11. Characteristics of Volcanic Soils around Mt. Mayon, the Philippines

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1. Characteristics of Typical Volcanic Soils, Andisols

Located on the Pacific Ring of Fire, there are many volcanos in the Philippines and Japan and, therefore, the lands and soils are likely to be influenced by the past and current volcanic activities to some extent. This chapter starts from brief description on well-developed volcanic soils and their characteristics. Based on international soil classification systems, such soils are classified into Andisols in Soil Taxonomy (Soil Survey Staff, 2014) and Andosols in WRB (FAO, 2014). The term of "*Kurobokudo*" is used in the Japanese classification (Committee Soil Class. Nomencl., 2017). The concepts, definition and characteristics are similar between these soil classes despite some differences in the criteria for the classification.

In Japan, volcanic ash has spread extensively over the land, especially eastward of volcanos, due to the influence of the westerlies as represented by the distal tephra. As a result, Kurobokudo accounts for the largest area (31%) among the soil classes in Japan, followed by Brown Forest Soils (30%) and Lowland Soils (14%) (Obara et al. 2016). On the global scale, however, Andisols are a minor soil class, accounting for less than 1 % of the land area. Thus, the Japanese soil scientists have led the study field related to volcanic soils in the world.

Andisols are defined by the dominant appearance of the Andic soil properties. Simply speaking, this Andic soil properties principally come from the peculiar clay mineralogy and the concomitant high contents of soil organic matter. The clay mineralogy is composed mainly of amorphous or quasi-crystalline clay minerals such as allophane and imogolite. The nature of these minerals is considerably different from that of crystalline silicate clay minerals common in non-volcanic soils. Abundant hydroxyl groups of these minerals can form organo-mineral complexes with humic substances and protect them from decomposition, resulting in a high level of soil organic matter. By this, aggregate structure can well-develop in Andisols, providing a favorable soil physical basis for plant growth with high water holding capacity, high water permeability, low compactness and good tilth. These features of Andisols are clearly expressed in the Japanese name "*Kuro-boku-do*". "*Kuro*" means black color derived from highly-humified soil organic matter, "boku" soft and fluffy property from the well-developing aggregate structure, and "do" soils. In fact, *Kurobokudo* was one of the local names used for such volcanic soils among farmers, and then it has been adopted in soil science.

Furthermore, "An-do" in Andosols derives from the Japanese synonym with a meaning of "An" for dark color and "do" again for soils while "sol" is "*solum*" meaning soil in Latin. "An-di" in Andisols is modified, replacing "o" with "i".

In contrast to the superior physical properties, the Andic soil properties show negative aspects in chemical properties. The availability of phosphorus (P), one of the three major essential elements for plants, is extremely low in intact Andisols due to the nature of the amorphous and quasi-crystalline clay minerals to adsorb P strongly. Despite abundant charge sites of the amorphous and quasi-crystalline minerals as well as humic substances, they are variable and pH-dependent, and therefore, the retention ability for cationic nutrients of Andisols such as potassium (K), calcium (Ca), magnesium (Mg) and ammonium (NH_4) would be low under a strongly acidic condition. Furthermore, some of Andisols show strongly acidic nature with a high level of soluble aluminum (Al) which would restrict root expansion of common crops.

In Japan, the major landuse of *Kurobokudo* in the past used to be grassland and pasture because of such drawbacks in the chemical properties. Nowadays, plentiful application of P fertilizers and liming materials has successfully converted *Kurobokudo* into productive agricultural soils, which accounts for 47 % of upland fields (vegetable fields and fruit gardens). However, rice farming is not always common because their favorable physical properties, in turn, would become the nuisance for wetting and drying works in paddy fields.

2. Volcanic Soils and the Previous Studies in the Philippines

What are volcanic soils in the Philippines? Despite a volcanic country, Andisols are the minor soil class, accounting only for 0.1 % (399 km^2) of the total land area (Table 1). Because of less influence of the westerlies at the low latitude, the mass of volcanic ash tends to deposit around a volcano. Volcanic soils close to the currently or recently erupting volcanos are immature to be classified into Andisols. Instead, they are likely to be the subgroups of Inceptisols (relatively young soils) with Andic soil properties in Soil Taxonomy (Soil Survey Staff, 2014). Otherwise, because of readily weatherable nature of volcanic ash, the warm and humid climate would accelerate the weathering process, resulting in the formation of Ultisols or Alfisols (both are highly weathered soils). Thus, mature Andisols are seldom found in the Philippines.

According to Carating et al. (2014; Introduction), historically, soil surveys in the Philippines have substantially started since 1930s. Successive soil survey sections of the government sector played a leading role for soil mapping and classification. The outcome of their endeavor was a series of soil maps published during 1970s. However, Amano (1985) pointed out that such early works had been insufficient for practical use because

Table 1 Major soil order and their extent of distribution based on soil taxonomy map of the Philippines (1: 1, 000, 000, Bureau of Soils and Water Management. Cited from Carating et al. 2014, p.238).

Soil order	Estimated area (ha)	Percent of total land area (%)
Inceptisols	144,652,684	48.8
Ultisols	8,113,453	27
Alfisols	3,973,611	13.2
Entisols	1,540,737	5.1
Mollisols	762,767	2.5
Vertisols	733,117	2.4
Oxisols	39,922	0.1
Andisols	39,854	0.1
Histosols	342	0
Total	29,856,487	99.5

The soil taxonomy map of the Philippines is based on Soil Taxonomy (Soil Survey Staff, 2014).

they had been based on the soil classification system of USA before the Second World War, which had lacked a concept of volcanic soils.

