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Contrasting Soil Properties of Allophanic and Non-allophanic Horizons of Volcanic Ash Soilin Tohoku District, Japan

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Abstract

This study examined the contrasting physical and chemical properties of allophanic and non-allophanic horizons in Japanese volcanic ash soils described in the Soil Survey Data Book before Land Reclamation. A total of 1133 investigation points and 4462 soil horizons from Tohoku District were divided into two groups based on their exchange acidity y1:allophanic horizonsy1< 6 and non-allophanic horizonsy1> 6. Volcanic ash soils from Tohoku District were characterized as dark, weakly adherent, soft, dry, humic, and active-Al rich. The soil acidities of the two horizons had significantly different pH, exchange acidity y1, and exchangeable Ca. Mean exchangeable Ca of Layer Ⅰ (topsoil), Ⅱ (subsoil), and Ⅲ (deeper subsoil) were 135±95, 98±83, and 78±80gkg-1, respectively, for allophanic horizons and 63±60, 52±49, and 59±59gkg-1, respectively, for non-allophanic horizons. The content of exchangeable Ca in the allophanic horizons was relatively high compared tonon-allophanic horizons (the ratio of non-allophanic/allophanic horizon exchangeable Ca was 0.47 and 0.53 in Layers Ⅰ and Ⅱ). The differences in exchangeable Ca are ascribed to differences in recent tephra deposition with non-allophanic horizons receiving approximately half that deposited in allophanic horizons.

Keywords: Andosols, andic properties, exchange acidity y1, soil properties, tephra deposition

1. Introduction

The Japanese Islands, belonging to the circum-Pacific volcanic belt, have approximately 250 Quaternary volcanoes. Consequently, most Japanese soils, except alluvial soils ,have been influenced by volcanic ash. Andosols, which are the most typical soil formed from volcanic ash, are the most important soils for upland farming in Japan (Saigusa and Shoji, 1984; Saigusa et al., 1992a). Andosols have several unique properties, such as thick black A horizons, high phosphorus retention, and low bulk density (Wada, 1985).Andosols can be divided into allophanic and non-allophanic classes on the basis oftheir dominant clay mineralogical composition (Shoji, 1984). Inallophanic Andosols, the clay fraction is dominated by allophane and imogolite and the potential for Al toxicity is low (Saigusa et al., 1980; Yoshida, 1971).Conversely, innon-allophanic Andosols, the clay fraction is dominated2:1 minerals and soils are strongly acidic (Yoshida, 1970). Because non-allophanic Andosols have large amounts of exchangeable Al, they often impose serious aluminum toxicity symptoms insensitive crops (Saigusa et al., 1980). Therefore, it is very important that Andosols are divided into allophanic and non-allophanicgroupingsfor soil management purposes. Previously, we reported on the distribution allophanic and non-allophanic Andosols in Japan (Matsuyama and Saigusa, 1994; Matsuyama et al., 1994; Saigusa and Matsuyama, 1998; Saigusa et al., 1993). Allophanic Andosols cover 4.51 million ha or 69.9% of the total Andosol land area in Japan while non-allophanic Andosols cover 1.95 million ha or 30.1% of Andosol land area.

Further, were ported on the soil formation conditions and spatial distribution patterns for non-allophanicand allophanicAndosols. Allophanic Andosolspreferentially form in thickHolocene tephra deposits while non-allophanic Andosols form in areas with minimal Holocene tephra deposition.

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Shoji (1985) summarized the common soil formation factors for non-allophanic Andosolsin northeastern Japan with regard to(1) parent material (volcanic ash belonging to rhyolite, quartz-andesite, and andesite); (2) climate (areas with high leaching-annual rainfall > 1100mm); (3) vegetation (large contributions by Miscanthussinensis); and (4) age (Holocene age [<10,000 years]).In addition to these four soil forming factors, we focused on the amount of active-Al in non-allophanic Andosols supplied by volcanic ash via weathering. We postulate that Al released by weathering of volcanic ash preferentially forms Al-humus complexes, with any remaining Al reacting with soluble Si to formallophane/imogolite. Therefore, thickness of Holocene tephra deposits is a very important factor when considering the genesis of allophanic vs non-allophanic Andosols. However, the pedogenic processes for non-allophanic Andosol genesis have not been fully elucidated and we can therefore notdescribe a precise quantitative model for allophanicvsnon-allophanic Andosol formations.

