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Water-Stable Aggregates of Strongly Acidic Allophanic Andosols affected by Heavy Application of Fertilizers

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Abstract

This research was performed to assess water-stable aggregates of strongly acidic allophanic Andosols affected by heavy application of fertilizers. A long-term field experiment with successive application of lime and fertilizers began in 1940 at the Fujisaka Branch of the Aomori Agricultural Experiment Station. The exchange acidity y_1 of the fertilizer plot for topsoil (0-13cm), subsoil (13-21cm), and subsoil (21-42cm) showed strong acidity. The potato yields in 2014 were 0.93 kgm^{-2} for the fertilizer plot and 3.12 kgm^{-2} for the lime+fertilizer plot. Strongly acidic allophanic Andosols with accumulation of acidic materials showed dissolution of part of the active Al fraction in the soil causing Al toxicity. The percentages of water-stable aggregates of the upper-subsoil layer (13-21cm) in the fertilizer plot were 39.9%±4.9% for the < 0.125 mm fraction, 17.4%±1.2% for the 0.125-0.25 mm fraction, 30.5%±3.5% for the 0.25-0.5 mm fraction, 9.3%±0.5% for the 0.5-1.0 mm fraction, 2.1%±0.3% for the 1.0-2.0 mm fraction, and 0.7%±0.4% for the > 2.0 mm fraction. The micro aggregate increased because of the decrease in the amount of roots by Al toxicity in the strongly acidic subsoil of the fertilizer plot. The taproot areas were estimated as 11.4 cm^2 for the fertilizer plot and 14.4 cm^2 for the lime+fertilizer plot on radiographs. The taproot area in the fertilizer plot was relatively low. Thus, we confirmed that the macro aggregate was decreased by restricting of the root system in the strongly acidic allophanic Andosols and the pores formed by roots were relatively small.

Keywords: Allophanic Andosols, pore formed by roots, strongly acidic, water-stable aggregate

1. Introduction

Andosols occurring in Japan are divided into allophanic Andosols and non-allophanic Andosols according to the composition of active-Al. Allophanic Andosols are mainly distributed in areas with thick depositions of Holocene and/or Late Pleistocene tephras and account for 4.51 million ha of the total land area of Andosols in Japan. On the other hand, non-allophanic Andosols are scattered inareas with poor deposition of tephras and account for 1.95 million ha of the total area of Andosols in Japan (Saigusa and Matsuyama, 1998). Both types of Andosols have unique properties, such as a thick black A horizon, high phosphate fixation, and low bulk density (Wada, 1985). The clay fraction of allophanic Andosols is dominated by allophane and imogolite. As this fraction has a weakly acidic character (Yoshida, 1971), plants are not exposed to Al toxicity in allophanic Andosols (Saigusa et al., 1980).

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On the other hand, the clay fraction of non-allophanic Andosols is dominated by 2:1 minerals and this fraction has a strongly acidic character (Yoshida, 1970). Judging from the acidic character of both Andosols, the exchange acidity y_1 is a suitable criterion for classifying uncultivated Andosols into allophanic and non-allophanic Andosols; i.e., exchange acidity $y_1 < 6$ in allophanic Andosols and $\geqq 6$ in non-allophanic Andosols (Saigusa et al., 1992b). The high level of exchangeable Al (exchange acidity $y_1 \geqq 6$) in non-allophanic Andosols causes severe Al toxicity in plants (Saigusa, et al., 1991). Therefore, it is very important to manage the soil acidity in non-allophanic Andosols for agriculture (Saigusa et al., 1992a).