In 1970s, Japanese soil scientists well-acquainted with volcanic soils and paddy soils in their country have started the collaboration with the Philippine colleagues. Kawaguchi and Kyuma (1977) assessed soil fertility status of lowland paddy fields in 10 tropical Asian countries upon the initiation of the Green Revolution and regarded the soil fertility in the Philippines to be superior among those countries, especially in terms of clay mineralogy and base status. Then, the detailed studies at Cagayan Valley, Central Luzon, Laguna, Bicol, Iloilo and Cotabato (Miura et al. 1997, 1998; Miura and Badayos 1999) clarified that high soil fertility of the lowland paddy fields could be ascribed to the alluvial deposit of basic volcanic materials which were the sources of soil nutrients and clay fractions with predominating highly-active 1.4 nm minerals. Meanwhile, Ostuka et al. (1988) proposed two different weathering and soil formation processes based on their investigation into clay mineral composition of volcanic soils at 9 volcanos in Luzon, Iloilo and Leyte Islands: one was the halloysite-forming sequence in the regions with clear wet and dry seasons, and the majority of their soils followed this sequence. The other was the allophane-forming sequence in the regions under a relatively perhumid climate, which overlapped the sequence of Japanese Andisols. They also suggested that inherent fertility of the volcanic soils in the Philippines was higher than that of Japanese Andisols judging from higher base status as well as similar levels of cation exchange capacity. These previous studies suggest that high fertility of lowland soils could be the basis for double or triple rice cropping practices in the Philippines.

Following those early studies conducted in a large-scale, the recent studies on in the Philippines tend toward the detailed investigation on volcanic soils within one volcano-sphere in order to clarify the mechanisms to control soil formation processes and characteristics. For example, the soils of Mt. Taal (Babiera and Takahashi 1997; Dela Cruz et al. 2003) and Mt. Pinatubo (Sasaki et al. 2003) in Luzon and Mt. Kitanglad in Mindanao (Poudel and West 1999) have been reported in relation to the influences of the distance and/or the toposequence from the crater (Figure 1).

Besides volcanic soils, Hamazaki and Paningbatan (1996) investigated the formation processes and characteristics of various Red-Yellow soils (highly weathered soils in many cases) across the Philippines. Recently, detailed studies on soils originating from limestone, sedimentary rocks or basaltic rocks as well as degraded soils have been conducted in Leyte Island by one enthusiastic group of local soil scientists (Asio et al. 2006; Navarrete et al. 2009, 2011, 2013). After 50 years of the study by Kawaguchi and Kyuma (1977) mentioned above, a research group including the author of this chapter has carried out a series of the follow-up studies in the Philippines (Nakao et al. 2021) as well as Thailand (Yanai et al. 2020) and Peninsular Malaysia (Tanaka et al. 2021) and found that soil fertility status of lowland paddy fields in all countries has been successfully improved by fertilizer application irrespective volcanic or non-volcanic soils.

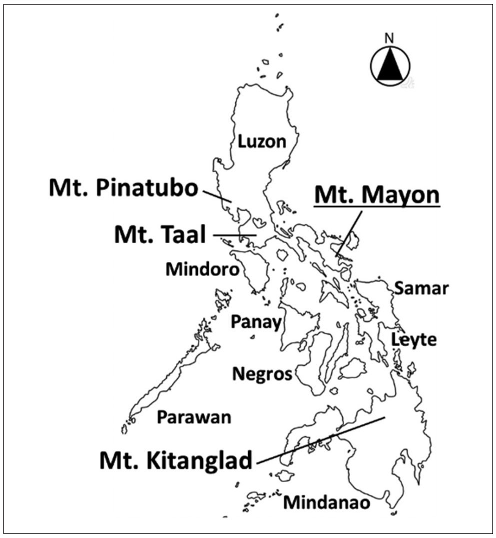

Figure 1 Map of the Philippines.

A quarter century ago, Hamazaki et al. (1996) pointed out that although careful soil management techniques appropriate for each soil with different characteristics should be indispensable for sustainable agricultural development, the Philippines was far away from entire understanding of their own soil resources. Despite the increasing number of soil science studies as mentioned above, this situation seems not to be much changed until the present (Introduction in Carating et al. 2014). Because of the expanding impacts of anthropogenic activities and the growing concerns of global and local environmental issues as well as food security, farther understanding is required on the soils in the Philippines.

3. A Study on Soil Characteristics around Mt. Mayon and in San Miguel Island in the Bicol Region

3.1 Mt. Mayon and San Miguel Island and the Agricultural Landscapes

Mt. Mayon is located at the southeastern end of the Bicol region in Luzon Island (Figures 1, 2). It is the single-peak, active stratovolcano with an altitude of 2463 m a.s.l.. The east foot goes down to Tabaco Bay. This volcano repeats eruption more than 50 times since the 17th century. The latest was on January 2018. The lava is predominated by basaltic andesite to andesitic. Meanwhile, San Miguel Island lies on the opposite side of Tabaco Bay, constituting the western end of the strip of islands in the Lagonoy Gulf.

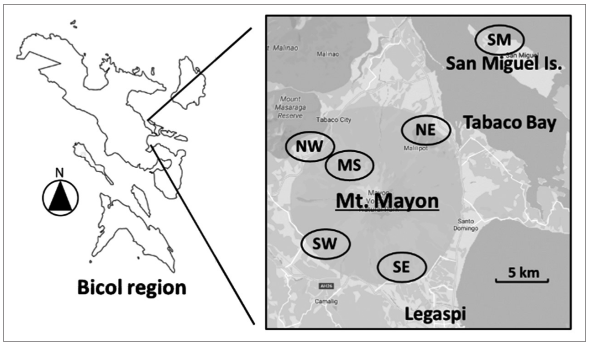

Figure 2 Location of Mt. Mayon and study sites (Google map).

