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ALLOPHANIC VS. NON-ALLOPHANIC HORIZONS: COMPARATIVE ANALYSIS OF SOIL PROPERTIES IN KYUSHU'S VOLCANIC ASH SOIL

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Abstract
Andosols, volcanic ash-derived soils, play a vital role in upland farming in Japan, with distinct categorization into allophanic and non-allophanic types. Allophanic Andosols, constituting 69.9% of the total Andosol land area in Japan, are prevalent in regions with significant Holocene tephra deposition. In contrast, non-allophanic Andosols, accounting for 30.1% of the total Andosol area, occur in areas with minor tephra deposition. Both categories exhibit distinctive characteristics such as a thick black A-horizon, high phosphate fixation, superior water retention, and low bulk density. Despite similarities in morphology, chemistry, and physical attributes, non-allophanic Andosols possess unique features due to the presence of 2:1 minerals. Notably, non-allophanic Andosols, characterized by substantial exchangeable aluminum (represented by exchangeable acidity y1), pose a significant challenge by inducing severe aluminum toxicity in common agricultural crops. Hence, distinguishing between allophanic and non-allophanic Andosols is crucial for effective agricultural management.

Keywords: Andosols, Allophanic Andosols, Non-allophanic Andosols, Volcanic ash-derived soils, Aluminum toxicity

1. Introduction

Andosols, which are typical soils formed in volcanic ash, are the most important soils for upland farming in Japan. Andosols in Japan are divided into allophanic and non-allophanic categories. Allophanic Andosols are mainly distributed in areas that have thick deposition of Holocene tephras and comprise 4.51 million ha or 69.9% of the total land area of Andosols in Japan. Non-allophanic Andosols, on the other hand, are predominantly found in areas that have experienced minor tephra deposition and comprise 1.95 million ha, or 30.1% of the total area of Andosols (Saigusa and Matsuyama, 1998). Both types of Andosols display unique properties such as a thick black A-horizon, high phosphate fixation, high water retention and low bulk density (Shoji et al., 1985). Although non-allophanic Andosols show similar morphological, chemical and physical properties to allophanic Andosols, they also have some distinct differences in properties due to the presence of 2:1 minerals (Saigusa et al., 1991). Since non-allophanic Andosols have large amounts of exchangeable Al (as represented by exchangeable acidity y_1), they often induce serious Al toxicity for common agricultural crops. Thus, from an agricultural management perspective, Andosols are appropriately divided into allophanic and nonallophanic types.

When comparing typical Japanese cultivated Andosols by dominant colloidal composition, the mean organic matter content of cultivated Andosols compared to uncultivated Andosols was about 14% lower for allophanic Andosols and about 50% lower for non-allophanic Andosols (Saigusa et al., 1991; Matsuyama et al., 1998). However, this comparison may be skewed by typical Andosols not being representative of the actual cultivated land base. Therefore, in the Tohoku District, we compared soil properties by colloidal composition with respect to reclaimed soils that were considered closer to the original characteristics of the actual cultivated soils (Matsuyama et al., 2017). This analysis found that the characteristics of allophanic and non-allophanic horizons of volcanic ash soils in the Tohoku District were not much different from their typical uncultivated Andosol counterparts.

The objective of this study was to examin differences between allophanic and non-allophanic horizons of volcanic ash soils in the Kyushu District through analysis of the large dataset reported in the Soil Survey Data Book before Land Reclamation. Results of this analysis will aid land managers in developing soil-specific, agricultural management practices for Andosols in the Kyushu District.

