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Productivity of Acidified Grassland Caused by Acidic Nitrogen Fertilizer and Aluminum Tolerance of Grasses and Legumes

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Abstract

Effect of nitrogen fertilizer application on yield of orchardgrass and soil solution composition of the soil was studied for a Tenpoku acid brown forest soil during a period of 10 years from 1974 to 1985. Soil solution pH of the surface soil in the grassland repeatedly treated with acidic fertilizer as ammonium chloride or ammonium sulfate decreased from 6.5 to 4.5 during a 2-year period. This acidification was caused by the decrease of the amount of cations with which anions such as NO_3^- or Cl^- are associated. With the decrease of pH, a large amount of Al was dissolved in the soil solution and phosphorus uptake by grasses was also retarded. Differences in acid tolerance among several grass species were estimated in the order of orchardgrass > timothy ≒ Kentucky bluegrass > red clover > perennial ryegrass ≒ redtop > alfalfa > white clover. Acid tolerance was correlated with root growth, phosphorus uptake, and aluminum translocation to the shoots. Growth decline of grasses in acid soil was caused by the decrease in phosphorus uptake due to the suppression of root elongation by aluminum. Effects of lime application on grass growth, soil solution composition, and microbial activity were analyzed. The critical pH of the surface soil for which lime was needed was found to depend on the aluminum tolerance of grass species as follows: orchardgrass, 5.0; timothy and Kentucky bluegrass, 5.1; perennial ryegrass, red clover, and redtop, 5.2; alfalfa and white clover, 5.4.

Discipline: Grassland/Soils, fertilizers and plant nutrition/Agricultural environment
Additional key words: aluminum, phosphorus uptake, root growth

Introduction

An important characteristic of grassland soil is its continuous utilization for perennial crop cultivation without plowing. In most grasslands in Hokkaido, farmers utilize the grassland for at least 8 to 10 years continuously. Meanwhile, harvest and chemical fertilizer application are performed 2 or 3 times a year. Repeated surface applications of chemical fertilizers cause drastic changes in the surface layer of the grassland soil as follows: 1) grassland acidification described in this paper, 2) nutrient[13] and 3) root[17] accumulation, 4) higher nutrient uptake activity of the root[12], 5) accumulation of organic residues[14,15], 6) increased activity of micro-organisms[3-5], and 7) soil compaction[16] caused by tractor traffic.

For the production of a sufficient amount of grass in a grassland, adequate fertilizer application is essential. Since soil acidification is caused by fertilizer application, grassland acidification is inevitable. Generally, under acid soil conditions, plant growth is suppressed mainly due to aluminum toxicity[1,2]. Therefore, effective countermeasures to prevent acidification from occurring are needed to maintain optimal grassland conditions and a high productivity. In the current study, the mechanism of grassland acidification and its effects on grass growth were analyzed, and the effect of lime application on acidified grassland was examined. Effective management methods for continuously productive grassland were proposed.

Grassland acidification and aluminum dissolution

1) *Methods*

In an orchardgrass (*Dactylis glomerata* L.) grassland renovated in 1974 and consisting of acid brown forest soil, ammonium sulfate, ammonium chloride and urea were topdressed annually at rates of 60, 120 and 240 kgN/ha for a period of 10 years until 1984. These rates cover nitrogen nutrition in the range of deficiency to excess. Superphosphate and potassium sulfate were applied at the rates of 44 kgP and 125 kgK/ha, respectively. Grass was cut 3 times annually (in early June, early August and late September). Fertilizers were applied 3 times annually before each cutting, one-third of the total rate each time, except for phosphorus. Phosphorus was applied once annually in early spring. Relationships between grass growth and soil acidification were analyzed based on the soil chemical properties and soil solution composition for which samples were taken periodically from layers at depths of 0–2, 2–5 and 5–10 cm.

2) *Grassland acidification*

Soil pH values and the amount of exchangeable Ca in different soil layers are depicted in Fig. 1. Soil pH values decreased rapidly by annual application of ammonium sulfate and ammonium chloride compared with the slow decrease in the urea plot. Remarkable decrease of pH was observed in the 0–2 cm layer of surface soil subjected to a higher rate of nitrogen application during 2 or 3 years. The decrease of the pH values in the 2–5 cm layer was slower and the pH reached a value of 4 from a value of 6 initially during the 5 to 8-year period. Therefore, full-acidification of the 0–5 cm layer was observed 5 to 8 years after fertilizer application. Urea plot showed a remarkably slower pH decrease compared to these plots. Only a 0.5 point decrease was observed in the initial 2-year period in the 0–2 cm and 2–5 cm layers followed by a small decrease. The 5–10 cm layer showed a slower pH decrease, which continued steadily for 5 years after the treatment at a rate of 240 kgN in the ammonium sulfate and ammonium chloride plots. Based on these results, grassland acidification was found to be proportional to the amount of nitrogen fertilizer applied. The surface layer of soil was markedly acidified, and the urea plot showed a very slow acidification process.

