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EVALUATION AND PROPOSED REVISIONS OF CRITERIA FOR ANDOSOLS IN THE WORLD REFERENCE BASE FOR SOIL RESOURCES

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The proposed criteria for Andosol classification in the World Reference Base (WRB) of Soil Resources were evaluated using the Tohoku University World Andosol Database (TUWAD). The WRB proposal defines a diagnostic andic horizon comprised of vitr-andic, alu-andic, and sil-andic subtypes, and eight second level soil units. Several notable refinements to the WRB criteria were apparent from evaluation of soil properties from TUWAD and are proposed as revised criteria. Our analysis indicated that the most effective criteria for differentiating the andic horizon were glass content, phosphate retention, oxalate extractable Al and Fe, pyrophosphate-extractable Al, and bulk density. The vitr-andic horizon is distinguished by its low degree of weathering, evident from its low oxalate extractable Al and Fe, low P retention, and high glass content. The ratio of pyrophosphate to oxalate extractable Al is used to separate andic horizons dominated by Al-humus complexes (alu-andic, $Al_p/Al_o \geq 0.5$), from those dominated by allophanic materials (sil-andic, $Al_p/Al_o < 0.5$). When Al_p data are not available, the Si_o value of 0.6 could be used as an approximate criteria. We also propose revisions to the nine second level soil units based on the dominant pedogenic processes occurring in Andosols: noncrystalline material formation and organic matter accumulation. These soil units are based on the degree of weathering (oxalate extractable Al, Fe, glass content), the dominant weathering agent (organic acids vs. carbonic acid), type (melanic or fulvic) and quantity of organic matter, and high 1.5 MPa water-holding capacity. The revised criteria determined by this study effectively differentiate Andosols based on their dominant pedogenic processes, and the relationship of soil properties to productivity and utilization.

The World Reference Base for Soil Resources (WRB) has been under development for the past 15 years with the stated objectives of providing an international system for common soil classification and to identify and assess global soil resources (Spaargaren 1994). The WRB classification system is designed to provide a basis for better correlation between national systems of soil classification. It incorporates the most recent pedological information within a sound scientific framework to enhance transfer of pedological data to related fields, such as agriculture, geology, hydrology, and ecology.

The basic framework of the proposed classification consists of two categorical levels and guidelines for developing classes at a third level (Spaargaren 1994). The current proposal contains 30 major soil groups differentiated by the primary pedogenic processes responsible for the characteristic soil features, except where special soil parent materials are of overriding importance. Classes at the second categorical level are differentiated according to predominant secondary soil forming processes that significantly affect the primary soil features or by soil-characteristics that have a significant effect on management and use. Morpho-

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logical properties, rather than chemical properties, are stressed in the development of diagnostic properties to facilitate field identification. The classification avoids the use of climatic characteristics to minimize the number of classes and to eliminate the need for long-term climatic data which are not always readily available or reliable.

Andosols are proposed as a major soil group based on the unique properties of their colloidal fraction originating primarily from formation in recent volcanic ejecta. Andosols are distinguished by the occurrence of a diagnostic *andic horizon* that has properties dominated by the presence of volcanic glass, or short-range-order minerals and/or immobile humus-sesquioxide complexes. Based on these mineralogical and colloidal properties, three subtypes of andic horizons are distinguished:

1) vitr-andic, dominated by volcanic glass and other primary minerals,
2) sil-andic, dominated by allophane and similar poorly crystalline secondary aluminosilicate materials, and
3) alu-andic, dominated by aluminum complexed by organic acids.

Eight second order classes or soil units are proposed based on soil properties that have a significant effect on management and use. Third level modifiers will be adopted to indicate important secondary soil properties and the presence of other diagnostic or buried horizons.

Since the diagnostic criteria for andic horizons and the proposed soil units have not been rigorously tested with field data, the appropriateness of the proposed criteria has not been validated. The objectives of this manuscript are: (i) to test the effectiveness of the diagnostic criteria used to define the Andosol soil group and related soil units; (ii) to propose modifications to the current proposal where appropriate; and (iii) to examine the relationships between morphological and chemical properties used in distinguishing Andosols. The Tohoku University World Andosol Database (TUWAD) contains physical and chemical data from soils throughout the world derived from volcanic ejecta, but mainly from temperate regions. It is used to evaluate the effectiveness of the proposed criteria for characterizing and distinguishing the Andosol soil group. However, other data, especially from tropical countries, have been used for development of the Andosol soil group in the WRB Soil Resources project (Quantin in Spaargaren 1994).

DOMINANT PEDOGENIC PROCESSES IN ANDOSOLS

Formation of noncrystalline (active Al and Fe compounds) materials and accumulation of organic carbon are the dominant pedogenic processes occurring in most Andosols (Shoji et al. 1993). This combination of processes, occurring preferentially in soils formed in volcanic ejecta, was termed "andosolization" by Duchaufour (1984). In contrast to podozolization, soil solution studies of Andosols indicate that there is no significant translocation of Al, Fe, and dissolved organic matter (Ugolini and Dahlgren 1991).

Formation of noncrystalline materials is directly related to the properties of volcanic ejecta as a parent material (Shoji et al. 1993). The fine particle-size, glassy nature of the particles, and the high porosity and permeability of volcanic ejecta, enhance chemical weathering rates. Rapid weathering releases elements faster than crystalline minerals can form, resulting in soil solutions becoming oversaturated with respect to metastable, noncrystalline materials such as allophane, imogolite, opaline silica, and ferrihydrite (Quantin 1992; Shoji et al. 1993). The rapid precipitation kinetics of noncrystalline materials results in preferential formation of these constituents.