Travelling along the peripheral road around Mt. Mayon, one can see different agricultural landscapes between the east and the west sides of this volcano. In the east side, paddy fields spread from gentle foot slopes in high elevation to lowlands until the coastline. Most of the paddy fields on the slopes are carefully terraced. In contrast, the major agriculture in the west side is upland farming of coconuts, abaca. corn and vegetables except for the depressions used for rice cultivation. Both upland and paddy fields are fertilized with significant amounts of chemical fertilizers (NPK and Urea) except for the case that farmers practice organic farming. Meanwhile, in San Miguel Island, sweet potato and sugarcane are planted with limited fertilizer application while lowland rice is planted exceptionally in small patches close to springs. Thus, three different belts of agriculture landscapes exist parallel to the coast.

3.2 Climate and Soils as Possible Determinant Factors for Different Agricultural Landscapes

What are the determinant factors for such different agriculture types? For lowland paddy cultivation, the minimum requirements are to supply plentiful water and to keep waterlogging condition until maturing of rice plants.

The climate in the Bicol region is classified to the tropical rainforest climate (Af) in the Köppen's classification with the wet season for seven to nine months and the dry season for less than 2 months. It is Type Ⅱ in the Philippine's classification without dry season but with a pronounced rainfall during November to January. The average daily temperature and annual precipitation are 27.5 ℃ and 3,432 mm during 1981 to 2010 at Legazpi, the largest city in Albay Province of the Bicol region. Monthly precipitation does not lower below 100 mm in a year. However, the precipitation and its pattern seem to fluctuate widely year by year and place by place depending on factors such as location, topography and the occurrences of typhoons: the prevailing westward-local wind containing high moisture from the sea may be blocked by Mt. Mayon, bringing plentiful rainwater to the east side but creating rain shadow in the west side. Typhoons frequently hit the Bicol region, which supply more rainwater to the east side.

Meanwhile, paddy soils must have a hard plow pan or the bedrock at a shallow depth so that water percolation is restricted during waterlogging. In this sense, we assumed that soil characteristics might be different between the west and the east sides of Mt. Mayon, which would affect farmers' adoption for agriculture types: the local wind from the sea might have transported volcanic ash westward, resulting in thin ash deposition and shallow soil formation in the east side, but thick deposition and deep soil formation in the west side. It might be also possible that the storms and typhoons hitting the east side would have eroded ash deposit on the slope and outcropped the bedrock at a shallow depth.

Regarding to upland farming in San Miguel Island with less dependence on chemical fertilizers, a part of plant nutrients, especially K, Ca and Mg as well as sodium (Na), might be supplied from sea salts from the surrounding sea.

3.3 Study Objectives and Methods

To verify the assumption that soil characteristics might differ between three belts of different agriculture landscapes around Mt. Mayon and in San Miguel Island, we launched the international joint study between Bicol University in the Philippines and Kochi University in Japan. This study can provide the information on soil fertility status to give the perspectives for appropriate soil conservation and sustainable agriculture schemes. The following is a part of the results from our ongoing research.

Soil survey was conducted on March 2019 in the four directions of Mt. Mayon (northeast, southeast, northwest and southwest). Three study sites were selected for each direction, named as NE1 to NE3, SE1 to SE3, NW1 to NW3 and SW1 to SW3, respectively. They were located around the perimeter of the foot slopes, about six kilometers apart from the crater (Figure 2). In addition, along Mt. Mayon Park Road connecting the foot and the Mayon Skyline View Deck on the mountainside (760 m a.s.l.) in the northwest direction, one study site was selected each at 300, 500 and 700 m a.s.l. as well as one site along a trekking trail above the Deck (800 m a.s.l.). They were MS1 to MS4 with decreasing altitude. Because most of paddy fields were used all year round and could not be surveyed, the study sites were upland crop fields and were planted with annual crops such as winged bean (*Psophocarpus tetragonolobus* L.), string bean (*Phaseolus vulgaris* L.) and okra (*Abelmoschus esculentusa* L.). MS1 was a degraded secondary forest patch composed of *Ficus spp*, *Macaranga spp* and so on. Meanwhile, in San Miguel Island, only two sites (SM1 and SM2) could be surveyed due to the time limitation. Both were upland fields after harvest of sweet potato (*Ipomoea batatas* L.). Because the area within 6 km was designated as the restricted area due to the eruption in 2018, we obtained the research permission from DENR (Department of Environment and Natural Recourses) and PAMB (Protected Area Management Board).

Soil profile description was carried out at the five sites of NE1, SE2, NW1, SW2 and MS3 by using a soil survey handbook (Japanese Society of Pedology) and a Munsell Soil Color Chart. Soil hardness was examined using a Yamanaka-type push-cone penetrometer. Bulk density was determined in a laboratory of Bicol University by using undisturbed 100 mL core samples from the depths of 0-10 cm and 20-30 cm in triplicate. Due to abundant presence of rock fragments, the samples at the depth of 20-30 cm in NE1 could not be collected while the sampling depth in SE2 was changed from 20-30 cm to 10-20 cm.