The amount of exchangeable Ca decreased annually in relation to soil pH. The Ca decrease was

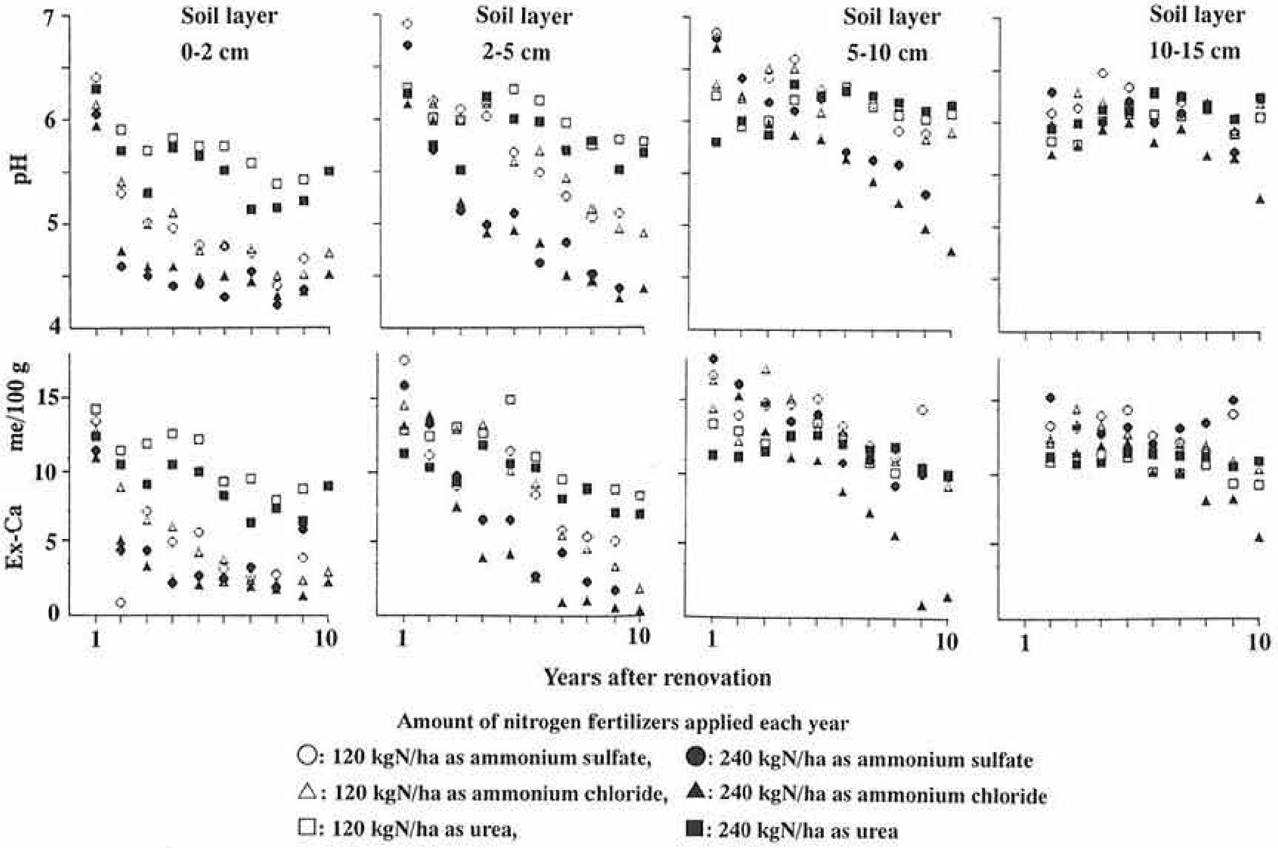

Fig. 1. Changes in pH and exchangeable Ca content of orchardgrass grassland soils cultivated continuously during 10 years with annual application of different amounts of 3 kinds of nitrogen fertilizers

synchronized with the decrease in soil pH, until the 5-10 or 10-15 cm layer below which the pH did not change apparently. These observations suggest that grassland acidification affected the entire 0-15 cm soil layer after several years of chemical fertilizer application.

3) Soil solution composition and acidification mechanism

Soil solution composition of the orchardgrass grassland soil treated with 2 kinds of nitrogen fertilizer, ammonium chloride and urea, was compared after 7 years of application of fertilizer (Fig. 2). In the ammonium chloride plot, nitrate and chloride ions originating from the fertilizers were the major anions. With time, the amount of cations like Ca dissolved in the solution became equivalent to that of the anions, and the cation concentration decreased. The nitrification of the ammonium ion which is contained in the acid-forming fertilizers caused the acidification originally, and the formation of protons which displaced base cations adsorbed on the soil colloid was an important step in the acidification. Since the extent of acidification corresponds to the amount of base element leaching, which is equivalent to the amount of anions, the amount of anions like chloride or sulfate applied with fertilizers is also a promotive factor of acidification. Dissolved cations leached down from the 0-2 cm to the 2-5 cm layers, and to the 5-10 cm layer with precipitation and acidification progressed in these layers. Eventually, the extent of acidification corresponded to the amount of anions contained in fertilizers. However in the case of the urea plot, where a smaller amount of protons was formed and which lacked anions, main anions were nitrate, and sulfate originating from potassium sulfate. Anion concentration was lower than that in the ammonium chloride plot. Therefore, cation concentration also remained lower, and the amount of base elements leaching down was very small. Furthermore, since urea shows a buffer action by the increase in the concentration of bicarbonate ion, the urea plot showed a very slow acidification.