Andosols typically have their colloidal fraction dominated by Al-humus complexes or allophane/imogolite in humid weathering environments, by halloysite under less humid conditions with a distinct dry season (Parfitt et al. 1983), or in buried soil layers with imperfect drainage (Aomine and Wada, 1962). Under humid weathering conditions, the composition of the colloidal fraction forms a continuum between pure Al-humus complexes and pure allophane/imogolite, depending on the pH and organic matter characteristics of the weathering environment. Aluminum-humus complexes form preferentially in pedogenic environments that are rich in organic matter and have a pH value of about 5 (Shoji and Fujiwara 1984). In this pH range, organic acids are the dominant proton donor, lowering pH and aqueous Al activities through formation of Al-humus complexes. Under these conditions, humus effectively competes for dissolved Al, leaving little or no Al available for coprecipitation with silica to form aluminosilicate minerals. Allophane and imogolite form preferentially in weathering environments, with pH in the 5–7 range and a low content of complexing organic compounds. Soil solution studies in Andosols show that allophane and imogolite form in situ primarily as a result of weathering by carbonic acid (Ugolini and Dahlgren 1991). Ferrihydrite is typically found as the dominant iron oxide in Andosols (Childs et al. 1991). Since Fe has a greater stability in oxides compared with humus complexes, concentrations of Fe-humus complexes are typically low.

Accumulation of organic matter is another characteristic property of many Andosols. Organic matter is protected against biodegradation by Al toxicity to microorganisms (Tokashiki and Wada 1975), sorption of degradation enzymes to active Al and Fe (Tate and Theng 1980), steric hindrance of functional groups to decomposer microorganisms due to sorption and complexation (Wada 1977), or phosphorus deficiency of microorganisms caused by high P retention (Brahim 1987). Organic matter stabilization occurs through formation of Al-humus complexes and sorption to allophane, imogolite, and ferrihydrite. This process of organic matter stabilization plays a major role in the formation of melanic and fulvic surface horizons (Shoji et al. 1993) in Andosols.

Although accumulation of organic matter in both melanic and fulvic surface layers results from interaction with short-range-order minerals and Al-humus complexes, they differ remarkably in their humus characteristics, reflecting differences attributable primarily to vegetation (Shoji 1988). Melanic horizons are very dark, humus-rich layers, formed primarily under grassland vegetation, and contain a humus fraction dominated by A-type humic acid. However, a few melanic Andosols have also been observed under forest in Italy (Quantin et al. 1985), Mexico (Quantin et al., personal communication), and the U.S. (Takahashi et al. 1994). In contrast, fulvic horizons commonly form under forest vegetation and exhibit a dark brown color, a high fulvic acid to humic acid ratio, and a humic acid fraction dominated by P-type humic acid with the lowest degree of humification (Honna et al. 1988).

RELATIONSHIP OF SOIL PROPERTIES TO PRODUCTIVITY AND UTILIZATION

Noncrystalline materials and humus contribute to the unique chemical and physical properties of Andosols, such as variable charge, high water-holding capacity, high phosphate retention, low bulk density, high friability, weak stickiness, formation of stable soil aggregates, etc. They also influence the productivity of Andosols greatly through their positive roles in retaining and supplying nutrient elements, retaining plant-available water, and development of a favorable rooting zone, as well as their potentially negative attributes of P fixation, low exchangeable base holding capacity, and eventually strong acidity and Al toxicity in alu-andic horizons.

Distinct differences in productivity are demonstrated for the proposed vitr-andic, alu-andic, and sil-andic soil units. Vitr-andic Andosols often exhibit the lowest productivity as a result of low water and nutrient-holding capacities; but phosphorus availability is generally adequate since concentrations of PO_4 fixing noncrystalline materials are low. Alu-andic Andosols display a wide-range of productivity attributable to the potential for Al toxicity, strong PO_4 fixation capacity, and low exchangeable base content. If these conditions are ameliorated, alu-andic soils may be very productive because of their ease of tillage, high plant-available water-holding capacity, and high nutrient retention capacity. Sil-andic Andosols have the highest inherent productivity related to their many excellent physical and chemical properties, such as ease of tillage, deep rooting environment, high plant-available water-holding capacity, absence of Al toxicity, and high nutrient retention. The major limitation of sil-andic Andosols is their strong PO_4 fixation capacity, which can be alleviated with proper fertilizer management.

Other soil properties associated with Andosols affect their potential productivity and utilization appreciably. Many Andosols contain polygenetic profiles (thaptic property) indicating repeated deposition of volcanic ejecta and subsequent soil formation. Stratification of materials with contrasting particle size may restrict water movement and result in formation of hard pans or solidified ash layers. To enhance productivity, these soils often require mechanical mixing to remove root limiting layers and improve water movement (Yamada et al. 1994; Quantin 1994).

