Environmental and Agricultural Significance of Volcanic Ash Soils

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Abstract

Volcanic ash soils begin to form with rapid restoration of vegetation soon after ash deposition and create a productive and comfortable environment. They also have various important functions such as accumulation of large amounts of organic carbon and nitrogen, plentiful storage of water, water quality improvement, and preservation of paleoenvironment and archaeological artifacts. Volcanic ash soils are among the most productive soils in the world. Nowadays they are most extensively utilized for growing high-value horticultural crops in Japan. The properties relating to their soil productivity are comprehensively described. In order to solve the serious problems caused by unsuitable management and to sustain volcanic ash soils, crop rotation, soil improvement, and precision agriculture and programmed fertilization are encouraged. Recommended rotations for with high economic advantages also include crops to control soil-borne diseases and nematodes, gramineous plants to enhance soil organic matter levels and crops having symbiotic interactions with arbuscular mycorrhiza that promote plant uptake of soil phosphorus. Some volcanic ash soils have soil horizons that strongly inhibit plant root development. Soil improvements such as deep cultivation and soil mixing are practiced for such soils. Programmed fertilization using controlled-release fertilizers with high performance is recommended especially for intensive agriculture on small-scale fields. Correctly programmed fertilization can be conducted at the best site by single basal application for most crops in Japan. With proper management volcanic ash soils are capable of high productivity and long-term agricultural and environmental sustainability.

Key words: crop rotations, functions of volcanic ash soils, programmed fertilization using CRFs, soil rejuvenation, sustaining volcanic ash soils

1. Significance as the Soil Environment

Though volcanic eruptions are highly destructive, this natural phenomenon is beneficial in the long term. Rapid restoration of vegetation and soil environment takes place on volcanic ash deposits soon after the ash deposition event. The periodic additions of volcanic ash generally improve the soil physical and chemical properties and renew the soil productivity. Volcanic ash soils provide a comfortable living environment and create a favorable landscape for recreation and human health. They also accumulate a large amount of organic carbon and nitrogen as important components of soil organic matter that are the main sources of nitrogen for plants, and various nutrients and energy for soil organisms. The accumulation of carbon is helpful in sequestration of atmospheric carbon dioxide, the most important greenhouse gas. Volcanic ash soils with well developed soil structures can hold a large amount of plant-available water and can decrease flood waters. Volcanic ash soils generally have sedentary multi-storied profiles and resist soil disturbance, truncation and displacement due to natural and human activities. They preserve highly useful information such as on paleosoil environments and paleovegetation, and archaeological remains and artifacts.

1.1 Rejuvenation of soil environments

Restoration of vegetation and soil environments on volcanic ash deposits

Volcanic ash is a suitable medium for plant growth providing physical support, essential plant nutrients and plant-available water. Therefore, rapid restoration of vegetation and soil environment commonly takes place on volcanic ash deposits as observed in the areas of Mt. Usu, Hokkaido, Japan, Mt. Pinatubo, Central Luzon, the Philippines, and Mt. St. Helens, Washington, USA (see page 71).

The 1977 – 78 Mt. Usu eruptions blew out a large amount of volcanic ash and deforested the summit with a 1 – 3 m thick ash deposit. The ash is characterized by dacitic rock type, predominance of volcanic glass with high vesicularity and a very coarse texture (Shoji, 1993). Though phosphorus is usually a limiting nutrient for most agricultural plants grown on volcanic ash soils, the Mt. Usu ash contains a substantial amount of plant available phosphorus (Shoji *et al.*, 1993b). This fact strongly suggests that nitrogen is the most important nutrient limiting revegetation of Mt. Usu summit.

The revegetation on Mt. Usu showed two patterns until 1990: seedling revegetation on the thick ash deposit and vegetative revegetation on the thin ash deposit (< 1 m) (Haruki and Tsuyuzaki, 2001; Tsuyuzaki, 2001; Tsuyuzaki and Haruki, 1996). The former was established by trees producing wind-dispersed seeds such as *Populus maximowiczii*, *Betula platyphylla* var. *japonica*, *Salix sachalinsis*, etc. The latter efficiently proceeded from resprouting of buried branches of *Polygnum sachalinse* and *Petasetus japonica* var. *giganteus*.

Mt. Usu volcanic ash soils show regosolic properties after 25 years of weathering (Shoji, 1993). They have thin organic (Oi and Oe: 2 – 5 cm) and AC horizons (2 – 5 cm) under various forests. The soil samples contain oxalate-extractable aluminum plus a half iron percentage totaling 0.42%, and their phosphate retention is 15.2% (mean of 20 soil samples from 5 pedons). It was noted that the content of plant-available phosphorus in the soils is almost comparable with that of the fresh ash (Truog soluble P_2O_5: 0.1 – 0.40 g per kg).

The violent eruptions of Mt. Pinatubo from June 9 to 16, 1991, were among the largest in the 20th century, and ejected a tremendous amount of volcanic ash on and around the volcano. Thus, lahar or volcanic ash moving down to the lowlands repeatedly occurred every rainy season, so wide agricultural areas in Central Luzon were covered with thick lahar deposits (PHIVOLCS, 1992). Mt. Pinatubo ash showed similar properties to those of Mt. Usu: dacitic rock type, abundance of volcanic glass with high vesicularity and a very coarse texture. It contains 1.7 g $P_2O_5\,kg^{-1}$ mostly occurring as apatite which enhances the plant-available phosphorus level of the ash deposits (Nakamaru *et al.*, 2000).

Two types of intense revegetation on the lahar deposits have been reported: revegetation by gramineous plant communities (Ota, 2002; Yoshida, 2002) and by leguminous and gramineous plant communities (Saito *et al.*, 2002). *Saccharum sponteneum* L. was the most important gramineous plant as a pioneer. A year and a few months after lahar deposition it appeared as patches on the lahar deposits which contained fine ash and a small amount of soil material, helping maintain suitable moisture content in the top layer of the deposit (Table 1). Such lahar deposits contained a trace amount of organic carbon and nitrogen (Sites N and S1). In contrast, a dense gramineous plant community was established seven years later and the lahar deposit rapidly accumulated organic carbon (0.8%) and nitrogen (0.066%) (Ota, 2002).

As noted before, nitrogen supply to the pioneer plants is the key to intense revegetation on volcanic ash. There are several possible sources of nitrogen supply to the vegetation as follows:

1. mineral nitrogen in rain water,
2. soil organic nitrogen mixed in the volcanic ash of lahar deposits
3. organic nitrogen of buried soil, and
4. microbiologically fixed nitrogen.

The mineral nitrogen in rain water and soil organic nitrogen mixed in the ash is small in amount, providing only a part of the mineral nitrogen needed to establish dense *Saccharum sponteneum* communities. Nitrogen supply of buried soil is strongly determined by the thickness of volcanic ash and characteristics of plant root systems. *Saccharum sponteneum* has a shallow root system (mostly < 20 cm), so it cannot efficiently utilize mineral nitrogen from the buried soil where the ash deposit is very thick. Thus, the major source of nitrogen is considered to be nitrogen fixed by symbiotic microorganisms of *Saccharum sponteneum* growning on ash deposits with suitable moisture content (Ota, 2002).

Another kind of intense revegetation on the volcanic ash of lahar deposits was established by the

Table 1 Revegetation and nitrogen accumulation of the surface soils in a Mt. Pinatubo lahar area in March of 1998 (Ota, 2002).

Sampling site	Lahar deposition (year)	Depth of lahar deposit (m)	Growth of vegetation*	Soil N content (mg kg^{-1})
N	1991 – 1996	> 1.25	Very sparse	10
S1	1991 – 1996	> 1.25	Sparse – patches	11
S3	1991 – 1995	> 1.25	Patches	58
F3	1991	0.75	Dense	662

* Dominant species: *Sacharum spontaneum.*

co-existence of gramineous and leguminous plants. This process was hypothesized as follows (Saito *et al.*, 2002). Firstly, gramineous plants such as *Saccharum sponteneum* start to grow from airborne seeds. It is highly probable that diazotrophic endophytic bacteria contribute to the growth of the seedlings of pioneer plants by nitrogen fixation. Secondly, the airborne or flood-dispersed spores of arbuscular mycorrhizal fungi colonize the gramineous plants and fungal density increases in the host plants. Thirdly, leguminous seeds such as *Calopogonium muconoides* and *Centrosema pubescens* are also dispersed into the volcanic ash and start to grow with the gramineous plants. Since leguminous plants are highly mycorrhiza-dependent and require more phosphorus uptake for their nitrogen fixation, the high population density of arbuscular mycorryizal fungi stimulate the intense growth of the legumes.

Once a gramineous and leguminous plant community with symbiotic microorganisms is established, the soil environment is rapidly restored as shown by vegetation and soil chemical data measured in 1999 – 2000 (Table 2). The gramineous and leguminous plant community (densely vegetated site) produced ten times as much dry matter and also absorbed more than 10 times as much nitrogen and phosphorus compared to the gramineous plant community (sparsely vegetated site). Thus the soil under the gramineous and leguminous plant community accumulated more than twice as much organic carbon and nitrogen compared to the soil under gramineous plant community. Nitrogen also was the major nutrient limiting establishment of plants in the vicinity of Mt. St. Helens. The nitrogen fixing lupin (*Lupinus spp.*) colonized thick pyroclastic flow surfaces, resulting in rapid plant regeneration and dramatic short-term changes in soil genesis (see page 73).

Soils in a volcanic zone versus soils in a nonvolcanic zone in Eastern Hokkaido

Volcanism commonly continues for a long time and volcanic eruptions are repeated. The periodic additions of volcanic ash generally improve the soil physical and chemical properties and renew the long-term soil productivity. Thus soils in the volcanic zone are markedly different in soil productivity and other aspects from the soils in the nonvolcanic zone as exemplified below.

Northeastern Hokkaido with a udic soil moisture regime and frigid soil temperature regime is tentatively divided into three zones according to the frequencies of volcanic ash deposition originated from Mts. Kamui-nupuri, Mashu, etc. The ash deposition was periodic and thicker in depth in Zone A (Nemuro Subprefecture) to the east of the source volcanoes, and fewer and thinner in Zone B (southern Abashiri Subprefecture) to the northeast of the source volcanoes, and none in Zone C (northern Abashiri Subprefecture) to the north of the source volcanoes. Therefore, each zone shows contrasting soil distributions (Tomioka, 1985). Regosolic, Ordinary and Cumulic Andosols are widely distributed in Zone A according to distance

Table 2 Vegetation and soil chemical properties of the gramineous plant community (sparsely vegetated site) and gramineous and leguminous plant community (densely vegetated site) in the Mt. Pinatubo lahar area (Saito *et al.*, 2002).