Previously (Matsuyama et al., 1999a; Matsuyama et al., 1999b; Matsuyama, 2003), we reported strongly acidic allophanic Andosols among the representative cultivated Japanese allophanic Andosols. The strongly acidic allophanic Andosols (exchange acidity $y_1 \geqq 6$) did not differ significantly from the weakly acidic allophanic Andosols (exchange acidity $y_1 < 6$) in contents of amorphous materials. However, these soils showed high exchange acidity y_1 and severe Al toxicity toward plants despite their status as allophanic Andosols. Matsuyama et al. (2005) investigated the acidification and soil productivity of strongly acidic allophanic Andosols and reported that cultivated allophanic Andosols affected by heavy application of fertilizers accumulated acidic materials, such as SO_4^{2-} and NO_3^-, gradually became strongly acidic. In addition, the subsoil productivity of strongly acidic allophanic Andosols was relatively low, as indicated by the reduction of crop production.

For crop production, it is very important to evaluate the physical as well as chemical properties of soil (Brady and Weil, 2010). Soils with a well-developed aggregate structure have relatively high capacities to store available water and air for crop roots, and evaluation of water-stable aggregate is important to determine crop production potential. The present study was performed to compare the water-stable aggregates of strongly acidic allophanic Andosols.

Materials and Methods

To examine the soil productivity, we used the Fujisaka Andosols with clay dominated by allophane in a long-term field experiment on successive application of lime and fertilizers at theFujisaka Branch of Aomori Agricultural Experiment Station. In the fertilizer plot, 12-15gNm^{-2} (ammonium sulfate for N), 15gP_2O_5m^{-2} (superphosphate for P), and 12gK_2Om^{-2} (potassium sulfate for K) have been applied every year since 1940. In the lime+fertilizer plot, 75gm^{-2} as slaked lime was applied together with the fertilizers mentioned above. Crop rotation consisted of flint corn, soybean, and potato.

Soil samples were collected from the topsoil and subsoil of the fertilizer plot and the lime+fertilizer plot in 1998. All laboratory determinations were performed on air-dried materials that had been passed through a 2-mm mesh sieve. The pH(H_2O) values of the soil samples were measured potentiometrically in water (1:2.5). The exchange acidity y_1 was determined by titration of 125mL of 1M KCl soil extract (100:250) with 0.1M NaOH. The amounts of acid oxalate-extractable Al, Si, and Fe (Alo, Sio, and Feo, respectively) and pyrophosphate-extractable Al and Fe (Alp and Fep, respectively) were determined based on the procedures described by Blakemore et al. (1981). Water-stable aggregate analysis was performed according to the standard method (Kemper and Rosenau, 1986: Tisdall and Oades, 1982: JSSSPN, 1997)

The structure of soil macropores (pores formed by roots) was determined by soft X-ray radiography (Tokunaga, 1995). Briefly, the soil samples for soft X-ray radiography examination were collected from an experimental plot without disturbance. Samples were trimmed into cubes measuring 4.15cm on a side. Pieces of withered roots were reinforced by a clay coating. The reinforced samples were then saturated with water through a vacuum saturation process. Following water saturation, samples were soaked in a contrast media solution (Diiodomethane (CH_2I_2)) for photographic examination. The contrast media was infiltrated into soil samples, and soft X-ray radiography was performed. The root contents were estimated using image analysis software (Image J; NIH).

Results and Discussion

Comparison of soil acidity and potato yield between the fertilizer and lime+fertilizer plots.

A long-term field experiment with successive application of lime and fertilizers has been conducted since 1940 at the Fujisaka Branch of the Aomori Agricultural Experiment Station. Table 1 show the contents of amorphous materials in Fujisaka Andosols, which is derived from Towada volcanic ash and is representative allophanic Andosols. The contents of the amorphous materials in the fertilizer plot were not significantly different from those in the lime+fertilizer plot.

