Soil Classification Following the US Taxonomy: An Indian Commentary

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Review

Soil Classification Following the US Taxonomy: An Indian Commentary

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More than 50 yr ago US soil taxonomy was adopted in India. Since then many researchers have contributed their thoughts to enrich the soil taxonomy. The National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) (Indian Council of Agricultural Research) as a premier soil survey institute has been consistently using benchmark soil series to understand the rationale of the soil taxonomy, keeping in view the soil genesis from different rock systems under various physiographic locations in tropical India. The present review is a humble effort to present this information.

One of the fundamental requirements of any natural science is to classify the proposed bodies or the objects studied (Joel, 1926). Soils do not exist as discrete objects like plants and animals but occur in nature as a complex and dynamic system, which makes grouping soils difficult. It was believed that the study of the soils could not advance as a science until a well-accepted classification system was developed (Joel, 1926; Marbut, 1935). In earlier days, soil classification systems were based mainly on geomorphological and geological concepts as reflected in the chemical and mineralogical properties of the parent materials. The concept of soil classification from the days of Dokuchaev (1883, 1949) was based on zonality. The United States formally used zonality-based systems from 1938 until the 1960s. Before about 1938 the United States used systems based on physiography and/or geology. A revised version of Marbut's classification system (Marbut, 1928) was published in 1938 (Baldwin et al., 1938) and was adopted by the US Soil Survey (Brevik, 2002). The soils used to be divided into three broad orders: (i) zonal soils (normal soils with characteristics reflecting the effect of climate and vegetation on well-drained stable landscape), (ii) intrazonal soils (well developed soils showing influence of local factors such as age, parent material, and relief), and (iii) azonal soils (poorly developed soils). Polinov (1923) and Kovda et al. (1967) developed the evolutionary approach of the soil classification. With the help of knowledge on major stages and trends in weathering and the formation of humus and clay minerals, higher categories of soil classification were conceptualized (Duchaufour, 1968). The concept of genetic profiles was used in early and current Russian soil classification schemes (Gerasimov, 1975; Gorajichkin et al., 2003). Cline's (1949) basic principles of soil classification were used as the foundation of global soil classification schemes, such as US soil taxonomy (Soil Survey Staff, 1975, 1999) and the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2006). The WRB was originally intended to be a conversion between national systems rather than being a classification system itself (Krasilnikov et al., 2009). The US classification schemes permitted classification of soils on the basis of surface and subsurface diagnostic horizons and other characteristics.

The concept of US soil taxonomy (Soil Survey Staff, 1999) centers on the basic theme of differentiating soils on the basis of the properties of the soils being classified where the factors of soil formation helps describe soils indirectly (Smith, 1986; Krasilnikov et al., 2009; Buol et al., 2011; Bockheim et al., 2014). It was conceived as a means of communicating soil information to other branches of science in general and soil science (pedology) in particular. US soil taxonomy has been described as a classification that is mainly concerned with the relationships among soils. Therefore, it is considered to be a narrower term than classification (Soil Survey Staff, 1975, 1999). In US soil taxonomy, soils are classified into six category levels from broadest to the narrowest: orders, suborders, great groups, subgroups, family, and series (Soil Survey Staff, 1999). The lowest category (Soil Survey Staff, 1999) is the series, which is based on the kind and arrangement of horizons and finer differences in soil properties. The soil series are again divided into phases on the basis of surface stoniness, slope, erosion, and/or other attributes that are not

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Abbreviations: AISLUS, All India Soil and Land Use Survey Organization; CEC, cation-exchange capacity; COLE, coefficient of linear extensibility; ECe, electrical conductivity of saturation extract; ECEC, effective cation-exchange capacity; ESP, exchangeable sodium percentage; HIV/HIS, kaolin-hydroxy interlayered vermiculites/kaolin-hydroxy interlayered smectites; IARI, Indian Agricultural Research Institute; ICAR, Indian Council of Agricultural Research; IGP, Indo-Gangetic Plains; K/HIV, kaolin-hydroxy-interlayered vermiculite; LE, linear extensibility; NBSS & LUP, National Bureau of Soil Survey and Land Use Planning; WRB, World Reference Base.

diagnostic in US soil taxonomy but are important for land use. It seems, therefore, that US soil taxonomy is an elaborate, universally acceptable, hierarchical system of soil classification showing well-defined differentiating criteria based on measurable soil and associated land characteristics. Most of the higher categories in US soil taxonomy depend on various properties that are produced by distinct soil forming processes. The essence of the system is that the nomenclature for the different taxa can itself provide information on soil forming processes. The other important aspect of US taxonomy is that it is an open-ended system and thus can accommodate any new concepts developed over time through concerted global research efforts. The system, as the soil itself, is dynamic, as evidenced by its continuous revision since 1975 for both comprehensive (Soil Survey Staff, 1975, 1999) and the abridged versions known as *Keys to Soil Taxonomy* (Soil Survey Staff, 1983, 1987, 1990, 1992, 1994, 1996, 1998, 2003, 2006, 2014). In spite of its several advantages, the taxonomy also suffers from some drawbacks. The usual criticism has been that the system is difficult to understand by scientists and end users working in other branches of science, in general, and soil science (except pedology), in particular.

In India, soil survey received recognition as an all-India activity following the report of the Stewart Committee in 1947. Upon realization that a detailed knowledge of soils is necessary for increasing agricultural production, the All India Soil Survey Scheme was launched in 1956. The same was expanded in 1959 as an All India Soil and Land Use Survey Organization (AISLUS). The work, however, was mostly confined to areas under different river valley projects. The soil map prepared at the Indian Agricultural Research Institute (IARI) in 1954 was again revised during 1964 and 1971 and the extent and distribution of the different soil classes in the map, and their equivalents available in the USDA system were used. The AISLUS was bifurcated in 1969 into two wings; the major portion concerning the research aspect of soil survey and mapping, correlation and classification became a part of the Indian Council of Agricultural Research (ICAR)-IARI, and that dealing with the detailed soil survey of river valley catchments remained with the Department of Agriculture, Government of India. The Planning Commission, Government of India appointed a Task Force on Land and Soil Resources, which submitted its report in 1972 highlighting the need for soil correlation, uniform nomenclature and appropriate soil mapping units. The Task Force recommended that soil correlation in all aspects should have statutory support for ensuring uniformity in mapping legend, soil series description, and map construction. All state soil survey agencies were made responsible to a central agency as far as soil correlation was concerned. The National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) under ICAR came into existence in 1976. The US soil taxonomy was adopted in India in 1969 (Dhir, 2004). Since then US soil taxonomy has been introduced as part of the course content in several agricultural universities for teaching soil science in India. To make the system understandable and useful, the NBSS & LUP, ICAR has been engaged in training technical personnel of all the Indian states and union territories. This has made the soil survey reports and the soil maps uniform in terms of their description of soils and their classifications. This process has generated a huge number of soil series throughout the country. Many researchers have pointed out the rationale of framing the concepts of orders, suborders, great groups, and subgroups. Efforts were also made to pinpoint various criteria for grouping soils at the family level of classification, namely soil textural and clay mineralogical class. Endeavors to describe tropical soils of India by improvising the US soil taxonomy rationale are still continuing. The present study is based on a few selected soil orders that were subjected to critical analysis with a view to make US soil taxonomy more rationale, understandable, and meaningful for the soils of tropical India.

Vertisols and Their Classification

Vertisols are deep, dark colored, clayey, and smectitic soils that exhibit cracks and slickensides (Table 1). Earlier studies suggested that the slow and steady process of haplodization induced by argillipedoturbation (Hole, 1961) inhibit the process of horizonation (Simonson, 1961) and favors the development of Vertisols with characteristic cyclic horizons (Bhattacharyya et al., 1999b). Extensive pedological research in the last decade on Indian Vertisols, however, does not support the earlier concept of Vertisol

Table 1. Grouping Indian black soils into Vertisols.

