (Yamane, 1997; Brady and Weil, 2002b). During the microbial breakdown of the manure, P is released slowly and can be taken up by plants before it reacts with the soil. Also, the manure can protect P from fixation by masking the fixation sites on the soil colloids, and by forming organic complexes (chelates) with Al, Fe and Mn ions, thereby limiting the reaction of these ions with P. Therefore it is possible that the P application with manure can create stable complexes turning the P more available for the plant.

The aim of this study was to verify if the animal manure and liming could increase the availability of P to the plant in the acid Andosol.

MATERIAL AND METHODS

EXPERIMENT 1

The experiment was conducted at the glasshouse in the Rakuno Gakuen University, Hokkaido, Japan, during 55 days (May 12, 2007 to July 5, 2007).

The experiment was realized in pots with 20 cm of height and 16.0 cm of diameter. On the base of the pot a channel of gravel was used to facilitate the distribution of water in the lower part of the

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soil in the pot. The soil used in the experiment was the cumuric Andosol (Nemuro-Shibetsu soil) and chemical properties of the original soil were shown in Table 1. The soil showed quite high level of phosphate absorption coefficient and acidity. These conditions mean that the soil can easily make available P such as chemical fertilizer P insoluble. The each pot was filled with 2.1 kg of the soil as dry soil basis. We maintained soil matric water potential in the pots at -31 kPa by irrigation of deionized water twice or third times per day during the experiment.

The animal manure used in the experiment was an anaerobically digested cattle slurry (ADCS) procured from the biogas-plant of Rakuno Gakuen University. The ADCS contains no food wastes and maize, so that its major components are feces and urine excreted by dairy cattle. Some chemical properties of the ADCS that were measured by conventional method were shown in Table 2.

Since we decided that the application rate of ammonium nitrogen (NH_4-N) derived from the ADCS was 0.5 g pot^{-1}, the application rate of the ADCS was equivalent to 285 g pot^{-1}, because NH_4-N content of the ADCS was 1.75 g kg^{-1} (Table 2). The application rate of the ADCS contained P and potassium (K) of 0.2 and 1.1 g pot^{-1}, respectively. These amounts of P and K were equal to 0.08 and 0.9 g pot^{-1} as chemical fertilizer, respectively, since the conversion factors from the nutrients in the slurry to those as the chemical fertilizer were 0.4 and 0.8, respectively (Matsumoto, 2008).

The treatments in the experiment were as follows (Table 3): Control (C), which had no animal manure and no chemical fertilizer; ADCS + fertilizer P (ADCS+P), the ADCS was mixed with the fertilizer P, superphosphate, and then the mixture was applied to the soil and mixed well with the soil; ADCS and fertilizer P (ADCS-P), the ADCS was mixed with the soil prior to fertilizer P application, and then the P was applied and mixed with the soil where the ADCS was applied; chemical fertilizer treatment + fertilizer P (CF), which received 0.5, 0.08 and 0.9 g pot^{-1} as N, P and K, respectively, which were equal to the amount of those as available nutrients derived from the applied ADCS, as described above, and fertilizer P was also applied. The chemical fertilizers used here were ammonium sulfate, superphosphate and potassium sulfate. The fertilizer P was applied at the rate of 1.0 g pot^{-1} (12.7g of superphosphate) to each treatment.

All the treatments were tested with and without addition of lime. The application rate of the lime was measured using the buffer curve method.

Table 1 Some chemical properties of original soil* used in pot experiments.

Chemical properties	Value
pH(H_2O)	4.61
Electric Conductivity (dS m^{-1})	0.21
T-N(g kg^{-1})	4.37
T-C(g kg^{-1})	76.3
Available P	
Bray No.2 method(mg kg^{-1})	55.1
Truog method(mg kg^{-1})	10.3
CEC($cmol_c$ kg^{-1})	21.1
Exchangeable Cations(mg kg^{-1})	
K	178
Ca	760
Mg	58
Phosphate absorption coefficient	2110
Y_1	4.7

*The soil is Cumuric Andosol (Nemuro-Shibetsu soil)

Table 2 Some chemical properties of anaerobically digested cattle slurry (ADCS) used in the experiments.

	Experiment	
	1	2
pH	7.8	7.7
EC*(S m^{-1})	1.8	1.7
Dry matter(g kg^{-1})	53.5	52.5
Nutrient content(g kg^{-1})		
NH_4-N	1.75	1.41
NO_3-N**	—	—
Organic N***	1.80	1.82
T-N	3.55	3.23
T-C	39.9	37.6
P	0.68	0.83
K	3.92	3.63
Ca	1.29	1.58
Mg	0.40	0.57
C/N	11.1	11.6

*Electric Conductivity
**not detected
***Organic N = (T-N) - (NH_4-N+NO_3-N)

Table 3 The details about the treatments and applied nutrients as chemical fertilizer in Experiment 1.