Soils in perhumid tropical environments frequently exhibit greater than 100% water content at 1.5 MPa water potential (hydric property) because of the unique water holding properties of noncrystalline materials. These soils require special management consideration with respect to tillage and engineering practices as a result of thixotropic properties; a sudden change of the soil material from a semirigid state to a fluid state when pressure is applied; and irreversible dehydration which lowers the water holding capacity and the soil aggregate stability drastically. Hydric soils have two additional productivity constraints: a very low exchangeable base-holding capacity

TABLE 1

Distribution of soils in the TUWAD by Soil Taxonomy soil temperature and moisture regimes†

Temp/Moisture Regime‡	Xeric	Ustic/Aridic	Udic	Perudic
Frigid/cryic	10	0	38	3
Mesic	9	1	64	0
Thermic	0	3	36	5
Hyperthermic	3	12	10	16

†A total of 50 pedons were not categorized because of insufficient data.
‡Soil Survey Staff 1994.

and some degree of anoxy in subsurface horizons. Another characteristic property of highly weathered and leached tropical Andosols is very low (<2-cmol(+) kg^{-1}) exchangeable base cation plus KCl extractable Al concentrations (acrudoxic property). These soils display low nutrient-holding capacity and require special management practices to maintain their productivity.

High KCl-extractable Al concentrations (alic property) are associated with a high potential for Al toxicity in sensitive plants. These soils require special management practices such as liming or growth of Al tolerant species to sustain agricultural productivity. In contrast, Andosols formed in drier climates or base-rich materials may be characterized by a neutral to slightly acidic pH and appreciable base cation concentrations (eutric property). These soils may be especially productive relative to their more acidic analogues exhibiting alic properties.

MATERIALS AND METHODS

The TUWAD contains physical and chemical data on 260 pedons and 1463 individual horizons from soils throughout the world derived from volcanic ejecta. These data were obtained from past studies by the authors, published literature and the Soil Conservation Service (1994). A breakdown of soils by Soil Taxonomy temperature and moisture regimes is shown in Table 1. The large number of soils in the udic soil moisture regime reflects the preferential formation of Andosols in humid environments.

All analytical data and procedures were reviewed for consistency before inclusion into the database. Standard analytical methods for characterization data were based on the methods used for determining andic soil properties in Soil Taxonomy (Kimble 1986; Soil Survey Staff 1994). The only notable exception to these methods was pH, which was determined using a range of soil:solution ratios between 1:1 and 1:2.5. Data obtained by nonstandard techniques were excluded.

EVALUATION OF DIAGNOSTIC PROPERTIES USED TO DEFINE ANDIC HORIZONS

We believe the proposed classification of andic horizons into vitr-andic, sil-andic, and alu-andic classes effectively differentiates Andosols based on the primary pedogenic processes and their degree of expression: formation of noncrystalline inorganic constituents (e.g., allophane, imogolite, ferrihydrite) and immobile humus-sesquioxide complexes. Characteristic physical and chemical properties of the three subtypes of

TABLE 2

Diagnostic criteria for andic horizons in the World Reference Base for Soil Resources (Spaargaren 1994)

A soil layer at least 30 cm thick that has one of the following characteristics:

Vitr-andic: Al_{ox} + $1/2Fe_{ox}$ = 0.4-2%; volcanic glass and other primary minerals >60%

Sil-andic: Al_{ox} + $1/2Fe_{ox}$ >2%; Si_{ox} ≥ 0.6%; Al_{py}/Al_{ox} <0.5; exchangeable Al <2 cmol (+)/kg fine-earth; pH > 4.5 if org. C >5% or pH > 5.0 if org. C <5%

Alu-andic: Al_{ox} + $1/2Fe_{ox}$ >2%; Si_{ox} <0.6%; Al_{py}/Al_{ox} ≥ 0.5; exchangeable Al >2 cmol(+)/kg fine-earth; pH <4.5 if org. C> 5% or pH < 5.0 if org. C <5%

andic horizons are shown in Table 2. An andic horizon must be at least 30 cm thick and start within 30 cm of the mineral soil surface to be diagnostic. Vitr-andic horizons exhibit minimal weathering and have a surface horizon with low concentrations of organic matter and clay; they often contain coarse tephric material. In contrast, both sil-andic and alu-andic horizons are moderately weathered. Surface horizons commonly display very dark colors, large accumulations of organic matter, and unique consistency such as low stickiness and high friability. Some sil-andic horizons show thixotropic properties (hydric properties) reflecting the high content of active Al and Fe.

Using TUWAD, we studied the suitability of the diagnostic differentiating values for physical and chemical properties of andic horizons as proposed by WRB. The results of this analysis follow.

Content of Volcanic Glass and Other Primary Minerals

The WRB proposes that vitr-andic horizons should contain more than 60% volcanic glass and other primary minerals. Some young soil horizons derived from a mixture of volcanic ash and nonvolcanic deposits will meet this requirement. Volcanic glass is the major component of volcanic ash and shows the least resistance to chemical weathering. Therefore, active Al and Fe (acid oxalate extractable) are released primarily from the weathering of volcanic glass. For this reason, volcanic glass content was selected as one of the requirements to define andic soil properties in Soil Taxonomy (Soil Survey Staff 1994). We propose that vitr-andic horizons should also be defined using only the volcanic glass content of the <2-mm fraction instead of the content of volcanic glass plus other primary minerals.

According to the relationship between volcanic glass content and formation of active Al and Fe ($Al_o + 1/2Fe_o$), a minimum volcanic glass content of 25% in the fine-earth fraction is necessary to produce $Al_o + 1/2Fe_o$ of 2% (Shoji et al., 1993). Thus, for an $Al_o + 1/2Fe_o$ concentration of 0.4% (lower limit for vitr-andic horizons), a minimum value of 20% volcanic glass should be present in the fine-earth fraction. The concentration of volcanic glass and $Al_o + 1/2Fe_o$ are inversely related as weathering proceeds as later described.