Soil samples were collected from the depths of 0-10 and 20-30 cm in triplicate in each study sites for laboratory analysis in Kochi University. They were mixed well to make one composite sample, air-dried and passed through a 2 mm mesh sieve. The samples were analyzed for general physicochemical properties as listed in Table 1. The data were log-transformed and compared between NE, SE, NW, SW and MS by using Turkeys' multiple comparison after one-way analysis of variance (ANOVA) (Excel Statistics for Windows, BellCurve, Tokyo). The data of MS1 under secondary forest and SM1 and SM2 were omitted from the data analysis because of the lack of replication.

Table 1 Simple description of soil physicochemical analysis.

Properties	Methods
pH (H_2O)	A glass electrode method with a soil to water ratio of 1:5.
pH (NaF)	A glass electrode method after 2 minutes for equilibration with a soil to 1 M NaF solution ratio of 1: 50.
Total C and N	Dry combustion method using a CN Corder (JM1000N; J-Science, Kyoto).
Exchangeable bases (Ca, Mg, K and Na)	After extraction using 1 M $CH3COONH_4$ adjusted to pH 7. 0, atomic absorption spectrophotometry for Ca, Mg, and K, and flame photometry for Na (AA-6800; Shimadzu, Kyoto).
CEC	After successive extraction using 10% NaCl following the extraction for the exchangeable bases, the indophenol blue method to determine NH_4 as CEC.
Exchangeable Al and H	After extraction with 1 M KCl, titration with 0.01 M NaOH for the determination of exchange acidity (Al + H) and titration with 0.01 M HCl for exchangeable Al.
Available P	The Bray II method.
Particle size distribution	A pipette method after dispersion of soil particles at pH 10, otherwise at pH 3.5.

3.4 Morphological Properties of the Soils around Mt. Mayon

Soil horizon stratification was clearly observed based mainly on soil texture class, color, hardness and the abundance of rock fragments (Photo 1, Table 2). Irrespective of study sites, the bulk of rock fragments were composed of slightly weathered fine gravels (0.2 mm to 1 cm in the major axis) and/or gravels (1 to 5 cm), which occasionally formed consolidated, hard layers. Soils were coarse-textured, ranging from sand to sandy loam classes with the dominance of coarse sand (200㎛ to 2 mm in diameter) than fine sand (20 to 200㎛) (see Table 4) except for two horizons in NE1 (clay loam in Ap and sandy clay loam in Bgir). The bulk density was high except for the 0-10 cm soils in NE1 and SE2 compared with a common level of less than 0.9 g mL^{-3} for Andisols (Table 3). Very low silt and clay contents (2 to 20㎛ and < 2㎛) and high bulk density indicate poor clay formation from volcanic ash. Some of the horizons at deep layers showed a darker color compared with the overlying and underlying horizons and could be regarded as the buried A horizon with a high content of soil organic matter. Based on these morphological properties, volcanic soils around Mt. Mayon were regarded to be immature and young due to the interception of the weathering and formation processes by repeating ash deposition. The fine texture in NE1 in the east side might be the result from loading of finer particles eroded from the upper part of the slope.

As expected, clear differences were found in soil morphological properties between the different directions of Mt. Mayon. In the east side (NE1 and SE1), the soils were shallow with the consolidated, hard rock layer at the bottom. They were relatively wet, and the seepage of groundwater was observed at the depth of 55 cm in NE1 and 35 cm in SE2, indicating a high groundwater level. The presence of distinct iron mottling at the Bgir horizons in NE1 and SE2 and the underlying Cgir, 2Cgir and 3Cgir horizons in case of NE1 indicates changing redox conditions of soils due to the fluctuation of the water table. The root zone was shallow and restricted down to the C horizon in NE1 and the Bgir horizon in SE2 probably because of the excessive moist condition unfavorable for upland crops. In fact, NE1 was used for vegetable production all year round but surrounded by other paddy fields while SE2 was rotated with single vegetable and double rice cropping and also surrounded by paddy fields. Meanwhile, the soils in the west side (NW1, SW2 and MS3) were deep and we could not reach the bottom end by manual digging. Despite dry soil condition, plant roots were recorded down to the 3C horizon in NW1 and the 7C1 horizon in SW2. Meanwhile, the root zone was shallow at the Bw2 horizon in MS3 due to the presence of the underlying gravelly 2C horizon. Thus, the differences in soil depth and moisture condition as well as precipitation seem to be the determinant factor for different agriculture landscapes between the east and west sides of Mt. Mayon.