Soil taxonomy category	Rationale	Remarks
Order	Other than thickness ($\geq$25 cm) and depth criteria (within 100 cm) soils should have · slickensides or · wedge-shaped peds and · $\geq$30% clay and · cracks (Soil Survey Staff, 2003)	To group a soil in Vertisol *presence of slickensides not mandatory*.
Subgroup	(A) For vertic subgroups of any other soil orders should have · $\geq$5-mm-wide cracks within 125 cm or · $\geq$6.0 linear extensibility (LE) within 100 cm (Soil Survey Staff, 2003) (B) Indirect evidence of vertic properties in soils if clay smectites $\geq$20% (Shirsath et al., 2000).†	A. If cracks not visible in wet field, LE (100 $\times$ weighted mean average of COLE) may be determined following standard method (Schafer and Singer, 1976). (B) (i) clay (<2 μm) smectites may be estimated following X-ray diffraction technique (Jackson, 1979) or (ii) clay smectites may be measured indirectly by LE values with the help of equation COLE = 0.263 (smectite %) + 0.771 (Shirsath et al., 2000; Bhuse et al., 2001).

† Also see Bhattacharyya et al. (1997).

formation because of the active operation of the clay illuviation process (Satyavathi et al., 2005; Pal et al., 2009, 2010), which is a more dominant pedogenic process than the argillipedoturbation. The clay enrichment in the subsoils thus justifies the subsoil horizon designation as "B" (Soil Survey Staff, 2014) instead of "A" in an earlier concept of Vertisols with no horizonation (Soil Survey Staff, 1975). Clay illuviation, a requisite for argillic horizon formation, is common in Vertisols of India, but presence of slickensides qualify them for Vertisols since this soil order (Vertisols) keys out before Alfisols in US soil taxonomy (Pal et al., 2012). Sehgal and Bhattacharjee (1988) investigated a few typical Vertisols of India and Iraq and suggested a rationale for soil taxonomic grouping to the level of great group. The significant genetic process resulting in the homogeneity and weak horizonation on one hand and a well-developed profile showing B horizons were compared. In view of the wide difference in available moisture during crop growth under rainfed situations, these authors proposed to subdivide the "ustic" moisture regime into "aridic," "typic," and "udic" for defining subgroups. According to US soil taxonomy (Soil Survey Staff, 1975), differences in moisture condition and color were considered to differentiate Chromusterts and Paleusterts at the great group levels. Conceptually the Chromusterts should be better drained than the Paleusterts. Sehgal and Bhattacharjee (1988) argued that the rationale for basic differences between Chromusterts and Paleusterts in terms of drainage and topographic situations do not conform to field reality and hence should not be the differentiating criteria at the great group level. The Vertisols showing typical characteristics of shrink–swell properties should thus be classified to Hapl-Usterts/Torrerts/Xererts (including, however, the formative elements), great groups with no cambic, gypsic or salic horizon(s) within 1 m of the surface (Sehgal and Bhattacharjee, 1988). Accordingly, they proposed new subgroups for five benchmark soils in India (Table 2). Later Vertisols in Gujarat state showed more than 15-cm-thick horizons with carbonate content equivalent to more than 15% $CaCO_3$ along with high electrical conductivity of saturation extract (ECe). In line with ICOMERT recommendations, these Calciusterts with high exchangeable sodium percentage (ESP) (>15) and ECe (15 dS m^{-1} within 1 m soil surface), were classified as Halic (for high ECe) and Sodic (for high ESP) at the subgroup level (Bhattacharyya et al., 1994a).

Soil taxonomists in India observed characteristics of the "mollic" epipedon in many benchmark Vertisols of central India like Otur (Typic Chromusterts), Achmatti (Typic Pellusterts), Kagalgomb (Typic Chromusterts), and Hungund (Typic Chromusterts) series (Murthy et al., 1982a). Keeping in view the importance of both the vertic and mollic characteristics, Srivastava and Prasad (1992) proposed that "mollic" also should be included to the subgroup level within the great groups of Chromusterts and Pellusterts. Usually shrink–swell phenomenon in Vertisols is positively correlated with the content of expansible mineral (Franzmeier and Ross, 1968; Smith et al., 1985; Karathanasis and Hajek, 1985), as indicated by a high coefficient of linear extensibility (COLE) and clay content dominated by smectites. Despite this fact, kaolinitic and mixed mineralogy classes were recognized in shrink–swell soils at the family level (Soil Survey Staff, 1975). Studies on Vertisols from El Salvador (Yerima et al., 1985, 1987), for example, indicate that kaolinite-rich fine clay systems show high values of COLE. Green-Kelly (1974) observed that soils with equal amounts of kaolinite and smectite were similar to smectite alone. Hajek (1985) reported that the mineralogy class of a few Vertisols in the United States is kaolinitic. These observations were, however, exceptions in contrast to the common smectitic mineralogy class for most of the Vertisols of the world (Dudal and Eswaran, 1988).

It is well documented that shrink–swell behavior is primarily governed by the nature of clay minerals, particularly their surface properties. Although soils containing all other clays shrink and swell with changes in moisture content, these phenomena are particularly extreme in smectites (Borchardt, 1989). Moreover, if kaolinite is understood to be a clay mineral that does not expand on solvation, it is difficult to reconcile its high shrink–swell capacity as it is actually nonexpanding in character. This contradiction leads soil scientists to question the validity of mixed and kaolinitic mineralogy classes among the shrink–swell soils (Bhattacharyya et al., 1997). From a comprehensive study on the correlation between vertic properties and type of clay minerals it was suggested that vertic properties of soils can only be a function of smectite content, even though its content is small and cannot be induced by kaolinite, despite its presence in large amounts (Table 3). Interestingly kaolin rarely makes 1% in fine clay (<0.2 μm), which increases to 3 to 5% of the total mineral suite in total clay (<2 μm) in these Vertisols. This indicated a

Table 2. Proposed classification of selected Benchmark soils.

Soil series	District (state)	Soil taxonomy (subgroup) Existing (in 1988)	Soil taxonomy (subgroup) Proposed†	Soil taxonomy‡
Kheri	Jabalpur (Madhya Pradesh)	Typic Chromusterts	Udic Haplusterts	Typic Haplusterts
Linga	Katol (Maharashtra)	Udic Chromusterts	Udic Haplusterts	Typic Haplusterts
Aroli	Nagpur (Maharashtra)	Typic Chromusterts	Typic Haplusterts	Typic Haplusterts
Sarol	Indore (Madhya Pradesh)	Typic Chromusterts	Typic Haplusterts	Typic Haplusterts
Nimone	Ahmednagar (Maharashtra)	Typic Chromusterts	Aridic Haplusterts	Aridic Haplusterts

† Sehgal and Bhattacharjee, 1988.
‡ Soil Survey Staff, 2014.

Table 3. Soil and site characteristics of selected Vertisols and their intergrades.†

Soil series	District (state)	Geology (parent material)	Physiography	Climate region	MAT	MAR	MSL	Soil taxonomy
					°C	mm	m	
Jambori1	Pune (Maharashtra)	Deccan basalt (basaltic alluvium)	Plateau	Humid tropical	25.5	>5000	1100	Typic Hapludalfs
Jambori2	Pune (Maharashtra)	Deccan basalt (basaltic alluvium)	Plateau	Humid tropical	25.5	>5000	1100	Typic Hapludalfs
Selu	Wardha (Maharashtra)	Deccan basalt (basaltic alluvium)	Narrow entrenched valley	Sub-humid tropical	28.6	982	300	Vertic Haplustepts
Pokhari	Pune (Maharashtra)	Deccan basalt (basaltic alluvium)	Micro depressions on plateau	Humid tropical	25.5	>5000	1000	Vertic Eutropepts
Sholmarigaon	Morigaon (Assam)	Alluvium (Brahmaputra alluvium)	Flood plain	Humid tropical	24.9	1860	60	Vertic Haplustepts
Katur	Katni (Madhya Pradesh)	Sandstone (alluvium)	Plain land	Subhumid tropical	25.0	1250	500	Vertic Haplustalfs
Aroli	Nagpur (Maharashtra)	Deccan basalt (basaltic alluvium)	Piedmont plain	Subhumid tropical	26.9	1127	340	Typic Haplusterts
Sarol	Indore (Madhya Pradesh)	Deccan basalt (basaltic alluvium)	Piedmont plain	Subhumid tropical	24.4	1050	560	Typic Haplusterts

† Source: Shirsath et al. (2000); MAT, mean annual temperature; MAR, mean annual rainfall; MSL, mean sea level.