Acid Oxalate-Extractable Aluminum and Iron Content

The WRB proposal utilizes $Al_o + 1/2Fe_o$ as one of the diagnostic criteria for distinguishing

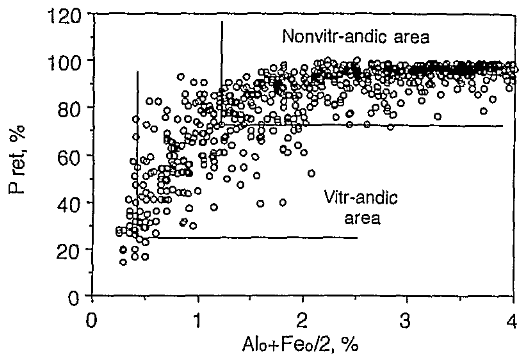

Fig. 1. Relationship between acid oxalate-extractable Al plus one-half Fe ($Al_o + Fe_o/2$) and phosphorus retention of Andosols. Data having $Al_o + Fe_o/2$ of 4% or less were shown for convenience.

subtypes of andic horizons, such as an $Al_o + 1/2Fe_o$ value of 2% to differentiate vitr-andic horizons or andic intergrades of other soil units from sil-andic and alu-andic (nonvitr-andic) horizons. However, we consider this differentiating value is too high as described below. The transition between vitr-andic and nonvitr-andic horizons should be based on criteria that have a significant effect on management and use rather than an arbitrary value.

Most Andosols having $Al_o + 1/2Fe_o = 2\%$ show phosphate retention greater than 90% (Fig. 1). Such Andosols have high phosphate fixation capacity and require heavy phosphorus fertilization in order to ameliorate phosphorus deficiency in plants. According to the relationship between phosphate retention and phosphorus fertilization of cultivated soils from Japan (Oda et al. 1987), heavy phosphorus application is not required for soils having phosphate retention less than 70%, which correlates with an $Al_o + 1/2Fe_o$ concentration of approximately 1.2% (Fig. 1). Thus, we propose an $Al_o + 1/2Fe_o$ value of 1.2% as the differentiating value between vitr-andic and nonvitr-andic horizons.

Acid Oxalate Extractable Silicon

Acid oxalate extractable silicon (Si_o) is used in the WRB proposal as one of the diagnostic criteria for separating sil-andic horizons ($Si_o \geq 0.6\%$) and alu-andic horizons ($Si_o < 0.6\%$). This value is generally relevant; however, some exceptions do exist because of variation of the "allophane" Al/Si ratio from 1 to 2 (Madeira, et al., 1994). According to the relationship between Al_p/Al_o and Si_o for nonvitric Andosols (Al_o +

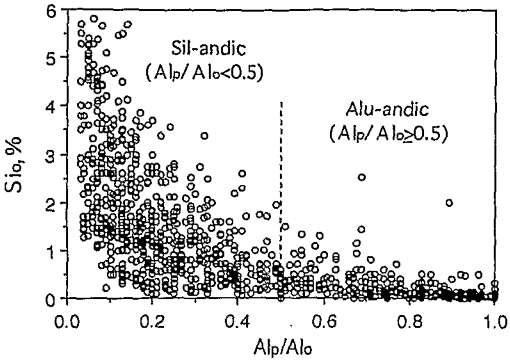

Fig. 2. Relationship between $Al_o + Fe_o/2$ and acid oxalate-extractable Si for soil horizons with $Al_o + Fe_o/2$ of 1.2% or more.

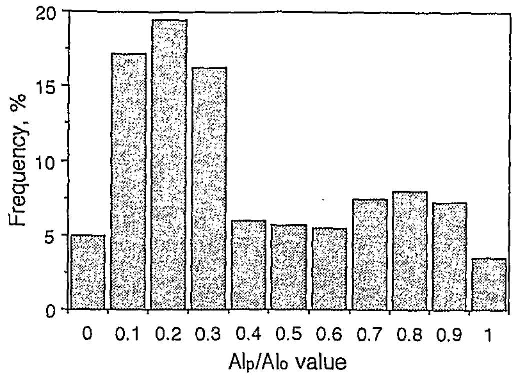

Fig. 3. Frequency distribution of pyrophosphate-to oxalate-extractable Al (Al_p/Al_o) in A horizons with Al_o + $1/2Fe_o$ of 1.2% or more.

$1/2Fe_o$ > 1.2%), the consistency between the Al_p/Al_o and Si_o requirements is greater than 95% (Fig. 2) for alu-andic horizons. As a result of the good agreement between Al_p/Al_o and Si_o criteria, we propose that the Si_o requirement is redundant and should not be used as a diagnostic criteria. This will avoid inconsistencies originating either when ferrihydrite is the dominant form of active Al and Fe in sil-andic horizons and Si_o concentrations are low or when alu-andic horizons also contain appreciable amounts of allophanic materials.

Al_p/Al_o for Differentiating Nonvitr-andic Horizons

An Al_p/Al_o ratio of 0.5 was selected by WRB as one of the requirements to separate sil-andic and alu-andic horizons. The validity of this value was supported by Saigusa et al. (1993), Matsuyama and Saigusa (1994), and Matsuyama et al. (1992, 1993, 1994), who analyzed 774 Andosol pedons in Japan. Based on data from the literature and TUWAD, we agree with the WRB proposed criteria for differentiating alu-andic (≥0.5) and sil-andic (<0.5) horizons. As shown in Fig. 3, the criteria effectively separate two kinds of A horizons based on the dominant weathering process acting upon the soil; alu-andic horizons are dominated by organic acid weathering and sil-andic horizons by carbonic acid weathering. However, when Al_p data is not available, the Si_o value of 0.6 could be used as an approximate criteria.