However, there were significant differences in pH(H_2O) and exchange acidity y_1 between the two plots. Figure1 shows the vertical distribution of soil pH (H_2O) in both plots. The soil pH(H_2O) values for the fertilizer plot were 3.95 for the topsoil (0-13cm), 4.04 for the subsoil (13-21cm), 4.25 for the subsoil (21-42cm), 5.43 for the subsoil (42-63cm), 5.77 for the subsoil (63-73cm), and 5.79 for the subsoil (73-78cm). On the other hand, the soil pH

Table 1: Contents of morphous materials in Fujisaka and osols

Soil	Sio(gkg^{-1})	Alo(gkg^{-1})	Feo(gkg^{-1})	Alp(gkg^{-1})	Fep(gkg^{-1})	Alp/Alo
Fertilizerplot						
Topsoil	9.9	25.5	6.5	5.9	1.9	0.23
Subsoil	10.4	25.3	5.0	5.7	1.3	0.23
Lime+fertilizerplot						
Topsoil	8.4	23.1	7.5	5.3	1.9	0.23
Subsoil	10.5	27.8	8.2	6.6	2.1	0.24

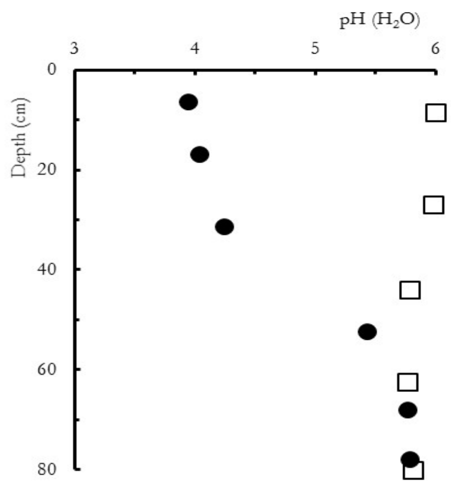

Fig. 1: Vertical distribution of soil pH

● Fertilizer plot □ Lime+fertilizer plot

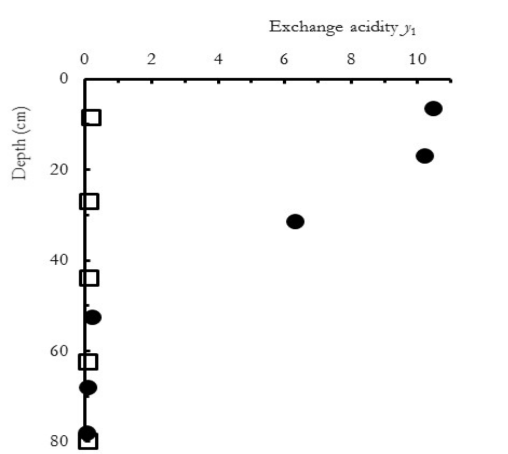

Fig. 2: Vertical distribution of exchange acidity y_1

● Fertilizer plot □ Lime+fertilizer plot

(H_2O) values for the lime+fertilizer plot ranged from 5.76 to 6.00 between the surface layer to a depth of 79cm. The soil pH(H_2O) values of the fertilizer plot for topsoil (0-13cm), subsoil (13-21cm), and subsoil (21-42cm) were strongly acid (pH < 4.0). The soil pH(H_2O) value of the fertilizer plot for topsoil and subsoil in 1948 were 6.16 and 6.11, respectively (Nomoto and Kamata, 1950). Therefore, the soil of the fertilizer plot has recently become strongly acid. Figure 2 shows the vertical distributions of exchange acidity y_1 in both plots. The exchange acidity y_1 of the fertilizer plot were 10.5 for the topsoil (0-13cm), 10.2 for the subsoil (13-21cm), 6.3 for the subsoil (21-42cm), 0.2 for the subsoil (42-63cm), 0.1 for the subsoil (63-73cm), and 0.1 for the subsoil (73-78cm). On the other hand, the exchange acidity y_1 were < 0.2 in all layers of the lime+fertilizer plot. The exchange acidity y_1 values of the fertilizer plot for topsoil (0-13cm), subsoil (13-21cm), and subsoil (21-42cm) were strongly acid. The exchange acidity y_1 of the topsoil and subsoil in the fertilizer plot in 1948 were 0.4 and 0.4, respectively (Nomoto and Kamata, 1950).