need to determine the minimum threshold value of smectite in the soil control section for the manifestation of vertic properties and to remove the existing ambiguity in the mixed mineralogy class. An endeavor by Shirsath et al. (2000) showed an excellent compatibility between the marked shrink–swell characteristics and smectitic mineralogy. These authors reported a significant positive correlation between COLE and the smectite content in the soil control section of selected soils (Fig. 1). The regression equation yielded a value of 20% for clay smectite content (linear extensibility, LE = 6) in the soil control section. Linear extensibility (LE) is measured within 100 cm of soils using horizon-wise COLE values (Soil Survey Staff, 2003). It is stipulated in US soil taxonomy (Soil Survey Staff, 1975) that the minimum value of LE is 6 for soils to be classified as "vertic." This means that soils with vertic properties must have a clay smectite >20% in the soil control section. The vertic properties in shrink–swell soils can, therefore, be manifested only if the soil contains a minimum threshold amount of 20% smectite. Therefore, for shrink–swell soils the mineralogy class should be only "smectitic." Later Bhuse et al. (2001) validated this model equation (Shirsath et al., 2000) and observed an excellent compatibility between semiquantitative estimates of clay smectite by X-ray diffraction analysis and quantitative content of smectite in Vertisols using Shirsath's model equation, which suggested that determination of LE value of Vertisols could be an improvised and less expensive method for quantitative estimation of clay smectite. Later a large number of Vertisols from the semiarid tropics of India was analyzed using the model of Shirsath et al. (2000) to estimate their smectite content (Bhattacharyya et al., 2007). This method can thus save time and energy to estimate mineral content albeit only for Vertisols developed mainly in the alluvium of the Deccan basalt.

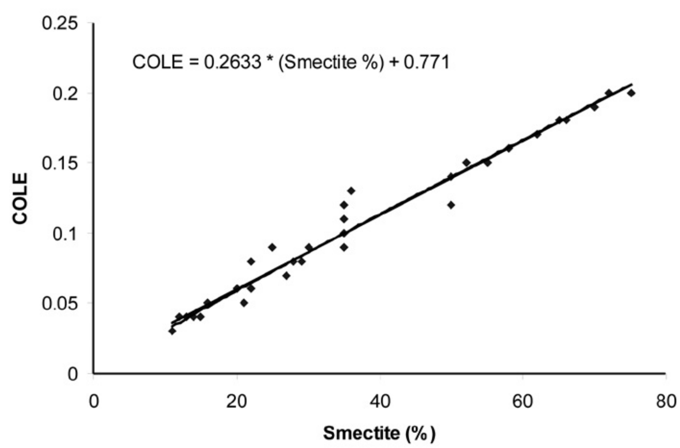

Fig. 1. Relation between coefficient of linear extensibility (COLE) and smectite content in soils (Source: Shirsath et al., 2000).

It is interesting to note that, other than the smectitic mineralogy class, US soil taxonomy (Soil Survey Staff, 2003) also provides a carbonatic mineralogy class for Vertisols and their intergrades. The conditions are that if carbonate (expressed as $CaCO_3$) plus gypsum, either in the fine-earth fraction (<2 μm) or in the fraction less than 20 mm in size (in the mineralogy control section) is >40% then the mineralogy class should be carbonatic. By and large, the Vertisols in India are calcareous (Pal et al., 2000a; Srivastava et al., 2002) with some exceptions (Bhattacharyya et al., 1993). In general, these calcareous Vertisols and their intergrades in India cover 229 million ha area (Pal et al., 2000a). However, many of these soils do not have $CaCO_3$ > 40% in their control section (Bhattacharyya et al., 2006, 2009b; Srivastava et al., 2002; Pal, 2003) (Fig. 2, Table 4). Nimone soils contain 40% $CaCO_3$ (Table 4) and thus qualify to have carbonatic mineralogy class at the family level of soil classification (Soil Survey Staff, 2003). But, it was observed that the presence of Ca-rich zeolites can obliterate the ill effect of inorganic C sequestered in these soils as $CaCO_3$.This is also evidenced by good crop performance in these soils (Table 5). The mineralogy class of Nimone soils, the authors (Bhattacharyya et al., 2009a) argued, should be smectitic in spite of >40% $CaCO_3$ in <20-mm fraction. However, Vertisols with true carbonatic mineralogy class may exist in absence of natural modifiers, which will lead to naturally degraded shrink–swell soils through the rapid process of inorganic C sequestration (Pal et al., 2009; Bhattacharyya et al., 2014). In view of contemporary natural chemical degradation process and geogenic presence of natural modifiers like Ca-zeolites and gypsum, the mineralogy class of US soil taxonomy should, therefore, be based on pedo-edaphic datasets (Bhattacharyya et al., 2009a).

The rationale for using ESP as 15 or more in one or more horizons within 40 cm of its upper boundary has been debated for diagnostic subsurface horizons like the natric (Soil Survey Staff, 1999). The presence of a natric horizon is characteristic of sodic soils. Compared to the critical limit of ESP value of 15 for deterioration of soil structure, many authors have argued that an ESP value of 6 could be limiting for soils with an abundance of fine clay and lacking in soluble salts (Shanmuganathan and Oades, 1983). Balpande et al. (1996) suggested that ESP of 5 should be used as the lower limit for sodic subgroups of Vertisols (without Ca-zeolite and gypsum) of central India, rather than 15 (Soil Survey Staff, 1994). They argued that even at such a low ESP of 5, these highly smectitic soils pose severe limitations for agriculture owing to the development of adverse physical conditions in terms of poor drainage (saturated hydraulic conductivity of less than 1 cm h^{-1}). It was also suggested that soils that do not contain smectite may not have the problem of drainage even at the ESP of 50 and above (Balpande et al., 1996).

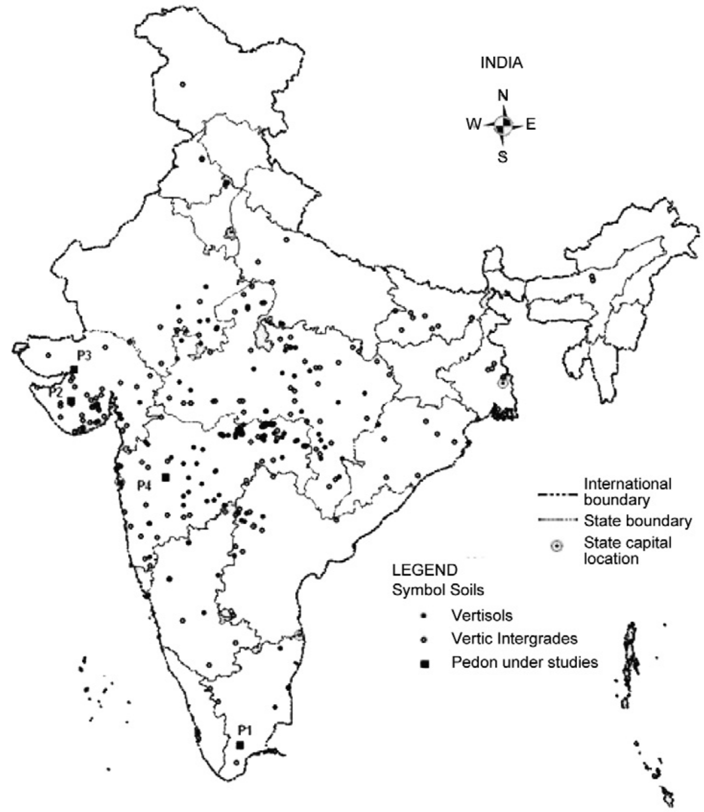

Fig. 2. Location of pedons representing shrink–swell soils (Vertisols and their intergrades) in India.

The presence of natural soil modifiers that have immense effects on the characteristics and use potential of soils has been a subject of study in soils (Ming and Mumpton, 1989) with special reference to the shrink–swell (Bhattacharyya et al., 2000b; Pal et al., 2006b) and associated red soils (Bhattacharyya et al., 1999a). Indian studies on Vertisols with Ca-zeolite (Pal et al., 2006b) indicate that a close relation between $CaCO_3$ of pedogenic and

Table 4. Calcium carbonate ($CaCO_3$) content in the selected Vertisols in different bioclimatic systems.

