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Pedodiversity, Biodiversity, and Soil Endemism in India

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Abstract: Pedodiversity (soil diversity) refers to the diversity within the pedo-environment. Pedodiversity is a measure of soil variation linked with edaphology and other soil ecosystem services, including biodiversity and soil endemism. Unlike other countries, pedodiversity and its quantitative study drawn little attention in India. Results showed that Shannon's diversity index increases as the soil taxonomic category changes from soil order to soil family across different zones in India. More values of Shannon's diversity index at the soil family level were due to increased taxa richness. The pedodiversity index and area relationship indicated higher values for south Indian states like Andhra Pradesh and Karnataka. Variation of soil was well-pronounced in the hilly areas compared to the plains in India due to the large variety of soil-forming factors in the hills. Taxa similarity between the zones decreased as taxonomic levels changed from soil order to soil family. At the state level, nearly seven states indicated < 0.5 taxa similarity suggesting distinctly different taxa in these states in the soil family category. Soils are unique in India, - with an estimated value of ~52% area, with rare soils covering about ~2 % area indicating soil endemism in India. This might assist administrators in conserving and preserving soil resources and decide appropriate land use planning. The quantified values of pedodiversity helped generate various theme maps on different pedodiversity parameters to develop first-hand information on the pedodiversity of Indian soils at the state level. Few studies have considered pedodiversity as a basis for regional biodiversity. The database generated for Indian soils in this paper may be helpful in developing a model understanding of regional pedodiversity and biodiversity for the tropical soils in the world.

Key words: *Tropical soils, pedodiversity, biodiversity, taxonomic category, taxa similarity, soil endemism.*

Introduction

Soils provide ecosystem services, such as a) provisioning, b) regulating, c) cultural, and d) supporting services (Figure 1). The first one includes food, raw materials, and water retention. Regulating services address the issues of climate, water regulation, carbon sequestration, soil erosion, and flood control. Supporting services include weathering, soil formation, and nutrient recycling. Cultural heritage makes part of the cultural services (Bhattacharyya 2021a).

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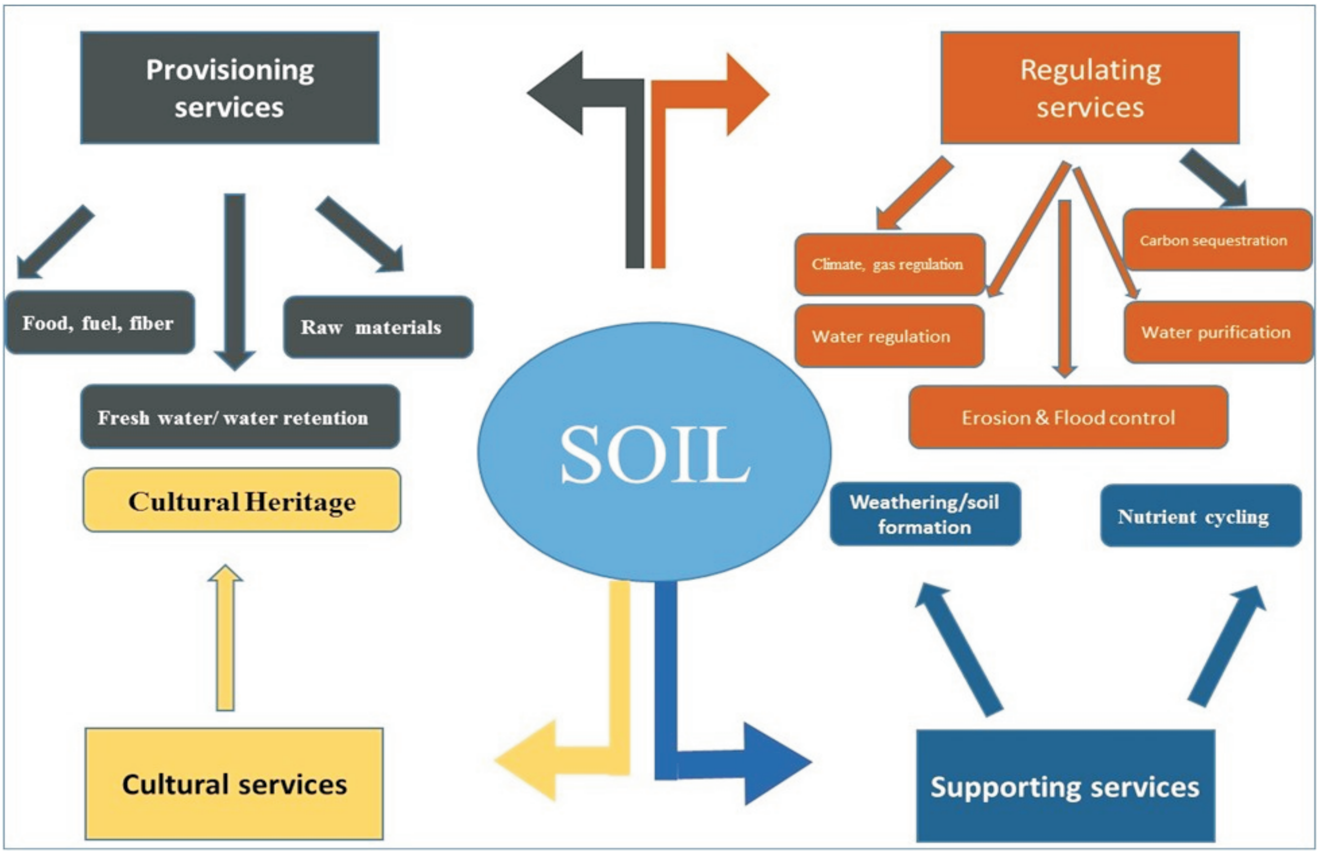

Fig. 1. Soil and its role in ecosystem services (Source: Bhattacharyya 2021b)

Soils are diverse throughout the globe. Terrestrial diversity, in most cases, centres on the above ground flora and fauna. The terrestrial ecosystem requires a special mention in explaining the diverse soil systems linked with pedodiversity and biodiversity (Bhattacharyya and Patil 2022; Copley 2000) to provide the ecosystem services mentioned above. Studies show a strong relationship between soil diversity (referred to as pedodiversity) and biodiversity for various regional and global planning (Amundson *et al.* 2003; Guo *et al.* 2003; Minhas 2006; Bhattacharyya 2021a, Bhattacharyya and Patil).

The soil-forming factors, especially climate, vegetation and topography, act on different rocks leading to the formation of different types of soils (Jenny 1941). Soil grouping is a general practice to suggest the planning and management of this natural resource. The concept of soil taxonomy is based on the basic theme of differentiating soils based on their properties, where the facts of soil formation help to describe soils indirectly (Bhattacharyya 2021b). It is conceived to communicate soil information to other branches of science, in general, and soil science, in particular. U.S. soil taxonomy has been described as a classification system mainly concerned with the relationship among soils (Bhattacharyya *et al.* 2021a).

