REVIEW ARTICLE

Soils of India: historical perspective, classification and recent advances

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Derived from a wide range of rocks and minerals, a large variety of soils occur in the Indian subcontinent. Soil-forming factors like climate, vegetation and topography acting for varying periods on a range of rock formations and parent materials, have given rise to different kinds of soil. The National Bureau of Soil Survey and Land Use Planning, Nagpur has developed a database on soils with field and laboratory studies over the last 30 years. This has generated maps and soil information at different scales, showing area and distribution of various soil groups in different agro-ecological subregions. The 1 : 250,000 scale map shows a threshold soil variation index of 4–5 and 10–25 soil families per m ha for alluvial plains and black soil regions respectively. Progress in basic and fundamental research in Indian soils has been reviewed in terms of soils, their formation related to climate, relief, organisms, parent materials and time.

Keywords. Parent materials, soil-forming factors, soil categories, soil map, rock formations.

KNOWLEDGE on the potential of soil resource and its limitations, present use and the methods of management for sustained production, is vital for the use of soil for production purposes. India can be called a land of paradoxes because of the large variety of soils. A girdle of high mountains, snow fields, glaciers and thick forests in the north, seas washing lengthy coasts in the Peninsula, a variety of geological formations, diversified climate, topography and relief have given rise to varied physiographic features. In the country, temperature varies from arctic cold to equatorial hot; rainfall from barely a few centimetres in the arid parts, to per-humid with world's maximum rainfall of several hundred centimetres per annum in some other parts. These conditions provide for a landscape of high plateaus, stumpy relic hills, shallow open valleys, rolling uplands, fertile plains, swampy low lands and dreary barren deserts. Such varied natural environments have resulted in a great variety of soils in India compared to any other country of similar size in the world. It is no wonder that with such a setting for soil formation, the early Indian soil scientists, located in different parts of the country, were attracted to a systematic study of soil genesis and classification[1].

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Beginning of soil study

The earliest investigations on soils of India by Voelcker dates back to 1893 and by Leather to 1898. They categorized the soils of the country into four major groups, namely the Indo-Gangetic alluvium, the black cotton soil or *regur*, red soil and laterite soil. Schokalskaya published a soil map of India in 1932 following the Russian concept and described 16 soil groups based on climate, vegetation, soil-forming materials, salinity, alkalinity, swamps and peats. In 1935, Wadia and his co-workers compiled a soil map of India with emphasis on geological formations and classified the soils as red, black (*regur*), laterite and lateritic soils of Peninsular India, delta, desert, *bhabar*, *terai* and alkali soils of the Indo-Gangetic Plains (IGP). Vishwanath and Ukil[2] published a soil map of India by placing the soils in different climatic zones. Integrating the effects of climate, vegetation and topography, 16 major and 108 minor soil regions were identified and brought under 27 units by Raychaudhari *et al.*[3]. Later a revised soil map of India was generated with 23 major soil groups under FAO/UNESCO's scheme on World Soil Map project. This map was refined with 25 broad soil classes represented on a 1 : 7 million scale map[4].

Table 1. The extent and distribution of the different soil classes of India as represented in the soil maps on 1 : 250,000 scale along with their equivalent according to United States Department of Agriculture, USA nomenclature system

Major soils (traditional name)	Extent ‘000 ha	Extent Percentage	Distribution in states	Soil orders US soil taxonomy
Alluvial	100,006	30.4	J&K, HP, Punjab, Haryana, Delhi, UP, Gujarat, Goa, MP, MS, AP, Karnataka, TN, Kerala, Puducherry, Bihar, Odisha, WB, ArP, Assam, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, A&N	Inceptisols, Entisols, Alfisols, Aridisols
Coastal alluvial	10,049	3.1	AP, Karnataka, TN, Kerala, WB, Gujarat, Odisha, Puducherry, Lakshadweep, A&N	Aridisols, Inceptisols, Entisols
Red	87,989	26.8	AP, Karnataka, Kerala, TN, Puducherry, Rajasthan, MP, MS, Gujarat, Goa, ArP, Assam, Manipur, Meghalaya, Nagaland, Mizoram, Tripura, Delhi, UP, HP, A&N	Alfisols, Ultisols, Entisols, Inceptisols, Mollisols, Aridisols
Laterites	18,094	5.5	AP, Karnataka, Kerala, TN, Puducherry, MS, Odisha, WB	Alfisols, Ultisols, Inceptisols
Brown forest	540	0.2	Karnataka, Maharashtra	Mollisols, Inceptisols
Hill	2,262	0.7	Manipur, Odisha, WB, Tripura, Nagaland	Inceptisols, Entisols
Terai	326	0.1	UP, Sikkim	Mollisols, Entisols
Mountain meadow	60	–	J&K	Mollisols
Sub-montane	104	–	J&K	Alfisols
Black	54,682	16.6	MP, MS, Rajasthan, Puducherry, TN, UP, Bihar, Odisha, AP, Gujarat	Vertisols, Mollisols, Inceptisols, Entisols, Aridisols
Desert	26,283	8.0	Rajasthan, Gujarat, Haryana, Punjab	Aridisols, Inceptisols, Entisols
Others*	28,305	8.6	–	–
Total	328,700	100	–	–

*Includes glaciers (0.4%), sand dunes (0.01%), mangrove swamps (0.04%), salt waste (0.01%), water bodies (0.1%), rock land (0.25%) and rock outcrops (7.8%). MP, Madhya Pradesh; MS, Maharashtra; UP, Uttar Pradesh; J&K, Jammu and Kashmir; TN, Tamil Nadu; AP, Andhra Pradesh; ArP, Arunachal Pradesh; WB, West Bengal; HP, Himachal Pradesh; A&N, Andaman and Nicobar Islands.

Based on information available on the soil classes, using USDA 7th approximation, the first US soil classification system for Indian soils was used to develop at the group level and a soil map of India on 1 : 6.3 million scale was published[5].

Soil map of India: new initiative

Because India is a large country, soil grouping has always been generalized. During the past 30 years the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), the premier soil research institute of the Indian Council of Agricultural Research (ICAR), mapped the soil resource of the country on 1 : 7 million scale at sub-order association level. One hundred and three soil sub-orders were recognized. For sustainable resource management, large-scale mapping of soil and climatic resources was initiated in 1986 using a three-tier approach comprising image interpretation, field mapping and laboratory analysis. This was followed by cartography and printing of maps for all the states and union territories on 1 : 250,000 scale. One hundred and seventy six false colour composite (FCC) and B/W infrared imageries on 1 : 250,000 scale were interpreted visually to prepare pre-field physiography-cum-photomorphic maps. Sikkim, Goa, Lakshadweep, and Andaman and Nicobar Islands were mapped on 1 : 50,000 scale using TM FCC. The map units are described in a manner that is intelligible to most land use planners. Recently, Bhattacharyya *et al.*[6] compiled and presented soil information at the level of family association following the USDA taxonomy.

Area and distribution of soil groups

Twenty-four major soil groups described by Govinda Rajan and Rao[7] have been reduced to 11 major soil groups in the present study (Table 1). It may be mentioned here that the soil maps (1 : 250,000) and their legends do not show the major soils and their traditional names. We faced a problem to classify soils as red, laterites and hilly since at many places these names overlap. Moreover, recent findings on shrink–swell soils (generally known as black soils) have shown them to be red in colour[8], which makes the common name of red and black soils redundant. As Latin names may not be decipherable by many scientists and end-users, traditional names, their extent and the nearest synonym in the US soil taxonomy have been mentioned in Table 1 and Figure 1. The soil resource mapping programme (SRM) of the entire country between 1986 and 1996 generated an extensive database on soils, their area and characteristics to enable grouping them following the soil taxonomy[9]. Relative proportion of major soils and other details are shown in Tables 2 and 3, and Figures 1 and 2.

Soils in different zones of India

The soil resources vary in agro-ecological sub-regions (AESRs) in terms of soil reactions, base saturation, nutrient-holding capacity, organic matter content and length of growing period (LGP) to support a host of agricultural and horticultural crops (Table 4). Because India is a large country we divided it into major zones, viz. northern, western, central, southern, eastern, northeastern and islands.