Bioclimatic system†	Rainfall	Soil series (pedon no.)‡	Soil classification	$CaCO_3$ (<20 mm)	Clay CEC	BS§	Soil mineralogy	
							Soil taxonomy¶	Proposed
	mm			%	cmol+ kg^{-1}	%		
Semiarid (dry)	660	Kovilpatti (P1)	Gypsic Haplusterts	12	91	100	Smectitic	Smectitic
Semiarid (dry)	635	Semla (P2)	Typic Haplusterts	18	98	108	Smectitic	Smectitic
Arid	533	Sokhda (P3)	Typic Haplusterts	33	73	115	Smectitic	Smectitic
Arid	520	Nimone (P4)	Sodic Haplusterts	42	63	110	Carbonatic	Smectitic

† Bhattacharyya et al. (2006).
‡ For pedon location please see Fig. 1. (Bhattacharyya et al., 2009b).
§ BS, base saturation.
¶ Soil Survey Staff (2003).

Table 5. Comparison of crop performance between carbonatic and noncarbonatic Vertisols†.

Crops	Crop yield	
	Carbonatic Vertisols (e.g., Nimone soil series)	Noncarbonatic Vertisols
	Mg ha^{-1}	
Sugarcane	150	90
Ratoon	75–90	60– 70
Cotton (irrigated)	1.8–2.0	1.8– 2.0
Wheat	4.5	3.0– 3.5
Sorghum (rainfed)	1.2	1.0– 1.2

† Source: Bhattacharyya et al. (2009b).

nonpedogenic origin (Pal et al., 2000a,b), and exchangeable Ca, Mg, and Na for the zeolitic sodic Vertisols exists. The release of Ca^{2+} ions from soil modifiers prevents a rise in pH and ESP and improves the soil hydraulic properties to obliterate the effect of high ESP. As suggested, the lower limit of sodicity at ESP > 40 for soils of the Indo-Gangetic Plains (IGP) (Abrol and Fireman, 1977), at ESP >5 but <15 for Indian Vertisols (Kadu et al., 2003), or the limit of ESP 6 for Australian soils or >15 for all soil types (Soil Survey Staff, 1999, 2003) appears to be redundant for the zeolitic sodic Vertisols of India. In view of the pedogenetic processes controlling the hydraulic properties of soils mediated through dispersibility, the most important factor for soil degradation (Sumner, 1995), grouping soils on the basis of saturated hydraulic conductivity (K_s) appears logical. A value of K_s < 1 cm h^{-1} (as weighted mean over the 0–100 cm soil depth) instead of existing ESP or SAR to group sodic soils from the nonsodic counterparts was recommended (Pal et al., 2006b). Table 6 indicates that despite being sodic, Sokhda soils (Vertisols) show a comparable K_s to Nabibagh, which is a Vertisol. In contrast, the Paral soils (Sodic Haplusterts) developed in nonzeolitic basalt alluvium have a high ESP value and also show much lower K_s values in most horizons (0.1–1.7 cm h^{-1}). It is worth mentioning that Vertisols commonly known as black soils, black cotton soils, regur, or Chernozems are also found as red in (Munsell) color (2.5YR hue). These soils meet all the parameters of Vertisols. This is in contrast to the commonly accepted colors of Vertisols, which range from 2.5 Y to 7.5 YR hue. These red Vertisols are formed in red bolls that are found as intertrappean in between Deccan basalt flows of the Peninsular India (Kolhe et al., 2011; Bhaskar et al., 2014).

Mollisols and Their Classification

Mollisols represent dark-colored, base-rich (mollic epipedon) soils of the steppes and cover extensive subhumid to semiarid areas of North and South America, Europe, and Asia. Most of the soils have a grass vegetation after they were deforested. Most of these soils formed in a prairie ecosystem, but they also occur in forests (Soil Survey Staff, 1999) (Table 7). Mollisols in the United States have formed mostly in Quaternary materials on gentle to moderate slopes. They occur in a wide range of landscapes ranging from flat alluvial plains to undulating plains and mountains (Fenton, 1983). The major intention of defining the mollic epipedon was to provide differentia to distinguish the soils that have traditionally been used to produce grain from those that are too

Table 6. Exchangeable sodium percentage (ESP) and hydraulic conductivity values of three representative Vertisols.†

Depth	Horizon	pH water (1:2)	$CaCO_3$	ESP	K_s	Type of basalt rock
cm			%		cm h^{-1}	
			Nabibagh soil (Typic Haplustert)			
0–23	Ap	7.8	3.8	0.6	1.5	Zeolitic basalt
23–42	Bw1	7.9	4.5	0.6	2.9	
42–81	Bss1	8.0	4.2	0.9	2.1	
81–122	Bss2	8.0	4.1	0.9	1.7	
122–150+	Bss3	8.0	5.3	0.9	1.1	
			Paral Soil (Sodic Haplustert)			
0–9	Ap	8.0	9.7	1.4	1.7	Nonzeolitic basalt
9–35	Bw1	8.2	9.9	4.1	0.5	
35–69	Bss1	8.4	10.2	8.1	0.2	
69–105	Bss2	8.4	10.4	14.2	0.3	
105–132	Bss3	8.5	10.2	16.7	0.1	
132–150	Bss4	8.5	11.8	21.0	0.1	
			Sokhda Soil (Calcic Haplustert)			
0–11	Ap	8.2	21.9	3.6	3.2	Zeolitic basalt
11–37	Bw1	8.4	21.4	4.4	3.0	
37–63	Bw2	8.7	21.5	9.1	1.5	
63–98	Bss1	8.8	22.0	16.2	0.4	
98–145	Bss2	8.6	21.6	28.0	0.2	
145–160	BC	8.5	11.6	31.3	2.1	

† Adapted from Pal et al. (2006a); ESP, exchangeable sodium percentage; K_s, saturated hydraulic conductivity.

Table 7. Proposed modification for Mollisol criteria.

Soil taxonomy category	Rationale	Remarks
Mollisol	With other criteria of US soil taxonomy (Soil Survey Staff, 1999, 2003) the thickness of mollic epipedon may be $\geq$18 cm (minimum thickness) (Olson et al., 2005).	1. The purpose is to accommodate eroded phase of Mollisols in the soil order. 2. The important fact is to adopt soil conservation measures to control soil erosion.

dry to cultivate without irrigation (Smith, 1983). These soils have been reported to be nonacidic and less weathered, concentrated mostly in temperate, semiarid, and humid climates. In contrast to the US taxonomic rational for the Mollisol order, acidic and fairly weathered Mollisols in the zeolitic Deccan basalt areas were reported in the hills of central and western India under forest in the present tropical humid climate (Bhattacharyya et al., 2005, 2006). These authors rationalized the concept of formation and persistence of the mollic epipedon in humid tropical environments. These Mollisols are formed due to better water storage effecting the retention of more soil organic matter to maintain the mollic epipedon. Better moisture storage was possible due to the presence of smectite having high surface area. The continuous supply of bases from Ca-zeolites of basalt is responsible for the stabilization of smectite in the humid environment (Bhattacharyya et al., 1993, 2006; Pal et al. 2006a). Formation and persistence of Mollisols in the hills of central and western India expands the basic rationale of the US soil taxonomy for the formation of a group of organic matter-rich, dark colored, Ca-saturated, soft, clayey, smectitic, but acidic Mollisols (Table 8).

Mollisols have been considered an important group of soils, showing high quality in terms of supporting vegetation through sustained release of nutrients. Many Mollisols once under forest and now under cultivation are subjected to erosion due to loosening of soils on slopes. Since Mollisols are primarily based on the identification of the mollic epipedon, the eroded phase often may not permit such soils to be grouped under the Mollisol order; instead those soils are classified as mollic intergrades of Alfisols, Inceptisols, and Entisols. Due to erosion causing such conversion of soil order, Mollisols in the sub-Himalayan foothill areas of India at present qualify as Alfisols due to intense agricultural activities during the last few decades (Pal et al., 2012). In the United States, a criterion was proposed to reduce the minimum thickness requirement of the mollic epipedon from 25 to 18 cm as an amendment to US soil taxonomy, and this would apply to only those soils subjected to accelerated erosion due to cultivation (Olson et al., 2005) (Table 7). Although such an amendment would permit once shallow intergrades of other soil orders to group as Mollisols, nevertheless the loss of fertile topsoils cannot be restored by this rationale.