This is important for Indian soils since this country provides an example of varied land and physiographic features resulting in the diversity of soils. High mountains, temperate, tropical, and sub-tropical climates, deserts, diverse geological formations, topography, and relief make a spectacular site of various physiographic features. The temperature in India varies from arctic cold to equatorial hot, and the annual rainfall is from a few centimetres in the deserts to a humid climate experiencing several hundred centimetres. These factors provide a high-elevation plateau, hills, interhill basins, uplands, fertile plains, hydromorphic, swampy lowlands, and barren deserts. These natural environment variations have resulted in pedodiversity in India compared to any other country of similar size in the world.

Studies on Indian soils were initiated in 1893 by Voelckel (Bhattacharyya 2021a). In earlier days, Indian soils were classified into two groups (based on variations of soil fertility), such as *Urvara* (Sanskrit: fertile) and *Anurvara* or *Usara* (Sanskrit: sterile). According to *Arthashastra* (300 BC), Indian soils were considered diverse and, therefore, unsuitable for all crops. Soils and crops were reported to vary due to climate. They were classified as *jangala* (Sanskrit: dry places/plants: xerophytes), *anupa* (Sanskrit: marshy or swampy land), and *sadharana* (Sanskrit: a region with ordinary plants: mesophytes) (Bhattacharyya 2021b). Scientific interest in understanding the diversity of Indian soils began with the initiation of studies by the Geological Survey of India in 1846 (Raychaudhuri 1979).

Four major soil types, Indo-Gangetic alluvial soils, black (regur) soils, red soils, and laterite and lateritic soils, were reported in 1898. In 1932, a soil map of India showing 16 soil groups was published to show the effects of climate, vegetation, soil-forming materials, salinity, alkalinity and pits. Based on ecological diversity, various types of soils were demonstrated in a compiled soil map of India generated by Wadia and his group in 1935. The climatic variability was utilized for the first time in India to address the pedodiversity through a soil map of India by Vishwanatha and Ukil (1943). In 1963, a comprehensive study on 27 diverse soil units was reported (Raychaudhuri 1979). Soil types, their extent, and the chronology of events to understand the diversity of Indian soils are detailed in table 1 and figure 2.

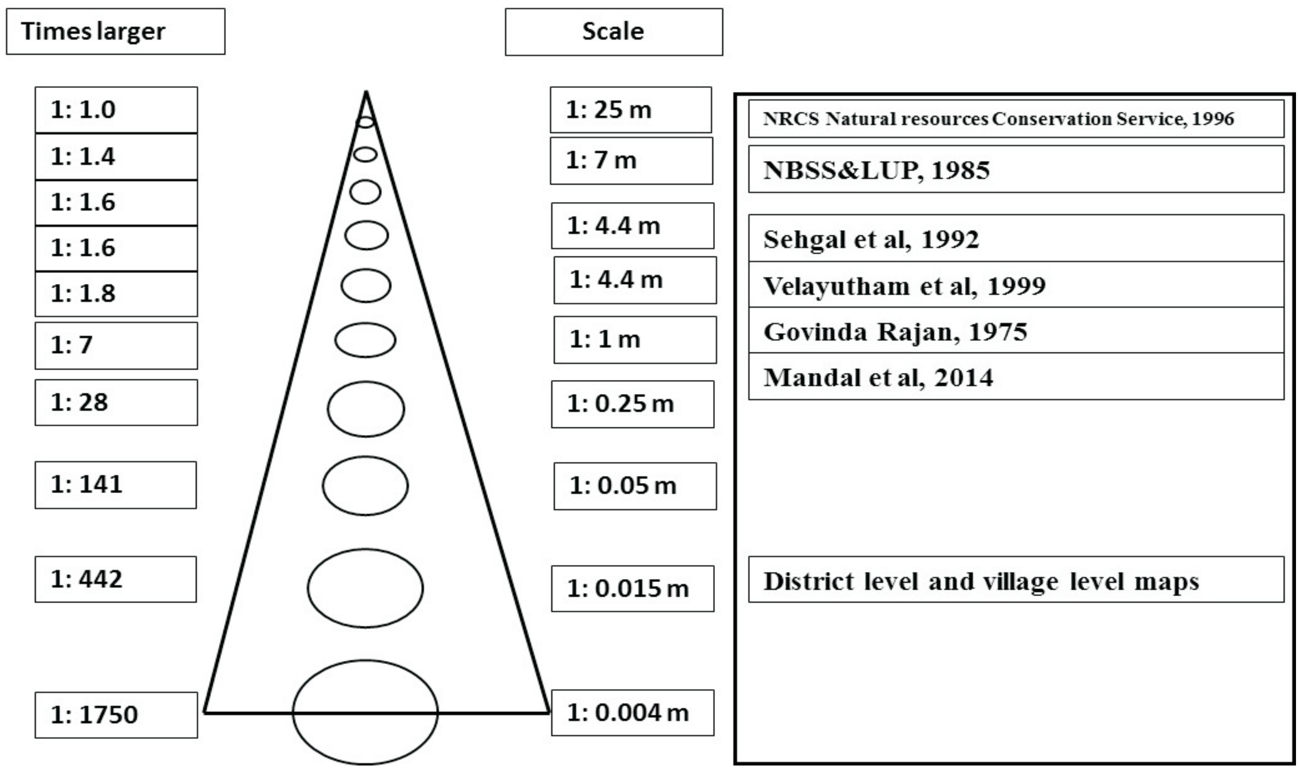

Fig.2. Chronology of soil studies in India (Source: Bhattacharyya 2021a).

Table 1. Distribution of major soils in India

Serial No.	Soil orders*	Major soils**	States	Extent	
				‘000 ha	Percent age
1	Inceptisols, Entisols, Alfisols, Aridisols	Alluvial	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	100,006	30.4
2	Aridisols, Inceptisols, Entisols	Coastal alluvial	AP, Karnataka, TN, Kerala, WB, Gujarat, Odisha, Puducherry, Lakshadweep, A&N	10,049	3.1
3	Alfisols, Ultisols, Entisols, Inceptisols, Mollisols, Aridisols	Red	AP, Karnataka, Kera la, TN, Puducherry, Rajasthan, MP, MS, Gujarat, Goa, ArP, Assam, Manipur, Meghalaya, Nagaland, Mizoram, Tripura, Delhi, UP, HP, A&N	87,989	26.8
4	Alfisols, Ultisols, Inceptisols	Laterites	AP, Karnataka, Kerala, TN, Puducherry, MS, Odisha, WB	18,094	5.5
5	Mollisols, Inceptisols	Brown forest	Karnataka, Maharashtra	540	0.2
6	Inceptisols, Entisols	Hill	Manipur, Odisha, WB, Tripura, Nagaland	2,262	0.7
7	Mollisols, Entisols	Terai	UP, Sikkim	326	0.1
8	Mollisols	Mountain meadow	J&K	60	-
9	Alfisols	Sub-montane	J&K	104	-
10	Vertisols, Mollisols, Inceptisols, Entisols, Aridisols	Black	MP, MS, Rajasthan, Puducherry, TN, UP, Bihar, Odisha, AP, Gujarat	54,682	16.6
11	Aridisols, Inceptisols, Entisols	Desert	Rajasthan, Gujarat, Haryana, Punjab	26,283	8.0
Others***				28,305	8.6
Total				328,700	100

*(Soil Survey Staff 2014) **(Bhattacharyya 2021a); ***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.