Sampling site	Gramineous plants		Gramineous and leguminous plants	
Dominant plant species	*Sacharum sponteneum* *Rhychelytrum repens*		*Calopogonium muconoides* *Centrosema pubescens*	
Seasons of sampling	Rainy (Sept. ’99)	Dry (Mar. ’00)	Rainy (Sept. ’99)	Dry (Mar. ’00)
Standing plant				
DW production ($g\ m^{-2}$)	97 ± 26	76 ± 4	1081 ± 569	813 ± 285
Plant N uptake ($g\ m^{-2}$)	0.22 ± 0.06	0.17 ± 0.01	9.3 ± 0.49	3.90 ± 1.26
Plant P uptake ($g\ m^{-2}$)	0.11 ± 0.03	0.08 ± 0.01	1.20 ± 0.6	0.76 ± 0.38

	Gramineous plants	Gramineous and leguminous plants	Difference between the two sites
Soil pH(H_2O)	6.1	6.0	ns
Total soil C ($mg\ kg^{-1}$)	1700	3900	**
Total soil N ($mg\ kg^{-1}$)	85	249	**
Available soil P (Truog) ($mg\ kg^{-1}$)	264	215	ns

from the source volcanoes, while Brown Andosols are most extensive, followed by Regosolic and Ordinary Andosols in Zone B. The major soils on the plain land in Zone C are Pseudogleys (Tomioka, 1985).

Volcanic ash depositions in Zone A took place more than 10 times during the last 7,000 years (Kondo, 1985). Therefore, Regosolic Andosols most extensively occur in the area near the volcanoes, and have multi-storied soil horizons. For example, Bekkai soil classified as Thaptic Udivitrand (see Table 9 on page 94) has five humus horizons from the surface to 1 m depth. These horizons fail in the requirements for both melanic and fulvic surface soils and the Bw horizons are weakly developed. The Bekkai soil shows high organic carbon concentrations in the humus horizons and CEC values of 3 – 30 $cmol_c\ kg^{-1}$. All the horizons except the upper two humus horizons show virtual absence of KCl-extractable Al.

Ordinary and Cumulic Andosols have formed from the same volcanic ashes of the Regosolic Andosols in the area far from the volcanoes. They show improved physical and chemical properties and enhanced soil productivity. Because each ash deposit is finer and thinner, the weathering rate is greater and composite horizons are formed.

Brown Andosols in Zone B are mostly derived from recent volcanic ash deposits and late Pleistocene volcanic ash flow deposits. The Abashiri soil (Pedon 1 in Shoji *et al.*, 1990) is an example of Brown Andosols as described above (Table 3). It shows the cumulative properties: the A1–2A horizons developed in the ash deposits of 250–550 years old, the 3A1 – 3Bw2 horizons from an ash flow deposit of 12,000 years old and the C horizon from an older ash flow deposit. The A1 horizon has a fine granular structure and the 2AC to 3Bw1 horizons, a subangular blocky

Table 3 Description of Abashiri soil.

Source	Shoji, Hakamada and Tomioka, 1990
Location	Kiyosato, Shari, Hokkaido
Classification	Brown Andosol (medial amorphic, frigid Typic Hapludand)
Physiography	Level tableland
Elevation	61 m M.S.L.
Water table	Not observed
Permeability	Moderate
Vegetation	Broadleaved trees
Erosion	None
Parent material	Rhyolitic volcanic ash falls (0 – 20 cm; 250 – 550 years old) and volcanic ash flows (20 – 92 cm; 11,720 ± 220 years old)

Horizon	Depth (cm)	Morphological properties
O	4 – 0:	Partially decomposed organic matter.
A1	0 – 14:	Black (7.5 YR 2/1) moist; moderate fine granular structure; very friable and slightly sticky; abrupt boundary.
2AC	14 – 20:	Brown (7.5 YR 4/4) moist; weak medium subangular blocky structure; very friable and slightly sticky; abrupt boundary.
3A1	20 – 32:	Dark brown (7.5 YR 3/3) moist; weak medium subangular blocky structure; very friable and slightly sticky; abrupt boundary.
3Bw1	32 – 58:	Brown (7.5 YR 6/6) moist; weak medium subangular blocky structure; very friable and slightly sticky; abrupt boundary.
3Bw2	58 – 92:	Brown (7.5 YR 5/5) moist; weak prismatic structure; friable and slightly sticky; clear boundary.
4C	92 –100+:	Brown (7.5 YR 4/6) moist; weak prismatic structure; firm and sticky; abrupt boundary.

Table 4 Selected physical and chemical properties of Abashiri soil (Shoji *et al.*, 1990).

Depth (cm)	Horizon	Clay content (%)	Bulk density ($g\ cm^{-3}$)	Organic C (%)	pH (H_2O)	KCl-extr. Al ($cmol_c\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	Base sat. (%)	P ret. (%)	Al_o+1/2Fe_o# (%)	Allophane§ (%)
0 – 14	A1	5	0.64	4.2	6.0	0.1	17.8	59	53	0.88	1.6
14 – 20	2AC	6	0.48	1.6	6.5	tr	10.6	49	59	1.14	2.8
20 – 32	3A1	21	0.62	2.4	6.6	tr	16.7	51	92	3.93	12.6
32 – 58	3Bw1	21	0.55	1.7	6.7	tr	14.6	48	93	4.63	17.1
58 – 92	3Bw2	27	0.75	0.7	6.5	0.1	16.9	35	94	5.37	21.5
92 – 100+	4C	29	0.88	0.3	6.5	0.1	24.4	64	72	1.94	4.4

Aluminum plus 1/2 iron percentages by ammonium oxalate.

§ Allophane percentages determined by ammonium oxalate extractable Si × 7.1.

structure, and the 3Bw2 to 4C horizons, a prismatic structure. However, all the horizons except the 4C horizon show a friable and slightly sticky consistency.

The Abashiri soil shows bulk densities of less than 0.9 g mL^{-1} in all the horizons (Table 4). The clay content is very low (5 – 6%) in the surface horizons from young ash while it is considerably higher in the other horizons from the old ash flow deposits (20 – 29%). Major components of clay fractions are 2:1 layer silicates, Al-humus and volcanic glass in the A1 horizon, 2:1 layer silicates and allophane-imogolite in the 2AC horizon, allophane-imogolite in the 3A1 to 3Bw2 horizons, and halloysite and allophane-imogolite in the 4C horizon. The Abashiri soil has a large volume of total porosity and plant-available water (Shoji *et al.*, 1990).

Accumulation of organic carbon or humus is moderate in the surface horizons because these young horizons are less weathered, as shown by low values of acid oxalate extractable Al and Fe and P retention. In contrast the old horizons demonstrate high values of these analyses. The values of CEC and base saturation are 10.6 – 24.4 $cmol_c\,kg^{-1}$ and 35 – 40%, respectively. Therefore, soil acidity is mostly slightly acid to neutral and KCl extractable Al which may be toxic to plant roots is virtually absent. As described above, the Abashiri volcanic ash soils are high in soil productivity so that they are suitable for producing high quality crops.

The Pseudogleys in Zone C in non-volcanic zones are formed from a fine Pleistocene terrace deposit and are locally called "heavy clay soils". This naming suggests that they have serious physical and engineering constraints.

The Monbetsu soil was selected to show the characteristics of Pseudogleys as described above (Tables 5, 6). The surface horizons (A1 and A2) show black to brown colors but the Bg and BCg horizons, a light gray color, indicating a characteristic of gleying due to water stagnant and anaerobic conditions. The A2 to BCg horizons have moderate prismatic structures with clay and organic films. The Bg to C2g horizons are also characterized by very sticky and very plastic consistency.

The physical properties of the Pseudogleys are strongly determined by fine texture and abundance of layer silicates. The Monbetsu soil shows clay contents of 44 – 55% in the A1 to BCg horizons, bulk densities greater than 1.1 gm L^{-1} and air phase ratios less than 10% in all the horizons except the A1 horizon. These physical properties greatly reduce drainage, plant root elongation and tractability of agricultural machines.

The Monbetsu soil shows a very high organic carbon concentration only in the A1 horizon. The CEC and base saturation values range from 20.5 to 48.2 $cmol_c\,kg^{-1}$ and from 26 to 55%, respectively. The soil acidity is strongly acid to moderately acid and the ΔpH values are high in most horizons, suggesting an abundance of KCl-extractable Al. In fact, all the horizons except the A1 horizon contain KCl-extractable Al of 5 – 11 $cmol_c\,kg^{-1}$ that can cause

Table 5 Description of Monbetsu soil.

Source	Hokkaido Development Bureau, 1972
Location	Numanoue, Monbetsu city, Hokkaido
Classification	Pseudogley (Typic Haplaquept)
Physiography	Plain land on the middle terrace
Elevation	Not described
Water table	Not described
Permeability	Very poor
Vegetation	Alder, white birch, bamboo grass, bracken, etc.
Erosion	None
Parent material	Clayey terrace deposit

Horizon	Depth (cm)	Morphological properties
O	3 – 0:	
A1	0 – 13:	Black (10 YR 1/1) moist; moderate fine granular structure: firm; clear boundary.
A2	13 – 20:	Grayish yellow brown (10 YR 6/2) moist; few mottlings; moderate coarse prismatic structure with clay and organic films; firm; clear boundary.
Bg	20 – 37:	Light gray (10 YR 8/1) moist; moderate medium prismatic structure with organic films; firm, very sticky and very plastic; gradual boundary.
BCg	37 – 67:	Light gray (10 YR 7/1) moist; moderate coarse prismatic structure with clay and organic films; firm, very sticky and very plastic; gradual boundary.
C1g	67 – 138:	Bright yellowish brown (10 YR 6/8) moist; weak coarse prismatic structure; very firm; gradual boundary.
C2g	138 – 160+:	Grayish yellow brown (10 YR 6/2) moist; weak coarse prismatic structure; firm, very sticky and very plastic.

Table 6 Selected physical and chemical properties of Monbetsu soil (Hokkaido Development Bureau, 1972).

Depth (cm)	Horizon	Clay content (%)	Bulk density ($g\ cm^{-3}$)	Three phase ratio (%)			Organic C (%)	pH (H_2O)	pH (KCl)	KCl-extr. Al ($cmol_c\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	Base sat. (%)
				Solid	Water#	Air						
0 – 13	A1	44	0.41	20	50	30	10.5	5.2	4.1	2.9	48.2	30
13 – 20	A2	48	1.19	45	47	9	3.0	5.6	4.1	5.4	28.6	26
20 – 37	Bg	55	-	-	-	-	0.9	5.4	3.9	11.1	27.6	30
37 – 67	BCg	50	1.18	43	54	3	0.4	5.8	3.8	8.8	22.9	47
67 – 138	C1g	35	1.22	45	51	4	0.2	5.9	3.8	6.1	20.5	55
138 – 160+	C2g	33	1.31	48	49	2	0.3	5.9	3.8	9.4	35.6	36

Field moist.

serious Al toxicity to plants roots.