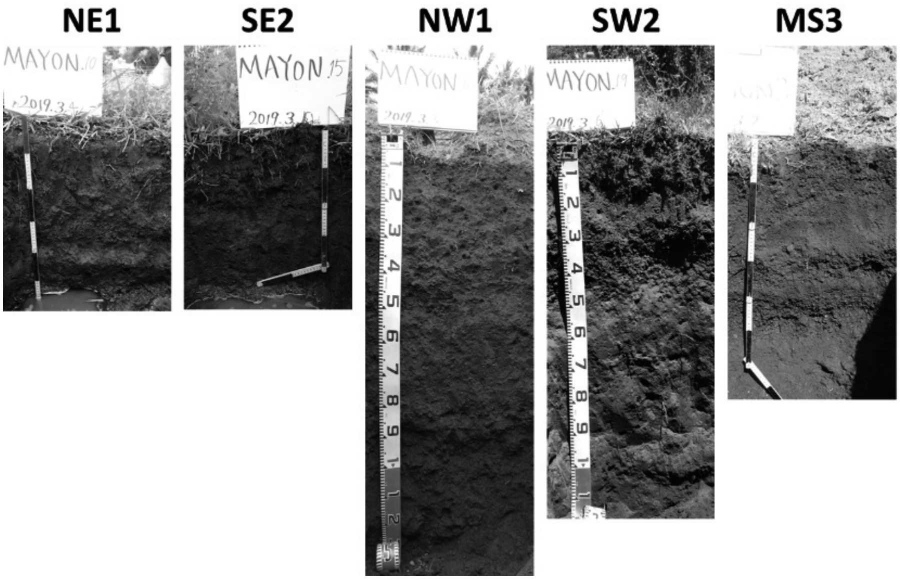

Photo 1 Soil profiles in NE1, SE2, NW1, SW2 and MS3

Table 2 Soil morphological properties at NE1, SE2, NW1, SW2 and MS3

Hor.	Depth (cm)	Description
NE1 (N13º19'21", E123º44'08", 26 m a.s.l., slope direction: N30° E, slope gradient: 1°)		
Ap	0-11	10YR2/3 (brownish black); clay loam; few slightly weathered fine gravels; moderate medium subangular blocky structure; many very fine to medium roots; penetr. 10 mm; clear smooth boundary to
Bgir	11-18	2.5Y3/3 (dark olive brown); common distinct, irregular mottling with 7.5YR4/6 (brown); sandy clay loam; few slightly weathered fine gravels; moderate medium subangular blocky structure; common very fine to medium roots; penetr. 12 mm; clear smooth boundary to
Cgir	18-26	10YR3/2 (brownish black); common faint, root-like mottling with 10YR4/6 (brown); soil texture undeterminable; dominant slightly weathered fine gravels and gravels (almost gravel layer); structureless; few fine to medium roots; penetr. unmeasurable; clear smooth boundary to
C	26-32	10YR3/3 (dark brown); sandy loam; soil texture undeterminable; dominant slightly weathered fine gravels; moderate fine subangular blocky structure; very few very fine roots; penetr. 16 mm; clear smooth boundary to
2Cgir	32-34	10YR3/3 (dark brown); few distinct, root-like mottling with 7.5YR4/6 (brown); sandy loam; no rock fragment; massive structure; no roots; penetrometer 12 mm; clear smooth boundary to
3Cgir	34-40	2.5Y4/4 (olive brown); common distinct, root-like mottling with 5YR3/6 (dark reddish brown); sandy loam; no rock fragment; massive structure; no roots; penetr. 15 mm; clear smooth boundary to
4C	40-60 +	2.5Y3/1 (brownish black); soil texture undeterminable; dominant slightly weathered fine gravels; no roots. seepage of ground water at 55cm
SE2 (N13º10'37", E123º42'35", 90 m a.s.l., slope direction: S20° E, slope gradient: a flat, terraced field		
Hor.	Depth (cm)	Description
Ap1 (ridge)	0-10	10YR2/2 (brownish black); sand; few slightly weathered fine gravels; moderate fine granular structure; many very fine to medium roots; penetr. 12 mm; gradual smooth boundary to
Ap2	10 = 22 =	10YR2/2 (brownish black); sand; few slightly weathered fine gravels; moderate medium to coarse subangular blocky structure; many very fine to medium roots; penetr. 12 mm; clear smooth boundary to
Bgir	22-30	10YR3/3 (dark brown); few distinct, irregular mottling with 10YR5/8 (yellowish brown); sand; many slightly weathered fine gravels; moderate medium subangular blocky structure; few very fine to fine roots; penetr. 17 mm; clear smooth boundary to
2C	30-40	10YR3/3 (dark brown); sand; many slightly weathered fine gravels and gravels; structureless; no roots; penetr. unmeasurable; gradual wavy boundary to
3C	40-45 +	10YR2/2 (brownish black); sand; abundant fresh fine gravels; structureless; no roots; penetr. unmeasurable; seepage of ground water at 45cm
NW1 (N13º18'21", E123º38'18", 246 m a.s.l., slope direction: N40° W, slope gradient: 1°)		
Hor.	Depth (cm)	Description
Ap1 (ridge)	0-15	10YR3/3 (dark brown); loamy sand; common slightly weathered fine gravels and few slightly weathered gravels; moderate fine subangular blocky structure; many very fine to medium roots; penetr. < 1 mm; clear smooth boundary to
Ap2	15-27	10YR2/3 (brownish black); loamy sand; common slightly weathered fine gravels and few slightly weathered gravels; moderate medium subangular blocky structure; common very fine to fine roots; penetr. 9 mm; clear smooth boundary to

Bw	27-35	10YR3/4 (dark brown); sandy loam; many slightly weathered fine gravels; moderate medium subangular blocky structure; common very fine to fine roots; penetr. 15 mm; gradual smooth boundary to
2AC	35-49	10YR3/4 (dark brown); loamy sand; abundant slightly weathered fine gravels and few slightly weathered gravels; moderate fine to medium subangular blocky structure; few very fine to fine roots; penetr. 19 mm; clear smooth boundary to
3C	49-60/65	7. 5YR3/4 (brownish black); sand; dominant slightly weathered fine gravels and gravels; structureless; very few very fine to fine roots; penetr. 18 mm; clear wavy boundary to
4A	60/65-73	10YR3/4 (dark brown); loamy sand; many slightly weathered fine gravels; moderate medium angular blocky structure; no roots; penetr. 17 mm; gradual smooth boundary to
4C1	73-83	10YR3/4 (dark brown); sand; dominant slightly weathered fine gravels and gravels; structureless; no roots; penetr. 21 mm; clear smooth boundary to
4C2	83-105	10YR4/4 (brown); loamy sand; many slightly weathered fine gravels; moderate medium angular blocky structure; common very fine to fine roots; penetr. 18 mm; gradual smooth boundary to
5C	105-127	10YR4/6 (brown); sand; dominant slightly weathered fine gravels and gravels; structureless; no roots; penetr. 18 mm; clear smooth boundary to
6A	127-140	10YR4/6 (brown); loamy sand; many weathered fine gravels; structureless; no roots; penetr. 18 mm; gradual smooth boundary to
6C	140-135 +	10YR4/6 (brown); sand; abundant weathered fine gravels and gravels; structureless; no roots; penetr. 15 mm