Treatment	Abbreviation of the treatment	Application rate of the available nutrients*a as chemical fertilizer (g pot^{-1})			Commercial lime (CL)	Applied extra P
		N	P	K	(g pot^{-1})	
Control	C	–	–	–	–	–
Control and lime	C+CL	–	–	–	23	–
Fertilizer P was mixed with ADCS*b prior to application.	ADCS+P	0.5 (1.0)*c	0.08 (0.2)	0.9 (1.1)	–	1.0
The same above and lime	ADCS+P+CL	0.5 (1.0)	0.08 (0.2)	0.9 (1.1)	23	1.0
ADCS was mixed with soil and then P was applied to the soil-ADCS mixture	ADCS-P	0.5 (1.0)	0.08 (0.2)	0.9 (1.1)	–	1.0
The same above and lime	ADCS-P+CL	0.5 (1.0)	0.08 (0.2)	0.9 (1.1)	23	1.0
Chemical fertilizer*d	CF	0.5	0.08	0.9	–	1.0
The same above and lime	CF+CL	0.5	0.08	0.9	23	1.0

*a N, NH_4-N in the ADCS; P, Total P in the ADCS x 0.4; K, Total K in the ADCS x 0.8, where 0.4 and 0.8 is a conversion factor from the nutrient in the ADCS to available nutrient as chemical fertilizer of P and K, respectively (Matsumoto, 2008).
*b Anaerobically digested cattle slurry.
*c Number in the parenthesis is the application rate of total nutrient derived from the applied ADCS.
*d Application rate of chemical fertilizer was depend on the available nutrients derived from the applied ADCS.

The lime requirement to reach the target pH 6.0 was 23 g pot^{-1} of commercial lime (CL).

Corn (*Zea mays* L.; the variety, New Dent 100 days) was used to test the uptake of the nutrients. Each treatment was tested in 3 replications.

At 55 days after the seeding, the plants were harvest, divided in leaves, stems and roots, and then dried at 70 ℃ for more than 48 hs, and weighed. The dried plant samples were ground and analyzed. Soil samples were also collected. Particularly the soil surrounded with roots was taken by shaking vigorously roots with soil, and the soil taken by this procedure was regarded as rhizosphere soil. The rhizosphere soil was added to the bulk soil and mixed well. Plant samples were analyzed by conventional method, of which digestion method was wet ashing with sulfuric acid and hydrogen super oxide, to measure the content of the nutrients in the sample. N of the plant sample was measured using the steam distillation method. P was determined using the vanadomolybdate yellow color method. K, Ca and magnesium (Mg) were analyzed using the atomic absorption spectrophotometer (AAnalyst 100, Perkin Elmer Co. Ltd., Tokyo). For the soil sample, Exchangeable K, Ca and Mg were also analyzed using the atomic absorption. Mineral N (nitrate (NO_3-N) and NH_4-N, extractable with 100g L^{-1} potassium chloride (KCl)) was measured with FIA system (Flow Injection Analysis, FOSS Japan Co. Ltd., Tokyo). Available P was determinate using Bray No.2 and Truog methods and they were expressed hereafter as Bray-P and Truog-P, respectively.

EXPERIMENT 2

The Experiment 2 was realized in similar procedures to the Experiment 1 and the period of the experiment was 54 days (August 2, 2007 to September 24, 2007).

The treatments tested in this experiment were as follows (Table 4): Control (C), which had no addition of the ADCS and chemical fertilizers; 0.5 g NH_4-N (0.5N), 0.5 g pot^{-1} of NH_4-N derived from the ADCS was applied and it was equal to 355 g $pot^{-1}$of the ADCS used in the experiment (Table 2); 1.0 g NH_4-N (1.0N), which received an equal quantity of 1.0 g pot^{-1} of NH_4-N derived from the ADCS that was 711 g pot^{-1} of the ADCS; chemical fertilizer (CF), the same quantity of N, P and K present in the treatment 1.0N was applied as chemical fertilizers.

In this experiment we used two kinds of lime. One is the CL and the other was reagent lime (RL) that has 99.5 % of purity of calcium carbonate and did not contain any Mg. Each treatment

Table 4 The details about the treatments and applied nutrients as chemical fertilizer in Experiment 2.