2. Materials and Methods

Classification of allophanic and non-allophanic horizons

We compiled and analyzed several soil properties (e.g., soil depth, soil color, physical properties, and chemical properties) for the Kyushu District reported in the Soil Survey Data Book before Land Reclamation (hereafter SDL, MAFF, 1960; 1962; 1964; 1965). The SDL report characterized soils into four groups: volcanic ash soil, non-volcanic ash soil, bog soil, and half-bog soil. Volcanic ash soils originate from tephra while nonvolcanic ash soils formed in inorganic parent materials other than tephra. However, in the 1950's, Kato (1970) reported that "Non-volcanic Andosols" were widely distributed in the Tokai District, Japan. "Non-volcanic Andosols" have several soil properties similar to Andosols; however, their clay fraction contains minimal allophane (currently "Non-volcanic Andosols" are categorized as non-allophanic Andosols). Based on Kato's findings, we postulated that "Non-volcanic Andosols" should be widely distributed in Japan. In this study, we considered volcanic ash soils to have phosphate absorption coefficients greater than 15 $gP_2O_5kg^{-1}$ (Matsuyama et al., 2005; Saigusa et al., 1992a). This characterization is based on a phosphate absorption coefficient greater than 15 $gP_2O_5kg^{-1}$ to be considered representative of volcanic ash soils in Japan. From an agronomic viewpoint (Saigusa, 1989; Saigusa, 1991), soil horizons were further stratified into three depth layers: topsoil(0-15cm), subsoil(15-30cm), and deeper subsoil(30-50cm), which are referred to hereafter as LayersI, IIand III, respectively. Soil horizons occurring at the boundary of the15cm and 30cm depth limits were double-counted in both the overlying and underlying layers. We determined two soil horizon groups (allophanic vs non-allophanic) based on exchange acidity y_1: an exchange acidity $y_1 < 6$ for allophanic horizons and an exchange acidity$y_1 > 6$ for nonallophanic horizons (Saigusa et al., 1992b).

Soil characterization methods

Chemical and physical properties for each soil horizon from the SDL were determined using routine characterization methods from the 1950s: humus content (Tyurin method), pH(H_2O) and pH(KCl) (glass electrode method), exchange acidity y_1 (1M KCl-extraction method), exchangeable Ca (titration method), and phosphate absorption coefficient (colorimetric method). Several physical properties (soil color, soil texture, gravel, stickiness, consistence (dry), tilth and wetness) were reported in the SDL. We evaluated these properties using a simple scoring methodology described in Table 1. Physical properties were determined according to the methods described in the Ministry of Agriculture, Forestry, and Fisheries of Japan (1960) and in Yokoi (1987). A brief description of scoring methods follows: soil color (five grades of soil color recorded at the soil profile); soil texture (five grades based on the percentage of particles < 0.01 mm as described by the Japanese Agricultural Scientific Societies); gravel (five grades based on gravel percentage; stickiness (five grades describing adhesion of wet soil when pressed between thumb and index finger); consistence (dry) (four grades based on the crushing strength of an air-dried clod); tilth (three grades for hardness of tillage, light: slightly sticky in wet condition and slightly hard in dry condition, heavy: very sticky in wet condition and very hard in dry condition); and

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wetness (five grades based on the moisture condition when grasped in the palm). Statistical analyses were performed by Bell Curve for Excel (SSRI Co., Tokyo).

Table 1. Soil property scores.

Soil property	Score 0	1	2	3	4	5
Soil color	-	black	brownishblack / dark brown	brown / bright brown	yellowish brown / yellow	red / reddish brown
Soil texture	-	sand	sandy loam	loam	clay loam	clay
Gravel	0	5 - 10 %	10 - 30 %	30 - 50 %	> 50 %	-
Stickiness	0	slight sticky	sticky	very sticky	strong sticky	-
Consistence (dry)	0	soft	hard	very hard	-	-
Tilth	-	light	moderate	heavy	-	-
Wetness	-	dry	moderate	moist	wet	very wet

3. **Results and Discussion**

Number of investigation points and soil horizons in Tohoku District

This study examined 748 investigation points and 1570 soil horizons in the Kyushu District (Table 2). Soil horizons were divided into allophanic (1035 horizons) and non-allophanic horizons (535 horizons) according to exchange acidity y_1. Andosols are widely distributed in Oita, Miyazaki, Kumamoto and Kagoshima prefectures of the Kyushu District (Saigusa and Matsuyama, 1998). There were relatively large numbers of allophanic horizons in Oita, Miyazaki, Kumamoto and Kagoshima prefectures. Conversely, non-allophanic horizons in the Kyushu District were found in relatively large numbers for Nagasaki and Kumamoto prefectures. Table 3 shows the number of allophanic and non-allophanic horizons for the three soil layers: topsoil (0-15cm), subsoil (15-30cm), and deeper subsoil (30-50cm), i.e., LayersI, II and III, respectively. There were more allophanic horizons than non-allophanic horizons in each soil layer.