SW2 (N13º12'03", E123º39'18", 239 m a.s.l., slope direction: S40° W, slope gradient: 4°)

Hor.	Depth (cm)	Description
Ap (ridge)	0-12	2.5Y4/2 (dark grayish yellow); loamy sand; common slightly weathered fine gravels; weak medium subangular blocky structure; many very fine to medium roots; penetr. 8 mm; clear smooth boundary to
AC	12-18	2.5Y3/2 (brownish black); sand; many slightly weathered fine gravels and gravels; massive structure; common very fine to medium roots; penetr. 11 mm; clear smooth boundary to
2A	18-35	10YR3/3 (brownish black); loamy sand; common slightly weathered fine gravels and gravels; weak fine subangular blocky structure; common very fine to fine roots; penetr. 10 mm; clear smooth boundary to
3A	35-45	10YR3/4 (dark brown); soil texture undeterminable; dominant slightly weathered fine gravels containing pumice and gravels (almost gravel layer); structureless; very few very fine to fine roots; penetr. unmeasurable; clear smooth boundary to
4C	45-51	10YR2/3 (brownish black); loamy sand; dominant slightly weathered fine gravels and gravels (almost gravel layer); structureless; very few very fine to fine roots; penetr. unmeasurable; clear smooth boundary to
5C	51-58	10YR2/3 (brownish black); sand; few slightly weathered fine gravels and gravels; weak fine subangular blocky structure; very few very fine to fine roots; penetr. 6 mm; gradual wavy boundary to
6C	58-65/71	10YR2/2 (brownish black); sand; dominant slightly weathered gravels to large stones; structureless; very few very fine to fine roots; penetro. 7 mm; clear smooth boundary to
7C1	65/71-75/82	10YR2/2 (brownish black); sand; many slightly weathered fine gravels containing pumice; massive structure; very few very fine to fine roots; penetr. 12 mm; clear wavy boundary to

7C2	75/82-92/94	10YR2/3 (brownish black); sand; few slightly weathered fine gravels; massive structure; very few fine roots; penetr. 7 mm; gradual smooth boundary to
7C3	92/94-110	10YR2/2 (brownish black); sand; abundant slightly weathered gravels; structureless; many very fine to medium roots; penetr. 8 mm; gradual wavy boundary to
7C4	110-120 +	10YR2/2 (brownish black); sand; dominant slightly weathered gravels; structureless; no roots; penetr. unmeasurable; gradual smooth boundary to

MS3 (N13º17'37", E123º39'55", 535 m a.s.l., slope direction: N50° W, slope gradient: 12°)

Hor.	Depth (cm)	Description
A	0-11	10YR2/2 (brownish black); sandy loam; common slightly weathered fine gravels; moderate medium subangular blocky structure; common very fine to fine roots; penetr. 16 mm; clear smooth boundary to
Bw1	11-23	10YR3/4 (dark brown); sandy loam; common slightly weathered fine gravels; moderate to coarse subangular blocky structure; few very fine to fine roots; penetr. 20 mm; clear smooth boundary to
Bw2	23-28	10YR3/4 (dark brown); sandy loam common slightly weathered fine gravels; moderate medium subangular blocky structure; very few very fine roots; penetr. 19 mm; abrupt smooth boundary to
2C	28-35	10YR3/3 (dark brown); soil texture undeterminable; gravel layer (slightly weathered, φ< 1 cm); structureless; no roots; penetr. 15 mm; abrupt smooth boundary to
3C	35-40	10YR3/4 (dark brown); sand; many slightly weathered fine gravels (φ< 0.5cm); structureless; loose; no roots; penetr. 8 mm; abrupt smooth boundary to
4C	40-53	2.5Y3/3 (dark olive brown); soil texture undeterminable; gravel layer (slightly weathered, φ< 2 cm); structureless; no roots; penetr. 6 mm; abrupt smooth boundary to
5A	53-60/65	10YR3/4 (dark brown); loamy sand; common slightly weathered fine gravels; massive; no roots; penetr. 16 mm; Al test +; clear wavy boundary to
6C	60/65-80 +	10YR2/1 (black); soil texture undeterminable; gravel layer (slightly weathered, φ< 2 cm); structureless; no roots; penetr. unmeasurable

Penetr.: the reading of a Yamanaka-type push-cone penetrometer. In general, soil hardness with the reading of about 10 mm is adequate for plants. When the reading exceeds 25mm, plant roots cannot expand into such hard soils.

Table 3 Bulk density (g mL^{-1}).

	NE1	SE2	NW1	SW2	MS3
0~10 cm	0.76	0.83	0.98	1.41	1.09
20~30 cm	ND[1)]	1.13[2)]	0.87	1.32	1.03

Average values for triplicated samples.
1) no sample collected, 2) the depth was 10-20 cm.