In Japan, approximately 1.55 million ha of virgin land was converted to cropland in the 1950s to increase the food self-sufficiency rate.The reclamation was facilitated by adetailed soil survey summarized in the Soil Survey Data Book before Land Reclamation (MAFF, 1962; MAFF, 1962; MAFF, 1964; MAFF, 1965). These data books contain a huge amount of information on soil properties prior to cultivation (Matsuyama et al., 1999; Matsuyama et al., 2012). Therefore, we can outline the characteristics of Andosols throughout Japan prior to land reclamation and alteration by land management activities. The objective of this study was to determine differences between allophanic and non-allophanic horizons of volcanic ash soils in the Tohoku District through analysis of the large dataset reported in the Soil Survey Data Book before Land Reclamation.

2. Materials and Methods

Grouping of allophanicand non-allophanichorizons

We compiled and analyzed the soil property data(soil depth, soil color, physical properties, and chemical properties) reported in the Soil Survey Data Book before Land Reclamation (hereafter SDL). The SDL report characterized soils into four groups: volcanic ash soil, non-volcanic ash soil, bog soil, and half-bog soil. Volcanic ash soils are defined as those originating from tephra while non-volcanic ash soils formed in inorganic parent materials other than tephra. In the 1950's, Kato (1970) reported that "Non-volcanic Andosols" were widely distributed in Tokai District, Japan. "Non-volcanic Andosols" have several soil properties similar to Andosols; however, their clay fraction contains minimalallophane (currently "Non-volcanic Andosols"are categorized as non-allophanic Andosols).Based on Kato's findings, we postulated that "Non-volcanic Andosols" should also bewidely distributed in the Tohoku District of Japan. In this study, weconsidered volcanic ash and non-volcanic ash soils with phosphate absorption coefficients greater than 15 gP2O5kg-1 as volcanic ash soil (Matsuyama et al., 2005; Saigusa et al., 1992b). This characterization is based on aphosphate absorption coefficient greater than 15gP2O5kg-1 being considered representative of volcanic ash soilsin Japan. Froman 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 Layers Ⅰ, Ⅱ,and Ⅲ, respectively. The soil horizon including the border at 15cm or 30cm were double counted in both the upper and lower layers. We determined two soil horizon groups (allophanicvs non-allophanic) based on exchange acidity y1:an exchange acidity y1< 6 for all ophanichorizons and an exchange acidityy1> 6 for non-allophanic horizons (Saigusa et al., 1992c).

Soil characterization methods for soil properties

The chemical and physical properties of each soil horizon from the SDL were examined using routine characterization methods in the 1950s: humus content (Tyurin method), pH (H2O) and pH(KCl) (glass electrode method), exchange acidity y1 (1M KCl-extracted 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 also reported in the SDL. We evaluated these properties using a simple score methodology described in Table 1. The physical properties were determined according to the methods described in the Ministry of Agriculture, Forestry, and Fisheries of Japan13 and in the study of Yokoi (Yokoi, 1987). Statistical analysis was performed by BellCurve for Excel (SSRI Co., Tokyo).

Table 1. Soil property scores.

Soil property*1	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

Note:*1 Soil color (five grades of the original soil color 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 the percentage of gravel content; Stickiness (five grades describing the adhesion of the wet soil when pressed with a thumb and an 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 a wet condition and slightly hard in a dry condition, heavy - very sticky in a wet condition and very hard in a dry condition); Wetness (five grades based on the moisture condition when grasped in the palm)

3. Results and Discussion

Number of investigation points and soil horizons in Tohoku District

This study examined 1133 investigation points and 4462 soil horizons in Tohoku District (Table 2).

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

Prefecture	investigation point number	soil horizon number	allophanic horizon number	non-allophanic horizon number	Andosols area*1 (×10^4ha)
Aomori	251	612	488	124	29.3
Iwate	307	1240	925	315	82.3
Akita	123	568	182	386	15.7
Miyagi	92	532	313	219	18.3
Yamagata	116	487	118	369	14.6
Fukushima	244	1023	701	322	18.9
Total	1133	4462	2727	1735	179.1

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

Soil horizons were divided into allophonic horizons (2727 horizons) and non-allophonic horizons(1735 horizons) according to exchange acidity y1. And osolsarewidely distributed in Iwate and Aomori prefectures of Tohoku District (Saigusa and Matsuyama, 1998) resulting in many investigation points in the seprefectures. There were relatively large numbers of allophanic horizons in Iwate and Fukushima prefectures.

Conversely, the non-allophanic horizons in Tohoku District were more evenly distributed among prefectures. Table 3 shows the number of allophanic and non-allophanic horizons in the three layers: topsoil (0-15cm), subsoil (15-30cm), and deeper subsoil (30-50cm), i.e., Layers Ⅰ, Ⅱ, and Ⅲ, respectively. There are moreallophanic horizons than non-allophanic horizons in each soil layer.