Therefore, in addition to the acidification of the soil pH(H_2O), the soil of the fertilizer plot has become strongly acidic since 1940. Figure 3 shows the fresh weight of potato obtained from the field experiment in 2014. The potato yields in 2014 were 0.93 kgm^{-2} for the fertilizer plot and 3.12 kgm^{-2} for the lime+fertilizer plot, which were significantly different ($p < 0.001$). In contrast, the potato yields in 1940 were 2.73 kgm^{-2} and 2.66 kgm^{-2} for the fertilizer plot and for the lime+fertilizer plot, respectively (Aomori Agricultural Experiment Station, 1987, personal communication). Thus, the potato yield of the fertilizer plot has decreased to about one-third compared with the initial yield over the past ~70 years. Similar trends of low yield in the fertilizer plot were observed for soybean and flint corn cultivated as rotation crops (data not shown). Heavy application of potentially acidic fertilizers causes an increase in acidic materials in soil, and gradually decreases the soil pH through the leaching of exchangeable bases. Such strongly acidic allophanic Andosols with accumulation of acidic materials dissolve a portion of the active Al fraction in the soil causing Al toxicity in plants. In addition, it is very important for soil management to note that the exchange acidity y_1 of the subsoil, which is influenced indirectly by fertilizer application, has exceeded a value of 6.

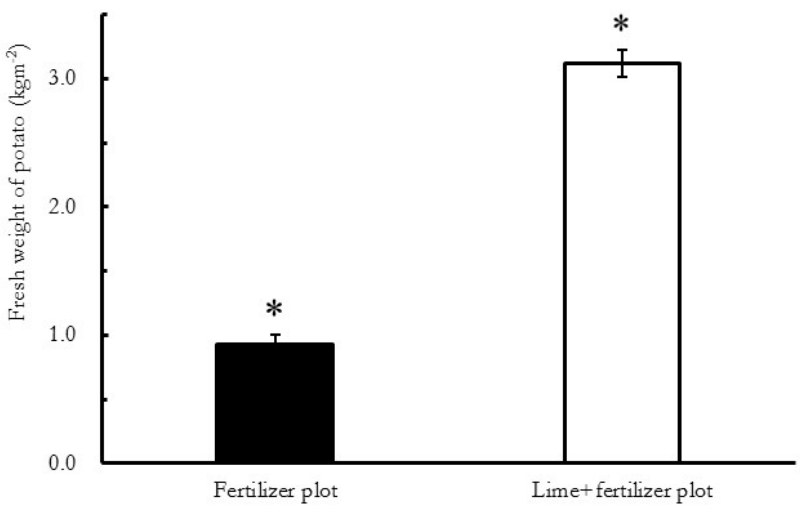

Fig. 3: Fresh weight of potato in the fertilizer plot and lime+fertilizer plots. Bars denote standard deviation. *: Significance at 0.1% level.

Comparison of water-stable aggregate between the fertilizer and lime+fertilizer plots

Figure 4 shows the distribution of water-stable aggregate in topsoil for both fertilizer and lime+fertilizer plots. The percentages of water-stable aggregate of topsoil (0-13cm) in the fertilizerplot were 40.7%±2.7% for the < 0.125 mm fraction, 17.2%±0.8% for the 0.125-0.25 mm fraction, 29.9%±2.1% for the 0.25-0.5 mm fraction, 9.4%±0.8% for the 0.5-1.0 mm fraction, 2.4%±0.4% for the 1.0-2.0 mm fraction, and 0.4%±0.2% for the > 2.0mm fraction, and there were no significant differences compared with the lime+fertilizer plot. The particle size distribution of the topsoil was estimated to reflect the influence of tillage. On the other hand, the percentage of water-stable aggregate of the upper-subsoil layer(13-21cm) in the fertilizer plot were 39.9%±4.9% for the < 0.125 mm fraction, 17.4%±1.2% for the 0.125-0.25 mm fraction, 30.5%±3.5% for the 0.25-0.5 mm fraction, 9.3%±0.5% for the 0.5-1.0 mm fraction, 2.1%±0.3% for the 1.0-2.0 mm fraction, and 0.7%±0.4% for the > 2.0mm fraction (Figure 5).