Diversity is widely considered synonymous with a difference; thus, pedodiversity should indicate the difference in soils. Various factors, either natural or anthropogenic, cause differences in soils. To understand the diversity of soils, the knowledge of the potential and source of soil resources and their limitations to quantify pedodiversity for its use in agriculture and non-agriculture purposes are vital. Therefore, an attempt has been made here to describe the methodology to measure pedodiversity for Indian soils using U.S. soil taxonomy (Soil Survey Staff 2014) and its probable impact on soil degradation and soil endemism.

Materials and Methods

Materials

Using the soil information from the resource management programme, the soil database was generated for the present study (Bhattacharyya 2021a,b). In India total of seven zones (north, west, central, southern, eastern, northeastern, and islands) were identified. Physiography, climate, dominant soils and other information are detailed in the table 2. The soil data were arranged in seven zones: northern, western, central, southern, eastern, northeastern, and islands. For each zone, the database was again organized for different states to quantify pedodiversity (Figure 3).

Fig.3. Various states in India

Table 2. General information about different zones in India

Zones	Elevation Range m above msl	Temperature (range ^{0}C)	MAT (range ^{0}C)	MAR mm	Vegetation	Geology	Factors of soil diversity	Dominant soils
Northern	66-6100	-30 to 40	0 to 32	100-2600	*Cedrus*, Willows, Alpine, Subalpine forests, Oak, Fir, Xerophytes, *Tectona*, Sal (*Shorea)*, *Acacia*, *Ziziphus*, *Behda* (*Terminalia)*, *Shorea*, *Madhuka sp*., *neem* (*Azadirachta*), *Pine* (*Pinus*), Birch (*Betula*), Alpine, Rhododendrons, Shisam (*Dalbergia sissoo*), Poplar	Sedimentary, metamorphic, igneous rocks, Alluvial	Climate, Geology, Organisms (Vegetation), Time (in plains)	Inceptisols, Entisols, Aridisols, Mollisols, Alfisols
Western	0-534	2 to 42	24 to 28	100-2000	*Acacia*, Cactus, Halophytes, *Madhuka sp.*, *Anogeissus latifolia*, red sandalwood (*Pterocarpus indicus*), *Tectona*, Shisam (*Dalbergia sissoo*), *Behda* (*Terminalia)*	Sandstone, marine alluvium, Phyllite, schist, Miliolite Limestone, Porbandar sandstone, Basalt, igneous plutonic complex (gabbros (tholeiitic and alkalic), diorites, lamprophyres, alkali-syenites and rhyolites)	Climate, Geology	Entisols, Aridisols, Inceptisols, Vertisols
Central	7-1167	6 to 46	24 to 34	600-3000	*Shorea*, *Madhuka sp.*, *Anogeissus latifolia*, *Tectona*, *Acacia*, red sandalwood (*Pterocarpus indicus*), Shisam (*Dalbergia sissoo*), *Behda* (*Terminalia)*, *Dipterocarpus*, Jackfruit (*Artocarpus*), *Dysoxylum*, Cyclostemon, silk tree/ shirish (*Albizzia*), mangrove (*Ryzophora*)	Tertiary Rocks, Vindhyan Rocks, Cuddapah Rocks, Basalt, Marine alluvium	Geology, Climate, Time (in plains)	Inceptisols, Vertisols, Alfisols, Entisols
Southern	0-900	15 to 40	23 to 29	400-3000	*Acacia*, *Ziziphus sp*., *Madhuka sp.*, *Dipterocarpus*, *Behda* (*Terminalia)*, Jackfruit (*Artocarpus*), *Casuarina*, mangrove (*Ryzophora*), red sandalwood (*Pterocarpus indicus*), Shisam (*Dalbergia sissoo*), *Bombax*	Archaean granodiorite, tourmalines, Khondalite, Marine alluvium, Fluvio-alluvium, sandstone and shale, Schist, Mariane alluvium, pink granites and pegmatites	Geology, Climate	Inceptisols, Entisols, Vertisols, Alfisols,

Eastern	0-2500	3 to 40	13 to 32	1200-3000	*Shorea*, *Bombax*, Shisam (*Dalbergia sissoo*), *Behda* (*Terminalia)*, *Michelia*, *Dysoxylum*, silk tree/ shirish (*Albizzia*), *Dipterocarpus*, Cane, Ferns, Pinus, *Pandanus*, Casuarina, mangrove (*Ryzophora*), looking-glass mangrove (*Heritiera littoralis*)	Granite, Khondalite, Charnockite, granulite, leptynite, granitic gneiss laterite and Augen gneiss, Laterites, Basalt, Alluvium, Sandstone, Gneiss, Schist, Slate and Quartzite (Archaean), pink granites and pegmatites	Climate, Organisms (Vegetation), Time (in plains)	Alfisols, Inceptisols, Entisols, Mollisols, Ultisols
North-eastern	10--5000	3 to 34	13 to 32	1200-3200	*Shorea*, *Bombax*, Amla (*Emblica officinalis)*, *Michelia*, *Duabangagrandiflora*, *Dipterocarpus*, *Dysoxylum*, Cane, Ferns, Pinus	Oldest Precambrian gneissic complex, Tipam Sandstone, Tertiary rocks (Siwalik), sandstones, siltstones, claystone, carbonaceous shales, graphitic schist and dark grey slate, Alluvium	Climate, Organisms (Vegetation)	Alfisols, Ultisols, Inceptisols, Entisols
Islands	0-732	2 to 30	26 to 27	1600-3000	Littoral evergreen forests, seagrass, creepers	Sandstone, siltstone and shale, Corals, marine alluvium	Climate, Geology	Inceptisols, Entisols

Pedodiversity can be captured well if the information is gathered at the larger scale of soil mapping. Pedodiversity reported at a 1:7 million scale was based on 103 types of soils at the suborder level (Bhattacharyya 2021a). Using image interpretation (remote sensing data), soil survey, laboratory data, and GIS and cartography, a more extensive database was generated with its states as a database unit (Bhattacharyya 2021a) (Table 2). Distribution of soil orders, suborders, great groups, subgroups, and families show a wide diversity of Indian soils (Bhattacharyya 2021a). Revised datasets show seven orders, 22 suborders, 78 great groups, 220 subgroups and 1197 families for the soils in India (Figure 4; Table 3). Inceptisols occupy a larger area in India, followed by Entisols, Alfisols and Vertisols (Figure 5).