The northern zone consists of six states (Uttar Pradesh, UP as an undivided state) and covers 20% area of the country. Soil families show more variation in soils in UP followed by Jammu and Kashmir (J&K) and Himachal Pradesh (HP; Table 3). Among the six states, Vertisols are reported only in UP. There are, however, reports of shrink–swell soils in J&K[10]. The northwestern part of the country – Punjab and Haryana – shows the presence of a few Aridisols. Mollisols are reported from J&K, HP and UP (Table 2).

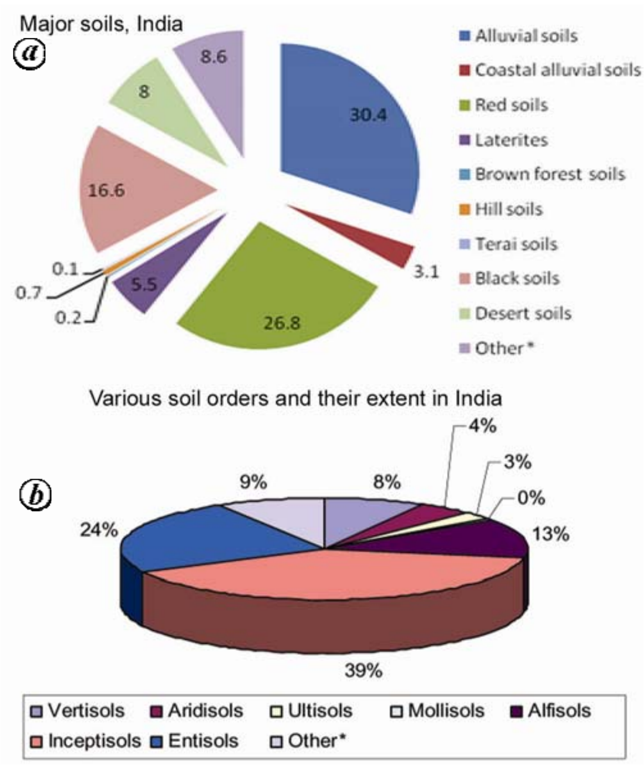

Figure 1. ***a***, Major soils of India (values in per cent); ***b***, Various soil orders and their extent in India.

The western zone consists of three states and covers 16.5% area of the country. Number of soil families indicates greater variation in soils in Gujarat followed by Rajasthan (Table 2). Aridisols dominate expectedly in Rajasthan. Interestingly, all the three states have Alfisols and Ultisols (later reported only in Goa; Table 2). The present-day climate in Gujarat and Rajasthan does not permit the formation of these soils. The soils indicate a change of climate from wetter to dry regime.

The central zone consists of three states (including Chhattisgarh) and covers 23% area of the country. Number of soil families indicates more variation of soils in Madhya Pradesh (MP) and this state has double the area under Vertisols compared to Maharashtra (Table 2). Mollisols are reported from both MP and Maharashtra.

The southern zone consists of five states and covers 19.3% area of the country. Number of soil families indicates more variation in soils in Andhra Pradesh (AP) followed by Karnataka and Tamil Nadu (TN; Table 3). Occurrence of Vertisols in Kerala has been recently reported[11]. It is interesting to note that the four southern states contain fertile Mollisols and support such occurrences in the humid tropical climate as described later (Tables 2 and 3).

The eastern zone consists of five states (including Jharkhand) covering 13% area of the country. Number of soil families indicates more variation in soils of Odisha followed by Bihar, Sikkim and West Bengal (Table 3). Vertisols have been reported from Bihar, Odisha and Mollisols from Sikkim (Table 2). Occurrence of Vertisols and their intergrades have also been reported from West Bengal, Bihar and Odisha.

The northeastern zone consists of seven states and occupies 7% area of the country. Number of soil families suggests more variation in soils of Assam followed by Arunachal Pradesh, Tripura and Mizoram (Table 3). The northeastern zone is dominantly occupied by weathered soils like Alfisols and Ultisols. Expectedly higher elevation ranges of Arunachal Pradesh, Meghalaya and Manipur contain dominant proportions of Ultisols (Table 2).

The islands consist of two Union Territories covering 0.2% area of the country. Andaman and Nicobar islands have a considerable area under Mollisols other than the dominant Inceptisols and Entisols (Table 2).

The number of soil families in a few states (UP, Rajasthan, MP, AP, etc. in Table 3) is higher than in other states, suggesting that the number of soil families per million hectare (SF m ha^{-1}) can be a better indicator of soil variation. A closer look at Table 3 indicates that most of the states in the northeastern region (NER) show more SF m ha^{-1} than other states, because NER and other hilly states like HP show more soil variation due to different physiographic, geological and other soil-forming factors that have given rise to different soil mapping units (Table 3). Because of the limitations of 1 : 250,000 scale of mapping, threshold soil variation index of 4–5 and 10–20 SF m ha^{-1} has been worked out respectively, for

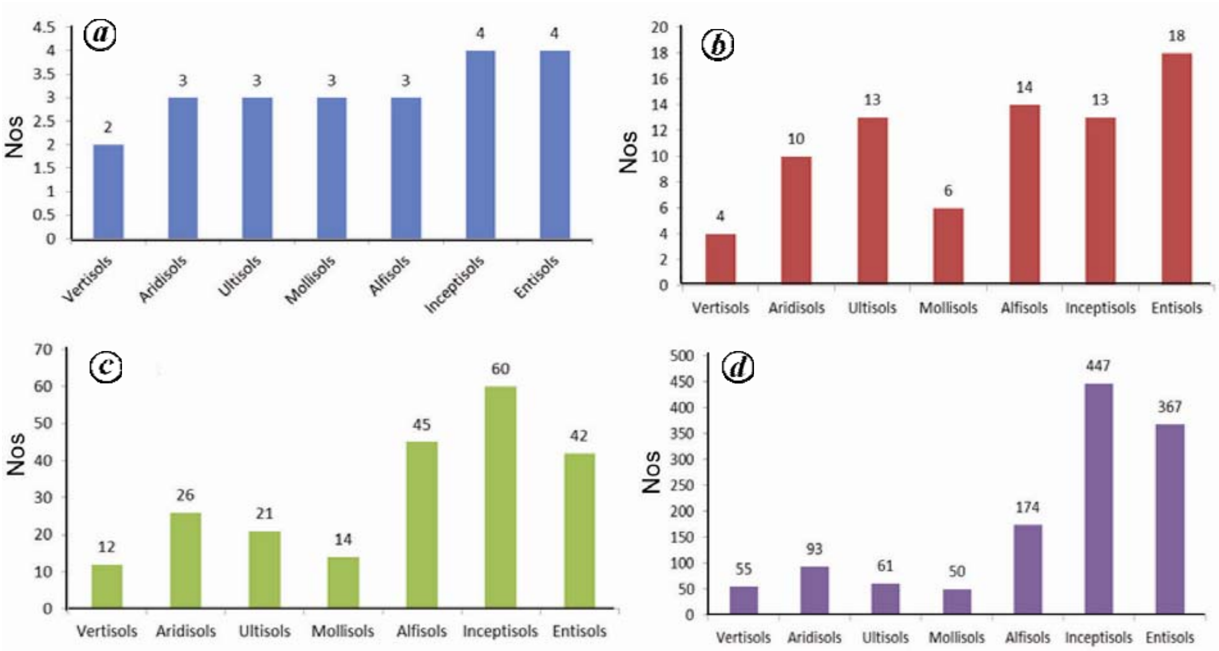

Figure 2. Occurrence of total sub-orders (***a***), great groups (***b***), subgroups (***c***) and families (***d***) in various soil orders identified in India.

alluvial IGP and black soil regions (BSR) and hilly areas of India (Table 3).

Higher microbial population was recorded in surface soils compared to sub-surface soils in all the ecosystems studied (Table 4; Figure 3). Rainfed, followed by hill and mountain systems, recorded significantly higher microbial population compared to other ecosystems. Though coastal system indicated lesser microbial population, its diversity (*H*′) was higher compared to other ecosystems[12]. While higher dominance index (*D*) and evenness (*E*) were observed in hill and mountain systems, diversity index (*H*′) was the lowest among the ecosystems indicating the dominance of bacteria over other microbial groups. Although arid ecosystem showed lesser microbial population and diversity index (*H*′), its evenness (*E*) index is good. Among the physical and chemical factors, optimum soil pH, higher organic carbon, low bulk density and higher saturated hydraulic conductivity indicating better drainage in the surface soils supported higher microbial populations relative to deeper layers.