The levels in the < 0.125 mm fraction and 1.0-2.0 mm fraction were significantly different between the fertilizer plot and the lime+fertilizer plot ($p < 0.05$).

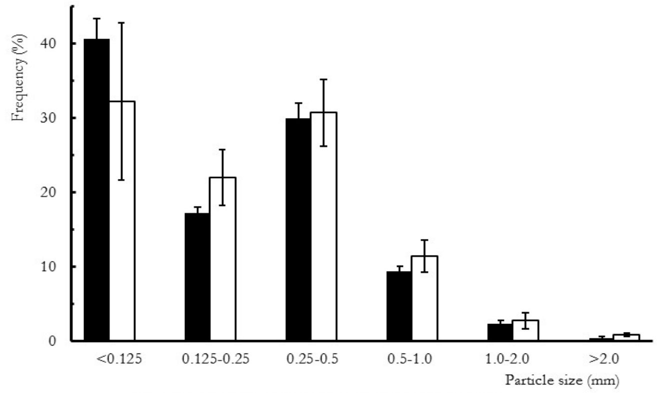

Fig. 4: Distribution of water-stable aggregate in topsoils
■ Fertilizer plot □ Lime+fertilizer plot

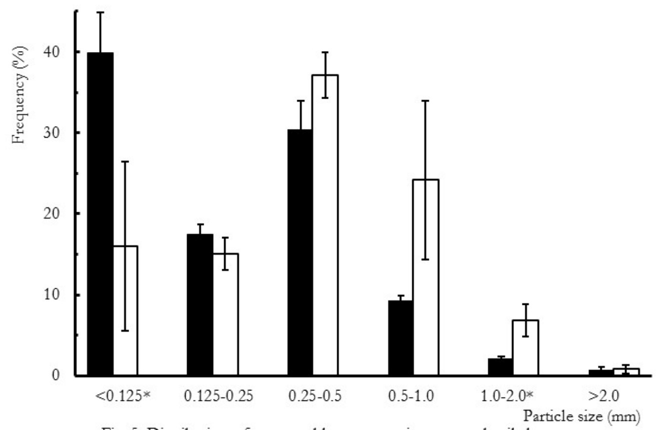

Fig. 5: Distribution of water-stable aggregate in upper-subsoils layer
■ Fertilizer plot □ Lime+fertilizer plot
*: Significance at 5% level

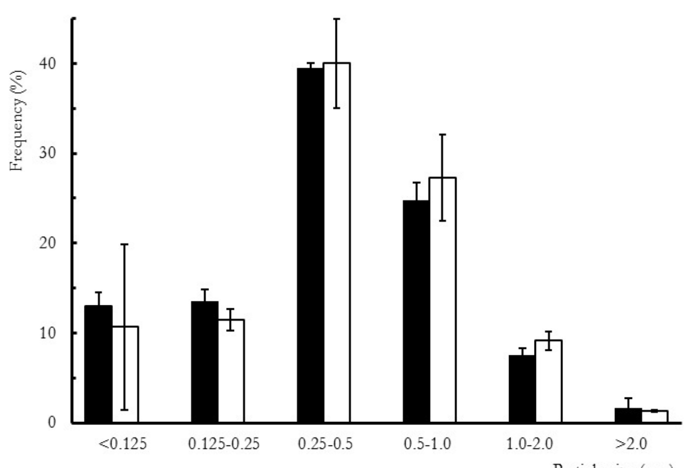

Fig. 6: Distribution of water-stable aggregate in lower-subsoil layer
■ Fertilizer plot □ Lime+fertilizer plot