Alfisols, Ultisols, Oxisols, and Their Classification

Although development of soil survey and US soil taxonomy marked a significant accomplishment for morphological

Table 8. Mollisols formed in weathered basalt from Western and Central India.†

Depth	Horizon	Elevation	Land use	Munsell color (moist)	Structure‡	Clay (<2 μm)	AWC§	pH water	Organic C	CEC¶	COLE#	Smectite	Zeolite
cm		m above msl††							g kg^{-1}	cmol+ kg^{-1}		%	
Vertic Haplustoll, Village Gunjhari, district Mandla, Madhya Pradesh, India													
0–6	A1	850	Forest (*Tectona grandis, Madhuka indica*)	5YR 2.5/1	1f gr	30	15	5.9	35	52.2	0.11	32	16
6–20	A2			5YR 2.5/1	1f gr	39	16	5.8	30	59.8	0.12	31	22
20–37	Bw1			5YR 2.5/2	1f sbk	29	18	5.8	20	59.8	0.11	36	17
37–74	Bw2			5YR 2.5/2	2m sbk	31	18	5.9	12	67.4	0.14	31	16
74–106	Bw3			5YR 4/3	2m sbk	31	19	5.6	8	71.7	0.16	38	18
106–150	Bw4			5YR 4/3	2m sbk	28	19	5.5	5	73.9	0.16	38	18
Vertic Argiudoll, Village Nigdale, district Pune, Maharashtra, India													
0–15	A1	1150	Forest (*Terminalia chebula, Carissa caranades, Ficus glomerata*)	7.5YR 3/2	1f gr	51	15	5.7	20	18.6	0.10	29	Nil
15–40	Bw			7.5YR 3/2	1f gr	53	17	5.7	12	18.5	0.14	24	Nil
40–74	Bt1			5 YR 3/3	2m sbk	61	18	5.7	7	18.7	0.16	20	Nil
74–108	Bt2			2.5YR 3/4	3c sbk	61	17	6.1	4	18.6	0.17	25	Nil
108–146	Bt3			2.5YR 3/4	2m sbk	59	18	6.1	3	18.7	0.15	26	Nil
146–175	BC1			2.5YR 3/4	2m sbk	53	18	6.1	1	20.0	0.13	23	Nil
175–190	BC2			2.5YR 3/4	2m sbk	51	15	6.1	1	19.5	0.13	17	Nil

† Source: Bhattacharyya et al. (2006).
‡ 1f gr, weak fine granular; 1f sbk, weak fine subangular blocky; 2m sbk, moderate medium subangular blocky; 3c sbk, strong coarse subangular blocky.
§ AWC, available water content.
¶ CEC, cation exchange capacity.
# COLE, coefficient of linear extensibility (Schafer and Singer, 1976).
†† msl, mean sea level.

description and classification of soils with considerable precision, some properties are still inadequate for accurate evaluation in the field. Because of the serious difficulty for positive field identification of clay skins in highly weathered soils (Beinroth, 1982; Rebertus and Buol, 1985), the kandic horizon introduced in US soil taxonomy was often used for classification of soils showing advanced weathering stages in the humid tropical to subtropical parts of the world. The northeastern part of India includes many such soils (Bhattacharyya et al., 1994b; Sen et al., 1994) (Table 9). Using the criteria of US soil taxonomy (Soil Survey Staff, 1999), a few selected soils from Manipur and Meghalaya were classified as Ultisols since cation exchange capacity (CEC) and effective cation exchange capacity (ECEC) of clay supported the presence of kandic horizons instead of grouping them into Inceptisols (Soil Survey Staff, 1975). The increase in KCl-extractable Al with depth, particularly in parent materials, suggests a relation to the amount of weatherable aluminosilicates present in soil and parent material that indicate that these soils have crossed the stage of Inceptisol (Inception) to reach the Ultisol stage. The "kandi" group of Alfisols and Ultisols are common in India. The introduction of this subsurface diagnostic horizon and inclusion of "kanhapl" intergrade helped group many low activity clay Inceptisols into Alfisols (>35% base saturation) or Ultisols (<35% base saturation). Although the Inceptisols have been grouped properly as Kandi (c) Alfisols and/or Ultisols, the formation and existence of Oxisols have been debated (Chandran et al., 2005; Pal et al., 2014). The kandic horizon provides a basis for differentiation among soils with clay accumulation in the subsoils. The presence of an argillic horizon could not explain the diagnostic criteria to differentiate all Ultisols and Alfisols from Oxisols and Inceptisols. The proposed kandic horizon is such a diagnostic horizon that it can separate low CEC Ultisols and Alfisols (comparable to Oxisols but not Oxisols; see Table 10) from the high CEC Ultisols and Alfisols. The important property of Oxisols is that they should be almost devoid of weatherable minerals (<10%), and thus further weathering may not supply nutrients for sustaining plant growth. Moreover, the advanced stage of weathering might obliterate the boundary differentiation between horizons and as such clay films may be absent (Table 11). The conditions for their formation in the tropical climate with stable landscape and siliceous/acidic parent material are available in the Indian subcontinent, yet Oxisols are not reported (Bhattacharyya et al., 1993, 2000a; Krishnan et al., 1996; Sen et al., 1999; Velayutham and Bhattacharyya, 2000).

Oxisols with a higher amount of extractable acidity were reported from Puerto Rico (Beinroth, 1982). The dominant presence of minerals such as kaolinite and gibbsite (Jones et al., 1982)

Table 9. Use of argillic and kandic subsurface diagnostic horizons in grouping of north-eastern India. †

Depth	Diagnostic horizons	Clay (<2 μm)	Organic carbon	pH (1:1) Water	pH (1:1) KCl	KCl extractable cations Al^{3+}	KCl extractable cations Total bases	Clay ECEC	Clay CEC
cm		%	g kg^{-1}			cmol(p+) kg^{-1}			
				Typic Kandihumult (Manipur)					
38–86	Argillic	52.5	9.0	4.7	3.5	5.4	0.9	12.0	16.4
86–120	Kandic	51.5	6.0	4.8	3.6	5.3	0.6	11.4	15.1
				Typic Haplohumult (Manipur)					
14–50	Argillic	36.6	16.0	3.9	3.7	1.2	1.2	8.7	26.2
				Typic Haplohumult (Manipur)					
33–76	Argillic	43.3	10.0	4.8	3.6	4.2	1.6	13.4	21.9
				Typic Kandihumult (Meghalaya)					
31–62	Kandic	31.1	20.0	5.0	4.8	Nil	0.8	2.6	13.2
62–95	Kandic	26.5	6.0	5.1	6.0	Nil	1.2	4.7	16.0

† Adapted from Bhattacharyya et al. (1994b); ECEC, effective cation exchange capacity; CEC, cation exchange capacity.

Table 10. Salient characteristics of kandic and oxic subsurface horizons in Alfisols, Ultisols and Oxisols.

Diagnostic horizon	Alfisols	Ultisols	Oxisols
		Kandic/Oxic	
Apparent CEC (cmol(p+) kg^{-1} clay)	≤16	≤16	≤16
Apparent ECEC	≤12	≤12	≤12
Presence of clay films	may/may not	may/may not	No
		Clay increase	
· when < 15% clay in surface	≥3% (absolute)	≥3% (absolute)	<3% (absolute)
· when 15–40% clay in surface	≥20% (relative)	≥20% (relative)	<20% (relative)
· when > 40% clay in surface	≥8% (absolute)	≥8% (absolute)	<8% (absolute)
Weatherable minerals	–	–	<10% (50–100 μm fractions)
Horizon boundary (inferred)	clear	clear	diffuse

Table 11. Classification of Indian soils into Inceptisols, Ultisols, and Alfisols.