Treatment	Abbreviation of the treatment	Application rate of the available nutrients*a as chemical fertilizer (g pot⁻¹)			Application rate of lime	Applied extra P
		N	P	K	(g pot⁻¹)	
Control	C	−	−	−	−	−
Control and commercial lime	C+CL	−	−	−	23	−
Control and reagent lime	C+RL	−	−	−	17	−
0.5g pot^{-1} as NH_4-N derived from the ADCS*b	0.5N	0.5 (1.2)*c	0.1 (0.30)	1.0 (1.3)	−	1.0
The same as 0.5N and commercial lime	0.5N+CL	0.5 (1.2)	0.1 (0.30)	1.0 (1.3)	23	1.0
The same as 0.5N and reagent lime	0.5N+RL	0.5 (1.2)	0.1 (0.30)	1.0 (1.3)	17	1.0
1.0 g pot^{-1} as NH_4-N derived from the ADCS	1.0N	1.0 (2.3)	0.2 (0.59)	2.0 (2.6)	−	1.0
The same as 0.5N and commercial lime	1.0N+CL	1.0 (2.3)	0.2 (0.59)	2.0 (2.6)	23	1.0
The same as 0.5N and reagent lime	1.0N+RL	1.0 (2.3)	0.2 (0.59)	2.0 (2.6)	17	1.0
Chemical fertilizer*d	CF	1.0	0.2	2.0	−	1.0
The same as CF and commercial lime	CF+CL	1.0	0.2	2.0	23	1.0
The same as CF and reagent lime	CF+RL	1.0	0.2	2.0	17	1.0

*a N, NH_4-N in the ADCS; P, Total P in the ADCS x 0.4; K, Total K in the ADCS x 0.8; 0.4 and 0.8 is a conversion factor from nutrient in the ADCS to available nutrient as chemical fertilizer of P and K, respectively (Matsumoto, 2008).
*b Anaerobically digested cattle slurry.
*c Number in the parenthesis is the application rate of total nutrient derived from the applied ADCS.
*d Application rate of chemical fertilizer was depend on the available nutrients derived from the applied ADCS.

was tested without lime, with the CL and with the RL. The lime requirement for target pH 6.0 was calculated by the buffer curve method.

All treatments, except for the treatment C with or without lime, received 1.0 g P pot^{-1} as superphosphate. In particular, the fertilizer P was mixed with the ADCS prior to application to the soil in the pot. In this experiment, therefore, the application method of the fertilizer P was only one. All treatments were tested in 3 replications.

After 54 days plants were harvested, and divided in leaves, stems and roots. The samples were dried, weighted, and ground for analysis. Plant and soil samples were analyzed using the same methods of the Experiment 1.

RESULTS

Experiment 1

Plant growth

The corn grown in the treatments both C and C+CL showed severe P deficiency and there was no significant difference in the dry matter weight

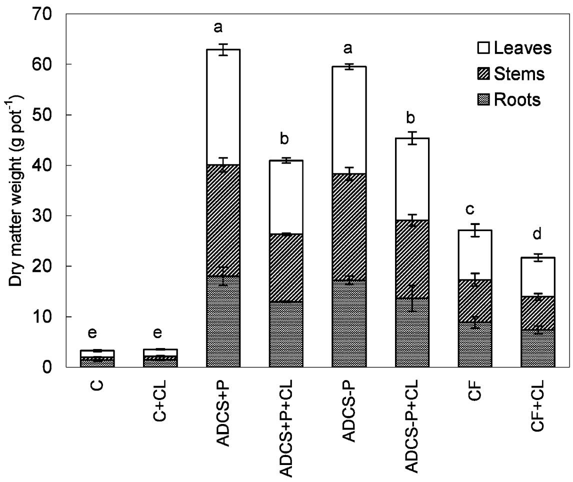

Fig. 1 Dry matter weight of leaves, stems and roots in the treatments of the Experiment 1. Vertical Bars indicate the standard deviation. Means followed by different letters are statistically significant ($P<0.01$ or $P<0.05$).

(DMW) between them (Fig. 1). Thus it was clear that limiting factor for corn growth in the experiment was P and the liming without P application could not significantly affect the plant growth.

The treatments that received both ADCS and P without lime (ADCS＋P, ADCS-P) had the greatest growth among the treatments (Fig. 1) and there was no statistically significant difference between them. The difference in the P application method, therefore, did not have significant effect on the corn growth.

The treatments with liming had significantly lower DMW compared with the treatments without liming, except for the treatment C. If we compared the DMW among the treatments with lime and without lime, the ADCS＋P＋CL had 35% less DMW compared with that of the ADCS＋P. Similarly in the case of the ADCS-P, the treatment that did not receive lime had 23% more the DMW compared with that of liming. The treatment CF had also the same results; the CF without lime had 20% more the DMW than that with lime.

Fig. 1 showed clearly that the treatments with addition of the ADCS revealed significantly higher DMW than that of the treatment CF, although the same rate of NH_4-N was applied to the pots of the both treatments.

Nutrients absorption by the plants

The amount of N, P and K uptake by the plants were corresponding to their growth. Plants that showed higher DMW could uptake higher levels of those nutrients (Fig. 1 and Table 5). The plants grown in the treatments that received the ADCS had higher N and K uptake by the plants compared with the treatment CF and CF＋CL, although the N and K content in the plants grown in the treatments receiving the ADCS was lower than those in the plants grown in the CF treatments (Table 6). There was no statistically significant difference in P content in plants among the treatments that received fertilizer P. P uptake by the plants in the treatments where the ADCS was applied, however, was significantly more than that in the CF treatments in spite of the liming treatment. When we evaluated the P availability of the applied fertilizer P based on the P uptake by the plants, the result described above suggested that the availability in the treatments where the ADCS was applied increased apparently more than that in the treatments CF (CF and CF＋CL). In this case, however, it should be noted that N uptake by the plants grown in the treatments receiving ADCS was significantly more than that in the treatments CF, although all treatments, except for the treatment C, received the same rate of the applied NH_4-N.