Soil Acidity for Nonvitr-andic Horizons

Soil acidity ($pH[H_2O]$) is determined primarily by the types and amounts of soil colloids and their base saturation. The WRB proposal employs $pH(H_2O)$ values as a tentative field diagnostic criteria for separating sil-andic and alu-andic horizons (Table 2). As shown in Fig. 4, however, the frequency distributions of $pH(H_2O)$ values for alu-andic and sil-andic horizons display significant overlap. Furthermore, soil acidity is changed easily by management practices such as liming. Thus, we propose that pH should not be used as a diagnostic criteria for separation of sil-andic and alu-andic horizons although a $pH(H_2O)$ of less than 4.5 determined on field-moist samples could be useful to discriminate some alu-andic horizons.

Phosphate Retention Percentage

Phosphate retention is easily and accurately determined and provides valuable information on chemical and mineralogical properties that are especially important for agronomic management. The WRB proposal does not use phosphate retention percentages as a diagnostic chemical property of Andosols. Phosphate retention percentage in combination with $Al_o + 1/2Fe_o$ are among the most useful diagnostic chemical criteria for andic horizons as was concluded for the definition of andic soil properties in Soil Taxonomy (Soil Survey Staff, 1994). As described above, an $Al_o + 1/2Fe_o$ value of 1.2% is proposed to separate vitr-andic and nonvitr-andic horizons. Since acid oxalate can partially dissolve magnetite contained in volcanic ash, Shoji et al. (1987) proposed the additional requirement of P retention greater than 25% to separate volcanic ash-derived Entisols and vitric Andosols. This proposal was introduced into the definition for

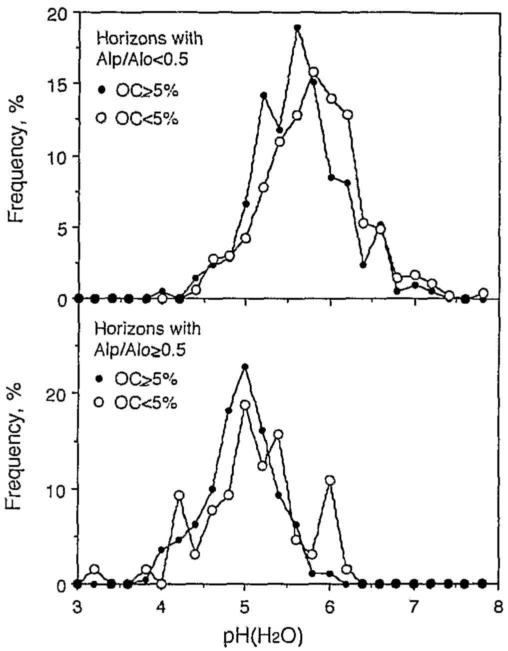

Fig. 4. Frequency distribution of pH(H_2O) in soil horizons with Al_p/Al_o < 0.5 and $Al_p/Al_o \geq 0.5$. These horizons have $Al_o + Fe_o/2$ of 1.2% or more.

andic soil properties of Soil Taxonomy (Soil Survey Staff 1994). We propose that this additional requirement also be used for defining vitr-andic horizons. We further propose a phosphate retention value of 70% for separation of nonvitr-andic horizons and vitr-andic horizons. This value has practical significance since it is the critical value used to determine levels of phosphorus fertilizer application in cultivated soils of Japan.

Water Retention at 1500 kPa (1.5 MPa)

Large amounts of high tension water are retained by noncrystalline colloids, especially in perhumid environments. As a result, 1.5 MPa water retention increases with increasing Al_o + $1/2Fe_o$, as shown in Fig. 5, as well as with increasing Al/Si ratio of weathering products (Quantin 1982, 1985). The 1.5 MPa water retention shows considerable variation, especially regarding degrees of soil drying and cultivation. Therefore, it is not useful as a diagnostic property to distinguish vitr-andic from other andic horizons. Vitr-andic horizons have 1.5 MPa water retention values generally less than 25%, while nonvitr-andic horizons show 1.5 MPa water retention primarily between 20 and 240% (Quantin 1985). However, a 1.5 Mpa water retention value greater than 100%, measured for natural undried samples, is a useful criteria to characterize sil-andic horizons that have "hydric" properties as proposed in the WRB proposal (Table 3).

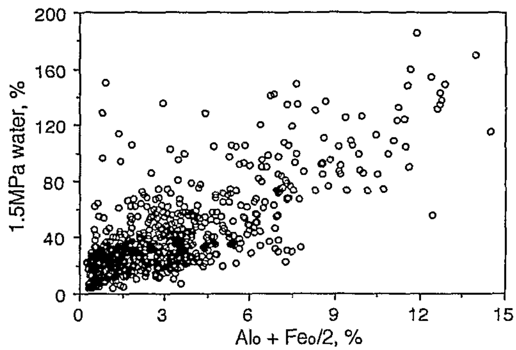

Fig. 5. Relationship between $Al_o + Fe_o/2$ and 1.5 MPa water retention of Andosols.