3.5 Physicochemical Properties of the Soils around Mt. Mayon

The averages of soil physicochemical properties are given in Table 4. As a whole, the soils collected around Mt. Mayon were acidic both at the depth of 0-10 cm and 20-30 cm. The level of cation exchange capacity (CEC) was relatively low less than 10 $cmol_c\ kg^{-1}$ due to coarse soil texture. The ratio of effective CEC (ECEC; the sum of exchangeable bases and Al) to CEC was low even for the case of NE and SE of which pH (H_2O) was 6.2 and 6.4, respectively, indicating the dominance of variable charge characteristics, reflecting the Andic soil properties. Exchangeable bases almost accounted for ECEC. They were dominated by Ca, and Mg to a lesser extent, while the levels of exchangeable K and Na were low. The levels of exchangeable Al and H were negligible, suggesting that Al toxicity is not to be the matter for crops.

It should be noted that the soil properties in MS2 to MS4 (crop fields) except available P were virtually similar to those in MS1 (a degraded secondary forest patch). This result suggests that a substantial loss of fertilizer nutrients might occur unless taken up by crops although the comparison should be carefully done because of non-replicated sample and the higher elevation and location close to the crater for MS1. In contrast, despite supposed P adsorption due to the Andic soil properties, the content of available P was higher in MS2 to MS4 than in MS1, which could be ascribed to the positive effect of P fertilizer application similarly to the case of Japanese Andisols. Considerable improvement of soil P availability was also found in the above-mentioned follow-up studies on lowland paddy fields (Yanai et al. 2020, Tanaka et al. 2021, Nakao et al. 2021).

Similarly to the morphological properties, some differences between the east side (NE and SE) and the west sides (NW, SW and MS) were found in the soil physicochemical properties. The levels of total C and N were significantly lower in the east side than in the west side, probably due to a higher decomposition rate of soil organic matter under moist condition in the former. Exchangeable Mg and Na was significantly higher in the east than the west side with similar trends for Ca and K, suggesting the input of basic cations from sea salt in the east side. Meanwhile. in the west side, levels of exchangeable bases and available P were relatively high in MS compared with NW. This might be ascribable to the location of MS close to the smoking crater. These elements are likely to be supplied continuously to soils as fine particles in the smoke.

It is interested from the viewpoint of soil science that pH (NaF) values were higher than 9.5 in the west side but lower than 9.5 in the east side. This pH (NaF) is one of the criteria to identify volcanic soils, for which threshold is above 9.5. This distinction method is based on the reaction in which abundant active Al fractions in volcanic soils react with F- and release OH-, resulting in a large increase in the pH value. Based on the similar result of volcanic soils around a hot spring in central Java, Indonesia, Yuliani et.al (2017) suggested that high concentration of SO_4^{2-} might block the aluminol OH groups to react. In fact, Takayanagi (1997) detected high SO_4^{2-} concentrations in spring water at the foot of Mt. Mayon close to our SE sites, probably due to the dissolution of volcanic hydrogen sulfide gas.

Table 4 Averages of soil physicochemical properties.

		Northeast (NE)	Southeast (SE)	Northwest (NW)	Southwest (SW)	Mountain slope (MS2 to MS4)	Mountain slope (MS1*)	San Miguel Island (SM)
		n=3	n=3	n=3	n=3	n=3	n=1	n=2
				0-10 cm depth				
pH (H_2O)		6.2a	6.4a	5.6a	5.7a	5.8a	6.43	6.4
pH (NaF)		9.3ab	8.8a	11.0b	10.9b	10.8b	10.7	8.5
Total C	g kg^{-1}	26.4ab	16.0a	42.1b	28.8ab	36.6ab	38.7	19.4
Total N	g kg^{-1}	2.6ab	1.7a	4.2b	2.8ab	3.5ab	2.8	1.8
C/N ratio		10.3a	9.6a	9.9a	10.1a	10.3a	13.9	11.0
Avail. P	mg P kg^{-1}	192a	128a	182a	239a	351a	42	3.5
Exch. Ca	cmol$_c$ kg^{-1}	2.92a	2.97a	1.29a	1.50a	2.26a	4.00	8.07
Exch. Mg	cmol$_c$ kg^{-1}	0.55bc	2.09c	0.30ab	0.14a	0.45b	0.70	6.20
Exch. K	cmol$_c$ kg^{-1}	0.26a	0.20a	0.12a	0.10a	0.15a	0.13	0.15
Exch. Na	cmol$_c$ kg^{-1}	0.24b	0.21b	0.10a	0.08a	0.09a	0.06	0.23
Sum bases	cmol$_c$ kg^{-1}	3.97ab	5.47b	1.80a	1.81a	2.94ab	4.89	14.64
Exch. Al	cmol$_c$ kg^{-1}	0.03a	0.09a	0.10a	0.15a	0.08a	0.03	0.01
Exch. H	cmol$_c$ kg^{-1}	0.11a	0.11a	0.11a	0.11a	0.14a	0.14	0.11
CEC	cmol$_c$ kg^{-1}	8.68a	9.21a	9.04a	8.26a	8.37a	8.18	13.49
ECEC	cmol$_c$ kg^{-1}	4.00b	5.57b	1.90a	1.96a	3.02ab	4.92	14.64
ECEC/CEC		0.51b	0.61b	0.22a	0.24a	0.37ab	0.60	1.09
Base sat.	%	50.7ab	60.1b	20.6ab	22.7a	36.3ab	59.8	108.6
Clay	%	10.4a	9.5a	7.7a	6.4a	8.1a	8.3	26.7
Silt	%	11.6a	7.7a	7.9a	12.4a	9.6a	16.4	20.1
Fine sand	%	34.4b	27.3ab	14.6a	34.1b	29.0ab	40.4	29.6
Coarse sand	%	43.5a	55.5a	69.8a	47.1a	53.2a	34.8	23.7
				20-30 cm depth				
pH (H_2O)		6.5a	6.6a	5.7a	5.9a	5.7a		6.4
pH (NaF)		8.9a	8.9a	11.1b	10.7b	10.9b		8.6
Total C	g kg^{-1}	13.5ab	8.1a	38.3b	25.3ab	24.0ab		13.6
Total N	g kg^{-1}	1.5ab	0.9a	3.7b	2.5ab	2.4ab		1.4
C/N ratio		9.2ab	8.7a	10.0ab	10.3b	9.9ab		10.0
Avail. P	mg P kg^{-1}	111a	72a	74a	117a	141a		1
Exch. Ca	cmol$_c$ kg^{-1}	2.62a	2.44a	1.07a	1.82a	1.00a		6.75
Exch. Mg	cmol$_c$ kg^{-1}	0.67bc	2.48cd	0.25ab	0.13a	0.24ab		6.44
Exch. K	cmol$_c$ kg^{-1}	0.20a	0.09a	0.10a	0.09a	0.11a		0.09
Exch. Na	cmol$_c$ kg^{-1}	0.18b	0.20b	0.08a	0.08a	0.06a		0.41
Sum bases	cmol$_c$ kg^{-1}	3.67ab	5.21b	1.49a	2.11ab	1.41a		13.7
Exch. Al	cmol$_c$ kg^{-1}	0.04a	0.05a	0.06a	0.06a	0.03a		0.01
Exch. H	cmol$_c$ kg^{-1}	0.08a	0.09a	0.06a	0.12a	0.11a		0.11
CEC	cmol$_c$ kg^{-1}	7.12a	5.89a	7.85a	7.89a	6.99a		21.10
ECEC	cmol$_c$ kg^{-1}	3.70b	5.26b	1.55a	2.17ab	1.44a		13.71
ECEC/CEC		0.55bc	0.95c	0.20a	0.27ab	0.21a		0.66
Base sat.	%	54.4bc	94.6c	19.3a	26.5ab	20.1a		65.6
Clay	%	8.8a	6.5a	7.2a	6.5a	5.5a		41.5
Silt	%	10.7a	6.0a	7.6a	10.0a	12.7a		18.6
Fine sand	%	34.3b	25.8ab	15.5a	32.2b	24.2ab		21.7
Coarse sand	%	46.1a	61.7a	69.7a	51.3a	57.7a		18.1