P application method to the ADCS did not affect significantly P uptake by the plants, because the P uptake by the plants in the ADCS＋P was not significantly different from that in the treatment ADCS-P.

Liming had not increasing effect on the P availability of the fertilizer P to the plants. Ca content in the plants grown in the treatments receiving lime was higher than that in the no lime treatments, but Ca uptake by plant grown in the liming condition was less than that in the no lime

Table 5 Nutrient uptake in whole plant of forage corn grown in different treatments in Experiment 1. Means followed by different letters are statistically significant ($P < 0.01$ or $P < 0.05$).

Treatment*	Nutrient uptake (mg pot^{-1})				
	N	P	K	Ca	Mg
C	72 e	1.8 e	132 d	16 d	7 f
C＋CL	62 e	2.1 e	128 d	18 d	19 f
ADCS＋P	794 a	58.1 a	1222 a	253 a	114 c
ADCS＋P＋CL	663 b	41.2 b	1183 a	196 b	153 b
ADCS-P	737 ab	53.6 a	1245 a	210 b	96 d
ADCS-P＋CL	711 b	43.6 b	1141 a	211 b	174 a
CF	515 c	24.0 c	897 b	135 c	36 e
CF＋CL	387 d	23.4 c	757 c	123 c	106 cd

*See table 3.

Table 6 Nutrient content in whole plant of forage corn grown in different treatments in Experiment 1. Means followed by different letters are statistically significant ($P<0.01$ or $P<0.05$).

Treatment*	Nutrient content (%)				
	N	P	K	Ca	Mg
C	2.22 a	0.05 b	4.06 a	0.49 b	0.20 d
C＋CL	1.75 bc	0.06 b	3.66 b	0.51 b	0.54 a
ADCS＋P	1.26 d	0.09 a	1.94 f	0.40 c	0.18 de
ADCS＋P＋CL	1.62 c	0.10 a	2.89 d	0.48 b	0.37 c
ADCS-P	1.29 d	0.09 a	2.19 f	0.37 c	0.17 e
ADCS-P＋CL	1.57 c	0.10 a	2.52 e	0.47 b	0.38 c
CF	1.90 b	0.09 a	3.31 c	0.50 b	0.13 f
CF＋CL	1.79 bc	0.11 a	3.49 bc	0.57 a	0.49 b

*See table 3.

treatments. This was due to less DMW in the liming treatments. Plants grown in the treatments with the CL showed significant higher levels of Mg content and uptake. These results suggested that the CL used in the experiment was possibly characterized as dolomite, although the bag of the CL showed clearly that the CL is calcium carbonate.

Soil pH and available nutrients in the soils

In the treatments where the CL was applied, their soil pH increased by the liming and it was significantly higher than that in the treatments with no liming (Table 7). Treatments where the CL was not applied but manure was present (ADCS+P and ADCS-P) had statistically lower pH if compare with that in the treatments where the CL was added. Even in these treatments that did not received the CL, however, their soil pH was significantly higher compared with that in the treatment CF, because the applied ADCS showed a high pH (Table 2). The treatment C and CF had relatively lower soil pH, when these treatments had no addition of the CL or the ADCS.

As describe above, the liming affected significantly the soil pH, however the plant growth was not affected by the soil pH as shown in Fig. 1 and also the liming did not cause a significant difference to the available P, particularly Bray-P, in the soil at the end of the experiments.

The amount of available N and Exchangeable K was higher in the treatments that had a lower growth of the plants. This was due to less N and K uptake by the plants. Bray-P and Truog-P in treatments where P was applied showed similar level among the treatments and there was no statistically significant between them except for the treatment of ADCS+P where the plant growth and P uptake was the best. Exchangeable Ca levels were higher in treatments with liming. Exchangeable Mg showed extremely high levels in treatments receiving the CL.

EXPERIMENT 2

Plant growth

Similarly to the results of the Experiment 1, the plants grown in the treatment C, C+CL and C+RL showed severe P deficiency. The plant growth in the other treatments where fertilizer P was applied was significantly better than that in the treatment C. These results confirmed the findings in Experiment 1 that P was the limiting factor for the plant growth in the soil.

It was clear from the results of the DMW (Fig. 2) that the treatments 1.0N and 0.5N with no lime application showed the greatest growth of the plants. The application of the RL did not give better results of the DMW compared with those in the treatments with no lime. There was no statistically significant difference in the DMW between the treatments with the CL and the RL.

Table 7 Soil pH and available nutrients left in the soil at the end of the Experiment 1. Means followed by different letters are statistical significant ($P<0.01$ or $P<0.05$).