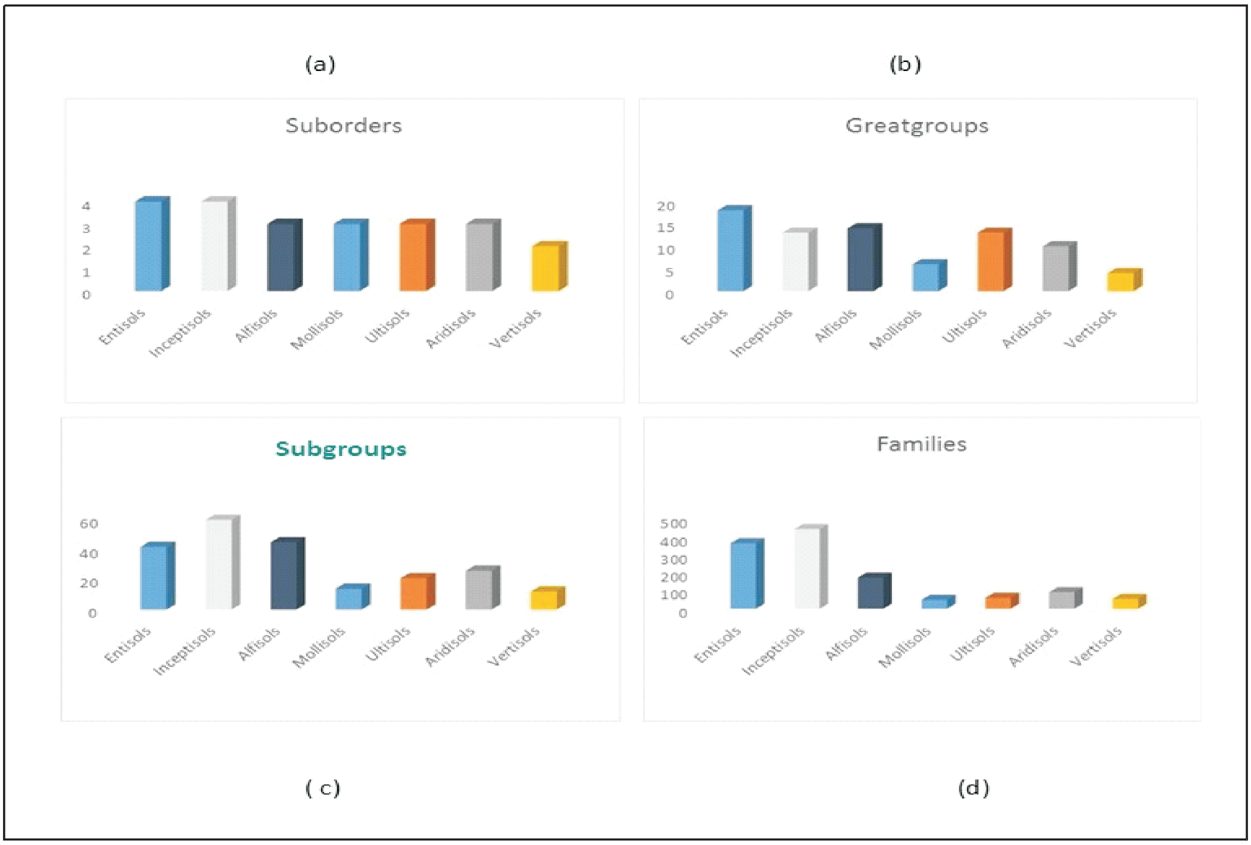

Fig. 4. Occurrence of total sub-orders (*a*), great groups (*b*), subgroups (*c*), and families (*d*) in various soil orders identified in India (Source: Bhattacharyya 2021a).

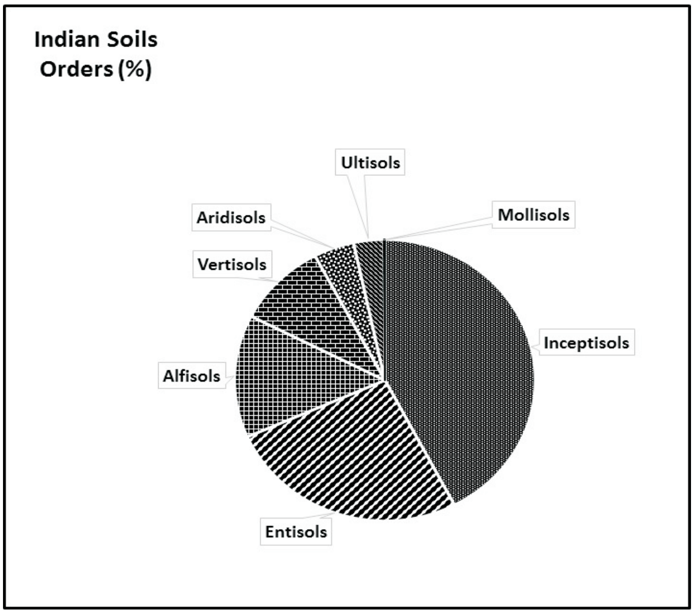

Fig.5. Soils at the order level of US Taxonomy in India (Source: Bhattacharyya 2021a).

Methodology

Pedodiversity, due to the combined influence of different soil-forming factors, is preserved within the soil since it can memorize various episodes of changes in soil properties in the course of soil formation (Bhattacharyya 2014; 2021a). Since India has a diversity of bio-climate, geology, agro-climate, agro-ecological regions (AERs) and agro-ecological sub-regions (AESRs), pedodiversity is observed in different parts of India separated as various zones. Since soil family is the highest category for which datasets are available now, this has been considered the ideal representative of pedodiversity.

The Pedodiversity index (PDI) was assessed using the concept of occurrence of soil family (Soil Survey Staff 2014) per unit area (Table 3) (Bhattacharyya 2021a). The total area of each taxon helped estimate the pedodiversity indices (PDI) in soils at the country (India), zones, and state levels. The area of each taxonomic unit was obtained from the available datasets as reported in the soil taxonomic database for Indian soils (Bhattacharyya 2021a). The total area of each taxon from all the zones and states was revised. Diversity indices were estimated using the area abundance of each taxon in all five (5) soil taxonomic categories: order, suborder, great group, subgroup, and family. For the soil series, the datasets are incomplete, hence not considered here. Richness, evenness, and diversity were the parameters considered for assessing pedodiversity. Richness is the total number of soil taxa present in an area. The area equitability of each soil taxon suggests evenness. The higher the richness and evenness, the higher the diversity which suggests its dependence on the former two parameters (richness and evenness).