Table 2. Number of investigation points and soil horizons in Kyushu District.

Prefecture	investigation point number	soil horizon number	allophanic horizon number	non-allophanic horizon number	Andosols area*1 (×10^4ha)
Oita	109	215	135	80	20.1
Fukuoka	20	42	10	32	0.6
Saga	28	59	12	47	0.1
Nagasaki	98	191	44	147	2.0

Miyazaki	177	429	393	36	21.3
Kumamoto	142	339	197	142	24.3
Kagoshima	174	295	244	51	39.5
Total	748	1570	1035	535	107.9

*1 These data were cited from Saigusa and Matsuyama (1998)

Table 3. Number of allophanic and non-allophanic horizons in each soil layer.

Soil layer	allophanic horizon number	non-allophanic horizon number
LayerI(0-15 cm)	534	304
LayerII(15-30 cm)	661	357
LayerIII(30-50 cm)	576	273

Soil physical properties of allophanic and non-allophanic horizons

Table 4 shows the modal values for physical properties in allophanic and non-allophanic horizons. Based on the modal values for allhorizons, the generalized similarities were summarized as follows.

Table 4. Modal values of the physical properties in allophanic and non-allophanic horizons.

Soil layer	soil texture	color	soil gravel	stickiness	consistence (dry)	tilth	wetness
all horizon							
LayerI(0-15 cm)	2 (4)	4 (3)	0 (1)	1 (2)	1 (2)	1 (2)	1 (2)
LayerII(15-30 cm)	2 (4)	4 (5)	0 (1)	1 (2)	1 (2)	2 (1)	2 (1)
LayerIII(30-50 cm)	4 (2)	5 (4)	0 (1)	1 (2)	1 (2)	2 (1)	2 (3)
allophanic horizon							
LayerI(0-15 cm)	2 (1)	4 (3)	0 (1)	1 (0)	1 (0)	1 (2)	1 (2)
LayerII(15-30 cm)	2 (4)	4 (3)	0 (1)	1 (2)	1 (2)	2 (1)	2 (1)
LayerIII(30-50 cm)	4	4	0	1	1	2	3

	(2)	(5)	(1)	(2)	(2)	(1)	(2)
non-allophanic horizon							
LayerI(0-15 cm)	2 (4)	4 (5)	0 (1)	2 (1)	1 (2)	2 (1)	1 (2)
LayerII(15-30 cm)	4 (3)	4 (5)	0 (1)	2 (1)	2 (1)	2 (3)	2 (1)
LayerIII(30-50 cm)	4 (3)	5 (4)	0 (1)	2 (3)	3 (2)	2 (3)	2 (1)

(Submodal values are given in parentheses
Soil color: Soil color was brownish black/dark brown in LayersI and II compared to yellowish brown/yellow in LayerIII.
Soil texture: Soil texture was clay loam in LayersI and II compared to clay in LayerIII.
Gravels: Gravel percentage was zero in all three layers.
Stickiness: Adhesion of the wet soil was slight sticky in all three layers.
Consistence (dry): The crushing strength of an air-dried clod was soft in all three layers.
Tilth: Hardness of tillage was light in LayerI compared to moderate in LayersII and III.
Wetness: The moisture condition was dry in LayerI compared to moderate in LayersII and III.
Results indicate that the volcanic ash soils are dark, weakly adherent, soft, and dry; these results are consistent with the previous findings of Yokoi (1961), Shoji et al. (1993) and Nanzyo and Shoji (1992). Comparing the physical features of allophanic and non-allophanic horizons in more detail, there was little difference between allophanic and non-allophanic horizons. The dominant clay fraction of Andosols was different between allophanic and non-allophanic Andosols: allophane/imogolite in allophanic Andosols and 2:1-2:1:1 minerals in nonallophanic Andosols (Shoji et al., 1985). Reflecting the difference in clay mineralogy, the non-allophanic Andosols easily become muddy and compressed because of their relatively low plastic limit and weak aggregate strength (Inahara, 1989; Maeda et al., 1978). These differences between the allophanic and non-allophanic horizons are evident in their differences for stickiness and consistence.