It is obvious from the foregoing that there are remarkable differences in morphological, mineralogical, physical and chemical properties between the Brown Andosols in Zone B and the Pseudogleys in Zone C. From an agronomic point of view, the Brown Andosols have excellent physical properties for plant growth and management, such as large water-holding capacity available to plants, favorable conditions for root elongation, high tractability, etc. They also have suitable chemical properties such as slightly acid to neutral reaction, virtual absence of toxic Al, moderate CEC values and soil organic matter concentrations, etc. On the other hand, the Pseudogleys have poor soil tilth, difficult root penetration, and low tractability because of their fine texture, poor drainage and abundance of layer silicates. They also have a large amount of toxic Al in both the surface and subsurface horizons, strongly limiting plant growth. Thus, various improvement practices such as mole and tile drainage, liming, deep cultivation, subsoil breaking, and sand addition to the Ap horizon have been traditionally recommended.

Amenity

Volcanic ash soils widely occurring in Japan also provide a comfortable living environment or amenity and create a favorable landscape for recreation and human health. Construction applications for both individual living sites and communities are favored by excellent soil physical properties such as medium texture, low bulk density, and friable consistency of the soils. In addition to these physical properties, the large water-holding capacity is highly helpful for gardening on volcanic ash soils. Many Japanese people consider that vigorous plant growth and healthy soil properties (Doran *et al.*, 1996) create a comfortable environment.

There are a great number of scenic spots in Japan and many of them are volcanic landscapes. The unique morphology of volcanic mountains and changes in vegetation according to elevation create very attractive landscapes. Volcanic ash soils on the landscape are an excellent medium for vigorous growth of vegetation. The landscape seasonally changes and shows different picturesque sceneries throughout the year. Thus, numerous people enjoy sightseeing and outdoor sports in volcanic landscapes.

Amenity conservation is one of the environmental conservation functions of agricultural land or soil. It includes landscape conservation, microclimate modification, recreation and human health, and residential area conservation (Yokohari *et al.*, 2000). Volcanic ash soils can substantially contribute to amenity conservation.

1.2 Carbon and nitrogen stocks in volcanic ash soils

The soil can accumulate large amounts of carbon and nitrogen as important components of soil organic matter (SOM). SOM is the main source of nitrogen (N) for plants. For example, approximately two thirds of N in wetland rice and a half of N in most upland crops are microbiologically mineralized from SOM (Shoji and Mae, 1984). SOM is also the main source of nutrients and energy for soil organisms, so their population and diversity decline with a decrease in SOM. It increases cation exchange capacity and acts as a pH buffer. It also contributes to developing stable soil structures, enhances water-holding capacity and improves soil tilth.

There is an increasing concern about SOM in relation to mitigation of climate change by soil carbon sequestration. It is estimated that carbon held in SOM is approximately twice that occurring in the atmosphere as CO_2 and is three times more than that in all the vegetation as organic compounds (IPCC, 2001). However, SOM has been seriously decreased by intense cultivation and soil erosion.

Volcanic ash soils are a major soil in Japan. They store a great quantity of SOM which consists mainly of stable humic acids. For example, 40% of agricultural land in Hokkaido is occupied by volcanic ash soils (Table 7). Of the volcanic soil groups, cumulic and gley cumulic volcanic ash soils account for 24% of the total acreage of volcanic ash soils. Since their humus horizons have a depth of at least 30 cm and organic C of more than 7%, both soils contain more than 100 Mg organic C ha^{-1}.

There are many volcanic ash soils which have extremely thick humus horizons with a very dark color. They were formed by repeated ash depositions and pedogenesis since the late Pleistocene as exemplified by the Imaichi in Kanto and Takaono in Kyushu (Table 8). The Imaichi soil shows composite humus horizons of 86 cm and contains 48.2 kg organic C m^{-2} (482 Mg organic C ha^{-1}) and 2.17 kg organic N m^{-2} (21.7 Mg organic N ha^{-1}). The Takaono soil also has composite humus horizons of 410 cm and has 112.4 kg organic C m^{-2} (1,124 Mg organic C ha^{-1}) and 6.58 kg organic N m^{-2} (65.8 Mg organic N ha^{-1}). Since most field crops uptake 100 to 300 kg N ha^{-1}, the stored organic N in both soils is estimated to be several hundred fold the plant uptake of N.

There are several factors contributing to remarkable accumulation of SOM in volcanic ash soils. SOM of volcanic ash soils is commonly predominated by humic acid with the highest degree of humification (type A humic acid) and is complexed with active Al and Fe in the soils. Thus, the mean mineralization rate of organic C of volcanic ash soils is 3.02×10^{-3} day^{-1} (mean of 10 soils) while that of nonvolcanic ash soils, 7.74×10^{-3} day^{-1} (mean of 8 soils) (Takenaka and Hayano, 1999). Gramineous vegetation also contributes to increasing SOM by plentiful supply of cellulose and lignin-rich plant materials to the soil as discussed later. Burial of volcanic ash soils by re-

Table 7 Distribution of volcanic ash soils in Hokkaido (Tomioka, 1985).

Soil group	Distribution (%)#
Volcanogeneous Regosols	6.5
Gleyic Volcanogeneous Regosols	1.6
Regosolic Andosols	3.5
Gleyic Regosolic Andosols	0.3
Brown Andosols	6.3
Ordinary Andosols	11.5
Gleyic Ordinary Andosols	0.7
Cumulic Andosols	6.8
Gleyic Cumulic Andosols	2.9
Total	40.1

Percentage of the total area of agricultural lands.

Table 8 Organic carbon and nitrogen stocks in Imaichi and Takaono soils with thick high-humic horizons.

Depth (cm)	Horizon	OC (%)	ON (%)	Storage (kg m^{-2}) OC	Storage (kg m^{-2}) ON	Age (YBP)
Imaichi soil# (Imaichi City, Tochigi Prefecture)						
0 – 13	A1	19.8	1.02	9.0	0.46	
13 – 23	A2	17.8	0.85	7.5	0.36	
23 – 32	2A3	16.8	0.74	6.7	0.29	
32 – 46	2A4	16.0	0.66	8.7	0.36	
46 – 58	3A5	12.1	0.49	5.5	0.22	
58 – 74	3A6	10.5	0.45	7.0	0.30	
74 – 86	4A7	1.9	0.09	1.2	0.05	
86 – 121	4C	1.0	0.05	2.6	0.13	
Total				48.2	2.17	
Takaono soil§ (Ootsu Town, Kumamoto Prefecture)						
0 – 24		12.7	1.03	14.3	1.16	
24 – 60		7.1	0.54	12.3	0.93	
60 – 80		8.0	0.54	6.6	0.44	
80 – 108		11.7	0.61	14.7	0.77	9,950
108 – 130		6.6	0.30	7.1	0.32	13,400
130 – 182		5.8	0.33	13.9	0.77	15,100
182 – 220		3.0	0.19	4.8	0.30	
220 – 238		4.2	0.17	3.6	0.14	
238 – 270		5.4	0.33	8.8	0.54	21,500
270 – 285		4.5	0.20	3.5	0.16	23,500
285 – 303		4.9	0.25	3.9	0.20	25,100
303 – 327		3.5	0.16	3.9	0.18	
327 – 350		3.1	0.13	3.2	0.13	
350 – 410		4.8	0.22	11.8	0.54	
Total				112.4	6.58	

Kurobokudo Co-operative Research Group (1986)
§ Kubotera, H. and I. Yamada (1995)

peated ash depositions protects against surface horizon loss by soil erosion and human activity and retards the mineralization of SOM.

1.3 Water storage and water quality improvement

Volcanic ash soils have well developed soil structures with various pore diameters so that they can hold a large amount of plant-available water as already described by M. Nanzyo. They can supply almost enough water to grow most agricultural plants in Japan though the plants have very high water requirement (amount of water in gram needed for producing dry plant matter of 1 g) ranging mostly from 100 to 600 (Shoji and Mae, 1984).

Volcanic ash soils under forests can decrease flooding during the rainy season and can relieve water shortages during the dry season. An analysis of the factors contributing to water storage of forest soils (Water Utilization Res. Inst., 1983) showed that the first factor is the kind of soil; the second, depositional mode of the soil material; and the third, the kind of substrata, and that volcanic ash soils have the highest scores in each factor (Fig. 1). When both volcanic ash soil and its substratum are very thick, water storage is remarkably enhanced. They can also substantially decrease the amount of flooding because gravitational water supplied by rainfall needs more time to move down through the thick soil and substratum.

Volcanic ash soils commonly contain a large amount of noncrystalline materials which have a large anion exchange capacity and plenty of active Al and Fe as described before. Therefore, they can help maintain and improve the quality of ground water, river water and other water bodies by removing and retaining nitrate and phosphate originating mainly from applied fertilizers. For example, fertilizer phosphorus remaining after crop harvest occurs mostly as sparingly soluble forms in the plowed layer so a large amount of the residual phosphorus is observed in the surface horizon of volcanic ash soils under intensive agriculture. A leaching experiment using soil columns also indicated that an allophanic volcanic ash soil can effectively retain phosphorus in polluted water (concentration: 100 ppm P) until the total amount of retained phosphorus reaches approximately 50% of the phosphorus sorption quotient of the soil (Akiyama *et al.*, 1991).

Volcanic ash soils can retain nitrate by anion exchange reactions. This nitrate is utilized by agricultural plants as exemplified below (Kitamura *et al.*, 1986). As presented in Table 9, a considerable amount of nitrate (70 kg N ha^{-1}) occurred in the subsurface horizons of an allophanic soil before transplant of tobacco plants. The plant absorbed mainly basal fertilizer N in the early growth stage and soil nitrate N in the late growth stage. Though plant recovery of fertilizer N reached greater than 60% at harvest, plant uptake of soil N was more than that of fertilizer N. Soils without positive charges repel anions such as nitrate and chloride. This pheno-

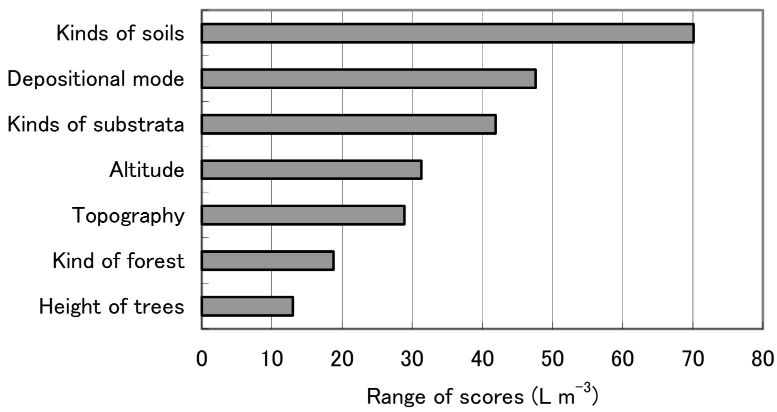


Fig 1 Analysis of factors contributing to water storage of forest soils (Water Utilization Res. Inst., 1983).

Table 9 Mineral N in an allophanic volcanic ash soil and uptake of fertilizer and soil N by tobacco plant (Kitamura *et al.*, 1986).