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

Soil layer	allophanic horizon number	non-allophanic horizon number
Layer Ⅰ (0-15 cm)	636	601
Layer Ⅱ (15-30 cm)	1054	625
Layer Ⅲ (30-50 cm)	987	696

Soil physical properties of allophanicand non-allophanichorizons

Table 4 shows the modal values for physical properties inallophanic 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 color	soil texture	gravel	stickiness	consistence (dry)	tilth	wetness
all horizon							
Layer Ⅰ (0-15 cm)	2	4	0	1	1	2	1
	(1)	(3)	(1)	(2)	(2)	(1)	(2)
Layer Ⅱ (15-30 cm)	2	4	0	1	1	2	2
	(4)	(3)	(1)	(2)	(2)	(1)	(1)
Layer Ⅲ (30-50 cm)	4	4	0	2	1	2	2
	(2)	(5)	(1)	(1)	(2)	(1)	(1)
allophanic horizon							
Layer Ⅰ (0-15 cm)	2	4	0	1	1	2	1
	(1)	(3)	(1)	(2)	(2)	(1)	(2)
Layer Ⅱ (15-30 cm)	2	4	0	1	1	2	2
	(4)	(3)	(1)	(2)	(2)	(1)	(1)
Layer Ⅲ (30-50 cm)	4	4	0	2	2	2	2
	(2)	(3)	(1)	(1)	(1)	(1)	(1)
non-allophanic horizon							
Layer Ⅰ (0-15 cm)	2	4	0	1	1	2	2
	(1)	(5)	(1)	(2)	(2)	(1)	(1)
Layer Ⅱ (15-30 cm)	2	4	0	1	1	2	2
	(4)	(5)	(1)	(2)	(2)	(1)	(1)
Layer Ⅲ (30-50 cm)	4	5	0	1	1	2	2
	(2)	(4)	(1)	(2)	(2)	(1)	(1)

Note: Submodal values are givenin parentheses

Soil color: Soil color was brownish black/dark brown in Layers Ⅰ and Ⅱ compared to yellowish brown/yellow in Layer Ⅲ. Soil texture:Soil texturewas clay loam in all three layers.
Gravels: Gravel percentage was zero in all three layers.

Stickiness: Adhesion of the wet soil was slight sticky in Layers Ⅰ and Ⅱ compared to sticky in Layer Ⅲ.

Consistence (dry):The crushing strength of an air-dried clod was soft in all three layers.

Tilth: The hardness of tillage was moderate in all three layers.

Wetness: The moisture condition was dry in Layer Ⅰ compared to moderate in Layers Ⅱ and Ⅲ.

These results indicate that the volcanic ash soils are dark, weakly adherent, soft, and dry, consistent with 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 is little difference between allophanic and non-allophanic horizons. The dominant clay fraction of Andosols was different between allophanicand non-allophanic Andosols: allophane/imogolite in allophonic Andosols and 2:1-2:1:1 minerals in non-allophanic Andosols (Shoji et al., 1985). Reflecting the difference in clay mineralogy, the non-allophanic Andosolseasily become muddy and compressed because they have a relatively low plastic limit andweak aggregate strength (Inahara, 1989; Maeda et al., 1978). However, these differences between the allophanic and non-allophanic horizons were not evident from the indexes in this study.

Soil chemical properties of allophanic and non-allophanic horizons

Table 5 shows the chemical properties of the allophanic and non-all ophanic horizons. The meanhumus contents of Layers Ⅰ, Ⅱ, and Ⅲ in the all ophanic horizonswere11.7±4.6, 9.4±5.0,and 7.0±4.8%, respectively, and decreased as soil depth increased. Similarly, the values in the non-allophanic horizons were 12.2±5.3, 10.2±5.5, and 7.6±5.4%, respectively. Adachi (1963) reported that approximately 70% of volcanic ash soils in Japanese reclaimed lands had humus contents exceeding 10%. Accordingly, itwas believed that the mean humus content of all ophanicand non-allophanic horizonswould be similar and that the humus content of both horizons would be relatively high. The meanphosphate absorption coefficients for soil layers ranged from 16.5 to 18.2gP2O5 kg-1in the allophanic and non-allophanic horizons. The mean values were larger than 15gP2O5 kg-1corresponding to Andosol classification. The mean values in allophanic horizons were higher than those in non-allophanichorizons comparing each Layer.