Bulk Density

Low bulk density in Andosols is attributed to the development of stable microaggregates with high microporosity and large accumulations of organic matter. Thus, it was employed as one of the requirements for determining andic soil properties in Soil Taxonomy (Soil Survey Staff 1994). As shown in Fig. 6, Andosols showing Al_o + $1/2Fe_o \geq 2\%$ typically have bulk density values ranging from 0.9 to 0.2 Mg m^{-3}. We propose inclusion of a maximum bulk density value of 0.9 Mg m^{-3} for nonvitr-andic horizons with Al_o +

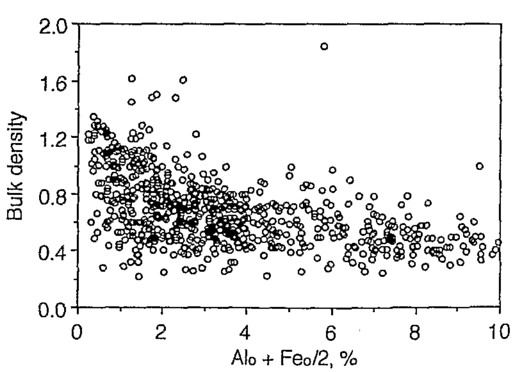

Fig. 6. Relationship between $Al_o + Fe_o/2$ and bulk density of Andosols. Data having $Al_o + Fe_o/2$ of 10% or less were shown for convenience.

TABLE 3

Proposed second level soil units and keyout order for Andosols in the World Reference Base for Soil Resources†

Vitric Andosols: Andosols having either a vitr-andic horizon or a particle size distribution coarser than silt loam for all horizons within 100 cm of the surface.

Hydralic Andosols: Other Andosols having *both* an alu-andic horizon and, within 100 cm of the mineral soil surface, layers 35 cm or more thick that have a water retention at 1500 kPa, measured on undried samples, of 100% or more of the oven-dried fine earth.

Pachalic Andosols: Other Andosols having *both* an alu-andic horizon and more than 6% (by weight) organic carbon in the fine earth fraction and the color of an umbric horizon throughout a depth of 50 cm from the mineral soil surface downwards.

Alic Andosols: Other Andosols having an alu-andic horizon to a depth of at least 50 cm of the mineral soil surface.

Hydric Andosols: Other Andosols having within 100 cm of the mineral soil surface, layers 35 cm or more thick which have a water retention at 1500 kPa, measured on undried samples, of 100% or more of the oven-dried fine earth.

Pachic Andosols: Other Andosols having more than 6% (by weight) organic carbon in the fine earth fraction and the color of a mollic or umbric horizon throughout a depth of 50 cm from the mineral soil surface.

Eutric Andosols: Other Andosols having a mollic horizon 30 cm or more thick or, throughout the upper 50 cm of the soil, either a base saturation (by 1*M* NH_4OAc) of 50% or more or a sum of exchangeable bases of more than 25 cmol(+)/kg fine earth.

Silic Andosols: Other Andosols.

†Spaargaren 1994.
The definition of andic horizons to classify an Andosol is given in Table 2.

$1/2Fe_o \geq 2\%$ to distinguish these Andosols from other soil groups that have high active Al and Fe and high P retention (e.g., Ferralsols and Acrisols).

Exchangeable Aluminum

Exchangeable Al (1 *M* KCl) is the primary source of toxic Al in Andosols (Saigusa et al. 1980). A critical exchangeable Al concentration of 2 cmol(+) kg^{-1} fine-earth was adopted as the criterion for alic Andosols in Soil Taxonomy (Soil Survey Staff 1994). An exchangeable Al value of 2 cmol(+) kg^{-1} fine-earth is also proposed by WRB as a diagnostic requirement for separating sil-andic (exch. Al < 2-cmol(+) kg^{-1} fine-earth) and alu-andic (> 2-cmol(+) kg^{-1} fine-earth) horizons. The TUWAD indicates that a considerable number of alu-andic horizons ($Al_p/Al_o > 0.5$) have exchangeable Al < 2-cmol(+) kg^{-1} fine-earth (Fig. 7). This may result from agricultural practices such as liming that can easily change levels of exchangeable Al. Thus, we propose that the use of exchangeable Al be eliminated as a diagnostic criteria for distinguishing alu-andic and sil-andic horizons. However, it should be noted that this criteria may be useful for characterizing uncultivatd alu-andic horizons.

REVISED DEFINITION OF ANDIC HORIZONS

Based on our study of the characteristic physical and chemical values for andic horizons using the TUWAD, we propose the following revised definitions and keyout order for andic horizons.

Nonvitr-andic Horizons

Nonvitr-andic horizons (sil-andic and alu-andic horizons) must meet the following requirements:

1. A 30-cm or greater layer starting within 30 cm of the mineral soil surface,
2. An $Al_o + 1/2Fe_o$ value of 1.2% or more,
3. A phosphate retention of 70% or more, and
   a. For horizons having $Al_o + 1/2Fe_o$ values of ≥2.0%, a bulk density measured at 33 kPa water retention of <0.9 Mg m^{-3}, and
   b. For horizons having $Al_o+1/2Fe_o$ values of 1.2 to <2.0%, a volcanic glass percentage in the fine-earth that when plotted

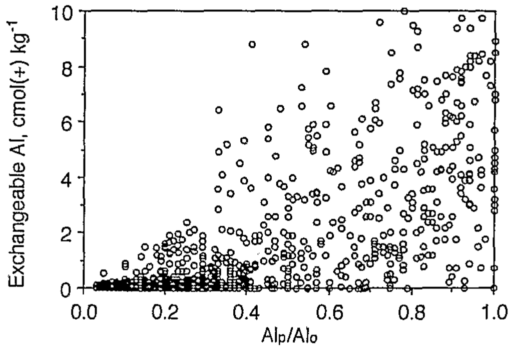

Fig. 7. Relationship between Al_p/Al_o and exchangeable Al of horizons with sil-andic and alu-andic properties.