Date	Mineral N in soil (kg ha^{-1})			Plant N (kg ha^{-1})			Plant recovery of fert. N (%)
	Fert. N	Soil N 0 – 20 cm	Soil N 20 – 100 cm	Fert. N	Soil N	Total	
June 11	95	22	70	8.3	2.4	10.7	6.9
July 4	17	16	67	54.5	14.4	68.9	45.4
July 23	1	6	46	79.6	33.0	112.6	66.3
Aug 31 (harvest)	0.2	1.0	24	74.5	86.8	161.3	62.1

N.B.: Fertilizer application using conventional fertilizers: N; 120, P_2O_5; 240, K_2O; 300 kg ha^{-1}.
Plant recovery of fertilizer N: determined by the tracer method using ^{15}N labeled fertilizer.

menon accelerates the loss of nitrate from the soil system, finally contributing to lowering water quality in the environment.

1.4 Preservation of paleoenvironments and archaeological artifacts

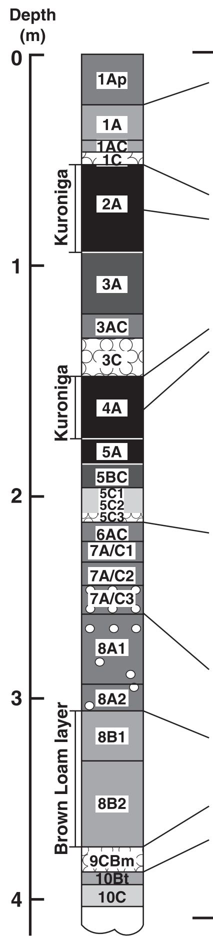
Intermittent volcanic ash deposition and repeated pedogenesis commonly create sedentary multi-storied soils in Japan. For example, the Takko soil in southeastern Aomori Prefecture, Tohoku has a five-storied soil profile formed from Towada Holocene ashes (Saigusa *et al.*, 1978) and the Miyakonojo soil in Miyazaki Prefecture, Kyushu, an eight-storied soil profile from Holocene ashes of several volcanoes (Inoue, 2001). Such sedentary multi-storied volcanic ash soils notably resist soil disturbance, truncation, and displacement due to natural and human activities. Thus they serve as a heritage to preserve in their materials and profiles highly useful information which is integrated over the period of pedogenesis.

Preservation of the soil environment

Soil burial by intermittent ash depositions strikingly reduces the effects of climate and organisms on the buried soils. For example, there occurs notable reduction of diurnal changes in soil temperature and moisture, organic matter supply from the vegetation and microbial activity. Therefore, their weathering rate is significantly lowered, so the soil properties are substantially preserved for several thousands of years after burial as Inoue (2001) has shown by comprehensive studies on the Miyakonojo soil.

The Miyakonojo soil shows a very deep, multi-storied profile formed from repeated volcanic ash depositions ranging from 23,000 to 88 YBP (Fig. 2). It had two intense humus accumulation periods: 6,500 to 4,200 YBP and 4,200 to 500 YBP. The 4A and 2A horizons contain organic carbon concentrations greater than 10%.

All the soil horizons have bulk density values smaller than 0.85 g mL^{-1} and most of them (except the young soil horizons (1,500 YBP) and the lowermost horizon) show phosphate sorption quotients greater



BD	PSQ	OC	HA type	Age
0.81	11.5	43.7	P	← AD 1914
0.84	13.5	31.7	A	
0.72	10.1	19.6	A	
0.76	4.5	4.6	A	AD 1471
0.49	24.9	122.9	A	← AD 1235
0.43	22.7	49.4	A	
0.44	19.9	22.3	A	
0.50	15.7	8.4	A	ca. 4.2 ka
0.45	25.0	110.1	A	← ca. 5.7 ka
0.39	25.7	88.7	A	
0.37	24.8	45.3	A	
0.42	21.4	12.9	B	
0.43	15.9	7.2	B	
0.68	17.1	9.4	A	ca. 6.5 ka
0.53	18.9	23.3	A	
0.62	20.3	47.1	A	
0.67	21.4	35.5	A	ca. 7.5 ka
0.58	19.5	29.6	A	
0.55	22.4	40.4	A	ca. 11.5 ka
0.59	22.5	36.6	A	
0.62	21.5	24.8	A	
0.54	21.0	17.7	A	
0.61	22.4	17.5	B	ca. 23 ka
0.58	21.2	12.5	B	
0.62	14.1	3.5	Rp	

Organic carbon contents (g kg^{-1}) — Very high (200-100) · High (100-50) · Medium (50-30) · Low (30-0)

Tephra — Pumice · Volcanic ash

Fig. 2 Selected properties of Miyakonojo volcanic ash soil (Inoue, 2001).
BD; bulk density (Mg m^{-3}), PSQ; phosphate sorption quotient (g P_2O_5 kg^{-1}), OC; organic carbon (g kg^{-1}), HA type; humic acid type.

than 1500 mg P_2O_5 per 100 g soil (equivalent to phosphate retention of 85%). This fact demonstrates that the buried soil horizons still maintain andic soil properties even after 23,000 years.

Noncrystalline aluminosilicates such as allophane and imogolite, and halloysite are characteristic of clay weathering in volcanic ash soils. The abundance of allophane and imogolite commonly increases with an increase in silica leaching while the abundance of halloysite increases with a decrease in silica leaching or silica enrichment in the soil profile (Saigusa *et al.*, 1978; Parfitt *et al.*, 1984). This is also the case for the Miyakonojo soil which shows a predominance of allophane and imogolite in the surface to the 7A/C2 horizon (7500 YBP) and then increases in halloysite content in the deeper horizons which are subject to silica enrichment.

As the Japanese word "*Kurobokudo*" (meaning "black-flully soil) suggests, volcanic ash soils in Japan generally contain large amounts of very dark organic matter which is dominated by type A humic acid with the highest degree of humification. As presented in Fig. 2, the Miyakonojo soil also shows the existence of type A humic acid in all the humus horizons except the Ap horizon. SOM content of eight humus horizons ranges from 21.2% (OC: 12.3%) to 5.47 % (OC: 3.17%) with a mean value of 11.3% (OC: 6.54%). Most of these horizons meet the melanic color requirement (a color value, moist, and chroma of 2 or less).

Plant opal studies on volcanic ash soils have shown that development of the very dark humus horizons in "*Kurobokudo*" is attributable to grass vegetation induced by human activity since the late Pleistocene (Sase and Hosono, 1996; Sase and Kato, 1976; Sase and Kondo, 1974). Employing plant opal analysis, Inoue (2001) also confirmed the important contribution of gramineous plants to the accumulation of SOM in the Miyakonojo soil. Furthermore, he has indicated that the buried soil horizons still virtually maintain their original organic carbon concentrations. The factors in the high stability of soil organic matter under buried conditions are considered as follows: 1) predominance of type A humic acid, 2) formation of stable Al/Fe-humus complexes, and 3) low soil microbial activity.

Preservation of paleovegetation

As described before, volcanic ash soils in Japan have a very dark humus horizon from which the term "*Kurobokudo*" or "*Ando*" originated and grass vegetation is closely associated with the formation of the dark humus horizons. Since forest vegetation is natural and very common in Japan where a humid-temperate climate prevails, grass vegetation is induced by strong human activity such as fires, grazing, cutting, etc.

Grass vegetation types differ with differences in climatic conditions: *Miscanthus* type in the cool-temperate zone and *Miscanthus* type and *Pleioblastus* type in the warm-temperate zone (Numata, 1974). Therefore, the kind of gramineous plants contributing to the formation of dark humus horizons varies widely with differences in climatic conditions.

Plant opals are highly resistant to chemical weathering under acid soil conditions, so microscopic observation of soil materials is very useful for finding paleovegetation. In addition, the stable carbon isotope ratios of soil organic matter can be employed as indicators of vegetation and climate changes (Bouton, 1996; Yoneyama and Yoshida, 2000).

Figure 3 shows the vertical distribution of dry matter production of gramineae in the Holocene Miyakonojo soil horizons. *Miscanthus* (C_4 plants) is dominant in the 7A/C2 to 8A1 horizons. Then *Pleioblastus sect.* Medake and *Pleioblastus* Nezasa are remarkably increased, especially in the 4A to 5A horizons and 2A to 3A horizons. A tremendous number of plant opals were observed for these humus horizons. For example, 69,000 particles g^{-1} soil of Nezasa and 37,000 particles g^{-1} soil of Medake were counted in the lower part of 4A horizon. The highest dry matter production of each plant is estimated to be more than 300 g kg^{-1} soil. Thus plant opal analysis provides useful information integrated over the period of pedogenesis.

Preservation of archaeological artifacts

Numerous archaeological remains and artifacts have been extensively found in Holocene volcanic ash soils in Japan (for example, Kuwahata and Higashi, 1997; Takahashi *et al.*, 1983). This fact indicates that human activity was remarkably enhanced after the late Pleistocene.

Sedentary multi-storied volcanic ash soils are an excellent artifact preserver and a chronologic indicator with evidences of environmental conditions and human activity. They are clearly different in morphological, physical and chemical properties from archaeological artifacts and human-modified soils. In addition, low bulk density, and friable and nonsticky consistency of the soils are highly helpful in carrying out precisely and efficiently the excavation work.

Multi-storied volcanic ash soils provide a series of termination points for soil development so that archaeological artifacts chronologically occur in the soil profiles as exemplified in the Miyakonojo soil (Kuwahata and Higashi, 1997). In this profile numerous artifacts produced in the late Paleolithic, Jomon, Yayoi and Kofun periods are chronologically observed. The main tools contained in the soil horizons of the Paleolithic period (below approximately 3 m depth) are lithic artifacts. A variety of pottery types are present in the soil horizons of the Jomon to Kofun periods (above 3 m depth).