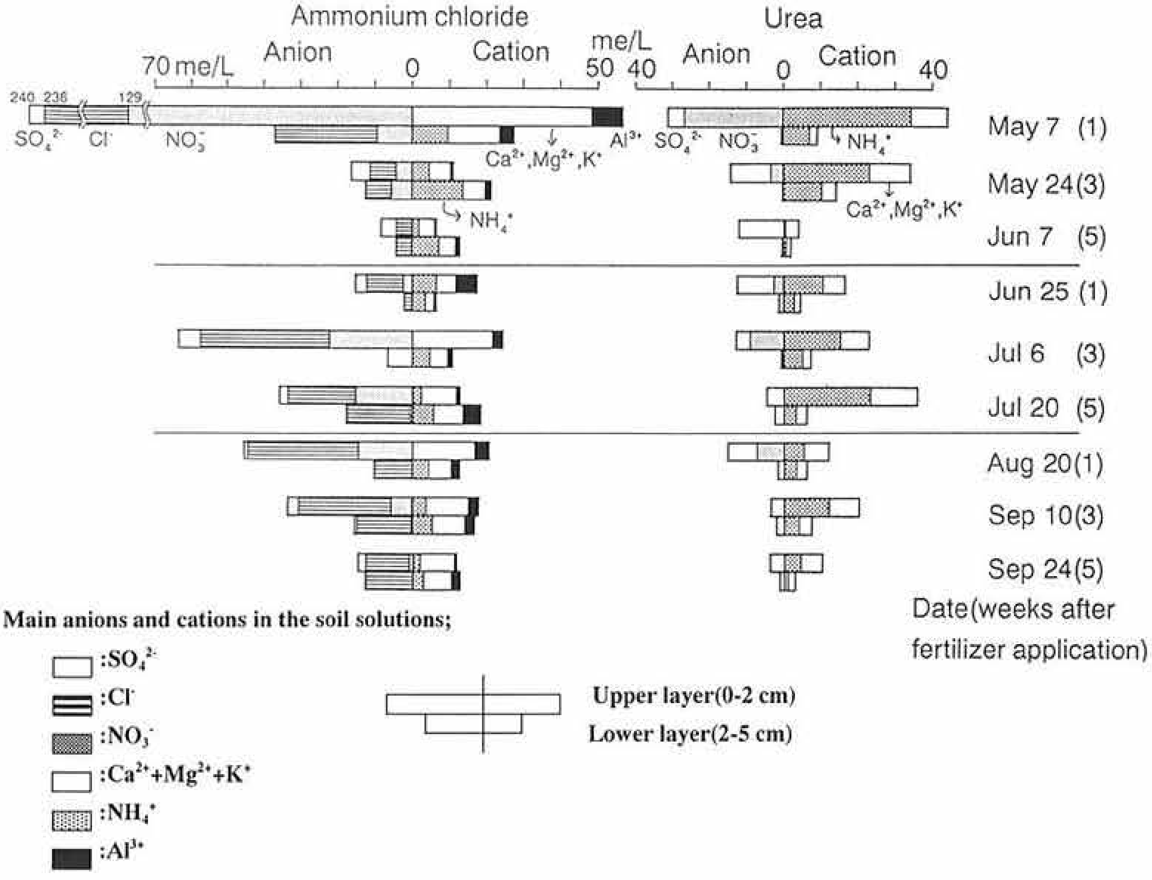

Fig. 2. Comparison of seasonal changes in several kinds of ions in the soil solution in the 0-2 cm and 2-5 cm layers of orchardgrass grassland soils treated with ammonium chloride and urea, 3 times in April, June and August

4) Aluminum dissolution

Changes in the aluminum (Al) concentration of the soil solution in orchardgrass soil treated with 3 kinds of nitrogen fertilizer were observed for a 2-year period (Fig. 3). According to the figure, Al concentration was higher in the order of ammonium chloride > ammonium sulfate > urea, and it was proportional to the amount of nitrogen fertilizer applied. Immediately after nitrogen fertilization, particularly ammonium chloride, Al concentration in the 0–2 cm layer exceeded 4 me/L except for the application in July. Thereafter, Al concentration in the 0–2 cm layer decreased and a considerably high concentration of Al was observed in the 2–5 cm layer. In both layers, higher Al concentration was obviously recognized in the ammonium chloride plot. The relationships among Al concentration, pH value and the concentration of other ions in the soil solution had been clarified[6,11]. The pH value of the soil solution in the ammonium chloride or the ammonium sulfate plots was about 4.0 and Al concentration also increased in inverse proportion to the decrease of the pH value. In another experiment, we observed that Al concentration increased when the pH value fell below 5.0[6,11]. Decrease in Al concentration with time is due to the uptake by grass plants or downward movement of the ions across the soil layers. As a result, Al dissolution into the soil solution is regulated by the pH and anion concentration.