Taxa richness (S) considers the number of taxa in each taxonomic category. Smith's evenness index (E) has been considered a measure of evenness (Guo *et al.* 2003). Shannon diversity index ($H^/$) has been used in this study since it is widely used to measure pedodiversity (Ibanez *et al.* 1998). O'Neil dominant index was assessed to understand the deviation of the calculated $H^/$ from the maximum diversity (O'Neil *et al.* 1988).

Smith's E was calculated with the following relationship (Equation 1) (Smith and Wilson 1996):

$$E = 1 - \frac{2}{\Pi} \arctan t\{(\sum_i^S [In(x_i)/S]^2)(Equation\,1)$$

Where S is taxa richness; x is the areal extent of ith, jth taxa. The taxa evenness E varies from 0 – 1, where 0 and 1 indicate the minimum and maximum evenness, respectively (Guo *et al.* 2003). To find out the pedodiversity, Shannon's diversity index $H^/$ (Shannon and Weaver 1949; Magurran 1988) was calculated using the following equation (Equation 2)

$$H^1 = -\sum_i^S p_i \times In(P_i)....(Equation\,2)$$

where S is taxa richness; p_i is the proportion of ith taxa; p_i is estimated by n_i/N; n_i is the area covered by ith taxa and N is the total area studied.

Shannon's maximum diversity (H_{max}) and maximum relative diversity indices (H_{maxr}) were calculated following these equations (Equations 3, 4) (Guo *et al.* 2003)

$$H_{max} = In(S).....(Equation\ 3)$$

$$H_{max} = In(S)/In(S._T.).....(Equation\ 4)$$

where S is taxa richness in different levels (country, zones, states, and districts); $S_{.T.}$ is the total taxa richness of India. O'Neil dominant index (D) was calculated with the following equation (O'Neil *et al.* 1988) (Equation 5)

$$D = In(S) + \sum_i^S p_i \times In(p_i)....(Equation\ 5)$$

Besides, Simpson's index (Ds) was also estimated to assess the dominance using the following equation (Equation 6):

$$Ds = \sum \{p_i\,(pi^{-1}) \div N(N-1)\}(Equation\ 6)$$

where pi and N are parameters as mentioned above.

Taxa richness, diversity and evenness indices for different zones and states were calculated following the above equations.

Table 3. Soil diversity in India*

Country/ States	Number		Number per million hectares
	Orders	**Soil Families**	**Soil Families (PDI)**
India	7	1197	(5)
Northern Zone	**6**	**381**	**38 (6)**
Jammu and Kashmir	4	93	4
Himachal Pradesh	4	56	10
Punjab	4	46	9
Haryana	4	41	9
Uttar Pradesh (including Uttarakhand)	5	145	5
Western Zone	**5**	**222**	**9 (4)**
Rajasthan	5	96	3
Gujarat	5	126	6
Central Zone	5	270	4
Madhya Pradesh (including Chhattisgarh)	5	175	4
Maharashtra	5	95	3
Southern Zone	**7**	**342**	**25 (5)**
Andhra Pradesh (including Telangana)	6	134	5
Karnataka	7	98	5
Tamil Nadu	6	75	6
Kerala	5	35	9
Eastern Zone	**4**	**233**	**17 (6)**
Bihar (including Jharkhand)	4	79	5
Odisha	4	98	6
West Bengal	3	56	6
North-Eastern Zone	**4**	**246**	**66 (11)**
Arunachal Pradesh	4	58	7
Assam	4	82	10
Manipur	4	32	14
Mizoram	4	41	19
Meghalaya	4	33	15

*Data of a few states were not included due to different scales of survey; the values increase when all the states and UTs are considered (Source: Bhattacharyya 2021a); PDI: Pedodiversity Index

Measurements of pedodiversity may not indicate the similarity of the taxa between the regions. Different soil taxa in regions may show the same pedodiversity. To study the taxa similarity, Sorenson's similarity measure was estimated using the following equation (Equation 7) (Magurran 1988).

$$CN = (2\sum_j N_j)/(N_a + N_b) \quad (Equation\ 7)\_$$

where $C_{.N.}$ is Sorenson's similarity measure, N_a and N_b are the sample area from two regions (regions A and B), respectively. Nj is the minimum value of the area abundance of j^{th} taxa in two samples (a or b) used for comparison. If C_N=0, taxa in the two samples are completely different, whereas taxa are exactly the same if C_N=1 (Guo e*t al.* 2003).

Results and Discussion

Occurrence of diverse soil families in different zones of India

The pedodiversity index (PDI) (H') estimated at the level of soil subgroups and the areal extent of various zones in India (Bhattacharyya 2021a) indicates a trend between areas of different zones studied versus pedodiversity (Tables 4 to 8). The northeastern, eastern and southern zones showed more pedodiversity, which supports commonly found significant biodiversity in these three zones (Table 2); however, this relation (Bhattacharyya 2016) was not in line with the previous results of pedodiversity for the USA (Guo *et al.* 2003) and the world (Iba'n˜ez *et al.* 1998; MacBratney *et al.* 2000) . This was because PDI has been related with soil subgroups unlike the series used in case of the USA. Pedodiversity (Beckett and Bie 1978) and biodiversity (Kilburn 1966) were reported to have a robust species (soil types)–area relationship. To justify area dependency of taxa richness, the family level of datasets was used in the present study.