Soil chemical properties of allophanic and non-allophanic horizons

Table 5 shows the chemical properties of the allophanic and non-allophanic horizons. The mean humus contents of LayersI, II and III in the allophanic horizons were (mean±std.dev) 11.1±5.8, 9.7±6.0, and 7.6±6.0%, respectively, and decreased with increasing soil depth. Similarly, the mean humus contents for non-allophanic horizons were 8.2±7.0, 6.7±6.9, and 4.4±5.3% for LayersI, II and III, respectively. Adachi (1963) reported that approximately 70% of volcanic ash soils in Japanese reclaimed lands had humus contents exceeding 10%. Accordingly, we posited that the mean humus content of allophanic and non-allophanic horizons would be relatively high, and the humus content of allophanic horizons would be higher than that of non-allophanic horizons.

Table 5. Several chemical properties in the allophanic and non-allophanic horizons.

Soil layer	humus (%)	pH (H_2O)	pH (KCl)	exchange acidity y_1	exchangeable Ca ($gCaO\ kg^{-1}$)	P absorption coefficient ($gP_2O_5kg^{-1}$)
allophanic horizon						

LayerI(0-15 cm)	11.1 ± 5.8a	5.7 ± 0.5a	5.0 ± 0.6b	1.7 ± 1.4c	88 ± 68a	19.3 ± 4.9b
LayerII(15-30 cm)	9.7 ± 6.0b	5.7 ± 0.5a	5.1 ± 0.6b	1.6 ± 1.3c	73 ± 64b	20.1 ± 4.9ab
LayerIII(30-50 cm)	7.6 ± 6.0c	5.7 ± 0.4a	5.2 ± 0.7a	1.3 ± 1.2c	61 ± 58c	20.9 ± 5.1a
non-allophanic hori zon						
LayerI(0-15 cm)	8.2 ± 7.0bc	5.2 ± 0.5b	4.4 ± 0.4c	14.2 ± 11.3b	60 ± 43bcd	17.6 ± 3.9c
LayerII(15-30 cm)	6.7 ± 6.9cd	5.2 ± 0.5b	4.4 ± 0.4c	15.0 ± 11.4b	53 ± 39cd	17.4 ± 4.1c
LayerIII(30-50 cm)	4.4 ± 5.3d	5.2 ± 0.5b	4.4 ± 0.4c	17.5 ± 15.4a	44 ± 35d	17.1 ± 4.1c

Significant differences in soil acidity occurred between allophanic and non-allophanic horizons. Both pH(H_2O) and pH(KCl) values for soil layers in non-allophanic horizons were lower than those in allophanic horizons with the differences ranging from 0.5 to 0.8 units. Exchange acidity y_1 is a useful and routine method for predicting the amount of potentially toxic Al for plants (Matsuyama et al., 2012). The mean exchange acidity y_1 of LayersI, II and III in allophanic horizons were 1.7±1.4, 1.6±1.3, and 1.3±1.2 compared to 14.2±11.3, 15.0±11.4, and 17.5±15.4 for non-allophanic horizons, respectively. Soils in non-allophanic horizons having an exchange acidity $y_1 > 6$ are typically a significant problem for agriculture due to Al toxicity, which results in formation of shallow rooting systems and decreased yields (Matsuyama et al., 1998; Saigusa et al., 1991).

Mean exchangeable Ca values in LayersI, II and III of allophanic horizons were 88±68, 73±64, and 61±58 gkg^{-1}, respectively, and gradually decreased with soil depth. Conversely, mean exchangeable Ca values for non-allophanic horizons were 60±43, 53±39, and 44±35 gkg^{-1}, respectively, and did not show any statistical differences between the three layers. Ratios for the mean exchangeable Ca content of non-allophanic to allophanic horizons were 0.67, 0.73, and 0.72 for LayersI, II and III, respectively. Yokoi (1961; 1987) suggested that the amount of recent tephra deposited at the soil surface affected the exchangeable Ca content of volcanic ash soils.

In this analysis, the mean ratio for exchangeable Ca contents of non-allophanic to allophanic horizons was approximately 0.7 in the three layers. This may reflect lower amounts of tephra deposition for non-allophanic versus allophanic horizons (i.e., less fresh weatherable material to release Ca).

Mean phosphate absorption coefficients for the three soil layers ranged from 17.1 to 20.9 gP_2O_5 kg^{-1} in the allophanic and non-allophanic horizons. Mean values were larger than 15 gP_2O_5 kg^{-1} corresponding to Andosol classification. The mean values in allophanic horizons were higher than those in the corresponding layers of non-allophanic horizons.