The above information on the occurrence of soil orders in different states and geographical areas of the country suggests that soil diversity is as large as that in the temperate zone. This is attributed to the variability in the environmental factors that control soil formation as reflected in their taxonomic grouping. The generalization made so far that Indian soils are highly weathered and impoverished in soil nutrients, is unlikely to have wide applicability in an agriculturally progressive country like India. The diversity of soils as evident from their occurrence in different states and AESRs needs explanation. All the soil-forming processes result in a succession of layers (horizons) nearly parallel to the ground and generally unconformable with bedding or other structures in the parent rock. Depending on the rapidity and degree of chemical weathering, the soil horizons become gradually prominent as in Inceptisols, Mollisols and Alfisols in that order[9] or obscure as in Oxisols. Soils develop on stable landscapes with the concomitant and simultaneous erosion (degradation) and deposition (aggradation). Soils then preserve a history of events on these landscapes which are identified by pedologists and other earth scientists as signatures of the influence of climate, parent materials and other soil-forming factors. There are cases where the successive horizons even in a restricted part of soil profile result from progressive alteration *in situ*, especially in tropical regions[13] like some parts of India. Various degradational and aggradational events as well as numerous pedogenetic processes thus make soils as a source of information about the past and the present, and help in formulating predictive models for the future. Any model designed to explain the distribution of soil types at any scale of mapping, should consider soil development processes controlled by five well-known factors, viz. climate, relief (topography), organisms, parent materials and time. Complete landscape studies, supported by soil information showing different pedogenetic episodes are important to earth scientists, soil surveyors and pedologists. These studies are, however, expensive, time-consuming and often demand a range of expertise beyond the resources of one institute and/or one worker. In other words, soil survey requires the assistance of soil scientists (both pedologists and edaphologists), agronomists, cartographers, geographers, remote sensing experts, chemists, climatologists, geologists and a host of other allied group of experts.

Table 2. Area (in '000 ha) and extent of zone-wise soil orders in different states of India based on 1 : 250,000 scale maps

	Soil order								
State	Total geographical area (TGA)	Vertisols	Ultisols	Aridisols	Mollisols	Alfisols	Inceptisols	Entisols	Others*
Northern zone									
Jammu & Kashmir	22,224	–	–	–	60	104	1,952	9,917	10,190
Himachal Pradesh	5,567	–	–	–	30	8	1,038	2,895	1,696
Punjab	5,036	–	–	770	–	224	2,818	1,175	49
Haryana	4,421	–	–	409	–	84	2,568	1,189	170
Delhi	148	–	–	–	–	–	82	19	47
Uttar Pradesh**	29,441	415	–	–	83	1,793	21,490	4,813	848
Total		415	–	1,179	173	2,213	29,948	20,008	13,000
Western zone									
Rajasthan	34,224	989	–	8,287	–	251	8,317	13,799	2,580
Gujarat	19,602	1,877	–	2,027	–	101	10,135	2,529	2,933
Goa	370	–	42	–	–	28	256	26	18
Total		2,866	42	10,314	–	380	18,708	16,354	5,531
Central zone									
Madhya Pradesh***	44,345	10,751	–	–	312	7,394	17,085	8,130	672
Maharashtra	307,713	5,603	–	–	276	559	12,387	9,818	2,119
Total		16,354	–	–	588	7,953	29,472	17,948	2,791
Southern zone									
Andhra Pradesh	27,504	2,238	–	810	510	8,347	9,992	2,981	2,626
Karnataka	19,179	2,802	1,511	1,046	162	5,454	4,341	3,162	700
Tamil Nadu	13,006	911	127	–	42	3,973	6,389	720	844
Kerala	3,886	–	2,299	–	48	56	912	191	380
Puducherry and Karaikal	49	11	–	–	–	2	15	10	11
Total		5,962	3,937	1,856	762	17,832	21,649	7,065	4,561
Eastern zone									
Bihar****	17,388	111	–	–	–	5,507	6,557	4,723	489
Odisha	15,571	908	–	–	–	4,979	7,425	1,620	638
West Bengal	8,875	–	–	–	–	2,221	4,301	2,061	292
Sikkim	710	–	–	–	75	–	243	284	108
Total		1,019	–	–	75	12,707	18,526	8,687	1,527
Northeastern zone									
Arunachal Pradesh	8,374	–	1,202	–	–	11	3,143	3,900	118
Assam	7,844	–	589	–	–	762	3,246	2,900	347
Nagaland	1,658	–	250	–	–	49	1,091	215	53
Manipur	2,233	–	860	–	–	63	827	428	54
Mizoram	2,108	–	549	–	–	49	761	589	160
Tripura	1,049	–	68	–	–	46	834	95	6
Meghalaya	2,243	–	910	–	–	85	1,002	245	–
Total		–	4,428	–	–	1,065	10,905	8,372	738
Islands									
Andaman & Nicobar	825	–	–	–	40	49	362	311	61
Lakshadweep	3	–	–	–	–	–	–	3	1
Total		–	–	–	40	49	362	314	62

*Includes glaciers, sand dunes, mangrove swamps, salt waste, water bodies, rock land and rock outcrops. **Uttar Pradesh, including Uttarakhand. ***Madhya Pradesh, including Chhattisgarh. ****Bihar, including Jharkhand.

Table 3. Different categories of soil taxonomy in soil resource mapping of states on 1 : 250,000 scale

State/soil information	TGA*	Soil order	Sub-order	Great group	Sub-group	Families	Soil map unit
Northern zone							
Jammu & Kashmir	22,224	4**	9	14	23	93 (4)++	140 (6)++
Himachal Pradesh	5,567	4	8	12	16	56 (10)	95 (17)
Punjab	5,036	4	8	11	18	46 (9)	124 (25)
Haryana	4,421	4	6	9	17	41 (9)	199 (45)
Delhi+++	148	3	4	4	6	12	31
Uttar Pradesh***	29,441	5	12	21	41	145 (5)	321 (11)
Western zone							
Rajasthan	34,224	5	8	16	31	96 (3)	375 (11)
Gujarat	19,602	5	10	19	40	126 (6)	370 (19)
Goa+++	370	4	7	12	18	27	25
Central zone							
Madhya Pradesh****	44,345	5	8	11	26	175 (4)	851 (19)
Maharashtra	30,771	5	7	8	18	95 (3)	356 (11)
Southern zone							
Andhra Pradesh	27,504	6	12	18	45	134 (5)	238 (9)
Karnataka	19,179	7	12	25	48	98 (5)	141 (7)
Tamil Nadu	13,006	6	12	17	43	75 (6)	285 (22)
Kerala	3,886	5	9	16	21	35 (9)	38 (10)
Puducherry & Karaikal+++	49	4	6	8	11	14	–
Eastern zone							
Bihar*****	17,387	4	9	19	39	79 (4)	175 (10)
Odisha	15,571	4	9	15	35	98 (6)	159 (10)
West Bengal	8,875	3	8	15	32	56 (6)	115 (13)
Sikkim+++	710	3	6	10	22	69	69
Northastern zone							
Arunachal Pradesh	8,374	4	9	14	26	58 (7)	46 (5)
Assam	7,844	4	9	16	33	82 (10)	83 (10)
Nagaland	1,658	4	6	10	12	40 (24)	34 (20)
Manipur	2,233	4	6	11	18	32 (14)	19 (8)
Mizoram	2,108	4	9	13	19	41 (19)	31 (15)
Tripura+++	1,049	4	7	11	20	42	43
Meghalaya	2,243	4	6	12	17	33 (15)	24 (11)
Islands							
Andaman and Nicobar+++	825	4	8	11	17	37	42
Lakshadweep+++	3	1	2	4	6	6	–

*Total geographical area in '000 ha. **These values indicate how many soil orders, suborders, great groups, subgroups and families are identified in these states. ***Uttar Pradesh, including Uttarakhand. ****Madhya Pradesh, including Chhattisgarh. *****Bihar, including Jharkhand. ++Parentheses indicate soil families per million ha (SF m ha^{-1}) and soil mapping unit per million ha (SMU m ha^{-1}). +++Surveyed in 1 : 50,000 scale and ignored for estimating threshold soil variation index.