5) Phosphorus uptake by grasses

Phosphorus (P) content of the grass, which

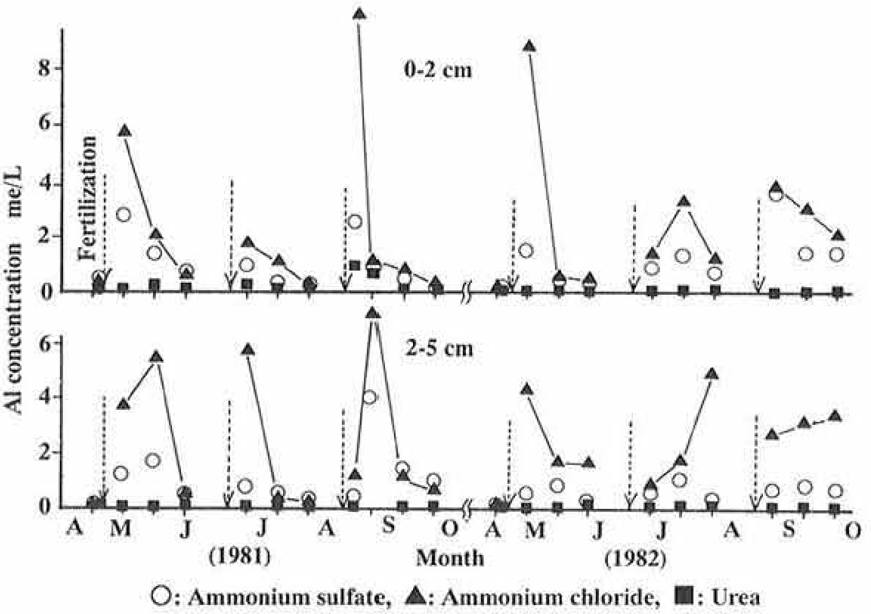

Fig. 3. Seasonal changes in Al concentration in the soil solution of orchardgrass grassland (240 kgN/ha, 0–2 and 2–5 cm layers)

Table 1. P concentration in the shoots, total P uptake of the shoots, and P utilization rate (mean values during 7 years (1976–1982))

Treatments	N-rate	P content in the shoots (%)			Total P uptake[a) (kgP/ha/year)	P utilization rate (%)[b)
		1st cut	2nd cut	3rd cut		
Ammonium sulfate	120	0.33	0.35	0.43	27.5	63
Ammonium chloride	120	0.31	0.31	0.42	24.9	57
Urea	120	0.33	0.42	0.48	28.8	66
Ammonium sulfate	240	0.31	0.30	0.37	33.2	76
Ammonium chloride	240	0.30	0.27	0.35	30.1	69
Urea	240	0.34	0.35	0.44	38.4	88

a): P uptake by shoots.

b): Calculated as % of total P uptake/total amount of P applied (44 kgP/ha/yr).

decreased in the presence of soluble Al, was higher in the order of urea > ammonium sulfate > ammonium chloride[6,11]. The amount of P uptake and fertilizer P utilization efficiency decreased in the acidified plots (Table 1), indicating that P uptake was suppressed as a result of Al dissolution by grassland acidification. On the other hand, available phosphate accumulated in the surface layer of the grassland in the order of ammonium sulfate ≒ ammonium chloride > urea, and P concentration in the soil solution was in the same order (data not shown[6,11]). In addition, Al adhesion to the rhizoplane of the acidified plot was observed[6,11]. These results indicated that the decrease in P uptake by the grass in the presence of soluble Al was due to the decrease in the uptake ability of the root with some relationship between Al and root, and not due to the decrease in the amount of P supplied from the soil.

Decline of grass growth in acidified grassland and acid tolerance of grass species

1) Yield of orchardgrass

Orchardgrass yield in the above mentioned experiment is shown in Table 2 and is expressed as the relative value to that in the urea plot. Orchardgrass showed a growth decline in line with the acidification after 3 years of treatment, with annual variations. Extent of decline in a year with low yield was more remarkable in the 240 kgN ammonium chloride plot. Annual variation in the effect of grassland acidification on the yield was attributed to the precipitation during the growth season of the grass[9,11]. The extent of decrease of grass yield caused by acidification varied considerably with the years. This fluctuation was strongly affected by precipitation: in a year with low precipitation, the decrease of grass yield was remarkable, while the extent of the decrease was limited in a year with high precipitation. The remarkable decrease of grass yield in an acidified grassland in a year with low precipitation was attributed to the high concentration of Al in the soil solution. Furthermore, since precipitation affects not only grass growth in acidified grassland but also that in non-acidified grassland, grass yield decreased by both precipitation and acidification. This relation was represented in the schematic model depicted in Fig. 4.