Comparison of soil properties between the Tohoku and Kyushu Districts.

In our previous report (Matsuyama et. al., 2017), we characterized volcanic ash soils in the Tohoku District to be dark, weakly adherent and soft. In addition, allophanic horizons were weakly acidic (mean exchangeable y_1 values ranged from 1.8 to 2.2 in the three layers) and non-allophanic horizons were strongly acidic (mean exchangeable y_1 values ranged from 12.4 to 14.6 in the three layers). In this section, we compare the soil properties in the Kyushu District with those of the Tohoku District. The physical properties of allophanic and non-allophanic horizons in the Kyushu District were similar to those in the Tohoku District (Table 4). However, when viewed in greater detail, the non-allophanic horizons of the Kyushu District had a soil color in Layer II that was lighter (slightly yellowish) and all three layers showed relatively high adhesiveness and high hardness when dried. There were also some differences in the chemical properties between the Kyushu and Tohoku Districts (Table 5). Mean humus contents of allophanic horizons in the Kyushu District were similar to those in the Tohoku District. On the other hand, the mean humus contents of non-allophanic horizons in the Kyushu District were 4.0, 3.5 and 3.2% lower than those in the Tohoku District in Layers I, II and III, respectively. Similar results were observed in comparison to the humus content of representative cultivated Andosols in Japan (Matsuyama et al., 1998). In general, volcanic ash soils are considered to be intrazonal soils based on soil formation. In other words, climate conditions should not have a significant impact on soil formation. However, Adachi (1963) and Kobo and Oba (1974a, 1974b) pointed out that there was a geographical distinction in humus composition among Japanese volcanic ash soils. In this report, judging from the relatively low humus content of the non-allophanic horizons in the Kyushu District and the fact that the soil color of the non-allophanic horizons tended to be slightly yellow, we postulate that the non-allophanic horizons found in the Kyushu District were Light-colored Andosols with lower organic matter content. Comparing between the Kyushu and Tohoku Districts, soil pH and exchange acidity y_1 were similar for each layer. The mean exchangeable Ca contents of the allophanic horizons in the Kyushu District were distinctly lower (47, 25, and 17 gkg^{-1} for Layers I, II and III) than those in the Tohoku District. The average annual temperature and precipitation are higher in the Kyushu District (for example, Aomori City (Tohoku District) 10.4 ℃ and 1300 mm versus Kagoshima City (Kyushu District) with 18.6 ℃ and 2270 mm; JMA data). As a soil formation environment, the Kyushu District has higher biological activity and a more intense weathering and leaching environment. Since allophanic horizons are generally formed in thicker tephra deposits, allophanic horizons may be more strongly affected by the weathering and leaching intensity (i.e., greater allophane content). The mean P absorption coefficients in the Kyushu district were 0.6-2.7 $gP_2O_5kg^{-1}$ higher than those in the Tohoku District. In volcanic ash soils, phosphorus mainly reacts with active aluminum, such as the allophane/iomogolite fraction (Matsuyama et al., 1998). This suggests that the volcanic ash soils in the Kyushu District may contain relatively more active aluminum because of greater weathering/leaching. The mean exchangeable Ca content of allophanic horizons in the Kyushu District tended to be relatively low. Non-allophanic horizons in the Kyushu District tended to be relatively low humus content, sticky and hard in dry condition. In the report on soil fertility in the Kyushu District, Miyauchi et al. (1976) reported that the buried volcanic ash layer (Nigatsuchi) distributed on the west side of Aso volcano shrunk into a very hard clod when dried on the surface, which was a big problem in farming. Igarashi et al. (1992) pointed out that the Kyushu District had relatively high rainfall, so leaching of exchangeable bases was severe and crop productivity was relatively low. It was also reported that the productivity of soil was closely related to the exchangeable base content in Kuroishibara volcanic ash soil on the west side of Aso volcano (Dei, 1960). In this area, strongly acidic horizons were scattered in the area having poor deposition of Holocene tephra. Such agricultural problems in Andosols will become clearer by dividing into two types of soil (horizon), allophanic and non-allophanic, which will lead to appropriate agricultural soil-management.

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