The northern zone, covering a 20 per cent area spread over seven states in India, has 381 diverse soil families according to U.S. soil taxonomy (Soil Survey Staff, 2014) (Table 3). Typical shrink-swell soils (Vertisols) are observed in Uttar Pradesh, and soils with vertic properties in Jammu & Kashmir and Ladakh (Bhattacharyya 2021a). Brown forest soils (Mollisols) are reported in Jammu & Kashmir (undivided), Himachal Pradesh, and Uttar Pradesh. The western zone covering 16.5 per cent area of the country showed 222 soil types representing Rajasthan, Gujarat, and Goa states. The presence of Ultisols and Alfisols in these dry climates suggests a change of climate from a wetter to a dry regime in these parts of the country. Pedodiversity can indicate various signatures of climate change stored in soils (Bhattacharyya 2014). The central zone consists of 3 states [Madhya Pradesh (including Chhattisgarh) and Maharashtra] and occupies 23 per cent area of the country. The pedodiversity in Madhya Pradesh (undivided) is more than in Maharashtra, as evidenced by 270 soil families in this zone (Table 3). Besides, Madhya Pradesh has double the area under typical black soils compared to Maharashtra. Brown forest soils (Mollisols) are reported in the Sapura and Western Ghats of Madhya Pradesh and Maharashtra. The South zone represents five states/Union Territories, such as Andhra Pradesh (undivided), Karnataka, Tamil Nadu, Kerala, Puducherry, and Karaikal, and covers 19.3 per cent of the area of the country. Out of five, four states showed the occurrence of fertile brown forest soils (Mollisols). They supported the hypothesis that Mollisols can also occur in a tropical climate with some conditions (Bhattacharyya 2021b). Typical black soils (Vertisols) are common in all these states. The occurrence of Vertisols in Kerala was reported later (Nair *et al.* 2006; Bhattacharyya 2021a) and is not part of the soil datasets presented here. However, while revising the soil map of the black soil region, Vertisols of Kerala and other parts of India were considered (Mandal *et al.* 2014). The Eastern zone consists of Bihar, Jharkhand, Odisha, West Bengal, and Sikkim and occupies 13 per cent of the country. A total of 233 diversified soils are reported from this zone. The northeastern zone is comprised of Arunachal Pradesh, Assam, Nagaland, Manipur, Mizoram, Tripura, and Meghalaya, covering an area of 7 per cent of the country. Pedodiversity is more in Assam, followed by Arunachal Pradesh, Tripura, and Mizoram. Low-activity clay soils are common in this zone (Bhattacharyya *et al.,* 1994), showing 246 diversified soils (Table 3). A total of 43 types of soils are reported from Indian islands consisting of 2 union territories that cover 0.2% area of the country. The Andaman and Nicobar islands have a large area under brown forest soils (Mollisols).

Pedodiversity in different states of India

Pedodiversity indices for each taxonomic category of soils in India are presented in tables 4 to 8. As the taxonomic category decreases from order to soil family, Shannon's diversity index increases due to increased taxa richness. Regarding taxa evenness, taxa in all taxonomic categories are not of equal area (the maximum E=1 occurs when all taxa in a particular category have a similar area). Lower evenness of taxa indicates that some taxa are relatively rare while others have a large area abundance. When diversity indices are considered, a comparison of similarity between Shannon's diversity index and the hierarchical Shannon's diversity index in each taxonomic level showed no noticeable difference, suggesting that either one can be used in pedodiversity studies.

Table 4. Pedodiversity indices in different geographical zones in India (Soil order)

Zones	S	$H^{/}$	O'Neill's D	H_{max}	H_{maxr}	Simpson's index (Ds)	1/D	E
India	7	1.471	0.475	1.946	1.000	0.285	3.510	0.312
Northern Zone	6	0.965	0.827	1.792	0.921	0.448	2.231	0.175
Jammu , Kashmir, Ladakh	4	0.522	0.864	1.386	0.712	0.706	1.417	0.142
Himachal Pradesh	4	0.594	0.792	1.386	0.712	0.600	1.668	0.108
Punjab	4	0.803	0.584	1.386	0.712	0.401	2.496	0.559
Haryana	4	0.964	0.423	1.386	0.712	0.453	2.208	0.348
Delhi	2	**0.484**	0.210	0.693	0.356	0.694	1.440	0.688
Uttar Pradesh and Uttarakhand	5	0.767	0.843	1.609	0.827	0.597	1.674	0.168
Western Zone	6	1.274	0.518	1.792	0.921	0.309	3.234	0.127
Rajasthan	5	1.211	0.399	1.609	0.827	0.329	3.041	0.255
Gujarat	5	1.122	0.488	1.609	0.827	0.420	2.380	0.265
Goa	4	0.878	0.508	1.386	0.712	0.556	1.800	0.546
Central Zone	5	1.137	0.472	1.609	0.827	0.376	2.659	0.283
Madhya Pradesh (including Chhattisgarh)	5	1.361	0.248	1.609	0.827	0.277	3.610	0.291
Maharashtra	5	1.170	0.439	1.609	0.827	0.343	2.914	0.248
Southern Zone	7	1.560	0.386	1.946	1.000	0.256	3.912	0.439
Andhra Pradesh and Telangana	6	1.395	0.397	1.792	0.921	0.298	3.358	0.442
Karnataka	7	**1.697**	0.249	1.946	1.000	0.205	4.889	0.433
Tamil Nadu	6	1.132	0.660	1.792	0.921	0.392	2.551	0.196
Kerala	5	0.911	0.698	1.609	0.827	0.501	1.997	0.259
Puducherry & Karaikal	4	1.233	0.154	1.386	0.712	0.312	3.206	0.654
Eastern Zone	5	1.154	0.455	1.609	0.827	0.346	2.894	0.147
Bihar and Jharkhand	4	1.094	0.292	1.386	0.712	0.339	2.951	0.088
Odisha	4	1.125	0.261	1.386	0.712	0.374	2.674	0.606
Sikkim	3	0.980	0.119	1.099	0.565	0.401	2.493	0.783
West Bengal	3	1.039	0.060	1.099	0.565	0.376	2.661	0.931
North Eastern Zone	4	1.171	0.215	1.386	0.712	0.342	2.925	0.566
Arunachal Pradesh	4	1.011	0.375	1.386	0.712	0.389	2.569	0.112
Assam	4	1.162	0.224	1.386	0.712	0.354	2.828	0.661
Nagaland	4	0.927	0.459	1.386	0.712	0.506	1.978	0.439
Manipur	4	1.158	0.229	1.386	0.712	0.339	2.947	0.464
Mizoram	4	1.179	0.207	1.386	0.712	0.324	3.087	0.436
Tripura	4	0.713	0.674	1.386	0.712	0.654	1.530	0.426
Meghalaya	4	1.092	0.295	1.386	0.712	0.378	2.646	0.489
Islands	4	1.051	0.335	1.386	0.712	0.399	2.507	0.490
Andaman and Nicobar	4	0.564	0.822	1.386	0.712	0.728	1.374	0.248

S=taxa richness in each taxonomy category; $H^{/}$=Shannon's diversity index; D = O'Neill dominant index; H_{max}=maximum diversity; H_{maxr}=maximum relative diversity; Ds= Simpson's index; 1/D= Inverse Simpson's index; E=Smith's evenness index

Table 5. Pedodiversity indices in different geographical zones in India (Soil suborder)