The NBSS&LUP has a host of experts who have carried out soil survey across the country. The data generated indicate that even if the soils belong to the same order in various parts of the country (say Alfisols)[9], their interaction with plants is different. These differences in the form of surface and subsurface diagnostic horizons[9] are due to various pedogenetic processes. This is the reason why Entisols (soils formed recently) as a uniform soil order, although reported from different parts of the country, are strikingly different in the Deccan basalt area compared to those in the IGP and/or coastal plains. The Lithic Ustorthents (Entisols) in the hilly forests (Sibneri soil series)[14] developed from basalts are shallow, smectitic and black in colour, and are justifiably mapped in the extended family of black soils[15]; the Entisols in the IGP, on the other hand, are very deep and often loamy to sandy/silty in texture and help in growing paddy. Entisols in the coastal areas and deserts are Psamments containing sand throughout the soil depth. Also, though soils grouped under Alfisols and Ultisols (red and hilly soils), Vertisols and Inceptisols (black and associated soils) and Mollisols (brown forest soils) appear similar in various zones, they are different in terms of properties and land use, as detailed in the subsequent sections. This is analogous to classification of plants and animals where some genus may have various species and subspecies.

Table 4. Selected properties of representative soils from major agro-ecosystems

		Physical properties				Chemical properties					Biological properties				
Depth (cm)	Horizon	Clay (%)	pH (water)	BD (Mg m^{-3})	sHC (mm h^{-1})	Organic C (%)	$CaCO_3$ (%)	CEC cmol (+) kg^{-1}	ESP	BS (%)	DHA (μTPFg^{-1} 24 h^{-1})	Urea (μNH_4 Mg^{-1} soil 24 h^{-1})	Bacteria (cfu g^{-1})	Fungi (cfu g^{-1})	Actinomycetes (cfu g^{-1})
Coastal ecosystem: Sagar soils, West Bengal: Typic Haplaquept															
0–14	Ap	36	5.8	1.3	0.5	0.81	1.5	18.5	11.1	94.9	2.8	14.2	24	3	13
14–42	Bw1	40	8.6	1.5	0.4	0.27	2.8	19.1	12.5	105.2	2.3	9.9	20	4	12
42–75	Bw2	42	8.4	1.4	0.01	0.15	1.7	18.7	14.6	103.4	1.7	7.0	17	2	10
75–110	Bw3g	42	7.8	1.4	0.00	0.15	1.5	18.5	12.0	91.4	1.3	4.1	15	2	8
110–135	Bw4g	34	7.6	1.3	0.00	0.23	1.5	17.0	19.1	104.0	0.9	1.8	14	2	7
Hill and mountainous ecosystem: Haldi soils, Uttarakhand: Typic Hapludoll															
0–15	Ap	14	6.7	1.4	4.1	0.96	1.4	60.0	1.4	78.4	3.0	23.6	32	2	13
15–39	Bw1	22	7.7	1.4	0.9	0.77	2.3	62.6	1.8	84.5	2.7	20.2	28	2	12
39–64	Bw2	23	7.7	1.4	0.9	0.50	1.2	61.7	1.7	85.9	2.3	17.2	24	2	9
64–88	BC	10	7.3	1.3	3.9	0.27	1.9	46.0	2.5	48.0	1.9	13.5	19	2	8
88–108	C1	11	7.5	1.5	8.2	0.23	1.3	53.9	1.6	40.2	1.5	10.9	15	1	6
108–130	2C2	9	7.7	1.5	18.9	0.19	1.9	28.7	2.4	65.9	1.2	9.8	11	1	4
130–160	2C3	8	8.6	1.8	12.3	0.23	1.0	33.9	4.0	89.9	0.9	8.4	9	0	3
Arid ecosystem: Masitawali soils, Rajasthan: Typic Torrifluvent															
0–28	Ap	6	8.9	1.5	1.6	0.39	4.7	24.3	41.5	107.3	2.5	18.4	19	1	11
28–44	A1	9	9.3	1.8	1.3	0.12	9.8	22.6	41.5	121.0	2.2	15.4	17	1	10
44–75	C1	16	9.0	1.7	0.05	0.07	21.1	31.3	49.8	120.3	1.7	12.9	14	1	8
75–105	C2	8	9.3	1.6	0.06	0.04	20.2	29.5	36.6	101.4	1.4	9.6	12	1	6
105–132	C3	6	9.2	1.5	4.5	0.04	12.4	19.1	23.1	81.3	1.0	6.5	9	0	5
132–160	C4	–	–	–	–	–	–	–	–	–	0.8	3.8	8	0	5
Irrigated ecosystem: Fatehpur soils, Punjab: Typic Haplustept															
0–15	Ap	9	7.5	1.3	13.7	0.69	1.1	4.3	4.5	96.6	2.5	15.5	22	2	17
15–37	B1	11	7.9	1.7	8.2	0.30	1.0	5.7	3.4	139.2	2.3	15.4	20	2	15
37–62	B2	13	8.0	1.7	8.2	0.15	1.4	6.5	2.5	135.8	2.1	15.5	18	2	13
62–90	B3	5	8.2	1.4	51.2	0.15	0.7	6.3	2.6	146.7	1.8	11.4	16	1	11
90–115	C1	9	8.0	1.5	16.6	0.11	2.2	7.0	2.1	130.6	1.4	10.7	14	1	9
115–140	C2	13	8.0	1.3	20.8	0.07	1.6	5.7	3.1	151.2	1.0	9.3	13	1	7
140–165	C3	12	8.0	1.5	19.3	0.03	0.5	4.3	3.8	156.7	0.8	8.3	11	0	6
Rainfed Ecosystem: Panjri soils, Nagpur: Typic Haplustert															
0–15	Ap	68	8.3	1.6	5.3	0.61	4.2	61.7	2.7	96.9	2.9	16.1	79	25	22
15–31	Bw	68	8.3	1.7	9.8	0.42	4.7	60.8	1.7	101.1	2.5	14.8	63	21	17
31–56	Bss1	67	8.4	1.8	6.4	0.34	4.4	61.7	1.4	96.7	2.0	10.0	50	16	14
56–78	Bss2	74	8.4	1.8	4.9	0.27	5.0	60.0	2.3	111.7	1.3	5.2	41	12	10
78–110	Bss3	74	8.4	1.8	4.5	0.12	5.1	65.2	2.3	109.4	1.0	3.0	28	9	6
110–150	Bss4	71	8.3	1.9	4.6	0.09	5.1	62.6	2.4		0.5	3.7	12	3	3

BD, Bulk density; sHC, Saturated hydraulic conductivity; CEC, Cation exchange capacity; ESP, Exchangeable sodium percentage; BS, Base saturation and DHA, Dehydrogenase enzyme.

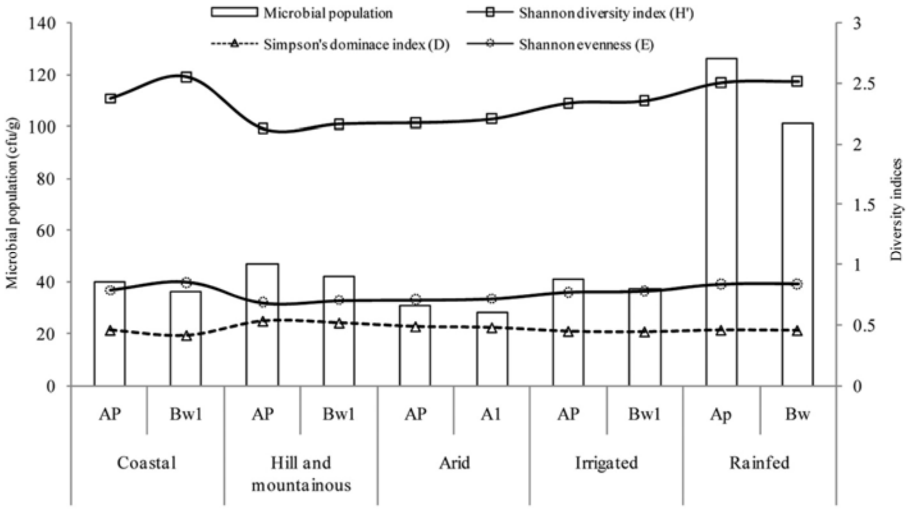

Figure 3. Ecosystems and their effects on soil microbial population and diversity.