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

Soil layer	humus	pH		exchange acidity y_1	exchangeable Ca	P absorption coefficient
	(%)	(H_2O)	(KCl)		(gCaO kg^{-1})	(gP_2O_5kg^{-1})
allophanic horizon						
Layer Ⅰ (0-15 cm)	11.7 ± 4.6a	5.7 ± 0.5a	5.0 ± 0.5b	2.2 ± 1.6c	135 ± 95a	17.2 ± 4.5bc
Layer Ⅱ (15-30 cm)	9.4 ± 5.0c	5.7 ± 0.5a	5.0 ± 0.5b	2.0 ± 1.5c	98 ± 83b	17.9 ± 4.7ab
Layer Ⅲ (30-50 cm)	7.0 ± 4.8d	5.7 ± 0.5a	5.1 ± 0.6a	1.8 ± 1.5c	78 ± 80c	18.2 ± 5.2a
non-allophanic horizon						
Layer Ⅰ (0-15 cm)	12.2 ± 5.3a	5.3 ± 0.5c	4.4 ± 0.4d	14.3 ± 8.9a	63 ± 60d	16.5 ± 4.2c
Layer Ⅱ (15-30 cm)	10.2 ± 5.5b	5.3 ± 0.5c	4.4 ± 0.4d	14.6 ± 9.2a	52 ± 49d	16.5 ± 4.0c
Layer Ⅲ (30-50 cm)	7.6 ± 5.4d	5.4 ± 0.5b	4.6 ± 0.5c	12.4 ± 11.1b	59 ± 59d	16.5 ± 3.9c

Note: Values are mean±SD. Mean values with same letters within a column are not significantly different at 1% level (Tukey-Kramer test).

Significant differences in soil acidity were observed between allophanic and non-allophanic horizons. Both the pH (H2O) and pH(KCl) values for soil layers in non-allophanic horizons were lower than those in allophanic horizons with the differences ranging from 0.3 to 0.6 units. Exchange acidity y1 is a useful and routine method for predicting the amount of potentially toxic Al for plants (Matsuyama et al., 2012).

The mean exchange acidity y1 of Layers Ⅰ, Ⅱ, and Ⅲ in allophanic horizons were 2.2±1.6, 2.0±1.5, and 1.8±1.5, respectively. Conversely, mean exchange acidity y1 innon-allophanic horizons were 14.3±8.9, 14.6±9.2, and 12.4±11.1, respectively. Soils in non-allophanic horizons having an exchange acidity y1> 6 are a significant problem for agriculture by causing Al toxicity, resulting in formation of shallow rooting systems and decreased yields (Matsuyama et al., 1998; Saigusa et al., 1991).

Mean exchangeable Ca values in Layers Ⅰ, Ⅱ, and Ⅲof allophanic horizons were 135±95, 98±83, and 78±80gkg-1, respectively, and gradually decreased with soil depth. Conversely, mean exchangeable Ca values fornon-allophanic horizons were 63±60, 52±49, and 59±59gkg-1, respectively, and did not show any stastical differences between the three layers. The ratios for the mean exchangeable Ca content of non-allophanic to allophanic horizons were 0.47, 0.53, and 0.76 for Layers Ⅰ, Ⅱ, and Ⅲ, respectively. Yokoi (1987; 1961) suggested that the amount of recent tephradeposited at the soil surface affects the amount of exchangeable Ca in volcanic ash soils. In the results of this study, the mean ratio for exchangeable Ca contents of non-allophanic to allophanic horizons was approximately 0.5 in Layers Ⅰ and Ⅱ. Therefore, it is suggested thatthe amount of tephra deposited in the non-allophanic horizons was about 50% that deposited in the allophanic horizons.

Previous studies concluded that allophanic Andosols were distributed in areas having thick deposits of Holocene tephra, while non-allophanic Andosols were distributed in areas having little or no recent tephra deposition (Saigusa and Matsuyama, 1998). These previous findings are consistent with our inference that the non-allophanic horizons received approximately half the amount of ash fall as the allophanic horizons based on mean exchangeable Ca content. We will continue to analyze soil survey data for these and other areas (e.g., in the Hokkaido, Kanto, Chubu, Nishi-nihon, and Kyushu Districts) to provide further support for this finding.

4. Conclusions

This study examined similarities and differences in the physical and chemical properties between allophanic and non-allophanic horizons in Japanese volcanic ash soils of Tohoku District. Soil acidity, indicated by soil pH, exchange acidity y1, and exchangeable Ca, was stronger in non-allophanic compared to allophanic horizons. Based on the content of exchangeable Ca, it is likely that deposition of recent tephra in the non-allophanic horizons was approximately half that in the allophanic horizons and is therefore an important factor in the genesis of allophanic versus non-allophanic horizons.

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