Soil taxonomy category	Rationale	Remarks
Soil orders—Inceptisols, Ultisols, Alfisols	If clay illuviation {ratio of clay (<2 μm)} in B horizons and A horizons ~1.2) identified from clay data but clay skins not identified in the field by 10X lens then "Method 1" (under Remarks) or by "Method 2" (under Remarks) will help in deciding soil order either as Alfisols/Ultisols (depending on base saturation criterion, Soil Survey Staff, 2003) or as Inceptisols.	"Method 1": Decrease in clay mica (<2 μm) with depth can be considered as incontrovertible evidence of clay illuviation (Pal et al., 1994; Pal 1997; Srivastava et al. 1998). "Method 2": Determination of total extractable acidity by $BaCl_2$–TEA, 1N KCl extractable H^+ and Al^{3+}. Estimation of CEC by sum of cations, ECEC, CEC clays and base saturation to confirm the presence of kandic horizon. If yes, soils may be grouped as Alfisols (if BS > 35%, BS to be determined by sum of cations) or Ultisols, if otherwise. If not, these soils will be grouped as Inceptisols. Comment 1: If these two methods are not followed the soils may be mistakenly grouped as Inceptisols. Comment 2: If base saturation not determined by sum of cations these soils (with kandic horizon) may mistakenly be grouped as Alfisols instead of Ultisols (Soil Survey Staff, 2003; Bhattacharyya et al., 1994b).
Subgroups	A. Calciustepts and Haplustepts may be grouped as† (i) Sodic Petrocalcic Calciustepts or (ii) Fluventic Sodic Calciustepts or (iii) Sodic Haplustepts or (iv) Fluventic Sodic Haplustepts if exchangeable sodium percentage (ESP) ≥15 B. Haplustepts may be grouped as Sodic Haplustepts if EC (dS m^{-1}) × thickness ≥900	ESP = (Exchangeable Na/CEC) × 100
Family level viz. mineralogy class of kandic Alfisols, and Ultisols and Oxisols‡	Mineralogy class should be mixed, if · clay CEC of sum of cations§ in soil control section¶ ≥ 24 cmol(p+) kg^{-1} (Smith,1986) (Method 1), even if · gibbsite content in < 2 mm fraction of soil is > 18%# in the soil control section (Chandran *et al.*, 2005) (Method 2)	Method 1: Clay CEC (sum of cations) = [exchangeable bases (NH_4OAc pH 7.0) + $BaCl_2$ = TEA acidity)/clay %] × 100 Method 2: semi-quantitative estimates of gibbsite content through X-ray diffraction analyses of clay samples (<2 μm) (Also see Chandran et al. 2005).††

† Saxena et al. (2004).
‡ Formation of Oxisols may be difficult to reconcile (Chandran et al., 2005).
§ Clay CEC of sum of cations should be an `important criterion for kandic Alfisols and/or Ultisols.
¶ Soil control section (SCS) is defined by a depth of 25 cm to (i) a lithic contact if it is within a depth of 1m (ii) a depth of 1m if regolith is >1 m thick (Soil Survey Staff, 1975).
# Mineralogy class, Allitic if gibbsite content 18–40% and Gibbsitic if >40% (Soil Survey Staff, 2003).
†† Gibbsites are not a product of contemporary pedogenesis and thus may not be considered for grouping present day soils so far as mineralogy class is considered (Also see Bhattacharyya et al., 2000b).

in these soils appear inconsistent in terms of their grouping to Oxisols. The clay CEC (>16 cmol+ kg^{-1} clay) also negates the presence of an oxic horizon reported from Oxisols of Brazil (Macedo and Bryant, 1987). In the Ultisols of Kerala, popularly known as laterite and/or lateritic soils, the presence of mica and hydroxy-interlayered vermiculite is common along with a dominant amount of gibbsite and kaolin-hydroxy-interlayered vermiculite (K/HIV). These soils also contain dominant proportion of gibbsites. Formation of gibbsites in the presence of 2:1 minerals discounts the hypothesis of antigibbsite effect (Jackson, 1963, 1964). An in-depth study of international reference on the laterites (Ultisols) in the state of Kerala indicated inconsistency in soil grouping (order) and the assignment of mineralogy class (Chandran et al., 2005). These authors envisaged that the transformation of Ultisols to Oxisols with time could be difficult to reconcile not only in the tropical part of India, but also elsewhere (Bhattacharyya et al., 1994b; Pal et al., 2012, 2014). This is notwithstanding the fact that there are reports of Oxisols in India (Nair and Chamuah, 1988; Murthy et al., 1982b) and elsewhere (Beinroth, 1982; Macedo and Bryant, 1987; Soil Survey Staff, 1999).

Many of the micaceous soils of the IGP of northwestern India are sodic and have a clay-enriched textural B horizon. These Alfisols sometimes lack identifiable clay skins, leading to their placement in the Inceptisol order. It was reported that the decrease in clay mica (<2 μm) with depth in the profile can confirm clay illuviation when clay skins are difficult to identify in the field (Pal et al., 1994; Pal, 1997). Recently Bhaskar et al. (2009) reported that soils of the Shillong Plateau, Meghalaya, India supporting the growth of pine forest had high extractable Al^{+3} content (>50%) in the Bt horizon and proposed a new subgroup (Alumic Hapludults). The concept of a Modic subgroup in Ultisols, showing an excellent environment for aerobic respiration has also been proposed (FAO, 1998; Bhaskar et al., 2009).

The influence of clay minerals in plant nutrition is known. While studying the relation between physiography and land use, a close relation was observed in soils of the hilly terrain of northeastern India. The hillocks (*tilla* lands) used mostly for rubber and horticultural crops are dominated by soils with <35% K/HIV (Table 9 and Fig. 3). High hills covered under forest are dominated by soils with 35 to 50% K/HIV, and valleys growing paddy (agriculture) are dominated by soils with >50% K/HIV. In the humid tropical weathering environment in India, the presence of vermiculite/high charge smectite is common. Minerals in clay fractions have not yet weathered to reach the stage of kaolinite. Thus, the mixed mineralogy class appears to be more appropriate for these soils. During humid tropical weathering, huge quantities of Al^{3+} ions are liberated to cause higher acidity (H^{+}), which was estimated as 149 kg ha^{-1}. It is reported that vermiculites adsorb Al^{3+} ions as hydroxy-cations to form kaolin-hydroxy interlayered vermiculites/kaolin-hydroxy interlayered smectites (HIV/HIS). The vermiculite minerals thus act as a natural sink to sequester Al^{3+} ions. A representative acid soil of Tripura state, representing the northeastern region of India, can sequester 65 kg ha^{-1} of Al in the first 30 cm depth. This is the reason these soils show a relatively high proportion of HIV effecting lower concentration of Al^{3+} ions in the soil solution (see Tables 12 and 13), which explains the importance of mixed mineralogy class in their appropriate grouping in soil classification (Bhattacharyya et al., 2010).

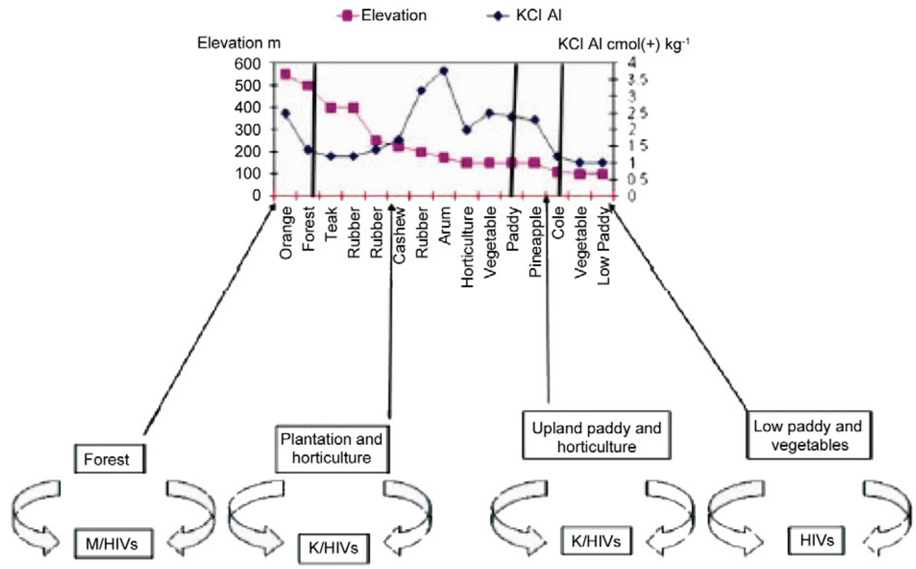

Fig. 3. Soil information system in terms of its various parameters and land-use options in Tripura (M/HIVs, mica-hydroxy-interlayered vermiculite; K/HIVs, kaolin-hydroxy-interlayered vermiculite mineral in clay fractions). Source: Bhattacharyya et al. (2010).