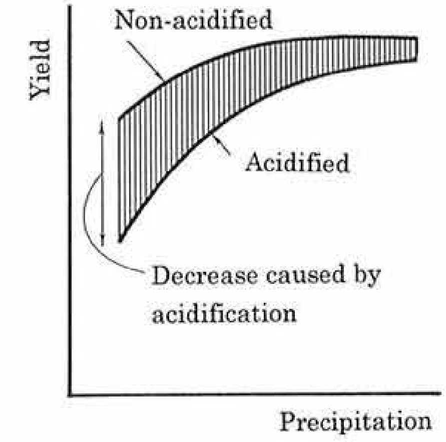

Fig. 4. Relationship between grass yield and precipitation
-A schematic model of soil acidification effect-

Table 2. Changes in the relative yield of orchardgrass[a)]

N-fertilizer	N-rate	Year									
		1975 1	’76 2	’77 3	’78 4	’79 5	’80 6	’81 7	’82 8	’83 9	’84 10
Ammonium sulfate	60	97	103	93	91	102	94	84	90		
	120	90	109	98	102	100	101	100	95		
	240	101	129	95	97	90	98	106	90		
Ammonium chloride	60	94	103	94	86	91	87	98	89	72	
	120	85	100	88	104	92	106	105	90	95	89
	240	100	110	86	94	82	96	105	85	95	77
Urea	60	(4.74)[b)]	(6.07)	(7.64)	(8.00)	(4.83)	(5.07)	(7.97)	(6.43)	(6.47)	
	120	(5.58)	(7.17)	(9.28)	(9.56)	(6.69)	(5.75)	(7.99)	(7.36)	(7.26)	(6.12)
	240	(5.50)	(8.86)	(11.92)	(13.24)	(9.82)	(8.51)	(10.50)	(10.14)	(10.57)	(8.66)

a): Yield is expressed as the relative yield of orchardgrass based on total dry weight to that in the urea treatment.

b): Numerals in the parenthesis indicate the dry weight of urea treatment (t/ha).

2) *Comparison of acid tolerance among grasses and legumes*

Based on the results described above, the concentration of Al dissolved into the soil solution plays a major role as a growth limiting factor in the acidified grassland. In the case of orchardgrass, even though the yield decreased with the decrease in P content, the extent of the decrease was not remarkable in a year with high precipitation. Since several grass species other than orchardgrass are cultivated in Hokkaido, it is anticipated that the influence of grassland acidification is different among the various species cultivated. Therefore, the tolerance to grassland soil acidity was compared among several grass species.

Al tolerance, which is an important factor in determining the tolerance to grassland acidification, should be evaluated based on 2 criteria: 1) solution Al concentration, which causes the growth decline (Al sensitivity), and 2) extent of growth decline under a certain concentration of Al in the soil solution (acid tolerance). This is because for practical management of a grassland it is important to determine 1) when grass growth begins to decline under acidifying conditions, and 2) the effect of acidification. Therefore, through 3 experiments using acid brown forest soil differing in the Al concentration of the soil solution, differences in acid tolerance were evaluated, by using a total score with 5 grades in relation to 1) Al sensitivity and 2) acid tolerance as shown in Table 3. Orchardgrass was ranked as the most tolerant species.

3) *Factors affecting acid tolerance and mutual relations*

Acid tolerance, which is defined as the growth ability under Al dissolved conditions, was correlated with root growth or root length, P content of the shoot, and Al translocation to the shoots[8,11]. Mutual relations of these factors are shown in Fig. 5. Differences in acid tolerance between grass species were proportional to both root growth and P content of the shoots, and inversely proportional to Al translocation to the shoots. Decrease in P uptake in the presence of soluble Al was controlled by the decrease in root weight in all the grass species studied. Growth decline in acid soil was mainly associated

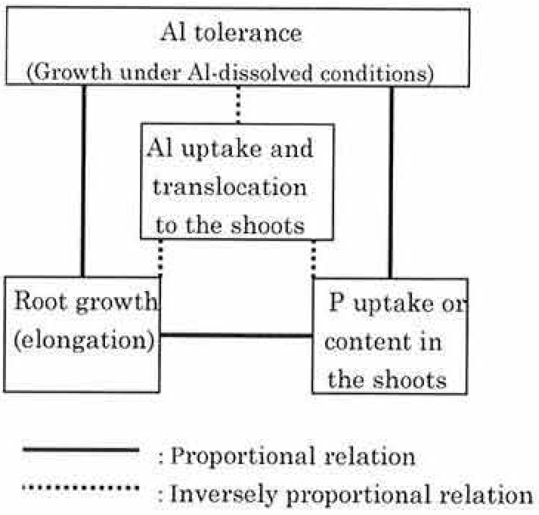

Fig. 5. Factors affecting acidity tolerance

Table 3. Evaluation of acidity tolerance among several grasses and legumes studied