The water-stable aggregate of the upper-subsoil layer (13-21cm) in the fertilizer plot was thought to consist of relatively small particles (< 0.125 mm). The percentages of water-stable aggregate of lower-subsoil layer(21-42cm) in the fertilizer plot were 13.0%±1.5% for the < 0.125 mm fraction, 13.5%±1.3% for the 0.125-0.25 mm fraction, 39.5%±0.6% for the 0.25-0.5 mm fraction, 24.8%±2.0% for the 0.5-1.0 mm fraction, 7.5%±0.8% for the 1.0-2.0 mm fraction, and 1.7%±1.1% for the > 2.0 mm fraction (Figure 6), and these proportions were not significantly different from the corresponding values in the lime+fertilizer plot. The macro aggregate develops from micro aggregate connected by root debris, sticky substances produced by bacteria and roots, and fungal hyphae (Yamane, 1986; Yokoi, 1987; Harris et al., 1964; Tisdall and Oades, 1982). The macroaggregate of the upper-subsoil was thought to be decreased because of the reduction in the amount of roots by Al toxicity in the strongly acidic subsoil of the fertilizer plot.

Comparison of pores formed by roots between the fertilizer and lime+fertilizer plots

Radiographs are shown in Figures 7 (fertilizer plot, 21-31cm) and 8 (lime+fertilizer plot, 20-30cm). Black stripes and black cloudy regions in the radiographs indicate macropores infiltrated by the contrast medium. Some taproots (root diameter > 1mm) were seen in both plots, but discontinuous fine root pores can also be seen in the lower parts of the radiographs (Figure 7 and 8).

Fig. 7: The radiograph in the fertilizer plot (21-31cm)

(The upper side of it corresponds to the surface soil.)

Fig. 8: The radiograph in the lime+fertilizer plot (20-30cm)

(The upper side of it corresponds to the surface soil.)

The taproot areas in the radiographs were estimated by image analysis as 11.4 cm^2 for the fertilizer plot and 14.4 cm^2 for the lime+fertilizer plot. The taproot area in the fertilizer plot was relatively low, indicative of a shallow root system in this plot. Indeed, the subsoil porosities were reported as 66% for the fertilizer plot and 74% for the lime+fertilizer plot, and the proportions of available water in subsoil for crops were 32% and 40% for the fertilizer plot and the lime+fertilizer plot, respectively (Aomori Agricultural Experiment Station, 1997). The decrease in pores formed by roots in the fertilizer plot affects the water holding capacity and permeability of the subsoil environment (Tokunaga, 1988; Tokunaga, et al., 1998).

Previously (Matsuyama et al., 2005), we reported a decrease in the subsoil fertility in strongly acidic allophanic Andosols associated with heavy application of fertilizer. The amount of nitrogen mineralization in the fertilizer plot was decreased by the reduction in crop residues (i.e., root residues). These results regarding physical properties of soil indicate that the macro aggregate was decreased by restricting the root system in the strongly acidic allophanic Andosols, and the pores formed by the roots are relatively small.

References

Aomori Agricultural Experiment Station, 1997. Annual report on result of experiment. p.521 (2).

Aomori Agricultural Experiment Station, 1987 (personal communication). Field data book on the long term experiment.

Brady, N.C. and R.R. Weil, 2010. Elements of the nature and properties of soils. Third Edition, p.96-97. Person Education, Inc., New Jersey.

Blakemore, L.C., P.L. Searle and B.K. Daly, 1981. Soil Bureau Laboratory Methods: A Methods for chemical analysis of soils. N.Z. Soil Bur. Sci.Rep., 10A.

Harris, R.F., G. Chesters, O.N. Allen and O.J. Attoe, 1964. Mechanisms involved in soil aggregate stabilization by fungi and bacteria. Soil Sci. Soc. Am. Proc., 28, 529-532.

JSSSPN, 1997. The standard soil analysis. p.40-43, p.195-197, Hakuyusha, Tokyo.