Progress in basic knowledge on Indian soils

During the last decade and a half, the focus of soil research has changed qualitatively because mineralogical, micromorphological and age-control tools have been used to measure the relatively subtle processes related to pedology of the present and past geological periods[16–33]. In order to understand the basic issues in soil genesis in various geographical regions for efficient use and management for agricultural development, a critical synthesis is made in the following paragraphs.

Black soils (Vertisols and their intergrades) in the extra-Peninsular region

Black soils, popularly known as black cotton soils, are usually deep to very deep and are dominated by smectitic clays. They are characterized by the presence of either slickensides or wedge-shaped peds, ≥ 30% clay and cracks that open and close periodically. These soils are grouped as Vertisols[9]. A group of soils belonging to other soil orders possesses the characteristics of black soils showing linear extensibility (LE) of 6.0 cm or more. High LE values are caused by smectitic clays that allocate these soils to vertic sub-group[9]. This fact assumes importance because Vertisols and the vertic intergrades of soils have similar characteristics and require similar land management for agriculture and allied uses. Presence of slickensides is not a must for classifying a soil into vertic intergrades. Recent studies show that Vertisols and their intergrades can also possess red colour[8]. Thus the term black soils for Vertisols and vertic intergrades is technically wrong. Revised estimation indicates that black soils occupy nearly 76.4 m ha (Figure 4)[15]. Reports also show the presence of Vertisols in IGP[32]. Maharashtra, MP and Gujarat have the major share of black soils in the country. Black soils are also reported from Kerala, J&K, Andaman and Nicobar Islands (Figure 4)[10,11,15]. The occurrence of shrink–swell soils in Kerala appears to be related to the fluvial deposit by rivers. The presence of such soils in J&K may be due to the presence of basic rocks in the complex rock system in the Himalayan regions.

Studies under the Global Environmental Facility sponsored Soil Organic Carbon (GEFSOC)[34] and National Agricultural Innovative Projects (NAIP) (Component 4)[35,36], were made on some benchmark shrink–swell soils in Chunchura (Hooghly district) and Gopalpur (Birbhum district) of West Bengal. These soils qualify for Vertisols[9] and their properties were found to be similar to the Vertisols in the Peninsular region. The smectitic clay minerals of the Vertisols in West Bengal were inherited from the alluvial parent materials and are comparable to those of the Deccan basalt areas[32]. Geomorphic history indicates that the Damodar river, like many other rivers in this part of IGP, was flowing in the easterly direction to meet the Bhagirathi during the middle of the 18th century[37,38], but has since shifted its mouth 120 km to the south. These rivers flow from west to east draining the Rajmahal Trap area which consists of 2000 feet of basaltic flows and dolerites. The rivers flowing in the vicinity of Rajmahal Trap are perennial in nature and huge amounts of smectite were formed presumably due to higher rainfall in that area. Therefore, in view of the geomorphic history and similar nature of smectites between Vertisols of West Bengal and Deccan Basalt area, it is most likely that the Vertisols in West Bengal are developed in the smectite-rich alluvium of the Rajmahal Traps carried by the rivers which once flowed towards the east.

Formation of Mollisols in tropical humid climate

In contrast to the generally observed non-acidic and less weathered Mollisols in temperate semiarid and humid

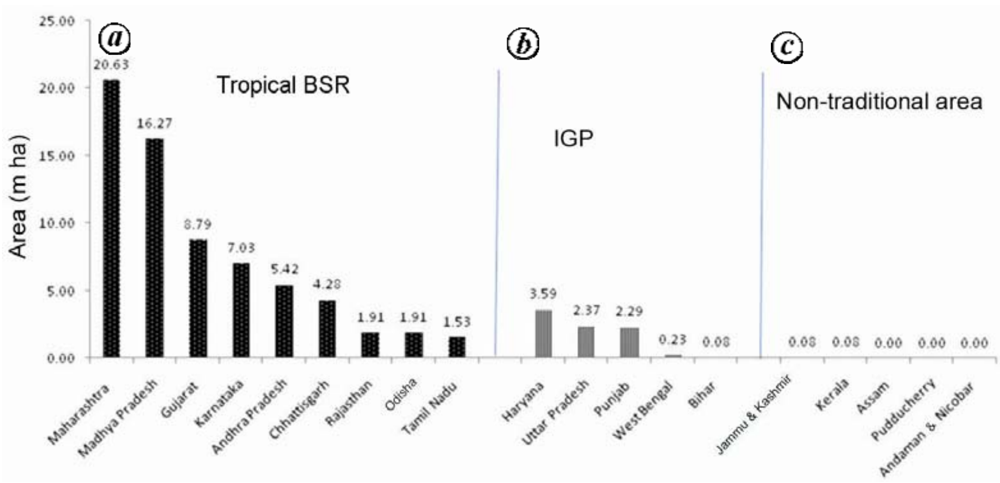

Figure 4. Black soils (m ha) in different states of India. ***a***, Tropical BSR (Maharashtra, Madhya Pradesh, Gurjarat, Karnataka, Andhra Pradesh, Chhattisgarh, Rajasthan, Odisha, Tamil Nadu); ***b***, Black soils in the IGP (Haryana, Uttar Pradesh, Punjab, West Bengal, Bihar); ***c***, Non-traditional area (Jammu & Kashmir, Kerala, Assam, Puducherry and Andaman & Nicobar Islands) occupying 0.0072, 0.0000146 and 0.0000071 m ha respectively).

Table 5. Some properties of Mollisols (brown forest soils) in humid tropical climate in India*

								Zeolite (%)		
Depth (cm)	Structure[a]	Clay (%)	AWC[b] (%)	pH (water)	OC[c] (%)	CEC[d] (cmol (+) kg^{-1})	LE[e]	Sand (> 50 μm)	Silt (50–2 μm)	Clay (2–0.2 μm)
Vertic Haplustoll, Mandla, Madhya Pradesh (forest: 850 m above msl)[f]										
0–6	1 f gr	30	15	5.9	3.5	52	11	Yes[g]	Yes	16
6–20	1 f gr	39	16	5.8	3.0	60	12	Yes	Yes	22
20–37	1 f sbk	29	18	5.8	2.0	60	11	Yes	Yes	17
37–74	2 m sbk	31	18	5.9	1.2	67	14	Yes	Yes	16
74–106	2 m sbk	31	19	5.6	0.8	72	16	Yes	Yes	18
106–150	2 m sbk	28	19	5.5	0.5	74	16	Yes	Yes	18
Vertic Argiudoll, Pune, Maharashtra (forest: 1150 m above msl)										
0–15	1 f gr	51	15	5.7	2.0	19	10	Yes	Nil[h]	Nil
15–40	1 f gr	53	17	5.7	1.2	18	14	Yes	Nil	Nil
40–74	2 m sbk	61	18	5.7	0.7	19	16	Yes	Nil	Nil
74–108	3 c sbk	61	17	6.1	0.4	19	17	Yes	Nil	Nil
108–146	2 m sbk	59	18	6.1	0.3	19	15	Yes	Nil	Nil
146–175	2 m sbk	53	18	6.1	0.1	20	13	Yes	Nil	Nil
175–150	2 m sbk	51	15	6.1	0.1	20	13	Yes	Nil	Nil

*Source : Bhattacharyya *et al.*[19]. [a]1 f gr, Weak fine granular; 1 f sbk, Weak fine subangular blocky; 2 m sbk, Moderate medium subangular blocky; 3 c sbk, Strong coarse subangular blocky; [b]AWC, Available water content; [c]OC, Organic carbon; [d]CEC, Cation exchange capacity; [3]LE, Linear extensibility; [f]msl, Mean sea level; [g]Peak of zeolite mineral identified in traces; [h]Peak of zeolite not detected.