Species	Al tolerance		Relative growth at 15 mgAl/L in the soil solution		Acidity tolerance (general estimation)	
	Al[a)] (mgAl/L)	Grade[b)]	Growth rate (%)	Grade[b)]	Total grade[c)]	Acidity tolerance[d)]
Orchardgrass	100	5	90	5	10	VS
Timothy	10–20	4	85	5	9	S
Kentucky bluegrass	15<	4	90	5	9	S
Red clover	<15	3	75	4	7	M
Perennial ryegrass	<15	3	70	3	6	M
Redtop	<15	3	70	3	6	M
Alfalfa	<4	1	70	3	4	W
White clover	<4	1	50	1	2	VW

a): Al concentration of the soil solution when the grass growth started to decline.
b): Scores expressed in 5 grades (highest: 5, lowest: 1).
c): Total scores of Al tolerance and relative growth.
d): VS: Very strong (tolerant), S: Strong, M: Medium, W: Weak (sensitive), and VW: Very weak.

with the decrease in P uptake which was caused by the suppression of root elongation by Al, and not by the suppression at the site of P metabolism in the plant shoot related to the dry matter production. On the other hand, grass tolerance to low P conditions in the soil decreased under low pH conditions, while the Al tolerance also decreased under low P conditions[11]. These results indicate that Al tolerance and low P tolerance are correlated through the effects on root growth.

Growth improvement by calcium carbonate application

1) Methods

(1) Field experiment

Using the same site of orchardgrass grassland as that described above which had been topdressed with ammonium sulfate, superphosphate, and potassium sulfate at rates of 120 or 240 kgN, 44 kgP, and 125 kgK/ha, respectively, for the previous 8 years, ground limestone was applied at 4 levels, 0, 2, 4, and 8 t $CaCO_3$/ha at the end of April 1983. The plot size was 2.25 m^2 with 4 replications. Soil and soil solution samples were taken periodically at depths of 0–2, 2–5, and 5–10 cm. The moisture content of the soil samples was adjusted to the field capacity and the samples were equilibrated for 7 days at 5°C. Then the soil solution was collected by centrifugation for half an hour at 12,000 rpm, equivalent to pF 4.2. Microbial analysis was performed using the fresh soil samples[7,11], and the numbers of bacteria and fungi were counted by the dilution plate method using egg albumin agar films with aniline blue. Reducing activity of 2,3,5-triphenyltetrazolium chloride (TTC), and decomposing activity of urea and fructose were determined by the method of Hojito et al.[7].

(2) Pot experiment

Grass plants grown in 3 acidified grasslands in cumulic andosol were transplanted to bottomless stainless pots (a/5,000) with roots and soil at a depth of 21 cm. Ammonium chloride and potassium sulfate were applied at the rates of 200 kgN, 166 kgK/ha, respectively and 2.5 t/ha of calcium carbonate was applied to the $+CaCO_3$ plot on May 22, 1989. Orchardgrass and timothy were grown until October 23, while grass shoots were cut 2 and 3 times for timothy and orchardgrass, respectively. After the final harvest, roots were isolated by water flow, and weighed.

2) Results

In the field experiment, annual dry matter yield slightly increased by lime application (Fig. 6). The amount of P and calcium (Ca) uptake increased, while the amount of nitrogen (N) did not change appreciably. Soil pH 6 months after lime application showed remarkable increases in the 0–2 cm layer but no changes below the 2–5 cm layer. Soil solution composition was affected by lime application in the 0–2 cm layer but the effects were not clear in the 2–5 cm layer. As a typical example, soil solution composition at 2 months after lime application to the 0–2 cm layer is shown in Fig. 7. The pH, Ca and sulfate concentrations increased remarkably,