Zones	S	$H^{/}$	O'Neill's D	H_{max}	H_{maxr}	Simpson's index (Ds)	1/D	E
India	23	2.122	1.013	3.135	1.000	0.180	5.564	0.055
Northern Zone	15	1.455	1.254	2.708	0.864	0.347	2.885	0.199
Jammu , Kashmir, Ladakh	9	0.840	1.358	2.197	0.701	0.610	1.640	0.190
Himachal Pradesh	8	0.859	1.220	2.079	0.663	0.544	1.838	0.123
Punjab	8	1.354	0.726	2.079	0.663	0.361	2.770	0.196
Haryana	6	1.169	0.623	1.792	0.571	0.421	2.375	0.388
Delhi	4	0.672	0.715	1.386	0.442	0.673	1.485	0.383
Uttar Pradesh and Uttarakhand	12	1.154	1.331	2.485	0.793	0.518	1.932	0.181
Western Zone	11	1.571	0.827	2.398	0.765	0.255	3.928	0.121
Rajasthan	8	0.873	1.206	2.079	0.663	0.468	2.137	0.097
Gujarat	10	1.367	0.935	2.303	0.734	0.385	2.598	0.177
Goa	7	0.821	1.125	1.946	0.621	0.493	2.030	0.273
Central	9	1.355	0.843	2.197	0.701	0.289	3.464	0.083
Madhya Pradesh (including Chhattisgarh)	8	1.382	0.698	2.079	0.663	0.276	3.626	0.090
Maharashtra	7	1.196	0.750	1.946	0.621	0.340	2.944	0.112
Southern Zone	18	**1.822**	1.068	2.890	0.922	0.233	4.299	0.154
Andhra Pradesh and Telangana	12	1.491	0.994	2.485	0.793	0.292	3.422	0.146
Karnataka	12	1.898	0.587	2.485	0.793	0.188	5.333	0.204
Tamil Nadu	12	1.245	1.240	2.485	0.793	0.383	2.612	0.152
Kerala	9	1.536	0.662	2.197	0.701	0.296	3.375	0.317
Puducherry & Karaikal	6	1.505	0.287	1.792	0.571	0.266	3.753	0.616
Eastern Zone	13	**1.994**	0.571	2.565	0.818	0.167	5.983	0.135
Bihar and Jharkhand	9	**1.938**	0.260	2.197	0.701	0.165	6.074	0.466
Odisha	9	1.663	0.534	2.197	0.701	0.233	4.289	0.298
Sikkim	6	1.023	0.769	1.792	0.571	0.394	2.536	0.169
West Bengal	8	1.805	0.274	2.079	0.663	0.196	5.114	0.489
North Eastern Zone	9	1.779	0.418	2.197	0.701	0.218	4.589	0.368
Arunachal Pradesh	9	1.164	1.033	2.197	0.701	0.367	2.726	0.151
Assam	9	1.683	0.514	2.197	0.701	0.175	5.703	0.385
Nagaland	6	1.017	0.775	1.792	0.571	0.498	2.009	0.190
Manipur	6	1.623	0.169	1.792	0.571	0.215	4.653	0.647
Mizoram	9	1.484	0.713	2.197	0.701	0.273	3.668	0.259
Tripura	7	1.082	0.864	1.946	0.621	0.475	2.107	0.120
Meghalaya	6	1.561	0.231	1.792	0.571	0.245	4.075	0.668
Islands	8	1.581	0.498	2.079	0.663	0.263	3.808	0.537
Andaman and Nicobar	8	1.577	0.503	2.079	0.663	0.264	3.790	0.529
Lakshadweep	2	**0.538**	0.156	0.693	0.221	0.647	1.545	0.775

S=taxa richness in each taxonomy category; $H^{/}$=Shannon's diversity index; D = O'Neill dominant index; H_{max}=maximum diversity; H_{maxr}=maximum relative diversity; Ds= Simpson's index; 1/D= Inverse Simpson's index; E=Smith's evenness index

Table 6. Pedodiversity indices in different geographical zones in India (Soil Greatgroup)

Zones	**S**	**H/**	**O'Neill's D**	**H_{max}**	**H_{maxr}**	**Simpson's index (Ds)**	**1/D**	**E**
India	75	2.749	1.568	4.317	1.000	0.132	7.595	0.099
Northern Zone	32	1.821	1.645	3.466	0.803	0.296	3.383	0.158
Jammu, Kashmir, Ladakh	14	1.344	1.295	2.639	0.611	0.408	2.454	0.130
Himachal Pradesh	12	1.324	1.161	2.485	0.576	0.357	2.803	0.163
Punjab	11	1.453	0.945	2.398	0.555	0.354	2.826	0.198
Haryana	9	1.327	0.870	2.197	0.509	0.400	2.501	0.206
Delhi	4	0.672	0.715	1.386	0.321	0.673	1.485	0.383
Uttar Pradesh and Uttarakhand	21	1.276	1.768	3.045	0.705	0.511	1.958	0.172
Western Zone	28	1.935	1.397	3.332	0.772	0.220	4.543	0.122
Rajasthan	15	1.821	1.511	2.708	0.627	0.220	4.537	0.198
Gujarat	19	1.572	1.136	2.944	0.682	0.373	2.679	0.172
Goa	12	**0.599**	2.346	2.485	0.576	0.592	1.691	0.777
Central	12	1.429	1.056	2.485	0.576	0.284	3.523	0.080
Madhya Pradesh (including Chhattisgarh)	11	1.493	0.905	2.398	0.555	0.265	3.773	0.086
Maharashtra	8	1.205	0.874	2.079	0.482	0.340	2.943	0.168
Southern Zone	41	**2.364**	1.350	3.714	0.860	0.162	6.154	0.153
Andhra Pradesh &Telangana	18	1.905	0.985	2.890	0.669	0.214	4.664	0.154
Karnataka	25	**2.471**	0.748	3.219	0.746	0.119	8.369	0.296
Tamil Nadu	17	1.703	1.130	2.833	0.656	0.288	3.473	0.159
Kerala	14	2.209	0.430	2.639	0.611	0.135	7.409	0.192
Puducherry & Karaikal	8	1.593	0.487	2.079	0.482	0.260	3.841	0.332
Eastern Zone	28	**2.470**	0.862	3.332	0.772	0.114	8.753	0.095
Bihar and Jharkhand	19	2.333	0.611	2.944	0.682	0.121	8.260	0.214
Odisha	15	2.158	0.550	2.708	0.627	0.145	6.879	0.221
Sikkim	10	1.645	0.657	2.303	0.533	0.226	4.432	0.120
West Bengal	15	2.107	0.602	2.708	0.627	0.171	5.865	0.246
North Eastern Zone	24	2.220	0.958	3.178	0.736	0.175	5.704	0.196
Arunachal Pradesh	14	1.431	1.208	2.639	0.611	0.334	2.996	0.185
Assam	16	2.161	0.611	2.773	0.642	0.141	7.091	0.131
Nagaland	9	1.192	1.005	2.197	0.509	0.473	2.115	0.235
Manipur	11	1.979	0.419	2.398	0.555	0.174	5.748	0.441
Mizoram	13	1.695	0.870	2.565	0.594	0.244	4.105	0.221
Tripura	11	1.169	1.229	2.398	0.555	0.471	2.121	0.096
Meghalaya	12	1.945	0.540	2.485	0.576	0.186	5.387	0.277
Islands	11	1.959	0.439	2.398	0.555	0.170	5.871	0.131
Andaman and Nicobar	11	1.963	0.435	2.398	0.555	0.171	5.848	0.566
Lakshadweep	4	0.769	0.617	1.386	0.321	0.598	1.672	0.964