Kemper, W.D. and R.C. Rosenau, 1986. Aggregate stability and size distribution. In Methods of Soil Analysis, Part 1, 2nd ed., p.425-442, American Society of Agronomy, Inc., Soil Science Society of America, Inc., Madison, U.S.A.

Matsuyama, N, 2003. Acidification of Andosols by heavy application of fertilizer and its problem of soil classification. Pedologist, 47, 117-121.

Matsuyama, N., K. Kudo, and M. Saigusa, 1999a. Active aluminum of cultivated Andosols and related soil chemical properties in Japan. Bull. Fac. Agri. And Life Sci. Hirosaki Univ., **1**, 30-36.

Matsuyama, N., M. Saigusa and K. Kudo, 1999b. Acidity of Japanese cultivated Andosols and significance of exchange acidity y_1 in their classification. Jpn. J. Soil Sci. Plant Nutr., 70, 754-761.

Matsuyama, N., M. Saigusa, E. Sakaiya, K. Tamakawa, Z. Oyamada and K. Kudo, 2005. Acidification and Soil Productivity of Allophanic Andosols Affected by Heavy Application of Fertilizer. Soil Sci. Plant nutr., 51, 117-123.

Nomoto, K. and Y. Kamata, 1950. On the influence of lime and compost upon the soil of the upland field in the Tohoku district. Bull. Tohoku Natl. Agric. Exp. Stn., 1, 173-176.

Tisdall, J.M. and J.M. Oades, 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci., 33, 141-163.

Tokunaga, K., 1988. X-ray stereo radiographs using new contrast media on soil macropores. Soil Sci., 146, 199-207.

Tokunaga, K., 1995. Soil void imaging method using contrast medium and X-ray stereography. p.1-237, Agricultural Upland Development Association, Tokyo.

Tokunaga, K., T. Sase and T. Ishida, 1998. Paleoclimate effect on the development of pore system formed by roots in cumulative volcanic ash soils strata at Tokachi region of Hokkaido, Pedrogist, 42, 88-96.

Saigusa, M. and N. Matsuyama, 1998. Distribution of allophanic Andosols and non-allophanic Andosols in Japan. Tohoku J. Agricultural Research., 48, 75-83.

Saigusa, M., N. Matsuyama, T. Honna and T. Abe, 1991. Chemistry and fertility of acid Andisols with special reference to subsoil acidity. In Plant-soil interactions at low pH, ed. Wright, R.J. and Baligar, V.C., p.73-80, Kluwer Academic Publishers, Netherlands.

Saigusa, M., N. Matsuyamas and T. Abe, 1992a. Electric charge characteristics of Andisols and its problems on soil management. Jpn. J. Soil Sci. Plant Nutr., 63, 196-201.

Saigusa, M., S. Shoji, T. Ito and T. Honna, 1992b. Revaluation of exchange acidity y_1 in Andisol. Jpn. J. Soil Sci. Plant Nutr., 63, 216-218.

Saigusa, M., S. Shoji and T. Takahashi, 1980. Plant root growth in acid Andisols from northeastern Japan: 2. Exchange acidity y_1 as a realistic measure of aluminum toxicity potential. Soil Sci., 130, 242-250.

Wada, K., 1985. The distinctive properties of Andisols. B.A. Stewart (Eds). Advance in Soil Science 2. p.173-229, Springer-Verlag, New York.

Yamane, I., 2000. Some problems in the plant root, Agriculture and horticulture, 75, 81-85.

Yokoi, T., 1987. Soil Science, p.78-81, Tokyo University of Agriculture, Tokyo.

Yoshida, M., 1970. Acid properties of montmorillonite and halloysite. Jpn. J. Soil Sci. Plant Nutr., 41, 483-486.

Yoshida, M., 1971. Acid properties of kaolinite, allophane and imogolite. Jpn. J. Soil Sci. Plant Nutr., 42, 329-332.