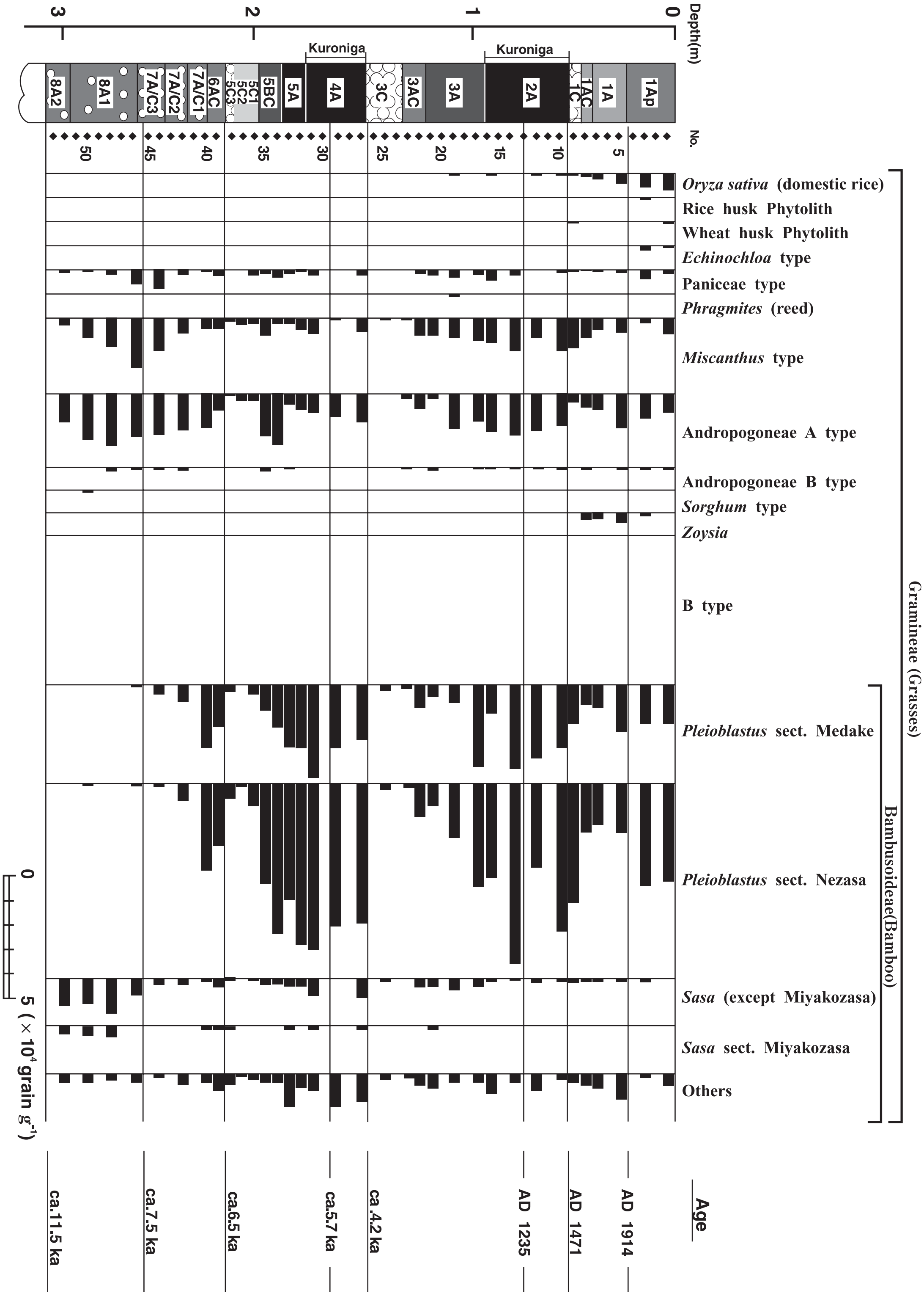


Fig. 3 Plant opal analysis of Miyakonojo volcanic ash soil (Inoue,2001).

2. Utilization of Volcanic Ash Soils and Their Properties Relating to Soil Productivity

2.1 Soil productivity

As reviewed by Shoji *et al.* (1993b), volcanic ash soils are among the most productive soils in the world and that explains why these soils have a high human carrying capacity. In contrast, volcanic ash soils in Japan formed under a humid-temperate climate were originally regarded as poorly productive soils because of very low content of plant-available phosphorus, low concentrations of exchangeable bases and strong acidity (Nomoto, 1958). However, these chemical constraints are easily improved by phosphorus fertilizer application and liming.

Some volcanic ash soils in Japan are especially productive for growing upland crops and their notable properties are summarized by Shoji (1979) as follows:

(1) Parent material: basaltic ash,

(2) Morphology: pachic (thick humus-rich horizon) indicating intermittent ash depositions and repeated pedogenesis,

(3) Physical properties: medium-texture and absence of sharply contrasting textural discontinuities, friable consistency, free drainage, and high plant-available water content, and

(4) Chemical properties: high base saturation, pH (H_2O) > 6.0, absence of toxic Al, accumulation of great amounts of organic matter, and good natural supply of plant nutrients.

Table 10 Vegetables suitable for growth in volcanic ash soils and important soil properties contributing to high quality production at special production localities.

Plants	Special production locality	Important soil properties
Chinese yam	Towada, Aomori Pref.	1. Low bulk density and friable consistency 2. Uniform physical and chemical soil properties
Edible burdock	Mito, Ibaraki Pref.	1. Good drainage 2. Uniform physical and chemical soil properties 3. Absence of toxic Al
Japanese radish, cabbage, and water melon	Miura, Kanagawa Pref.	1. Stable soil structure 2. Friable consistency 3. Fertile soils derived from basaltic tephras
Japanese radish, edible burdock, taro, sweet potato and ginger	Miyazaki Pref.	1. Friable consistency 2. Stable soil structure 3. Abundance of plant-available water 4. Absence of toxic Al

2.2 Utilization of volcanic ash soils

A variety of agricultural crops have been grown on volcanic ash soils : wheat, barley, rice, sweet potatoes, peanuts, vegetables, etc., in the warmer regions, and potatoes, wheat, sugar-beets, various beans, etc., in the cooler regions. However, utilization of volcanic ash soils in Japan has been largely changed with remarkably increased importation of grain crops since the 1970s. Nowadays volcanic ash soils are most extensively used for growing high value horticultural crops and their properties are conducive to development of production localities as exemplified in Table 10.

For example, Chinese yams (*Discoria batatas*) are a glutinous vegetable and Japanese people are very fond of their mashed raw material. High quality Chinese yams show a baseball bat shape that is easily broken. Therefore, excellent soil tilth is essential not only for smooth elongation of the roots but also for easy harvesting. The Towada area in Aomori Prefecture is the largest production center for Chinese yams, which were extensively introduced into this area in the 1970s as shown in Fig. 4. The acreage of Chinese yams reached a high value in the late 1970s and has since remained steady without significant change. The climate is characterized by cool summers for which root crops are well adapted. The major soils of the area are allophanic Melanudands and Hapludands formed from intermittent volcanic ash depositions (Shoji *et al.*, 1993a). The surface to the deep horizons of these soils have uniform physical and chemical properties due to cultivation that are suitable for growing high quality Chinese yam.

2.3 Properties relating to soil productivity

Chemical properties

Nitrogen: Although the percentage of readily mineralizable organic N in the pool of organic N is rather small in volcanic ash soils, these soils often accumulate high concentrations of organic matter that contains appreciable quantities of organic nitrogen. Therefore, volcanic ash soils commonly supply large amounts of mineral nitrogen to crops.

Saito (1990) compared the N mineralization potential (N_o) to the pool of total organic N (N_t) between volcanic ash soils and non-volcanic soils from northeastern Japan and showed that the percentage of mineralizable N (N_o / N_t values) of volcanic ash soils (mean: 3.5%) is less than half that of non-volcanic soils (mean: 8.2%). This suggests that organic N in volcanic ash soils is highly resistant to microbial decomposition. However, a comparison of soil-derived N with the amount of fertilizer N in the plants indicates that the supply of soil-derived N or natural supply of N is very important even for plants grown under heavy N fertilization: the soil-derived N absorbed by several agricultural crops (corn, sorghum, winter wheat, sugar beets and tobacco) grown on volcanic ash soils amounted to 62 – 101 kg N ha^{-1} (Shoji *et al.*, 1993b).

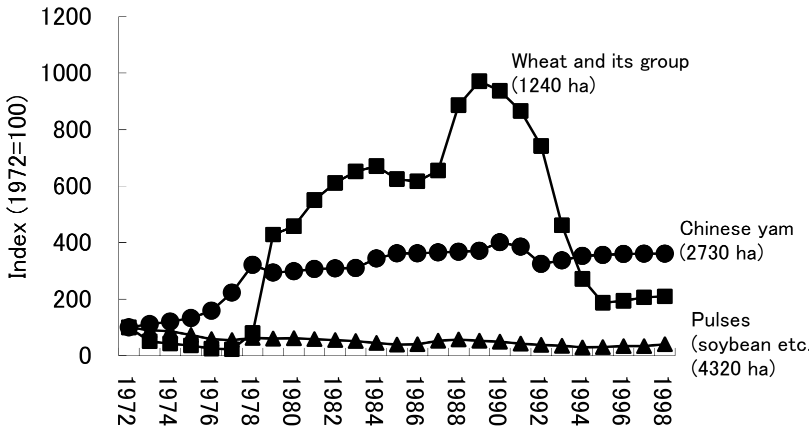


Fig. 4 Changes in acreage of upland crops in Aomori Prefecture (from the statistical data of the Ministry of Agriculture, Forestry and Fisheries, Japan).

Nitrogen is required in large quantities by most agricultural plants throughout their growth period. The use of N fertilizer has dramatically increased yields of agricultural plants, but recovery of N from ordinary fertilizer sources such as urea and ammonium sulfate by plants is generally not high. Inorganic forms of N, mainly nitrate-N, occur in the subsurface horizons of volcanic ash soils used for upland crops. The inorganic pool of N can significantly contribute not only to the yield of upland crops, but also to pollution of surface and ground water by leaching. Excess uptake of N especially in the later growth stages causes deterioration in the quality of the harvest. To resolve these problems, nowadays we can select the precision agricultural methods using controlled release fertilizers as discussed later.

Phosphorus: Phosphorus is often the growth-determining nutrient element for agricultural crops on recently reclaimed volcanic ash soils because its supply is often very low. The element is strongly sorbed by noncrystalline aluminum and iron materials, making it sparingly available for plant uptake.

Fresh volcanic ash contains a certain amount of phosphorus that is readily soluble in acid solutions. For example, fresh volcanic ash samples from Tohoku and Hokkaido contain total phosphorus ranging from 0.07 to 0.28% as P_2O_5 (average: 0.15%) (Nanzyo *et al.*, 1997). Apatite appears to be the primary phosphorus-bearing mineral and is fairly soluble in acid solutions contributing to rapid revegetation on volcanic ash deposits (Nakamaru *et al.*, 2000). Thus, phosphorus is not always a limiting nutrient element in revegetation of ash-covered lands, as mentioned earlier, contrasting with the fact that many crops suffer from severe phosphorus deficiency when they are grown on newly reclaimed volcanic ash soils.

Plants can absorb soluble phosphorus and weakly bound forms of phosphorus. Applied phosphorus readily reacts with weathering products of volcanic ashes such as noncrystalline aluminum and iron materials, resulting in the formation of insoluble metal-phosphorus compounds. According to a kinetic study of chemical weathering in young volcanic ash soils with udic soil moisture regimes from northeastern Japan (Shoji *et al.*, 1993c), it was predicted that only a few hundred years is required to form soils with acid oxalate extractable Al + Fe/2 $\geq$ of 0.4% and P retention $>$ 25%. Thus, most agricultural plants grown even on young volcanic ash soils show phosphorus deficiencies. Farming of these volcanic ash soils requires heavy application of phosphorus fertilizers to obtain optimum crop yields.

Not only low phosphorus supply, but also strong aluminum toxicity and low base saturation are common limitations for crop production in nonallophanic volcanic ash soils. Liming prior to phosphorus application is recommended for these soils. Recovery of fertilizer phosphorus by agricultural plants in volcanic ash soils commonly is less than 20%. Band placement of phosphorus fertilizer instead of broadcasting is commonly practiced in order to avoid the rapid chemical reaction of phosphate with active Al and Fe compounds that results in a decrease of phosphorus availability. In addition, *co-situs* application of controlled release fertilizers has been encouraged (Shoji and Gandeza, 1992).