climate, acidic and fairly weathered Mollisols on Deccan basalt occur in hills of the Satpura Range of MP and the Western Ghats of Maharashtra under forest cover in the prevailing tropical humid climatic conditions[19]. The formation of Mollisols in the zeolitized basaltic landscape over millions of years and their persistence in central and western India demonstrate that the quality of parent materials prevents the transformation of smectite to kaolin, helps in the retention of adequate amount of smectite and provides continuous supply of bases (Ca^{2+} ions) required for the formation of Mollisols even under tropical humid climate (Table 5)[19]. Mollisols (brown forest soil) in each of the study areas are a member of Mollisol–Alfisol–Vertisol association. The Mollisols of the Western Ghats have argillic horizons unlike those of the Satpura Range. This suggests that the Mollisols and the associated ferruginous Alfisols are formed in a stable basaltic landscape. It has been observed that the Alfisols are more acidic, have more clay and kaolin than the Mollisols (Table 6). Occurrence of such soils suggests that the Alfisols (under sparse forest) are more weathered than Mollisols due to better water influx in the former. Two different groups of soils can, therefore, be formed from similar parent materials under the same climate due to difference in density of forest vegetation. The associated ferruginous Alfisols were formed in tropical humid climate and are persisting since the early Tertiary[18]. The transformation of smectite to smectite/kaolin interstratified minerals during humid tropical weathering began at the end of the Cretaceous and continued during the Tertiary[39]. Many of these ferruginous soils date back to the Tertiary and Cretaceous[40]. In other words, they formed soon after the Deccan basalt erupted[41]. The foregoing suggests that although the soils in the study area are formed in humid tropical climate for millions of years, they have not reached the advanced stage of weathering represented by Ultisols and Oxisols[9]; instead, they have remained Alfisols and Mollisols[19].

Persistence of high-altitude Alfisols of humid tropical climate

On the formation and persistence of ferruginous Alfisols in the humid tropical climate, it has been reported[18] that the prevalence of high temperature and adequate moisture in the weathering environment should have nullified the effect of parent rock composition of the Deccan basalt, by resulting in kaolinite and/or oxidic mineral assemblages consistent with either residua[42] or haplosol model of soil formation[43]. On the contrary, dominance of smectite/kaolin interstratified minerals in clay fractions indicates that in spite of prolonged weathering since the early Tertiary, products of weathering of Deccan basalt have not yet reached the kaolinitic and/or oxidic mineralogy due to the presence of Ca-zeolites. Presence of Ca-zeolites creates a chemical environment sufficiently rich in bases, which prevents the formation of kaolinitic and/or oxidic clay minerals.

Alfisols of southern Peninsula as evidence of modifications in the landscape

The occurrence of Alfisols (ferruginous red soils) in both the Peninsular and extra-Peninsular areas in India is common. However, their physical and chemical properties are not identical. Alfisols on Peninsular gneiss are formed on very old landscapes and have clay content of about 10–15% in the Ap horizon, immediately followed by a well developed argillic (Bt) horizon with a clay content of > 30%. In the Bt3 or Bt4 horizons at a depth of about 60–70 cm, clay distribution shows either an increasing or a decreasing trend. The thin Ap horizon is a disturbed horizon due to soil erosion or ploughing. If this horizon is ignored, then the depth distribution of clay in such Alfisols shows an increasing trend up in the profile, a phenomenon generally seen in a juvenile residual soil profile. However, these Alfisols are developed on the old rock system of the earth and represent ancient soils. The clay deposition in the subsurface is caused by illuviation of clay particles. This process is active during the humid past. Judging by the present semi-arid climate of this area vis-à-vis the soil characteristics, these soils have been related to the ancient past episode with high rainfall. Therefore, depth distribution of clay (Figure 5) clearly indicates the truncation of soil profile developed during the humid tropical climate that prevailed in the past[21,31]. Such landscape reduction process in the past and present has created a unique spatially associated red–black soil complex in many parts of southern and western India[16,31,44].

Table 6. Selected properties of Mollisols and Alfisols in two different landscapes*

Properties	Satpura range		The Western Ghats	
	Mollisol	Alfisol	Mollisol	Alfisol
pH (water)	5.8	5.2	5.7	5.4
Clay (%)	34	50	52	56
Smectite (%)**	79	37	26	18
Kaolinite (%)**	12	54	60	67
Mica (%)	9	9	14	15

*Source: Bhattacharyya *et al.*[19]. **Minerals estimated following peak shift analysis[75].

Alfisols in the IGP – an enigma resolved

In many Alfisols of the IGP, clays increase with depth. The ratio of clay content in the clay-rich Bt horizon compared to that of the A horizon is > 1.2, which suggests that these soils are fairly well developed[23,24]. In such soils, the clay increases with depth to a maximum and then decreases until it remains constant or completely disappears. Illuviation of clay particles usually results in the development of clay skins[9] that can be recognized in the field with a 10× lens. However, clay skins cannot be seen clearly in any of the pedons despite > 30% increase in total clay in the *Bt* horizon. Difficulty in identifying

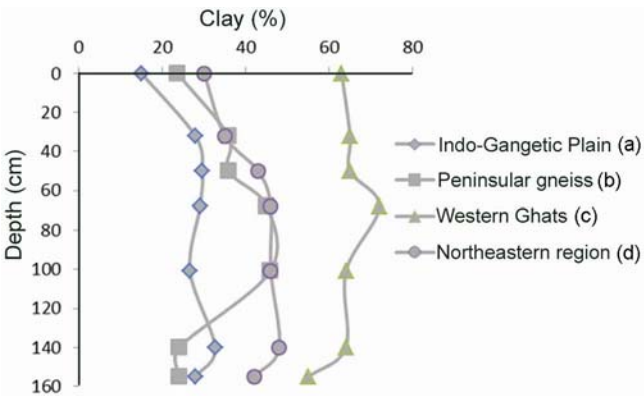

Figure 5. Distribution of clays in relation to depth in Alfisols and Ultisols from (***a***) the Indo-Gangetic Plains (Etah, Uttar Pradesh, semi-arid), (***b***) Peninsular gneiss (Karnataka, semi-arid), (***c***) the Western Ghats (Maharashtra, humid) and (***d***) Northeastern region (Itanagar, Arunachal Pradesh, humid).

clay skins in the clay-enriched B horizons is common in the IGP soils[45] and elsewhere[46] under semi-arid climate (Figure 5). However, thin sections of these soils do not show pure void argillans, but the presence of impure clay pedo-features provides incontrovertible evidence of clay illuviation in sodic environment[23,24,45].

Alfisols/Ultisols in the humid tropical climate

Alfisols/Ultisols in the humid tropical climate (HTC) are dominantly clayey, and clay skins are difficult to be identified in the field in the northeastern part of India. However, the soils in the Western Ghats show evidence of translocation and accumulation of clay in the form of clay skins[18] (Figure 5). Ultisols in Arunachal Pradesh show uniformity of parent materials. The clay distribution as a function of depth indicates that these soils are fairly well developed. This is in accordance with the views of Barshad[47], who indicated that in a fairly well-developed soil, as a result of pedogenic processes, clay increases with depth to attain a maximum and then decreases until it remains constant or completely disappears. More than 20% clay increase in the subsurface horizon over the surface qualifies for an argillic horizon in the Itanagar soil of Arunachal Pradesh[48]. Due to the probable truncation of the upper layers of these Ultisols, clay presently shows a sharp decline in the A horizon (Figure 5). Due to prominent clay illuviation in these soils, it appears that the landscape at lower elevations was more stable in the past. Rapid urbanization over the years has brought instability in these landforms resulting in truncated soils due to soil loss by erosion[48].