Treatment*	pH (H_2O)	Soil available nutrients (g pot^{-1})					
		N**	P		Exchangeable Cations		
			Bray	Troug	K	Ca	Mg
C	4.7 d	0.37 abc	0.11 c	0.02 c	0.19 bc	0.57 e	0.10 cd
C+CL	5.8 a	0.46 a	0.11 c	0.03 c	0.19 bc	3.84 c	1.35 a
ADCS+P	5.1 c	0.16 d	0.37 b	0.13 b	0.11 d	2.65 d	0.13 c
ADCS+P+CL	5.8 a	0.35 abc	0.41 ab	0.16 a	0.14 cd	5.63 b	1.31 ab
ADCS-P	5.1 c	0.14 d	0.42 a	0.16 a	0.14 cd	2.62 d	0.13 c
ADCS-P+CL	5.9 a	0.31 bc	0.41 ab	0.17 a	0.14 cd	5.57 b	1.28 b
CF	4.7 d	0.28 c	0.41 ab	0.13 b	0.23 ab	2.48 d	0.09 d
CF+CL	5.5 b	0.44 ab	0.41 ab	0.16 a	0.29 a	6.16 a	1.34 a

*See table 3.
**Soil was incubated under the condition of 60 % of water holding capacity of the soil and 30 ℃ for 4 weeks. After the incubation, the soil was extracted by 100g L^{-1} KCL solution.
The extracted mineral N (NH_4-N + NO_3-N) was the available N in the soil.

The DMW in the treatment 0.5N was significantly higher than that in the treatment CF, although total applied N in the treatment 0.5N was slightly more than that in the treatment CF (Table 4). Any kinds of lime application reduced significantly the plant growth in all treatments except for the treatment C, C+CL and C+RL.

Nutrients absorption by the plants

Plant analysis showed that N uptake by the plants grown in the treatment 1.0N was the highest level in the experiment. Application of any kinds of lime did not increase N, P and K uptake by the plants in any treatments compared with no lime (Table 8). N uptake by the plants between the treatment 0.5N and CF showed significant difference, although the total applied N in the treatment 0.5N was slightly more than that in the treatment CF. N content in the plants grown in the pots where the same rate of ADCS or chemical fertilizer was applied was not affected by the liming treatments (Table 9). P uptake by the plants was significantly higher in the 1.0N treatment than that in the other treatments, although no significant difference was observed on P content in all treatments which received the fertilizer P. Between the treatment 0.5N and CF, P uptake by the plants did not showed statistically significant difference.

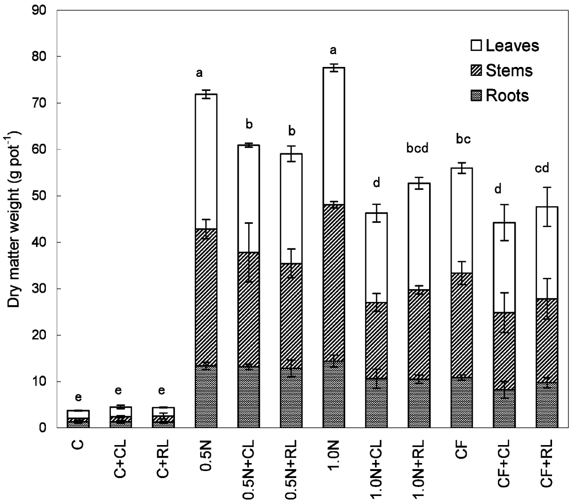

Fig. 2 Dry matter weight of leaves, stems and roots in the treatments of the Experiment 2. Vertical Bars indicate the standard deviation. Means followed by different letters are statistically significant ($P<0.01$ or $P<0.05$).

Ca uptake by the plants and content levels in the plants grown in the pots where the RL was applied were higher than those in treatments that received the CL. Mg uptake and content was higher in the treatments where the CL was applied than those in the treatments where the RL was applied. This was probably caused by the Mg present in the CL.

Soil pH and available nutrients in the soils

The soil pH of the treatments was improved by the application of the CL or RL (Table 10).

Table 8 Nutrient uptake by whole plant of forage corn grown in different treatments in Experiment 2. Means followed by different letters are statistically significant ($P<0.01$ or $P<0.05$).

Treatment*	Nutrient uptake (mg pot^{-1})				
	N	P	K	Ca	Mg
C	77 f	3.2 e	141 e	16 g	9 g
C+CL	73 f	4.5 e	147 e	20 g	26 g
C+RL	71 f	3.5 e	172 e	36 g	10 g
0.5N	855 c	67.7 b	1296 d	183 cd	106 cd
0.5N+CL	825 cd	61.9 bc	1345 d	180 cd	199 a
0.5N+RL	725 de	59.6 b	1332 d	270 a	102 cd
1.0N	1240 a	81.9 a	1905 a	170 cd	124 cd
1.0N+CL	654 e	54.0 cd	1583 b	156 de	152 b
1.0N+RL	804 cd	53.0 cd	1624 bc	230 b	90 de
CF	991 b	59.8 bc	1455 bcd	113 f	59 f
CF+CL	776 cde	49.8 d	1398 cd	129 ef	112 cd
CF+RL	789 cd	52.9 cd	1443 bcd	198 c	69 ef

*See table 4.