Potassium: Potassium along with nitrogen and phosphorus is one of the major nutrient elements required in large quantities by plants. Potassium is present in considerable amounts in fresh volcanic ashes; total potassium ranging from 0.5 to 4.0% as K_2O (Shoji *et al.*, 1975). Thus, a 10 cm depth of volcanic ash contains a large amount of potassium ranging from 7.5 to 60 Mg per ha as K_2O, assuming a bulk density of 1.5 g cm^{-3}. However, the available forms of potassium are often insufficient for continuous cropping, especially under humid climatic conditions.

The potassium supply of volcanic ash soils is strongly governed by the content of K in volcanic ash and soil clay mineralogy. It is low in the soils formed from basaltic ash due to the low content found in basalt. It is also strongly determined by whether weathering reactions lead to the formation of non-allophanic or allophanic soils. Potassium is largely retained by 2:1 layer silicates in nonallophanic soils and tends to accumulate with advance of weathering. In contrast allophanic clays do not show preferential retention of K, so the amount of K tends to decrease with the advance of weathering.

Application of potassium fertilizers influences contents of exchangeable potassium in volcanic ash soils. Continuous heavy applications of potassium have remarkably increased the exchangeable potassium levels in cultivated volcanic ash soils of Japan. The content differs widely and only a small number of volcanic ash soils show values less than 0.3 $cmol_c\ kg^{-1}$ which is the critical level for potassium deficiency in many agricultural plants.

Micronutrients: Several deficiencies of various micronutrients in volcanic ash soils have been reported. The most prevalent among them are Cu, Zn and Co. The abundance and availability of these micronutrients in volcanic ash soils are dependent on the abundance of the elements in the volcanic ash and on their release rates by chemical weathering (Shoji *et al.*, 1993b). For estimating their plant availability, chemical soil tests are usually used. The major categories of micronutrient extractants are dilute acids (e.g. 0.01 M HCl) and/or solutions containing chelating agents (e.g. EDTA).

Soil acidity: It was commonly considered earlier that there were few volcanic ash soils which had more than traces of KCl-extractable Al and pH values less than 5.2, even though their base saturation was well below 10% (Smith, 1978). This concept was completely altered by the discovery of nonallophanic volcanic ash soils in northeastern Japan that have a clay fraction dominated by 2:1 minerals, strong to very strong acidity, and the presence of large amounts of KCl-extractable Al (Shoji and Ono, 1978). In contrast with allophanic soils, nonallophanic volcanic soils cause serious acid injury or aluminum toxicity to plant roots. Even when the base saturation of allophanic volcanic ash soils is very low, they rarely have pH values less than 5 and few of these soils experience aluminum toxicity problems. However, some plants grown on such soils show retarded growth due to Ca deficiency.

One of the most effective ways of overcoming the factors limiting plant growth in acidic volcanic ash soils is lime application. This practice is rather easy if the objective is only to improve the acidity of surface soil. However, it is very difficult to improve subsoil acidity by liming because lime has such limited solubility that it reacts only in the surface soils. The subsoil substantially influences plant growth and yield because of its storage of large amounts of water and plant nutrients, so strongly acidic subsoil poses a limitation to crop performance. To improve subsoil acidity, surface application of gypsum or phosphogypsum is recommended because these chemical compounds have higher solubility compared with lime and its Ca and sulfate can move down to the subsoil (Saigusa *et al.*, 1994).

On the other hand, it is worth noticing that nonallophanic volcanic ash soils are regarded as a suppressive soil because the exchangeable or soluble Al can control some soil-borne diseases of crops such as common bean root rot (by *Fusarium solani* f. sp. *phaseoli*; Furuya *et al.*, 1979) and potato common scab (by *Streptomyces scabies*; Mizuno and Yoshida, 1993). Thus common bean farming in the Kitami district, Hokkaido, is adapted for that soil condition: the plant is grown at the concentration of toxic soil Al that is low enough so that phytotoxicity does not occur and high enough to ensure that the disease incidence is kept within limits (Furuya *et al.*, 1999). For potato farming, single basal application of ammonium sulfate to each tuber planting row is recommended. This application can efficiently lower the soil pH and increase the concentration of water soluble Al to suppress potato common scab (Mizuno *et al.*, 2000).

Physical properties

Most volcanic ash soils have excellent physical properties such as high water-holding capacity, favorable tilth, and strong resistance to water erosion. These properties contribute to enhancing the productivity of volcanic ash soils as shown in Table 10.

Development of aggregates in volcanic ash soils is closely related to the retention of large amounts of plant-available water. Young volcanic ash soils have a greater amount of macropores larger than 100 μm in diameter and a lesser amount of micropores (< 0.4 μm) and mesopores (0.4 – 6.0 μm). In contrast, moderately weathered volcanic ash soils have a large amount of micropores (< 0.4 μm) and mesopores (0.4 – 6.0 μm), contributing to the large plant-available water holding capacity (Furuhata and Hayashi, 1980). An unusually high amount of micropores in allophanic volcanic ash soils is attributable to the intra- and inter-particle pores of allophane (Wada, 1989).

Tilth is the physical condition of a soil related to its ease of tillage, fitness as a seed-bed, and its suitability for seedling emergence and root elongation. Most volcanic ash soils show excellent tilth. Cultivation of volcanic ash soils with low bulk density and friable consistency requires less energy and can easily produce favorable seed- and root beds. Volcanic ash soils show strong resistance to compaction even when they are intensively used for upland farming for a long time period. This indicates that the aggregates of these soils are highly stable, being cemented by noncrystalline materials and soil organic matter.

Water erosion often drastically diminishes the productivity of a soil. In general, volcanic ash soils show a strong resistance to water erosion. The related factors include rapid infiltration that reduces runoff and strong resistance to dispersion of soil aggregates. The rapid infiltration rate is determined by the content of macropores, the water permeability of the soil profile, and the water content of the soil. Most volcanic ash soils have large amounts of macropores and are highly permeable. Microaggregates in volcanic ash soils show strong resistance to dispersion.

3. Sustaining Volcanic Ash Soils

Volcanic ash soils in Japan are mostly utilized for upland farming, and various farming practices are employed to enhance agricultural production. However, unsuitable management, especially for intensive upland farming, often results in an unbalance of plant nutrients in the soils, decrease of soil organic matter crucial to overall soil quality, degradation of soil structures, and increased populations of soil borne diseases and nematodes. In order to solve these problems and to sustain volcanic soils, crop rotation, soil improvement, and precision agriculture with programmed fertilization using controlled fertilizers are encouraged.

Recommended rotations for crops with high economic advantages also include crops useful for controlling soil-borne diseases and nematodes, and gramineous crops to contribute to enhancing soil organic matter and biodiversity. As plant-available soil phosphorus and efficiency of phosphorus use are generally low in volcanic ash soils, heavy phosphorus application is commonly practiced by Japanese farmers so residual fertilizer phosphorus is notably increased. In order to efficiently use this phosphorus, crops that have strong symbiotic interactions with arbuscular mycorrizha are encouraged to be included in cropping systems.

Volcanic ash soils commonly show multi-storied profiles formed from different ashes. Some of them have soil horizons strongly inhibiting plant root development. Examples include a pumice or scoria derived soil horizon and an extremely weathered soil horizon. Soil improvement by deep cultivation and soil mixing, and liming and phosphorus application are most useful for enhancing soil productivity. Volcanic ash soils also show spatial variability in various respects, so precision agriculture is highly useful. On the other hand, programmed fertilization using controlled release fertilizers with high performance is most practical, especially for intensive agriculture on small-scale fields.

3.1 Crop rotations

It is well known that crop rotation has various contributing factors such as increased soil nutrient availability, development of favorable soil structures, improvement of soil water availability, enhanced biodiversity, weed control, and mitigation of damage from soil born diseases, nematodes, etc. Thus, use of crop rotation was repeatedly recommended to farmers. However, traditional crop rotation in Japan has been largely abandoned because of extensive availability of chemical fertilizers and agrochemicals since the 1960s.

Volcanic ash soils are one of two major agricultural soil groups in Japan and are mostly used for upland farming, which has notably changed with the drastic changes in the Japanese economic structure since the 1970s. The importation of grain crops has remarkably increased and their acreage in Japan has drastically decreased. It was in such an environment that high-value crops or horticultural crops were extensively introduced to volcanic ash soil areas.

Recently increasing impacts of intensive agriculture on the environment and safety of agricultural products have aroused a strong interest in the evaluation and reintroduction of crop rotation among agronomists and farmers. Thus, various crop rotation systems have been proposed and recommended in different areas as exemplified below. They involve a limited number of leading crops with high economic advantages and make full use of the excellent properties of volcanic ash soils such as friablility and non-sticky consistency, easy tillage, good aeration and drainage, high water-holding capacity, and absence of toxic Al. It is worth noticing that high-value root crops are extensively selected as leading crops because they are suitable for preservation and long-distance transportation, and are preferentially grown as specialties indigenous to volcanic ash soils in each area.

Southern Tokachi Subprefecture, Hokkaido

The volcanic ash soils in this area are mostly Brown and Ordinary Andosols with medium soil texture (Tomioka, 1985). They have multi-storied horizons formed from several Holocene volcanic ashes and were originally very low in plant available phosphorus. Therefore, phosphorus fertilizer has been heavily applied.

Most farmers of this area have practiced intensive agriculture to produce high quality potatoes and beans, and sugar beets which are protected by a government production program. However, use of agrochemicals to control soil-borne diseases and nematodes is mostly limited, so the farmers are encouraged to introduce crop rotation such as 4-year rotation of sugar beets – beans – winter wheat – potatoes (Extension Center for Agricultural Improvement in Southern Tokachi Subprefecture, 2001). This system can effectively control root-knot nematodes but is poor at checking root-rotting nematodes. Thus, including wild oats instead of winter wheat is recommended.

Recently, root crops such as Chinese yams, edible burdock, radish and carrots have been recommended to be included in the rotation systems. However, they also need cropping sequences to control nematode populations.

Eastern area of Aomori Prefecture

Volcanic ash soils with thick dark humus horizons in this district (Shoji *et al.*, 1993b) are extensively used to produce high quality Chinese yams (Department of Agriculture, Forestry and Fisheries, Aomori Prefecture, 2002). They are multi-storied soils formed from five Holocene ashes from the Towada caldera and have allophanic clay mineralogy and excellent physical properties useful for growing root crops as already described. Uniform physical and chemical properties from the surface to the deep horizons (0 – 110 cm) attained by deep cultivation are required for high quality Chinese yam farming.

Chinese yams are the leading crop with high economical advantages in this area (Fig. 4), but they are susceptible to a root-rotting disease, seriously reducing the yield and quality as shown in Table 11. This disease is easily caused by continuous monoculture of the plant so crop rotation is strongly encouraged. Involvement of high value root crops such as garlic, Welsh onion and Sudax in the rotation sequences can completely control the root-rotting disease. On the other hand, soil sterilization using chloropicrin is not as effective as crop rotation in controlling the disease.