Table 12. Soil information system vis-à-vis clay mineralogy and land use in Tripura.†

Physiographic position	HIS	HIV	K/HIV	Land use	Elevation ranges	KCl-Al
		%			m above msl	cmol(+) kg^{-1}
High hills	10–20	17–20	35–50	Forest	>400	1.5–2.5
Tilla lands	<10	<17	<35	Horticulture, plantation, agriculture	400–250	2.0–4.0
Valleys	>20	>20	>50	Agriculture	<250	<1.0

† Source: Bhattacharyya et al. (2010). HIS, hydroxy-interlayered smectites; HIV, hydroxy-interlayered vermiculites; K/HIV, kaolin interstratified with HIV.

Table 13. Soil taxonomy rationale for mineralogy classes for all orders.

Soil taxonomy category	Rationale	Remarks
Family mineralogy class	Mineralogy class of soils should be mixed (Smith, 1986)† if · clay CEC 24–40 cmol(p+) kg^{-1} in the SCS‡ and · soils do not qualify for (a) ferritic, (b) gibbsitic/sesquic, (c) ferruginous, (d) allitic, (e) kaolinitic, (f) halloysitic mineralogy classes (Soil Survey Staff 2003).	Clay CEC = [soil CEC (NH_4OAc pH 7.0)/clay %] × 100

† Also see Bhattacharyya et al. (1997).
‡ SCS, soil control section.

Inceptisols and Their Classification

The Inceptisols are considered as the last option to group a particular soil not meeting the criteria of other soil orders. As a result, many genetically and morphologically unrelated soils have been grouped as Inceptisols (Dhir, 2004). In India nearly 40% of soils are classified as Inceptisols (Bhattacharyya et al., 2009a), the corresponding figure for the world is 15.2% (USDA, 2006). The Inceptisols in India included red soils dominated by mixed/kaolinitic mineralogy class and black soils dominated by smectites with pH ranging from strongly acidic to slightly alkaline. Introduction of the kandic horizon has brought many red and hilly soils into the orders Alfisols and/or Ultisols. The benefit of introducing the kandic horizon may, however, be realized only when information on bases obtained from $BaCl_2$–TEA of the acid soils was used for US soil taxonomy (Bhattacharyya et al., 1994b).

The black (shrink–swell) soils of India are characterized by dark color, low chroma, and low organic matter. Many such soils, due to their shallow depth (<50 cm) are grouped under Inceptisols and mostly under vertic subgroups (Soil Survey Staff, 1975). Over time, the framework of soil grouping has undergone several modifications (Soil Survey Staff, 1975, 1987, 1999, 2003). The concept of grouping shallow black soils as proposed by Srivastava et al. (1990) into a "Leptovertic" subgroup has finally found a place in the Vertisol order as Leptic Haplusterts (Soil Survey Staff, 2003). Earlier, Inceptisols were keyed out at the suborder level on the basis of moisture regime (Aquepts), temperature regime (Tropepets), epipedons (Plaggepts, Ochrepts, Umbrepts), and presence of volcanic ash materials (Andepts) (Soil Survey Staff, 1975). Later the revised US soil taxonomy stressed more importance on the soil moisture regime to key out the suborders (Aquepts, Ustepts, Xerepts, and Udepts). Plaggepts were revised as Anthrepts. The cryic soil temperature regime found a place in the suborder (Cryepts). Tropepts, Ochrepts, and Umbrepts were removed. Andepts found a place in the suborder level of the new order Andisol (Soil Survey Staff, 2003). Aquepts were revised to include Epiaquepts and Endoaquepts at the great group level, keeping in mind the recommendation of the International Committee on Aquic Moisture Regimes (Soil Survey Staff, 1999). Aquic conditions in the soil system are those that undergo continuous or periodic saturation and reduction while the elements of aquic condition, such as type of saturation, degree of reduction and redoximorphic features were detailed by the committee, but the duration of saturation for creating an aquic condition was not specified. Out of the three types of saturation, such as endo, epi, and anthric saturation, the first two found places in the great group (e.g., in Inceptisols, they are Endoaquepts and Epiaquepts, respectively). Anthric condition has been referred as a variant of episaturation, which is usually associated with controlled flooding (e.g., in India for cropping in wetland paddies). This condition causes reduction process in the saturated and puddled surface soils with alternate oxidation during unsaturated conditions. Although the "Anthraquic" condition has been included in US soil taxonomy, this special type of saturation does not find any place in the great group and subgroup level. In absence of that, most of the soils in the IGP and other rice growing areas of India qualify for episaturation.

Salt-Affected Soils and Their Classification

The sodic (alkali) soils of the northwestern part of the IGP with high salts, ESP, pH, chromas and yellower hues key out as Typic or Aquic Calciorthids, Camborthids, and Haplustalfs, which does not spell out their saline-sodic nature (Sehgal et al., 1975). For land-use recommendations, the authors believed it will be useful to set these soils apart at some high categoric level in the system. Accordingly they proposed that the structural requirements for the natric horizon be modified to include horizons with high ESP ($\geq$40) but having simple blocky structure with or without tongues of eluvial material. New subgroups, namely Natric, within the orders of Inceptisols, Alfisols, and Aridisols are suggested for the high sodium-saturated soils lacking Natric horizons. For similar practical considerations, the high concentrations of salts in soils when associated with high ESP pose problems in leaching and consequently new subgroups, Salic and Salic Natric, within the orders of Aridisols and Alfisols were suggested. Salt-affected soils occupy 6.65 million ha area in India, nearly 36% of which occur in the IGP (Verma et al., 2007). The soils of recent floodplains irrespective of containing water soluble salts are classified as Aquepts and Ustepts. US soil taxonomy (Soil Survey Staff, 2003) may not thus serve the purpose of differentiating nonsaline/nonsodic soils with saline and/or sodic soils with special reference to the IGP, India (Verma et al., 2007). These authors proposed sodic intergrade for soils with ESP >15 to depict the actual soil properties. Similarly, for the salt-affected soils of active alluvial plains of the Indo-Gangetic Plains, India there is a need to introduce "salic" and "sodic" intergrades to the subgroup level depending on their properties for their meaningful interpretation for management (Verma et al., 2007) (Table 14). The soil map of India (NBSS & LUP Staff, 2002) indicated many sodic soils in the semiarid tract grouped into Aquepts, Udepts, Ustepts, Ustifluvents, and Ustorthents and thus ignored the sodic properties of these soils. The proposed classification of such salt-affected soils indicates actual soil properties depicting soil quality (Sehgal et al., 1986; Saxena et al., 2004; Verma et al., 2007) (Table 15).

Paleosols, Polygenetic Soils, and Their Classification

Paleosols are not covered by the US soil taxonomy since the concept was not endorsed by the USDA (Soil Survey Staff, 1999), yet paleopedologists have made efforts to apply US soil taxonomy in the study of paleosols. Paleosols are formed in a landform of the past (Ruhe, 1956; Yaalon, 1971) and can be either buried or nonburied. US soil taxonomy recognizes a soil as buried when it is covered by new soil material of at least 50-cm thickness (Soil

Table 14. Proposed subgroups of salt-affected soils of the Indo-Gangetic Plains. †

Existing soil subgroups	Proposed soil subgroups	Remarks
Petrocalcic Calciustepts	Sodic Petrocalcic Calciustepts	Soils with petrocalcic horizon and high ESP (>15)
Fluventic Calciustepts	Fluventic Sodic Calciustepts	Soils (Calciustepts) with high ESP (>15)
Typic Haplustepts	Sodic Haplustepts	Soils (Haplustepts) with high ESP (>15)
Fluventic Haplustepts	Fluventic Sodic Haplustepts	Soils (Haplustepts) with high ESP (>15)
Typic Haplustepts	Salic Haplustepts	Soils when EC (dS m^{-1}) $\times$ thickness $\geq$ 900
Typic Ustifluvents	Sodic Ustifluvents	Soils with ESP > 15
Typic Ustorthents	Sodic Ustorthents	Soils with ESP > 15

† Source: Verma et al. (2007).

Table 15. Grouping Entisols in India: logic.

Soil taxonomy category	Rationale	Remarks
Subgroup	Ustifluvents and Ustorthents should be grouped as sodic if exchangeable sodium percentage (ESP) $\geq$ 15 (Verma et al., 2007)	ESP = (exchangeable Na/CEC) $\times$ 100
Family level viz. Mineralogy class	Mineralogy class should be smectitic for all the shallow soils (Lithic Ustorthents) developed in the weathered basalt in Western and Central India	Mineralogy class may be confirmed by · Detailed investigations on clay minerals through X-ray diffraction technique or · estimating clay CEC [(soil CEC/clay%) $\times$ 100] (Smith, 1986; Bhattacharyya et al., 1997) · determining coefficient of linear extensibility (COLE) (Soil Survey Staff, 2003; Schafer and Singer, 1976) of soils.