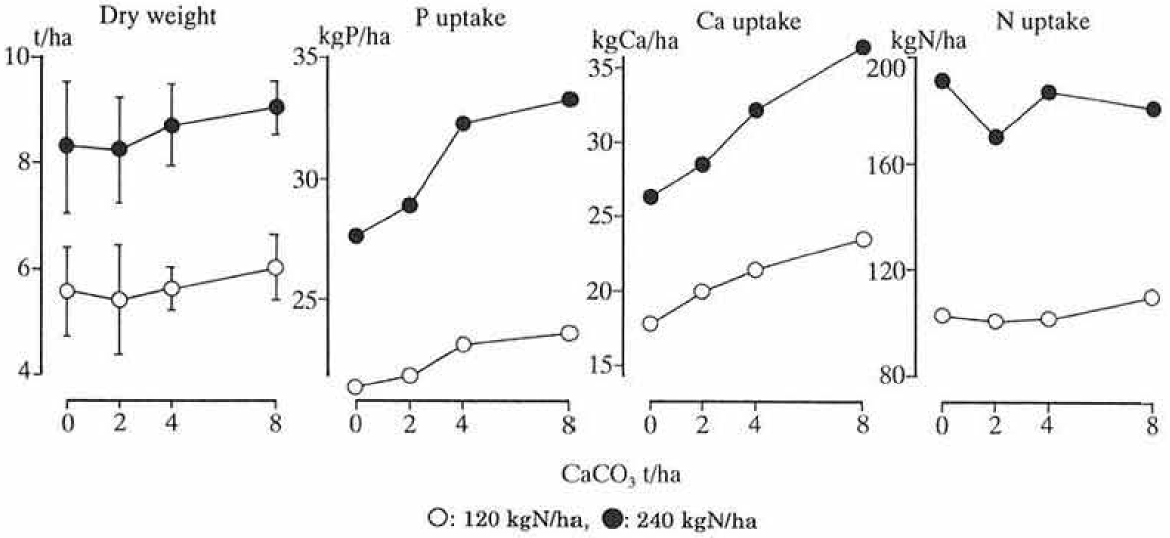

Fig. 6. Effect of lime application on dry weight and total uptake of P, Ca and N of acidified orchardgrass grassland

while the Al, N and P concentrations decreased. These changes were more conspicuous in the 240 kg N plot than in the 120 kg N one. The microbial activities of the 0–2 cm layer 6 months after lime application are shown in Table 4. TTC-reducing activity, fructose-decomposing activity, urea-decomposing activity and the bacterial counts increased in proportion to the amount of lime applied, while the number of fungal spores tended to decrease, although hyphal length increased. These results indicated the role of lime application in the increase of microbial activities.

In the pot experiment, soil pH increased by lime application from 4.5–4.9 to over 6.0, while the amount of available phosphate decreased slightly, and that of exchangeable Ca increased conspicuously (data not shown[10,11]). As a result, root weight increased (Fig. 8), and N, potassium, Ca and magnesium contents increased[10,11]. However the effect on the yield was not clear.

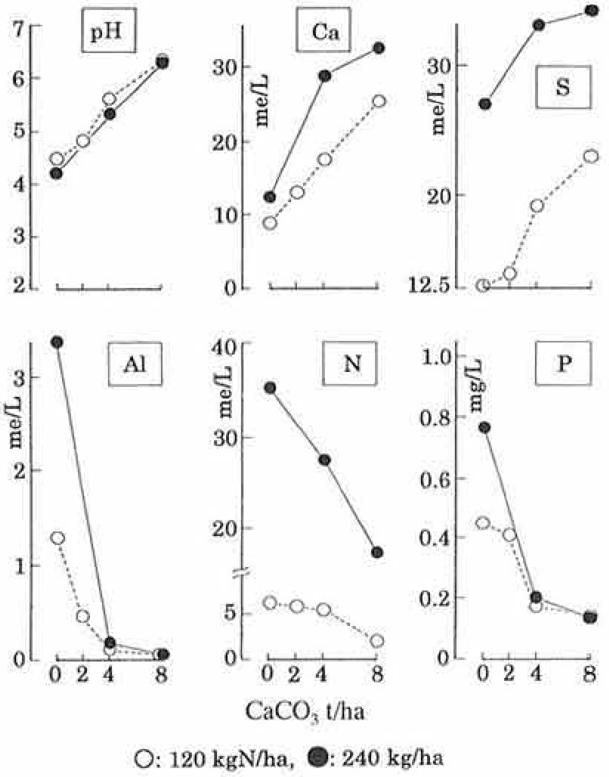

Fig. 7. Effect of lime application on the soil solution composition in acidified orchardgrass grassland 2 months after the application (0–2 cm layer in 1983)

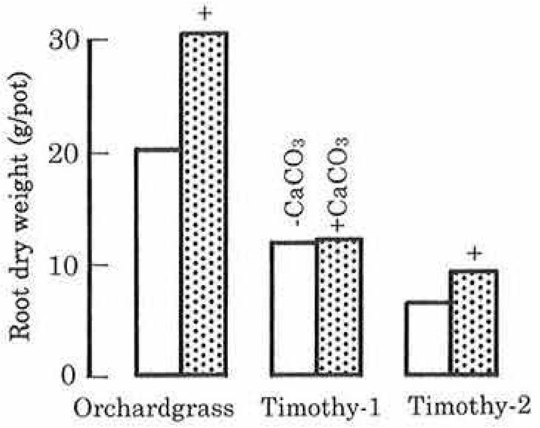

Fig. 8. Effect of lime application on root dry weight of orchardgrass and timothy (+CaCO$_3$: 10 gCaCO$_3$/pot)
Orchardgrass: Orchardgrass grassland (grazing), soil pH(0–5 cm): 4.48.
Timothy-1: Timothy grassland (cutting), soil pH(0–5 cm): 4.91.
Timothy-2: Timothy grassland (cutting), soil pH(0–5 cm): 4.87.