Southern Miyazaki Prefecture

As already described, volcanic ash soils in this area are multi-storied soils with thick humus horizons (Inoue, 2001) and have properties suitable for raising highly economical root crops such as sweet potatoes, edible burdock and radishes. These leading crops are very resistant to typhoons and water stress but are badly damaged by plant parasitic nematodes. Since many chemical nematocides are no longer available, a cropping system to effectively control nematode populations is the key technology for maintaining the production of high quality root crops. For this purpose, a desirable cropping sequence has been proposed as follows (Mochida, 2002): Sweet potatoes – root crops (radishes, edible burdock, carrots, etc.) – gramineous plants for feed. The gramineous plants also serve as cleaning and anti-nematic plants.

There are some recommended crop rotation sequences and their evaluations in this area. Of these systems two systems are shown in Table 12 (Miyakojo Council of Rational Fertilization and Prevention of Harmful Insects and Diseases, 2001). For example, System 1, involving sweet potatoes as the leading crop is helpful for improving soil physical and chemical properties. However, this system is likely to be damaged by soil-borne diseases and nematodes because it repeats sweet potato cultivation three times for 4 years and involves other crops sensitive to nematodes. System 6 lacks continuous monoculture and includes anti-nematic plants such as peanuts. Thus it can effectively control both soil-borne diseases and nematodes. However, edible burdock, taro and Welsh onions need heavy fertilization, probably resulting in water pollution.

Table 11 Crop rotation of Chinese yams to control root-rotting disease (Aomori Upland and Horticultural Crops Exp. Sta., 1995).

Cropping system		Experiment year						
		1st	2nd	3rd	4th	5th	6th	7th
Rotation 1	Crop	CY	CY	CY	WO	S/G	G/S	CY
	Disease attacked (%)	0	0	21.8				0
Rotation 5	Crop	S/G	G/S	CY	CY	S/G	G/S	CY
	Disease attacked (%)			0	0			0
Monoculture	Crop	CY	CY	CY	CY	CY*	CY*	CY
	Disease attacked (%)	0	0	2.5	40.0	16.5	11.0	97.5

Planted crops. CY: Chinese yams, WO: Welsch onions, G: garlic, S: Sudax (plowed into the surface soil). *Soil sterilization using chloropicrin before planting.

Table 12 Four-year crop rotation systems and their evaluations (Miyakonojo Council of Rational Fertilization and Prevention of Insects and Pests, 2001).

System	1st year	2nd year	3rd year	4th year
1	SP	SP	OT	RD
	IR	WO		SP
6	EB		WO	PN
		TR		IR

Recommended crops: SP = sweet potatoes, IR = Italian rye, WO = Welsh onions, OT = oats, RD = radishes, EB = edible burdock, TR = taro, PN = peanuts.

Crop rotation efficiently utilizing soil phosphorus

Volcanic ash soils generally contain large amounts of active Al and Fe that easily react with phosphorus to form poor soluble chemical compounds. Therefore, fertilizer efficiency of phosphorus use by plants grown on these soils is very low, so heavy doses of phosphorus fertilizer are commonly applied by many farmers. Consequently, remarkable accumulation of residual phosphorus occurs in the surface horizon of volcanic ash soils, so a cropping system to efficiently utilize soil phosphorus is eagerly desired.

There are two ways of using cropping systems to efficiently enhance plant uptake of poor soluble soil phosphorus. One is to involve plants in the system that can exude organic acids from their roots to dissolve soil phosphorus. Chickpeas, buckwheat, pigeonpeas, peanuts and rice belong to this plant group (Arihara, 1999). The other is to include plants that can have symbiotic interactions with arbuscular mycorrhiza (AM), promoting plant uptake of the soil phosphorus (Arihara and Karasawa, 2000; Karasawa and Arihara, 2000). This contribution of AM has been shown by the fact that there are close positive linear correlations between AM colonization and phosphorus uptake of maize and between phosphorus uptake and growth of maize raised in a volcanic ash soil (Arihara and Karasawa, 2000; Karasawa and Arihara, 2000).

As presented in Fig. 5, the grain yields of the succeeding maize are remarkably influenced by the kinds of the previous crops at both phosphorus-applied and non-phosphorus plots. For example, the grain yields of maize after sunflower are approximately three-fold at the phosphorus applied plot and six-fold at the non-phosphorus plot compared with those of maize after rape. The effect of previous crops to the growth and yield of succeeding crops is considered as follows: the previous crops enhance AM population in the soil helping increase AM colonization of the succeeding crops. The increased AM colonization enables the succeeding crops to uptake more soil phosphorus and thereby promotes their growth and yields.

3.2 Soil improvement

As described by M. Nanzyo, there are many physical, chemical and mineralogical characteristics indigenous to volcanic ash soils. Some of them contribute to important constraints on plant growth while others are useful for enhancing soil productivity. Selected topics are described here (Shoji *et al.*, 1993b).

Amelioration

The surface horizons of Japanese volcanic ash soils formed under a humid climate are divided into allophanic and nonallophanic groups according to clay mineralogy. The allophanic surface horizons have allophane-imogolite and Al/Fe humus complexes as major components of the clay fraction while the nonallophanic surface horizons have Al/Fe humus complexes and 2:1 layer silicates. Thus both groups contain large amounts of active Al and Fe so soil phosphorus fertility and plant use efficiency of phosphorus fertilizer are very low. In order to improve this problem, initial application of a large amount of phosphorus fertilizer by broadcasting and then yearly application of phosphorus fertilizer by banding are commonly practiced.

Allophanic surface horizons originally contain a small amount of exchangeable Ca ions reflecting strong leaching so it needs liming to supply Ca ions to the plant. On the other hand, the nonallophanic surface horizon has a substantial amount of exchangeable Al ions or toxic Al which may damage plant roots. Thus liming is necessary to mitigate toxic Al damage to the plant roots.

Subsoil improvement

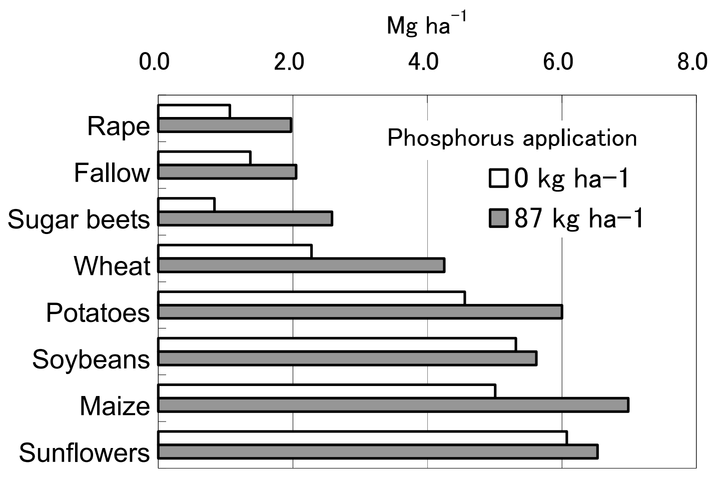


Fig. 5 Effect of cultivation of crops in 1990 on grain yields of succeeding maize in 1991 (Arihara and Karasawa, 2000).

Volcanic ash soils are generally formed from repeated volcanic ash falls. Therefore, it is not uncommon that their multi-storied horizons have notably different properties and some subsurface horizons show serious constraints on plant growth. Such subsurface horizon soils to the depth of approximately 1 m are improved as described below.

Soil horizon sequences to the depth of 1 m and improvement of problem horizons are summarized as follows (Kikuchi, 1987; Kubotera, 2001):

1. Ap horizon – very coarse textured soil – medium textured soil with high humus content.
   The second horizon is commonly formed from pumice or scoria and is less weathered. The countermeasure for this soil profile is to cultivate to the third horizon and mix the three horizons.

2. Ap horizon – medium- or fine-textured soil with a large amount of very active Al and Fe.
   The second horizon is most weathered and is very low in soil fertility. The countermeasure for this soil profile is to apply amendments such as fused phosphate, superphosphate and gypsum to the upper part of the second horizon without mixing them with the Ap horizon.

3. Ap horizon – indurated soil with a low degree of weathering – medium- or fine-textured soil.
   The second horizon has serious constraints such as inhibition of plant root elongation, difficult cultivation, and poor water permeability. The countermeasure is mechanical breaking or removal of the indurated horizon.

4. Ap horizon – medium or fine textured soil with high soil fertility.
   The second horizon includes not only volcanic ash soil but also alluvial soil. Deep cultivation (plowing) and mixing the Ap and second horizons can remarkably enhance soil productivity.

Conservation tillage

No-tillage has important conservation advantages such as minimum erosion, soil moisture conservation, and minimum fuel and labor costs. It can be easily introduced to upland farming of volcanic ash soils because they have a friable, nonsticky consistency, large total porosity, and strong resistance to consolidation by mechanical pressure.

In no-tillage the soil is left undisturbed and only furrows for planting and fertilization are prepared. When controlled release fertilizer is applied, single basal application with co-situs placement can be employed and can increase nutrient use efficiency and yields of crops (Inoue *et al.*, 2000).

3.3 Precision agriculture and programmed fertilization using CRFs

Spatial variability of volcanic ash soils and precision agriculture

Spatial variability of volcanic ash soils is strongly determined by repeated depositions, dispersal patterns, texture, and thickness of the volcanic ashes and mineralogy of the volcanic ash soils (Shoji *et al.*, 1993a). For example, the dispersal patterns of volcanic ash are highly dependent upon high altitude winds (commonly westerly in the middle and high latitudes), the violence of the volcanic eruptions, and type of volcanic ejecta. Volcanic materials blown by volcanic explosions commonly fall predominantly east of the volcanoes. Volcanic ash deposits show lateral and vertical variations in their texture and mineralogy. The largest and heaviest particles tend to fall nearest the volcanoes, while smaller and lighter particles fall at increasing distances. Such volcanic ash depositions are closely related to the spatial variability of volcanic ash soils. For example, vitric soils nearest to the volcano, haplic soils in intermediate areas, and melanic soils farthest from the volcano as described for the Towada volcanic ash soils (Shoji *et al.*, 1993a). Wetness of volcanic ash soils also contributes greatly to the accumulation of soil organic matter (SOM): low SOM content at dry sites and high SOM content at wet sites. Thus there are notable differences in the natural N supply and amount of plant-available water between the two areas.

Precision agriculture will be attractive for site specific management of large-scale fields of volcanic ash soils with high spatial variability. It is useful for balancing nutrient supply and demand, and for managing pesticides, water and tillage. The precise amount of fertilizer and other agricultural inputs can be determined by employing combined geographical information and global positioning systems (GIS–GPS), and applied to the fields by computer-controlled machinery.

Site-specific management of phosphorus and potassium will be more accurate in volcanic ash soils, because the testing for plant-available forms of these elements is reasonably reliable. However, testing for plant-available nitrogen is highly difficult because the natural nitrogen supply contains both mineralized nitrogen and mineral nitrogen and is considerably changeable. Therefore, programmed fertilization using high performance controlled-release fertilizers will be very helpful for intensive agriculture on volcanic ash soils.