Survey Staff, 1994). A covered surface of colluvium or landslide material of $\geq$50-cm thickness should, therefore, be considered a paleosol. The surface of these paleosols over a period of years will form the present-day soil to be surveyed and classified. The description of these soils may not highlight the existence of buried soil lying below the deeper layers. When environmental conditions change over a period, nonburied surfaces can become paleosols. The Paleopedological Sub-Commission recommended that only when the type or direction of soil forming processes changes, the soils are recognized as paleosols. Yaalon (1995), however, did not favor including such soils as paleosols. Besides, there are polygenetic soils showing different diagnostic features indicating more than one climatic episode (Pal et al., 1989, 2000b; Srivastava et al., 1998). Such soils, for example, ferruginous soils of southern Peninsular India, overlying the saprolites of metamorphic rocks and dominated by kaolinite or dioctahedral smectites, have been reported as relict paleosols (Pal et al., 1989; Chandran et al., 2000). Some authors also related color and ratios of various sand sizes with silt to indicate paleosols (Bronger and Bruhu, 1989; Dutta et al., 2001) from southern Peninsular India. These relict soils have been influenced by the climatic change from humid to drier conditions during the Plio-Pleistocene transition period. Alluvial soils that are older than 2500 yr BP of the central IGP are relict paleosols that experienced three climatic episodes during the Holocene period (Srivastava et al., 1998). The grouping of Vertisols in India shows a predominantly ustic moisture regime as evidenced by Usterts as the dominant suborders. It has been reported that reduced moisture formation of pedogenic calcium carbonate could lead to form the subsoil sodicity leading to different types of Vertisols at the subgroup and the great group levels even in the semiarid environment. We have identified a series of Vertisols in a climosequence (ranging from humid to arid bio climates), from Typic Haplusterts to Udic/Aridic/Sodic Haplusterts and finally to Sodic Calciusterts (Pal et al., 2000b, 2009; Pal, 2003) (Fig. 4). Soil taxonomic grouping can thus be a tool to trace the signatures of climate change.

Paleosols were grouped at various levels of suborders and subgroups of US soil taxonomy (Retallack, 1990). In India, an effort was made to group buried soils from Andhra Pradesh (Ray and Reddy, 1997). Soil-site characteristics indicate that these soils may be buried by allochthonous overburden forming a double profile. The authors (Ray and Reddy, 1997) suggested a Thapto-Tropofluventic subgroup of a Vertisol (Haplustert) and of an Inceptisol (Ustropept/Haplustept). Soil Survey Staff (1994) used thapto (Greek "thaptein" meaning "bury") to represent a buried Histosol or a buried histic epipedon. These authors used "thapto" to indicate any buried Entisol with fluvial characteristics in the tropical climate and also suggested a Thapto-Haplustalfic subgroup for a buried Alfisol (Ray and Reddy, 1997). There are efforts to identify the Paleosols according to the approaches of US soil taxonomy, first by recognizing the diagnostic horizons and other pedogenic features (Retallack, 1990, 1993). However, because many ancient buried Paleosols are often incomplete and difficult to reconstruct, even experienced workers find it difficult to recognize diagnostic features of the US soil taxonomy or the FAO scheme (Yaalon, 1995). Despite this difficulty the paleopedology community favored developing a separate soil group (Soil Survey Staff, 2003).

Conclusions

The main purpose of soil survey has always been to find the best fit in the overall framework of US soil taxonomy, as shown in this article. The rationale of US soil taxonomy lies in developing the same criteria at different categories. Since the concept of each taxonomic class is purpose-specific, comparisons of the merits of different types of taxonomy should always be made with taxonomies based on similar purposes.

Until the Seventh Approximation stage of US soil taxonomy, Indian soil scientists classified soils following the best fit. The interesting part of US soil taxonomy has always been its scope for improvement. This, in other words, as felt by many, indicates that this system should not be considered final since appropriate reasoning might always open a new category in the overall framework. Many scientists, actively engaged in soil survey, mapping, and classification have suggested new rationale for US soil taxonomy at various categorical levels. A commentary of such selected novel ideas from the Indian scientists is documented in this article, which could be used as an inspiration for researchers, students, and pedologists and could encourage them to bring forth many new concepts in this particular field.

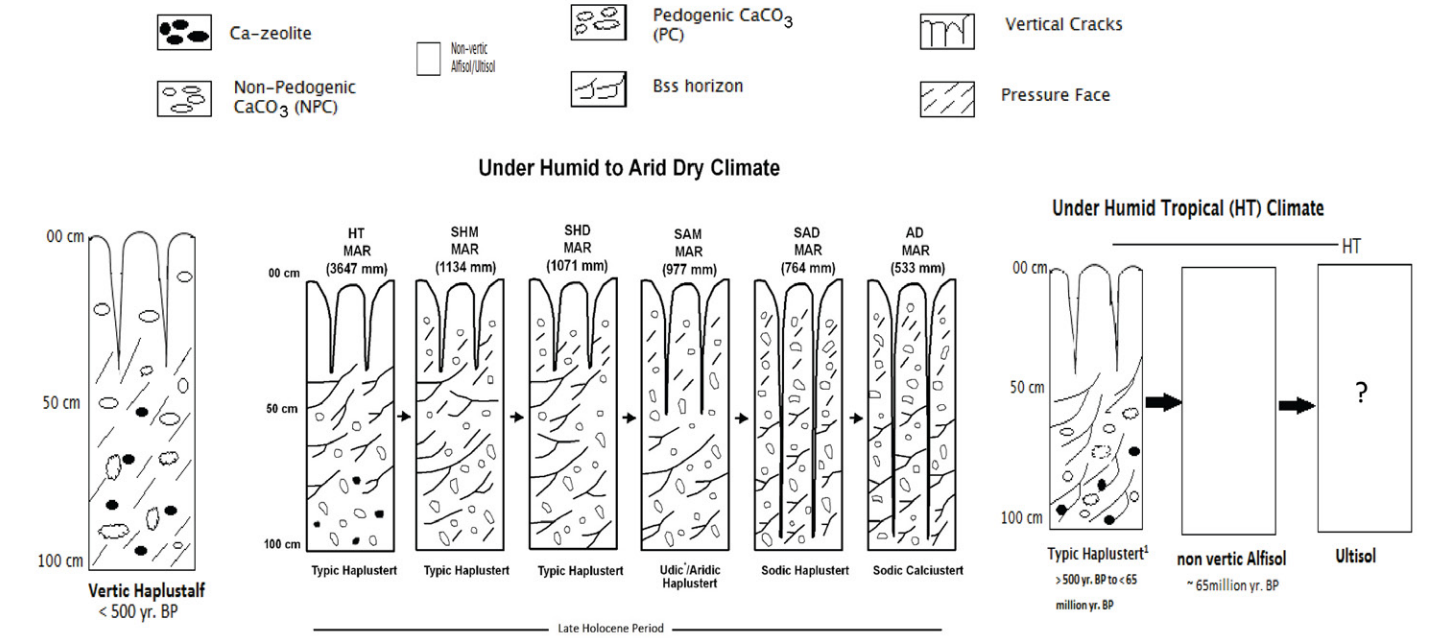

Fig. 4. Relation between climate and soil classification showing successive stages of pedogenic evolution in Vertisols of the drier tracts vis-a-vis those in the humid ecosystems. This links soil taxonomy with climate change signatures and the Paleosols. (HT, humid tropics; MAR, mean annual rainfall; SHM, sub humid moist; SHD, sub humid dry; SAM, semiarid moist; SAD, semiarid dry; AD, arid.)

Over the years many researchers have found the US soil taxonomy wanting in terms of grouping a particular type of soil. Many articles have been written in many scientific journals to address these issues, a few of which have been covered in this manuscript. This has immensely enriched the soil classification literature. It is hoped that many such works might find acceptance in the revised version of US soil taxonomy in future days. With the availability of electronic communication, "Rationale of Soil Taxonomy" is addressed through National Cooperative Soil Survey (NCSS) newsletter. It is hoped that with time, new concepts in basic pedology shall continue to strengthen the rational of US soil taxonomy to make it wholesome and user friendly.

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