Highly weathered soils of NER

While studying highly weathered soils of Puerto Rico, Beinroth[49] observed that low KCl extractable Al^{3+} ions are associated with gibbsite. Positive ΔpH (ΔpH = KCl pH – water pH) in the soil may indicate the presence of gibbsite[50,51] and/or more sesquioxides[52]. Usually soil pH in KCl solution is lower than that in water (due to exchangeable H^+ and Al^{3+}), but for strongly weathered oxic horizons, the converse is true and the effect is one of the diagnostics for Oxisols[53]. Very low cation exchange capacity (CEC) and effective CEC (ECEC; Table 7) of the representative Ultisols (Soil 4 in Table 7) along with a positive ΔpH, suggest a possibility to group these soils as Oxisols. However, a closer look at the characteristics of oxic horizon (diagnostic of Oxisols, the highly weathered remnant soils) vis-à-vis field and laboratory data (viz. clear boundaries between horizons, increase of clay down the profile and high mica content) does not support the presence of an oxic horizon. Therefore, the reported presence of Oxisols in different parts of the NER needs re-examination[54]. Recently, the Oxisols have been reported more as a concept than a reality[20].

A zero/positive ΔpH value indicates the presence of variable charge minerals such as gibbsite[20,50,54]. Usually ΔpH is negative and the degree of this negative value indicates relative proportion of weatherable minerals such as 2 : 1 secondary phyllosilicate minerals. Obviously, the presence of such minerals would show relatively high CEC. While comparing ΔpH values with clay CEC and base saturation, it was observed that lower ΔpH is associated with higher CEC, indicating a relation of reserve soil acidity with weatherable minerals (Figure 6). An attempt was made to find a relation between ΔpH and base saturation. A negative trend (Figure 6) has been observed indicating higher base saturation causes low ΔpH. While explaining the nature of soil acidity, Gangopadhyay *et al.*[55] observed that exchangeable Al was practically zero at pH 5.3 or more. The corresponding values for Odisha, Meghalaya and other soils from NER were 5.0 and 5.6 respectively[54,56]. These threshold values of exchangeable Al assume importance for recommending liming as a reclamation process as well as for appropriate estimation of the lime required for acidic paddy soils.

Potential of Indian tropical soils

The tropical soils in hot and humid conditions are generally thought to be deep, red, highly weathered and dominated by kaolinite and oxidic minerals. However, in Ultisols of Kerala (popularly known as laterites) clay minerals like mica, hydroxy interlayered vermiculite (HIV), gibbsite and kaolin (Kl) are common. Presence of gibbsite in these soils, formed from primary aluminosilicates, validates the model developed for similar soils of the sub-humid NE states of India. The model indicates that gibbsite occurs as remnants of an earlier weathering cycle characterized by neutral to alkaline pedochemical environment (Figure 6)[50]. Gibbsite has for a long time been considered an index mineral for advanced stage of soil weathering, as it was conceived to have formed from kaolinite. But such transformation appears improbable in acidic soil conditions because the desilication process is active only above pH 9 (ref. 57). Evidences show that gibbsite present in the Ultisols of the Shillong plateau in Meghalaya are formed in an alkaline pedo-environment[50]. The model for understanding the formation of gibbsite, indicates two important points: (i) gibbsite is present as a remnant of an earlier alkaline pedochemical environment, and (ii) its formation even in the presence of a considerable amount of 2 : 1 minerals discounts the hypothesis of the anti-gibbsite effect[58,59]. The presence of gibbsite in these soils should not, therefore, be considered as a conclusive proof of extreme weathering conditions of soils[60–62]. This fact assumes importance since Jackson's weathering index assigns gibbsite as a mineral with very high weathering index (WI 11). Because of the presence of gibbsite, Ultisols could belong to gibbsitic/allitic mineralogy class

Table 7. Argillic and Kandic horizons of selected Ultisols in the north-eastern region of India*

Depth (cm)	Diagnostic horizon[9]	Clay (%)	Organic carbon (%)	KCl extractable cations: Al^{3+} (cmol (+) kg^{-1})	KCl extractable cations: Total bases (cmol (+) kg^{-1})	Clay: ECEC** (cmol (+) kg^{-1})	Clay: CEC** (cmol (+) kg^{-1})	Soil reaction: Water pH	Soil reaction: NKCl pH	Soil reaction: ΔpH (KCl pH – water pH)
Soil 1 (Manipur: Typic Kandihumult)										
38–86	Argillic	52.5	0.9	5.4	0.9	12.0	16.4	4.7	3.5	–1.2
86–110	Kandic	51.5	0.6	5.3	0.6	11.4	15.1	4.8	3.6	–1.2
Soil 2 (Manipur: Typic Haplohumult)										
14–50	Argillic	36.6	1.6	2.0	1.2	8.7	26.2	3.9	3.7	–0.2
Soil 3 (Manipur: Typic Haplohumult)										
33–76	Argillic	43.4	1.0	4.2	1.6	13.4	21.9	4.8	3.6	–1.2
Soil 4 (Meghalaya: Typic Kandihumult)										
31–62	Kandic	31.1	2.0	nil	0.8	2.6	13.2	5.0	4.8	–0.2
62–95	Argillic	26.5	0.6	nil	1.2	4.7	16.0	5.1	6.0	+0.9

*Source: Bhattacharyya *et al.*[54]. **CEC, Cation exchange capacity; ECEC, Effective cation exchange capacity.

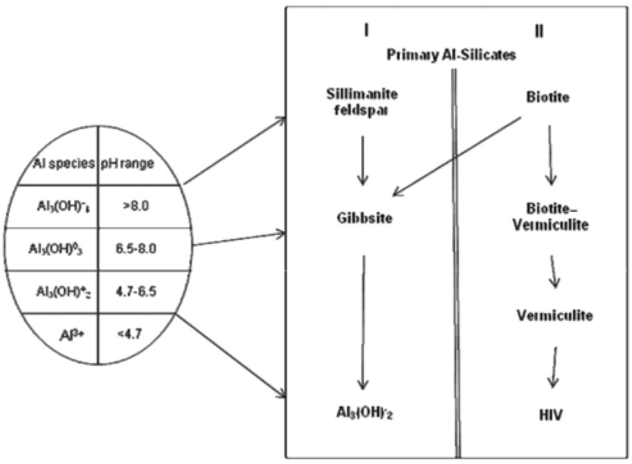

Figure 6. Gibbsite formation model in tropical soils. I. Direct formation of gibbsite from primary Al silicate. II. Formation of HIV through clay mineral intermediates (source: Bhattacharyya *et al.*[32]).

in soil taxonomy[9] (Table 8), but such classification fails to establish a legacy between the contemporary pedogenesis, mineralogy, use and management of these soils. The contemporary pedogenesis of Ultisols of Kerala (considered to be international reference for laterite), does not include desilication and the transformation of 2 : 1 layer silicates to kaolinite and further to gibbsite. The study hints that the chemical transformation of Ultisols to Oxisols with time is difficult to reconcile as envisaged in the traditional model of tropical soil genesis[20].

Hydromorphic paddy soils (Aquepts) in HTC

Flood plains, due to the lower topographic positions, are waterlogged leading to development of hydromorphic soils which are used mainly for growing paddy in the Ganga, Brahmaputra and Tripura valleys. Besides, commonly known black soils are also used for growing paddy in the Godavari, Krishna and Cauvery delta regions and some command areas in BSR. Although flood plains appear geomorphically alike, their soils vary widely over short distances both along and across the valley. Due to continuous or periodic submergence, these soils develop typical redoximorphic features[9] and are used for growing paddy.

Paddy soils in the Ganga Valley

Representative soils from the Ganga Valley show soil pH in the alkaline range. These are silty (Table 9) with some exceptions. Base saturation often exceeds 100% and this may be due to the presence of Na-zeolite as in Itwa soils and Ca-zeolites as in Ekchari and Madhpur soils. It is therefore suggested that calculation of base saturation from the CEC of soils (determined by the method of Richards[63]) and extractable bases (Ca and Mg by 1 N NaCl, and Na and K by 1 N ammonium acetate solution)[64] can provide clues for the presence of zeolites in soils. Most of these soils are in stable landscapes as evidenced by the clay illuviation in them.