Programmed fertilization using controlled release fertilizer (CRFs)

Nitrogen is a fertilizer element that most strongly determines yield, quality and safety of crops more than any other element. However, this element also contributes greatly to environmental degradation if applied excessively or improperly. Thus programmed fertilization using high performance controlled release N fertilizer can efficiently enhance the beneficial effects and improve the defects of nitrogen fertilization.

Recently, the total production of nitrogen fertilizers in Japan has decreased: the production in 2000 was 90.0% of that in 1995. In contrast, the production of coated nitrogen fertilizer (mainly polymer-coated urea) has been on a continuously increasing trend since 1983 and the ratio of 2000/1995 production is 136.8% (Nihon Kaseihiryo Kyokai, 2002). It is well known in Japan that coated nitrogen fertilizers have contributed to development of new agro-technologies for intensive agriculture.

A variety of controlled-release nitrogen fertilizers are marketed in Japan (Koshino, 2001). However, thermoplastic polyolefin-coated fertilizers (POCFs) such as the polyolefin coated urea named "MEISTER" appear to be the best from the viewpoint of accuracy of controlled release. They include two groups of release patterns: linear and sigmoidal as shown in Fig. 6. By selecting suitable formulations, it is easy to design fertilization programs that best meet the nitrogen demand of various crops. The release of the nutrient elements in POCFs is primarily determined by temperature, so their release patterns can be easily obtained by computer simulation (Shoji and Takahashi, 1999).

Programmed fertilization and single basal application

Conventional nitrogen fertilizers mostly show short duration of nitrogen supply under humid climate and paddy conditions, and low nitrogen use efficiency. Thus, split application is commonly practiced to improve these drawbacks. On the other hand, correctly programmed fertilization using CRFs is conducted by single basal application for most crops in Japan.

For example, paddy rice has two peaks of nitrogen demand: one comes at the intense tillering stage early in the growing season and the other, at the young panicle formation stage in the mid growing season. As presented in Fig 7, computer simulation can select a short linear formulation of POC urea (MEISTER) for the first peak, and a long sigmoidal formulation of POC urea (MEISTER) for the second peak. If there is a need to realize rapid establishment and good early growth for transplanted paddy rice, it is recommended to apply basally a blend including a conventional fertilizer and two CRFs (a short linear formulation and a long sigmoidal formulation). Single basal application using CRF blends is extensively practiced for many crops even if their growing season is very long. For example, the recommended N fertilization for tea plants in Kumamoto Prefecture is eight split applications using conventional N fertilizers and the total amount of applied N is 700 kg per ha per year. In contrast the innovative fertilization uses a blend of polyolefin-coated urea formulations (a short linear formulation and three long sigmoidal formulations of MEISTER) and is practiced by one-time application in early September as shown in Fig. 8. It can continuously supply N to tea plants to enhance the quality and yield of tea leaves and can significantly increase N use efficiency. Therefore, its N rate is considerably reduced compared with the conventional N rate, contributing to control of fertilizer pollution (Shoji and Higashi, 1999).

Best site placement

Since CRFs can continuously supply crops with nutrient elements little by little, meeting crops' nutrient demands, they can be placed by one application to the best site in the soil without the danger of fertilizer

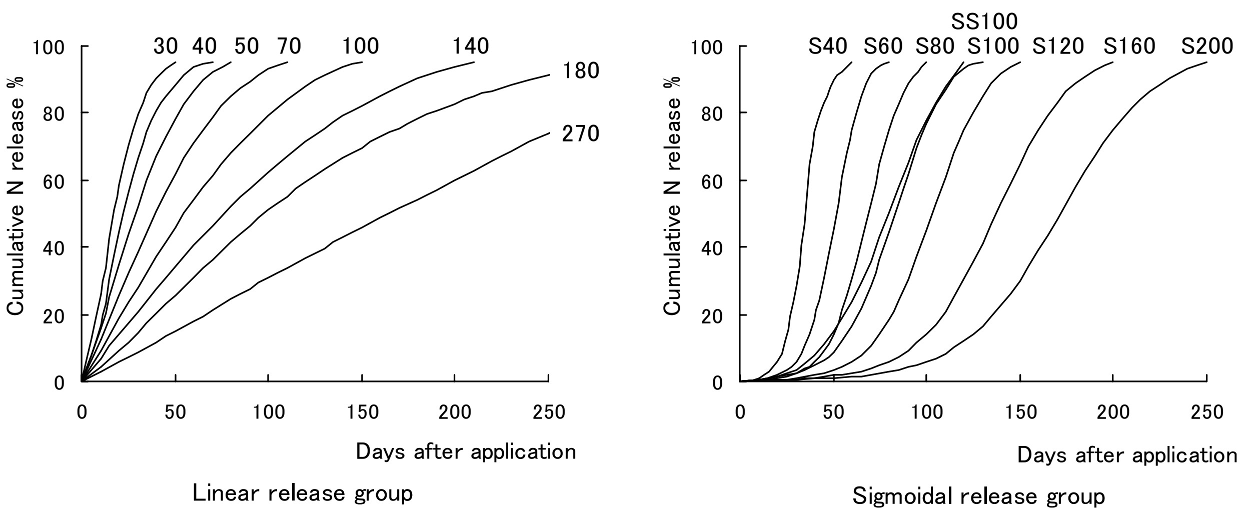


Fig. 6 Nitrogen release from polyolefin coated urea (international name: MEISTER; domestic name: LP-cote) in water at 25°C (courtesy of Chisso Corporation, 2002).
N.B.: Both groups have many formulations described using numbers. Each number shows number of days required to release 80% of the nutrient content.

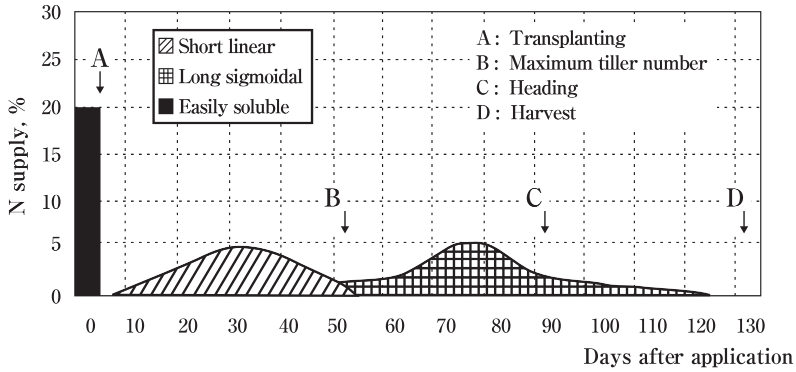
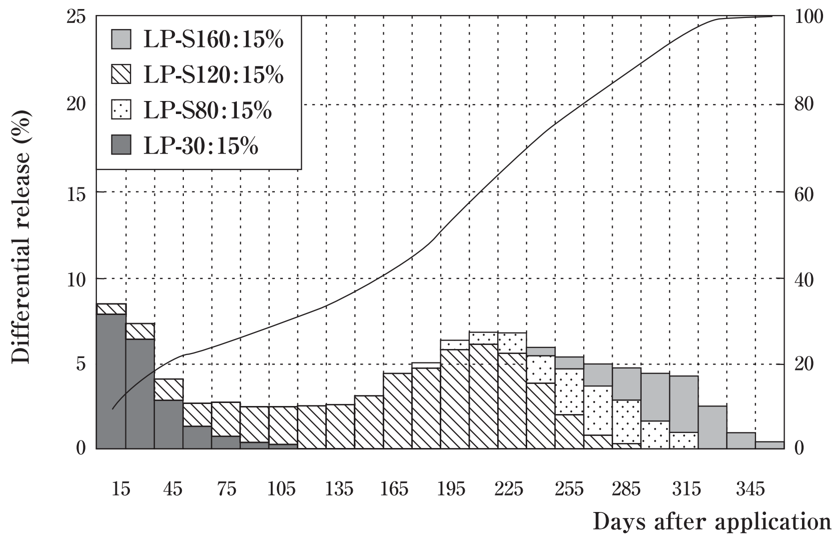


Fig. 7 Conceptual presentation of the N supply pattern of programmed fertilization of paddy rice by single basal application.
N.B.: easily soluble N, 20%; short linear MEISTER N, 40%; long sigmoidal MEISTER N, 40%.



Month	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.

Fig. 8 Nitrogen supply pattern of a polyolefin coated urea (MEISTER) blend for tea plants in Kumamoto Prefecture. Time of application was September 1 (courtesy of Chisso Corporation, 2002).
N.B.: Nitrogen supply is maximized in the early spring and early autumn to enhance the yield and quality of tea leaves.

injury to the crops. One example is single basal nursery fertilization of paddy rice that employs a sigmoidal polyolefin coated urea called "Naebako-makase" (a special formulation of MEISTER). It can supply fertilizer N meeting the plants needs during the whole growing season. This unique fertilization method developed by Kaneta *et al.* (1994) is called "co-situs sheet placement" by which all the N fertilizer "Naebako-makase" is applied on or beneath the rice seed layer in a nursery box. It could increase nitrogen use efficiency by approximately 100% compared to conventional nitrogen use efficiency (N use efficiency by innovative fertilization is 80%). The innovative fertilization proposed by Kaneta *et al.* (1994) has notably stimulated the creation of new fertilization methods for other crops as well in Japan.

Innovative agro-technologies and their contributions to improving the agro-environment

Various agro-technologies have been developed by making effective use of high quality CRFs. They include no-till transplanting culture with single basal nursery fertilization, no-till direct seeding crop culture by single basal fertilization, single basal fertilization by deep placement for soybeans, and multiple plantings of horticultural crops by one-time fertilization. The new agro-technologies using CRFs can contribute greatly to mitigation of water, atmospheric and biological environmental problems related to intensive agriculture (Shoji and Minami, 2002).

The advantages of high performance polymer-coated N fertilizers useful for intensive agriculture are summarized as follows:

1) The release control is highly accurate and computer simulated as a function of temperature, enabling preparation of rational fertilization programs,

2) Polyolefin coated urea contains 40% or more N and has a variety of linear and sigmoidal formulations, being most suitable to production of favorable blended fertilizers.

3) Single basal application can be practiced by best site placement even for multiple plantings,

4) Nitrogen use efficiency can be remarkably enhanced by innovative fertilization. Environmental degradation due to intensive fertilizer application can be minimized by maximizing fertilizer efficiency (Shoji and Minami, 2002), and

5) Enhancing the quality and safety of farm products by adjusting the N rate and ratio of mineral forms: decreasing the concentrations of nitrate and oxalic acid and increasing the concentrations of sugars, amino acids and ascorbic acid in some horticultural plants (Shoji and Higashi, 1999).

As already described, nowadays volcanic ash soils in Japan are mostly utilized for intensive horticultural cropping, so innovative agro-technologies using high performance CRFs are highly useful for sustaining the volcanic ash soils.

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