*MS1 was a degraded secondary forest and the soil sample was collected only from a depth of 0-10 cm. Different alphabetical characters indicate statistical difference among NE, SE, NW, SW and MS for each soil property at $p < 0.05$ based on Turkey's multiple comparison. EC: electric conductivity, Avail. P: available P, CEC: cation exchange capacity, Exch.: exchangeable, Sum bases: the sum of exchangeable Ca, Mg, K and Na, ECEC: effective CEC calculated as sum of exchangeable bases and Al, Base sat.: base saturation calculated as the percentage of exchangeable bases in CEC.

3.6 Physicochemical Properties of the Soils in San Miguel Island

The soils in San Miguel Island (SM1 and SM2) showed different features from those around Mt. Mayon. Because of low pH (NaF) values, the soils could be regarded as non-volcanic soils, probably originating from coral limestone. They were fine-textured (sandy loam to light clay) while a higher clay content at the depth of 20-30 cm than 0-10 cm. Thus, the soils were strongly weathered with clay illuviation. The levels of exchangeable bases except K were very high. The base saturation exceeded 100% at the depth of 0-10 cm, suggesting salt accumulation due to continuous input of sea salt to the surface soils in addition to the supply through weathering of the parent materials. In contrast, the level of available P was considerably low, reflecting insufficient inputs of the fertilizer.

3.7 Soil Characteristics and Recommendation for Soil Managements

Based on the morphological and physicochemical properties, the soils around Mt. Mayon can be regarded as young volcanic soils, of which weathering and formation processes were intercepted by repeated ash deposition. Despite the differences between the east and west sides, the soils seem to be classified into the subgroups of Inceptisols with the Andic soil properties or the related class in Soil Taxonomy (Soil Survey Staff, 2014) although the detailed soil analysis should be required to confirm the soil class. Meanwhile, the soils in San Miguel Island were considerably different from those around Mt. Mayon and seem to originate from coral limestone. The soils could be classified into a suborder of Alfisols.

The soil characteristics were influenced by physiographic environments. The soils in the east side of Mt. Mayon were shallow and considerably moist, which would lead to the prosperity of rice farming. Meanwhile, the soils in the west side of Mt. Mayon were deep and dry, for which the farmers seem to adopt upland farming. The soils in the east side and in San Miguel Island could be supplied with basic cations from sea salts while soils closed to the crater might be fertilized through natural nutrient input from the smoke.

Despite on-going research, we can tentatively make several recommendations for soil managements. For the soils about six kilometers around Mt. Mayon, split application of NK fertilizers is appropriate to prevent leaching loss due to a low clay content and the resulting low CEC values. The relatively high level of available P suggests the possibility to reduce the amount of P fertilizer although P application rates must be carefully examined considering P adsorption characteristics of volcanic soils. Liming materials are not necessary because exchangeable Al is negligible, and other Ca and Mg fertilizer might be also omitted or reduced in the east side with expected natural supply as sea salts. Meanwhile, the soils in San Miguel Island should require more application of NPK fertilizers to build up sufficient stocks of these elements as well as to adjust base balance against very high level of Ca and Mg.

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