Paddy soils in the Brahmaputra Valley

Like most of the other rivers in the humid tropics, the Brahmaputra River Valley is covered with alluvium which has been defined as unconsolidated sediment of Recent geologic age[65]. On the southern bank of the Brahmaputra, the alluvium is the result of deposition along highly meandering course of the river. The Brahmaputra River has

Table 8. Selected properties of Ultisols from Kerala*

Properties	Soil			
	Kanjirapally	Athirampuzha	Kinalur	Chingavanan
pH (water)	4.5	3.8	5.5	4.8
pH (KCl)	4.5	3.7	4.3	4.1
ΔpH	0	–0.1	–1.2	–1.3
Clay (%)	27	52	35	33
Clay CEC (sum of cations)	34	24	44	26
Gibbsite (< 2 mm)	25	19	31	45
Kaolin (< 2 μm)	48	53	27	39
Mineralogy class soil taxonomy[9]	Allitic	Allitic	Allitic	Gibbsitic
Mineralogy class proposed	Mixed	Mixed	Mixed	Mixed

*Source: Chandran *et al.*[20]. Values are for weighted mean average in 25–125 cm soil depth.

Table 9. Paddy soils in the Ganga Valley

Soil (soil taxonomy)[9]	pH (water)	pH (KCl)	ΔpH	SOC	Clay	Silt	Sand	Ca	Mg	Na	K	Clay CEC cmol (+)kg^{-1}	BS (%)
				(%)				Extractable bases cmol(p+)kg^{-1}					
Seoraguri (Typic Haplaquepts)	6.4	4.8	–1.6	0.74	22	69	9	3.96	1.29	0.15	0.074	51	50
Madhpur (Chromic Vertic Endoaqalfs)	8.2	6.9	–1.3	0.21	35	27	38	16.86	5.40	0.34	0.40	49	121
Ekchari (Vertic Endoaqualfs)	7.7	6.3	–1.9	0.60	37	56	7	10.71	3.38	0.65	0.34	46	90
Itwa (Aeric Ochraqualfs)	9.0	7.2	–1.8	0.40	27	59	14	7.91	3.67	5.68	0.34	40	131

Values are for weighted mean average in 25–125 cm soil depth.

widened its valley which is invariably veneered with alluvium varying both in thickness and composition, as evidenced by different kinds of soils found in the valley[48] (Table 10). Unlike soils in the Ganga Valley, paddy soils of the Brahmaputra plains are almost neutral and have high ΔpH. Moreover, they are more sandy than those of the Ganga Valley[66].

Paddy soils of Tripura Valley

Typical hydromorphic clay-rich paddy soils occur in Tripura Valley (Aquepts: Inceptisols with aquic moisture regime[9]; Table 10). The NER with alpine to humid tropical climate poses the problem of soil acidity, which is the major limiting factor for crop production. The paddy soils in Tripura are more acidic than those from other parts of the country. The clay CEC and base saturation are also low compared to other paddy soils.

Paddy soils in BSR

Paddy soils in BSR are alkaline, clayey with high bases and clay CEC (Table 10). Relatively high base saturation indicates presence of Ca-rich zeolites[18]. Such soils are often cultivated for rice as rainy season crop in Central India[67]. In the coastal Godavari delta region, black hydromorphic soils are used for growing paddy[68,69]. Saturated hydraulic conductivity (sHC) of 30 mm h^{-1} (weighted mean value in 0–100 cm soil depth) appears to be just adequate for keeping the standing water ideal for growth of paddy crop. In the absence of zeolite, such Vertisols would not have been suitable for rice cultivation. Interestingly, non-zeolitic Vertisols of western and central India are kept fallow in the rainy season. Representative paddy soils in various parts of the country indicate equilibrium water pH in the range 8.0–8.8 in BSR to as low as 4.9–5.2 in Tripura in the soil control section (25–125 cm soil depth).

Vertisols in a climosequence as an evidence of Holocene climate change

In response to the global climatic events during the Quaternary, the soils in many parts of the world witnessed climatic fluctuations, especially in the last post-glacial period. Climate changes have also been frequent during the Quaternary[70]. In India, climate changed from humid to semi-arid in rainfed areas during the Holocene[23,27,28]. It is observed that the major soil types of India under SAT environments are becoming calcareous and sodic, which ultimately modify the physical and chemical properties of soils. Such modifications resulting from regressive pedogenesis reduce the possibility of successful growing

Table 10. Characteristics of paddy soils in the northeastern and black soil regions

Soils (soil taxonomy)[9]	pH (water)	pH (KCl)	ΔpH	SOC (%)	Clay (%)	Silt (%)	Sand (%)	Clay CEC (cmol (p+)kg^{-1})	BS (%)
Brahmaputra Valley*									
Barbhagia (Typic Epiaquepts)	6.8	4.7	–2.1	1.2	18	20	62	40	97
Dighalbari (Typic Epiaquepts)	6.7	4.6	–2.1	1.0	16	22	64	61	97
Haldibari (Aeric Epiaquepts)	7.0	4.9	–2.1	0.7	25	14	61	45	93
Katani (Vertic Epiaquepts)	7.0	4.8	–2.2	0.7	31	60	9	46	94
Tripura Valley**									
Khowai (Typic Endoaquepts)	5.0	3.9	–1.1	1.0	27	20	53	28	38
Dukli–I (Fluventic Endoaquepts)	4.9	4.0	–0.9	0.5	35	27	38	17	40
Dharaicherra (Typic Endoaquepts)	5.2	3.8	–1.4	1.7	65	32	3	53	28
Nayanpur (Typic Endoaquepts)	5.1	3.7	–1.4	2.2	65	32	3	64	30
Barabil (Aeric Fluvaquents)	5.1	4.3	–0.8	0.7	29	55	16	15	42
Black soil region***									
Teligi (Sodic Haplusterts)	8.0	6.6	–1.4	1.1	51	25	24	98	111
Jajapura 1 (Vertic Haplustepts)	8.8	7.2	–1.6	1.0	52	16	32	65	109
Jhalipura (Typic Haplusterts)	8.4	7.0	–1.4	0.6	48	41	11	69	108

Values are for weighted mean average in 25–125 cm soil depth.
Source: *Bhattacharyya *et al.*[17]; **Bhattacharyya *et al.*[66]; ***Bhattacharyya *et al.*[69].

of crops[26,29]. The occurrence of Vertisols in weathered Deccan basalt, as well as in humid tropic (HT), sub-humid moist (SHm), sub-humid dry (SHd), semi-arid moist (SAm), semi-arid dry (SAd) and arid environments in the Indian Peninsula[27] suggests the influence of basaltic parent materials to form similar soils under different climatic conditions[71]. Although all these soils are grouped under the same soil order (Vertisols)[9], their morphological and chemical properties differ. Cracks > 0.5 cm wide extend down the zones of sphenoids and wedge-shaped peds with smooth or slickensided surfaces in HT, SHm, SHd and SAm soils. But cracks cut through these zones in SAd and arid soils only. Soil reactions and $CaCO_3$ content indicate that a reduction in mean annual rainfall (MAR) leads to the formation of calcareous and alkaline soils. Hence the soils are Typic Haplusterts (typical black soils) in HT, Typic/Udic Haplusterts in SHm, SHd and SAm climate, and Sodic Haplusterts (degraded black soils with high sodicity) and Sodic Calciusterts (degraded black soils with high sodicity and lime) in SAd and arid climate. Such examples help in knowing the signatures of climate change in soils in tropical and subtropical regions of India and elsewhere[27]. The importance of exact soil grouping using soil taxonomy to decode behaviour of climate and its change is also worthwhile to appreciate the fact that soils have a tremendous memory and store the past episodes carefully.

Concluding remarks

Different kinds of soils in India indicate that the soil diversity is quite large because of variability of several factors of soil formation. Generalizations about Indian soils made so far, are unlikely to have wider applicability in an agriculturally progressive country like India. This review will help establish a link between pedology and edaphology of Indian soils and also pave the way for developing a handbook on Indian soils to facilitate better management for optimizing crop productivity in the 21st century. Realizing the inherent capacity of tropical soils, Kellog[72] envisaged that some day the most productive agriculture of the world would be mostly in the tropics and this will depend on how rapidly institutions for education, research and the other public and private sectors of agriculture will develop. Amidst the renaissance in soil science[73], a massive demand would be to appropriately manage tropical and sub-tropical soils for their restoration and preservation. If they are not cared for, crops will fail even with good rainfall[74].

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