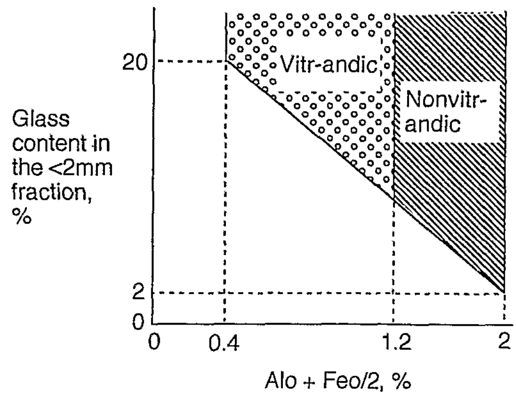

Fig. 8. Classification of vitr-andic and nonvitr-andic horizons based on the relationship between Al_o + $Fe_o/2$ and volcanic glass content in the fine-earth fraction for Andosols having Al_o + $1/2Fe_o$ of 0.4 to 2.0%.

against Al_o + $1/2Fe_o$ falls within the *Nonvitr-andic* area of Fig. 8, and no bulk density requirement.

Alu-andic Horizons

Alu-andic horizons must further meet the following requirement: An Al_p/Al_o ratio of 0.5 or more for the upper 30-cm or more of the nonvitr-andic horizon. If Al_p is not available, a Si_o value of 0.6% or less could be used as an approximate criterion instead of the Al_p/Al_o ratio.

Sil-andic Horizons

Sil-andic Horizons must further meet the following requirement: Other nonvitr-andic horizon.

Vitr-andic horizons are other horizons that must meet the following requirements:

1. A 30-cm layer starting within 30-cm of the mineral soil surface,
2. An Al_o + $1/2Fe_o$ value of 0.4 or more,
3. A phosphate retention value of 25 or more, and
4. A volcanic glass percentage in the fine-earth, that when plotted against Al_o + $1/2Fe_o$, lies above the diagonal line of Fig. 8.

The generalized relationship between Regosols and the three subtypes of andic horizons is shown diagrammatically in Fig.9.

EVALUATION OF SECOND LEVEL SOIL UNITS FOR ANDOSOLS

Eight soil units were proposed by WRB to differentiate Andosols at the second level according to secondary soil-forming processes and soil characteristics that significantly affect management and utilization (Table 3). The proposed WRB soil units emphasize high 1.5 MPa water retention (hydric), extremely high organic matter accumulation (pachic), and exchangeable base-rich soil layers (eutric). The effectiveness and distribution of these soil units were examined using the TUWAD although there is some deficiency of tropical Andosol references (Table 1).

The WRB proposal uses the term "alic" Andosol in describing Andosols with alu-andic horizons. This term is potentially confusing since "alic" is used in Soil Taxonomy (Soil Survey Staff, 1994) to describe soils with high exchangeable Al concentrations. While "alic" is used to describe Andosols with alu-andic horizons, no analogous

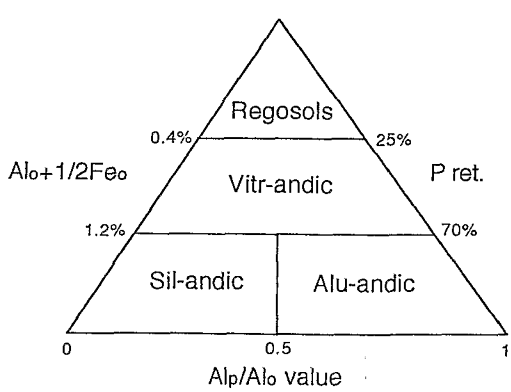

Fig. 9. The generalized relationship between Regosols and the three subtypes of andic horizons in the revised WRB classification.

TABLE 4

Proposed revisions to the second level soil units and keyout order for Andosols in the World Reference Base for Soil Resources

Vitric Andosols: Andosols having a vitr-andic horizon.

Melano-alu Andosols: Other Andosols having an alu-andic *and* a layer, starting within 30 cm of the minerals soil surface, with a cumulative thickness of 30 cm or more within a total thickness of 40 cm, that has a color value and chroma (moist-Munsell designation) of 2 or darker *and* $\geq$6% organic carbon as a weighted average and a minimum of 4% organic carbon in all layers.

Fulvo-alu Andosols: Other Andosols having both an alu-andic horizon *and* a layer, starting within 30 cm of the mineral soil surface, with a cumulative thickness of 30 cm or more within a total thickness of 40 cm, that has $\geq$6% organic carbon as a weighted average and a minimum of 4% organic carbon in all layers.

Haplo-alu Andosols: Other Andosols having an alu-andic horizon.

Hydro-silic Andosols: Other Andosols having a sil-andic horizon *and*, within 100 cm of the mineral soil surface, one or more layers with a total thickness of 35 cm or more that have a water retention at 1500 kPa (undried) of 100% or more in the fine-earth fraction.