Table 9 Nutrient content in whole plant of forage corn grown in different treatments in Experiment 2. Means followed by different letters are statistically significant ($P<0.01$ or $P<0.05$).

Treatment*	Nutrient content (%)				
	N	P	K	Ca	Mg
C	2.08 a	0.09 b	3.81 ab	0.43 b	0.24 c
C+CL	1.61 bc	0.10 ab	3.25 cd	0.44 b	0.58 a
C+RL	1.61 bc	0.08 b	3.91 a	0.82 a	0.22 cd
0.5N	1.19 f	0.09 ab	1.80 f	0.26 de	0.15 ef
0.5N+CL	1.36 def	0.10 ab	2.21 e	0.29 cd	0.33 b
0.5N+RL	1.23 ef	0.10 ab	2.26 e	0.46 b	0.17 de
1.0N	1.60 bc	0.11 ab	2.46 e	0.22 e	0.16 def
1.0N+CL	1.41 cde	0.12 a	3.42 bc	0.34 c	0.33 b
1.0N+RL	1.53 c	0.10 ab	3.08 cd	0.44 b	0.17 de
CF	1.77 b	0.11 ab	2.60 e	0.20 e	0.10 f
CF+CL	1.75 b	0.11 a	3.16 cd	0.29 cd	0.25 c
CF+RL	1.66 bc	0.11 a	3.03 d	0.41 b	0.14 ef

*See table 4.

Table 10 Soil pH and available nutrients left in the soil at the end of the Experiment 2. Means followed by different letters are statistical significant ($P<0.01$ or $P<0.05$).

Treatment*	pH (H_2O)	Soil available nutrients (g pot^{-1})					
		N**	P		Exchangeable Cations		
			Bray	Troug	K	Ca	Mg
C	4.7 f	0.39 b	0.12 d	0.02 g	0.25 c	1.08 h	0.13 d
C+CL	5.9 a	0.40 b	0.12 e	0.02 g	0.21 c	4.10 f	1.36 b
C+RL	5.7 b	0.40 b	0.12 e	0.02 g	0.25 c	5.82 e	0.12 d
0.5N	4.9 e	0.11 d	0.52 c	0.12 f	0.20 c	3.01 g	0.22 d
0.5N+CL	5.9 ab	0.18 cd	0.52 c	0.14 e	0.22 c	6.10 de	1.44 b
0.5N+RL	5.7 b	0.16 cd	0.55 bc	0.16 cd	0.20 c	7.67 b	0.21 d
1.0N	5.1 d	0.22 c	0.59 ab	0.14 e	0.69 b	3.36 g	0.38 c
1.0N+CL	5.8 ab	0.74 a	0.60 a	0.16 bc	0.94 a	6.62 cd	1.72 a
1.0N+RL	5.6 c	0.65 a	0.59 a	0.15 d	0.93 a	7.80 b	0.38 c
CF	4.4 g	0.09 d	0.62 a	0.13 f	0.70 b	3.70 fg	0.15 d
CF+CL	5.4 c	0.38 b	0.61 a	0.18 a	0.88 ab	7.25 bc	1.63 a
CF+RL	5.2 d	0.37 b	0.59 ab	0.17 ab	0.80 ab	9.80 a	0.16 d

*See table 4.
**The same as Table 7.

Treatments that received the CL had a higher effect on soil pH, comparing with the treatments where the RL was applied.

Available N left in the soil in the treatment 1.0N with the CL or the RL application was considerably high compared with that in the treatment without lime. This means that the liming does not have an increasing effect on the plant growth and N uptake by the plants grown in the pot where P was the limiting factor for the growth. The plants, therefore, leave the available N in the soil. Available Bray-P left in the soil in the treatment 0.5N did not showed significantly difference among the lime treatments and this trend was similar to the treatment 1.0N and CF. However the Truog-P left in the soil where P was applied with the CL or the RL was statistically higher than that in the treatment without lime that showed the greater growth of the plants and P uptake. Exchangeable Ca and Mg in the soil demonstrated that the former was higher in treatments where the RL was applied, however the latter were higher in treatments that received application of the CL.