Table 4. Effects of lime application on microbial and biochemical activities (120 kgN treatment, 0–2 cm layer, October 1983)

CaCO$_3$ rate (t/ha)	TTC*1) reducing activity*2) (mg)	Decomposing activities*2)		Numbers*3)		Hyphal length*3) (m/g)
		Fructose (mg)	Urea (mg)	Bacteria (10^6/g)	Fungal spores (10^6/g)	
0	37	271	150	12.8_a*4)	15.8_a	201
2	105	345	183	13.4_a	12.9_a	216
4	287	471	211	13.7_b	13.9_a	269
8	172	392	254	22.3_c	9.1_b	270

*1): 2,3,5-Triphenyltetrazolium chloride.
*2): These activities are expressed as mg of product formed or mg substrate decomposed per 100 g dry soil per day at 30°C.
*3): Expressed as value per 1 g of dry soil.
*4): a, b and c denote statistical difference. When the same subscripts are used, they are not significant at 5% level of significance.

3) Soil solution composition

The changes in the chemical composition of the soil solution by lime application were associated with the dissolution of lime in the solution, that is, when the Ca concentration and pH increased, Al concentration decreased. The fact that the Ca concentration in the solution increased only in the topmost 5 cm layer suggests that the amount of Ca that moved vertically downward into the layers below 5 cm during the 6-month period was small. Therefore, it was considered that lime should be applied before soil acidification reached the 5 cm layer.

4) Microbial activities

The microbial numbers and biochemical decomposing activities, which are closely correlated[11] and are important factors controlling the decomposition of organic matter, were enhanced by the pH increase associated with lime application. Since Al concentration in the soil solution also affects microbial activities[18], the decrease in the Al concentration in the soil solution contributed to the increase in microbial activities. This improvement in microbial activities promoted the decomposition of organic matter, and also reinforced, indirectly, the liming effect on the uptake of nutrients such as Ca or P.

5) Root growth and phosphorus uptake

The results of pot experiments revealed the promotive effect of lime application on root growth and nutrient uptake. Even though the increase in the Ca uptake was directly affected by the increase in the concentration of the solution, there was no drastic change in the conditions of supply of other nutrients from soil to grass roots. Particularly for P, the concentration in the soil solution decreased by lime application, as shown in the field experiment. This phenomenon can be ascribed to the fact 1) that root growth which was suppressed by Al recovered abruptly by lime application and the decrease in Al concentration, 2) and that, in spite of the decrease in the P concentration in the soil solution, P uptake increased mainly due to the abrupt increase in the uptake ability of the root. This assumption is consistent with former investigations in which it was found that P uptake was controlled mainly by the root length and that Al prevented the P uptake through root elongation suppression[6,10,11].

6) Timing and amount of lime application in relation to practical countermeasures

To alleviate grassland acidification, the application of liming materials in equivalent amount to that of anions contained in the fertilizers and naturally leached from the soil, at the time of fertilizer application was recommended. The equivalent amount of lime depends on the kind and amount of fertilizers used. Anion content is particularly important. To decide the timing of lime application for grassland in which acidification was advanced, soil pH at which Al concentration increased and P uptake decreased should be determined. That is, the critical pH of the surface soil (0–2 cm) for which lime was needed depended on the Al tolerance of grass species in acid brown forest soil, which was as follows: orchardgrass, 5.0; timothy and Kentucky bluegrass, 5.1; perennial ryegrass, red clover, and redtop, 5.2; alfalfa and white clover, 5.4. In addition, using, in conjunction, the management method for the timing of P fertilizer application[11], the grassland could effectively maintain a high productivity.

Conclusion

Grassland acidification is originally caused by the nitrification of the ammonium ion contained in the acid-forming fertilizers, and by the formation of protons which displace base cations adsorbed on the soil colloid. Since the repeated application of N fertilizers was the main cause, the extent of acidification was proportional to the amount of N fertilizers applied, and the surface layer of the soil was markedly acidified. Al was dissolved in the soil solution of acidified grassland at a soil pH below 5.0. Its concentration was proportional to the amount of N fertilizer applied and inversely proportional to the duration of the period after fertilizer application and to soil depth, and it was controlled by the soil pH and the concentration of anions in the soil solution. P uptake was suppressed due to Al dissolution by acidification. Differences in acid tolerance among several grass species were estimated, and acid tolerance was found to be correlated with root growth, P uptake, and Al translocation to the shoots. Growth decline in acid soil was caused by the decrease in P uptake due to the suppression of root elongation by Al.

To alleviate grassland acidification, the application of a liming material with an equivalent amount of anions to that contained in the fertilizers and naturally leached from the soil, at the time of fertilizer application was recommended. The equivalent amount of lime depends on the kind and amount of fertilizers used and anion content is particularly important. To decide the timing of lime application to a grassland with advanced acidification, the critical pH of the surface soil (0-2 cm) for which lime is needed should depend on the Al tolerance of grass species in an acid brown forest soil.

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