Melano-silic Andosols: Other Andosols having a sil-andic horizon *and* a layer, starting within 30 cm of the mineral soil surface, with a cumulative thickness of 30 cm or more within a total thickness of 40 cm, that has $\geq$6% organic carbon as a weighted average and a minimum of 4% organic carbon in all layers.

Eutric Andosols: Other Andosols having a sum of exchangeable bases of more than 15 cmol(+) kg^{-1} fine earth for the upper 30 cm or more of a sil-andic horizon.

Haplo-silic Andosols: Other Andosols having a sil-andic horizon.

term is used for Andosols with sil-andic horizons. We therefore, propose that Alu Andosols and Silic Andosols be used for designating Andosols with alu-andic and sil-andic horizons, respectively (Table 4).

Thick, humus-rich Andosols seem to be more extensive in the humid and cold regions than in the tropics and are of particular significance for soil-forming processes and land use. In order to classify these soils, we propose creation of melanic and fulvic soil units. These proposed soil units must have organic carbon more than 6% and a minimum thickness of 30 cm. A distribution between melanic (value/chroma </= 2 or darker) and fulvic (lighter than melanic color) provides important information about the biochemical properties of the organic matter related to the dominant vegetation (e.g., grassland vs. tree) contributing to formation of the organic rich layer. Pachic modifier is proposed at the third level to describe very thick melanic and fulvic horizons having 6% or more organic carbon and 50 cm or greater thickness.

Hydric Andosols are common in perhumid regions, and the thixotropic properties associated with these soils should be recognized as proposed by WRB. The hydric properties can be determined by various methods such as (i) measurement of water retention at 1.5 MPa on undried natural soil sample ($>$ 100%), (ii) irreversible dehydration ratio (from undried to air-dried soil; $>$ 90%), and (iii) virtual absence of permanent negative charge on clay minerals and presence of acric properties. Air-drying hydric soils leads to formation of microstructure that is very light, unstable, and very susceptible to erosion. Our examination of the distribution of hydric soils according to the WRB soil unit criteria revealed that hydralic Andosols are virtually absent (Fig. 10). Although hydralic Andosols contain a large amount of organic matter, which can retain high tension water, the major clay mineral is frequently Al-interlayered 2:1 layer silicates, which have a low water-holding capacity. Thus, we propose that the hydralic soil unit, as proposed by WRB, should be eliminated and only its hydric counterpart in the silic Andosols retained.

Eutric Andosols, especially of silic Andosols, are an important indicator of soil-forming processes and land use; therefore, these soils are proposed as a soil unit in WRB. They are fairly young soils in some transitional stage between

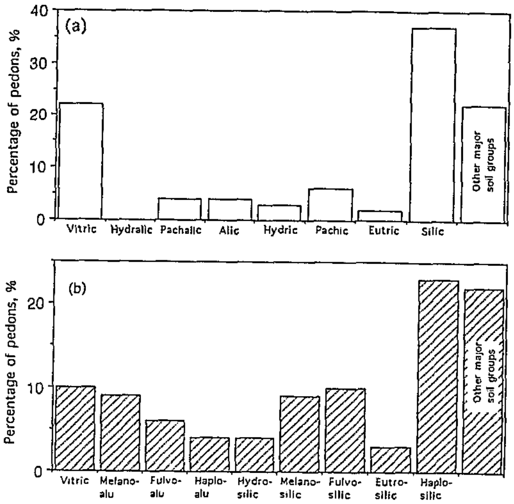

Fig. 10. Percentage distribution of soil units for soils derived from volcanic ejecta using data from TUWAD. (a) Classified according to Andosol classification of WRB. 1994. (b) Classified according to revised Andosol classification outlined in this paper. Glass content was not used in classifying pedons due to the limited availability of data.

vitric and silic Andosols or are derived from basaltic volcanic ash. They also appear in tropical, subtropical, or Mediterranian countries, frequently under an ustic moisture regime or at the boundary of an udic regime.

Eutric Andosols have very high potential fertility. For example, they have high concentrations of exchangeable Ca, Mg, and K cations and relatively low P retention. The requirements for eutric Andosols shown by WRB are high exchangeable base cation concentrations or high base saturation. The measurement of base saturation is known to be problematic because of the variable charge nature of Andosols. Therefore, we propose that eutric properties be based only on the sum of exchangeable base cations ($>$ 15-cmol(+) kg^{-1}). The threshhold of 25-cmol(+) kg^{-1} proposed by WRB is high according to TUWAD, and we propose revision to 15-cmol(+) kg^{-1}. Percentage of Eutro-silic Andosols was increased from 2 to 3% as a result of this revision.

In addition to pachic, we propose that third level modifiers be established for thaptic (polygenetic profiles), alic (Al toxicity potential), acrudoxic (sum of base cations and exchangeable Al $<$ 2-cmol(+) kg^{-1}), and dystric (exchangeable bases $<$ 5-cmol(+) kg^{-1}).

A comparison of the distribution of soil units between the WRB proposal and our revised proposal for soils contained in the TUWAD is shown in Fig. 10. More than 75% of the Andosols were classified as either vitric or silic by the WRB proposal. Hydralic Andosols are very rare in the WRB proposal because of their medial water retention at 1.5 MPa. In contrast, the revised proposal shows a more even distribution of soils among the soil units. Vitric soils were reduced by more than 50% in the revised proposal and melanic and fulvic soil units showed a nearly even distribution. Thus, the revised proposal appears to provide a more distinctive classification that is based on the primary pedogenic processes of noncrystalline material formation and organic matter accumulation.

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