DISCUSSION

Experiment 1

Since it is possible that the P application with the manures can create stable complexes turning the P more available to the plant (Yamane, 1997; Brady and Weil, 2002), we expected that the treatment ADCS＋P showed to promote the availability of the applied P to the plants. From the results in the treatment ADCS＋P and ADCS-P, however, we can point out that the application method of P cannot affect the availability of the applied P to the plants. Organic acids in the dairy cattle slurry form organic chelates with Al and Fe that can make the applied P insoluble, but the organic acids contents in the slurry decreased during the anaerobically digestion process (Matsunaka et al., 2002). It is likely, therefore, that the lower contents of the organic acids in the ADCS may eliminate the effect of the application method of P with the ADCS on the availability of the applied P to the plants. Further experiments are needed to clarify the results.

Our results showed that the ADCS apparently improve the availability of the applied P to the plants. However, N uptake by the plants in the treatments, which received the ADCS, was also higher compared with that in the CF treatment. The reason of this higher N uptake by the plants may be caused by different application rate of total N in the treatments. The CF treatment received just the quantity of NH_4-N present in the ADCS, but the treatments that received the ADCS were applied not only NH_4-N but also organic N from the ADCS. When the organic N is decomposed in the soil, it can increase the available N. And this increase in the available N derived from the decomposition of organic N in the ADCS in the soil supports to increase the plant growth and uptake more P form the soil. Therefore we considered that the apparent improving the P availability by the ADCS was caused by the following possibilities: a) N supplied from the ADCS to the plants was more than that from the CF and b) the increase in the N supply from the ADCS affected significantly the plant growth and c) the increase in the growth resulted in promotion of the P uptake by the plants.

In this experiment, the treatment of liming had statistically significant effect of decrease in the plant growth and in the P uptake by the plants. As shown in Table 7, it was clear that the liming improved the soil pH. Nevertheless the liming had the decreasing effect of the plant growth and P uptake by the plant. We could not explain the reason from our results.

We used the CL in the experiment. The CL was guaranteed as just calcium carbonate. However, among all data in this experiment, the nutrient that showed extremely difference between the treatments where the CL was applied or not was Mg. Our results showed that the CL had a character of dolomite that contained not only Ca but also Mg. Therefore there was a possibility that the Mg in the CL provided a bad effect to the plant growth and nutrients absorption. From the results of plant and soil analysis in the experiment, however, we considered that the reality of the possibility was very low. To confirm this we conducted the Experiment 2 by both use of the CL and the RL.

Experiment 2

As described above, the reason of the apparent improving effect of the ADCS on the availability of the applied P to the plants was possibly caused by different application rate of total N among the treatments of the ADCS＋P, ADCS-P and CF. Then, in the Experiment 2, we tried to compare the plant growth and P uptake by the plants between the treatments 0.5N and CF where the total applied N was slightly different from the treatment 0.5N. The P uptake by the plants did not showed significantly difference between them, although the DMW in the 0.5N treatment was statistically significant higher level than that in the CF treatment. This demonstrated that the cause of low uptake of P in the treatment CF in experiment 1 was the difference in the rate of applied N to the soil. Consequently it is concluded that the ADCS did not increase the availability of the applied P to the plants, when the applied NH_4-N from the chemical fertilizer was not so different from the total applied N, including organic N, from the ADCS. When the ADCS was applied onto the grassland surface, the organic N derived from the ADCS was not available to the grass (Matsunaka et al., 2003). When the ADCS was mixed with the soil, however, it is possible that during the microbial breakdown of the organic N of the ADCS in the soil, mineral N is gradually released from the ADCS as an available N to the plans. Therefore an easily decomposable organic N in the ADCS should be evaluated as an available N, when the ADCS was incorporated into the soil and mixed with the soil.

In this experiment, we found again that the liming using both the CL and the RL had no improvement of the plant growth and the P uptake by the plants. We confirmed that Mg released from the CL was no severe limiting factor for the plant growth and nutrients uptake based on the comparison of the results between the CL and the RL treatment. The amount of Mg in the treatments which received the CL was still high comparing with the other treatments but plants did not respond to the absence of this nutrient. Consequently we cannot surely explain the reason why the liming showed the decreasing effect on the plant growth.

General discussion

After analyzing these two experiments, we could conclude that ADCS did not increase the availability of applied chemical fertilizer P to the corn plant. Rather than that, it is important that a part of the organic N in the ADCS was decomposed by soil microorganisms and the available N was released from the ADCS, when the ADCS was incorporated into the soil

The other an unusual result was as follows: the treatments with the liming to improve soil acidity had not a greater growth and nutrients uptake than the treatments where the lime was not applied. With the analysis of the data from the experiments, deficiency of N, P, K, Ca and Mg were not the cause of this result.

A fact that could explain this effect is that the corn plant is relatively high tolerant to an acid soil environment (Tanaka and Hayakawa, 1975). It appeared, therefore, that the plants did not respond to the liming to improve soil acidity. The low level of Al in the soil used in this experiment may be also considered as the other reason for the no response of the corn plant to the liming, because the y_1 of the soil was very low. Therefore even if the soil pH is low, Al toxicity may not be occurred, allowing treatments that did not received lime had a reasonable growth of the plants. Furthermore, since the pH of the ADCS was high, the ADCS itself could improve the soil pH and consequently mitigated the damage of the plants from the soil acidity, when the ADCS was applied to the soil.

Application of the manures including the ADCS in part of the treatments may occur some interactions between nutrients in the manure and in soil solution. Combinations of nutrients are very common in the soil solution, causing unexpected results, and can be possibly related to this experimental result. Having these hypotheses, part of the results may be explained. Without further studies, however, it is not possible to find the answer to the question for such uncommon results.

Conclusion

From the results of this study we can conclude as follows: a) the ADCS could not increase the availability of the applied fertilizer P to the forage corn plant grown in the acid Andosol in spite of the liming condition, b) the mixing the ADCS with fertilizer P prior to the application could not increase the P availability of the applied P, and c) the liming to improve the soil pH cannot show better contribution to a greater growth of the plants and P availability of the applied P to the plant, and the reason of this uncommon result cannot be certainly explained.

Summary

The aim of this study was evaluate if the anaerobically digested cattle slurry (ADCS) and liming could increase the availability of the applied fertilizer P to the forage corn plant in acid Andosol. We conducted two pots experiment to verify the aim described above.

In the first experiment, The availability of fertilizer P to forage corn did not showed significant difference between the following two application methods of the P with the ADCS; 1) the ADCS was mixed with the P and then applied to the soil, and 2) the ADCS was mixed with the soil at first and after that, fertilizer P was applied. The ADCS could apparently increase the availability of the P to the plants, when the same rate of NH_4-N was applied but total applied N including organic N in the ADCS was considerably different between the ADCS and chemical fertilizer treatment. The treatments without lime had a greater growth of the plants comparing with the treatments with lime. Our results suggested the possibility that the released Mg from the commercial lime (CL) might affect the plant growth and P uptake.

In the second experiment, the ADCS and chemical fertilizer treatments were tested under the condition of the slightly difference in the total N application rate. The P availability did not showed significant difference between them. It was clear from the results comparing with the treatments of the reagent calcium carbonate, which contained no Mg, that the released Mg from the CL was not related to low growth of the plants grown in the liming treatment. Consequently the reason for the decreasing effect of the liming on the plant growth is not still certainly explained.

From the results of these two experiments we can conclude as follows: a) the ADCS could not increase the availability of the applied fertilizer P to the forage corn plant grown in the acid Andosol in spite of the liming condition, b) the mixing the ADCS with fertilizer P prior to the application could not increase the P availability of the applied P, and c) the liming to improve the soil pH cannot show better contribution to a greater growth of the plants and P availability of the applied P to the plant, and the reason of this uncommon result cannot be certainly explained.

要　　約

メタン発酵消化液（消化液）の施与と石灰による酸性改良が肥料リン（P）の飼料用トウモロコシに対する可給度を向上させるかどうかを明らかにするために，ポット試験を２回実施した。供試した土壌は強酸性の黒ボク土である。

試験１では，肥料Ｐを消化液とよく混合してから土壌に施与した場合と，消化液を先に土壌と混和し，その後で肥料Ｐを土壌に施与して混和した場合の，Ｐ可給度を比較した。両者には大きな差異が認められなかった。消化液および化学肥料からのアンモニア態窒素（NH_4-N）の施与量が同量である場合でも，肥料Ｐの可給度は消化液と併用された場合の方が，化学肥料だけの場合より見かけ上良くなった。酸性改良のために石灰を施与しても，酸性改良をしない場合より，トウモロコシの生育だけでなく，養分吸収が抑制された。この結果には，市販石灰から溶出する Mg の影響が懸念された。

試験２では，全Ｎ施与量がわずかに異なる条件設定を設けたところ，肥料Ｐが施与されたトウモロコシの生育は，消化液と併用された処理区のほうが，化学肥料だけで施与された処理区より優った。しかし，作物のＰ吸収には，両処理間で有意な差がなかった。このことから，試験１で施与Ｐの可給度が消化液の施与によって優ったのは，消化液施与区での全Ｎ施与量が化学肥料区より多く，それが作物生育を助長し，見かけ上Ｐ吸収量を増加させたと理解できた。したがって，消化液とともに肥料Ｐを施与しても，そのことが植物へのＰ可給度を向上させるとは考えにくい。また，Mg が混入していない試薬の炭酸カルシウムを用いて酸性改良しても，トウモロコシの生育や養分吸収が酸性改良をしない処理区より良好となることはなかった。したがって，石灰施与によるトウモロコシの生育や養分吸収が抑制されることの原因は本試験結果のみでは説明できなかった。

以上の結果から，次のような結論が得られた。１）消化液は肥料Ｐの飼料用トウモロコシに対する可給度を向上させるとはいえない。２）消化液と肥料Ｐを混ぜることによって肥料Ｐの作物への可給度が向上することはない。３）本試験では，土壌の酸性改良が作物生育や養分吸収を抑制した。この理由は本試験結果からでは十分に説明できない。

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