S=taxa richness in each taxonomy category; H/=Shannon's diversity index; D = O'Neill dominant index; H_{max}=maximum diversity; H_{maxr}=maximum relative diversity; Ds= Simpson's index; 1/D= Inverse Simpson's index; E=Smith's evenness index

Table 7. Pedodiversity indices in different geographical zones in India (Soil subgroup)

Zones	S	H/	O'Neill's D	Hmax	Hmaxr	Simpson's index (Ds)	1/D	E
India	232	3.686	1.761	5.447	1.000	0.058	17.377	0.121
Northern Zone	65	2.535	1.639	4.174	0.766	0.181	5.528	0.130
Jammu , Kashmir, Ladakh	28	1.876	1.456	3.332	0.612	0.282	3.552	0.162
Himachal Pradesh	16	1.773	0.999	2.773	0.509	0.253	3.946	0.201
Punjab	18	1.847	1.043	2.890	0.531	0.233	4.296	0.209
Haryana	17	1.618	1.215	2.833	0.520	0.332	3.009	0.189
Delhi	6	**0.803**	0.989	2.833	0.520	0.646	1.548	0.351
Uttar Pradesh and Uttarakhand	41	1.910	1.804	1.792	0.329	0.339	2.953	0.133
Western Zone	62	2.664	1.463	4.127	0.758	0.114	8.794	0.124
Rajasthan	31	2.328	1.106	3.434	0.630	0.159	6.273	0.188
Gujarat	40	2.662	1.026	3.689	0.677	0.105	9.511	0.195
Goa	18	2.277	0.614	2.890	0.531	0.150	6.645	0.471
Central	29	2.277	1.091	3.367	0.618	0.122	8.164	0.102
Madhya Pradesh (including Chhattisgarh)	26	2.265	0.993	3.258	0.598	0.123	8.125	0.114
Maharashtra	18	1.848	1.043	3.258	0.598	0.187	5.361	0.106
Southern Zone	90	**3.239**	1.261	4.500	0.826	0.072	13.880	0.183
Andhar Pradesh and Telangana	41	2.618	1.096	3.714	0.682	0.098	10.242	0.185
Karnataka	48	**3.073**	0.798	3.871	0.711	0.066	15.152	0.255
Tamil Nadu	38	2.469	1.169	3.638	0.668	0.152	6.596	0.233
Kerala	20	2.463	0.533	2.996	0.550	0.108	9.301	0.369
Puducherry & Karaikal	11	1.958	0.440	2.398	0.440	0.181	5.521	0.583
Eastern Zone	70	**3.274**	0.974	4.248	0.780	0.059	16.888	0.130
Bihar and Jharkhand	39	2.925	0.739	3.664	0.673	0.077	12.908	0.211
Odisha	35	2.784	0.771	3.555	0.653	0.094	10.623	0.272
Sikkim	22	2.286	0.805	3.091	0.568	0.144	6.949	0.176
West Bengal	32	2.963	0.503	3.466	0.636	0.071	14.143	0.329
North Eastern Zone	58	3.009	1.052	4.060	0.745	0.083	12.053	0.197
Arunachal Pradesh	26	2.066	1.192	3.258	0.598	0.183	5.460	0.091
Assam	33	2.901	0.595	3.497	0.642	0.070	14.371	0.267
Nagaland	12	1.670	0.815	2.485	0.456	0.260	3.844	0.243
Manipur	18	2.368	0.522	2.890	0.531	0.119	8.380	0.264
Mizoram	19	2.119	0.826	2.944	0.541	0.186	5.389	0.295
Tripura	20	2.020	0.976	2.996	0.550	0.225	4.439	0.164
Meghalaya	17	2.270	0.564	2.833	0.520	0.133	7.523	0.306
Islands	22	2.279	0.812	3.091	0.568	0.139	7.218	0.085
Andaman and Nicobar	18	2.172	0.719	2.890	0.531	0.151	6.612	0.112
Lakshadweep	6	0.931	0.861	1.792	0.329	0.561	1.782	0.346

S=taxa richness in each taxonomy category; H/=Shannon's diversity index; D = O'Neill dominant index; H_{max}=maximum diversity; H_{maxr}=maximum relative diversity; Ds= Simpson's index; 1/D= Inverse Simpson's index; E=Smith's evenness index

Table 8. Pedodiversity indices in different geographical zones in India (soil family)

Zones	S	$H^{/}$	D O'Neill	H_{max}	H_{maxr}	Simpson's index (Ds)	1/D	E
India	1247	5.877	1.251	7.128	1.000	0.020	49.633	0.151
Northern Zone	344	4.208	1.633	5.841	0.819	0.044	22.937	0.232
Jammu , Kashmir, Ladakh	93	3.739	0.793	4.533	0.636	0.083	12.120	0.228
Himachal Pradesh	56	3.321	0.704	4.025	0.565	0.072	13.943	0.229
Punjab	46	3.844	0.015	3.829	0.537	0.111	9.004	0.264
Haryana	41	2.710	1.003	3.714	0.521	0.113	8.842	0.236
Delhi	12	**1.105**	1.380	2.485	0.349	0.357	2.801	0.343
Uttar Pradesh and Uttarakhand	145	3.224	1.752	4.977	0.698	0.118	8.441	0.186
Western Zone	224	4.025	1.386	5.412	0.759	0.037	27.140	0.198
Rajasthan	95	3.314	1.240	4.554	0.639	0.069	14.576	0.214
Gujarat	125	3.819	1.009	4.828	0.677	0.049	20.211	0.201
Goa	27	2.993	0.303	3.296	0.462	0.089	11.260	0.598
Central	270	1.20	4.395	5.598	0.785	0.084	11.880	0.185
Madhya Pradesh (including Chhattisgarh)	175	3.147	2.018	5.165	0.725	0.090	11.148	0.119
Maharashtra	95	1.674	2.880	4.554	0.639	0.108	9.300	0.130
Southern Zone	265	**4.517**	1.062	5.580	0.783	0.024	40.863	0.217
Andhra Pradesh and Telangana	129	**4.078**	0.781	4.860	0.682	0.035	28.204	0.291
Karnataka	98	3.905	0.680	4.585	0.643	0.040	25.208	0.313
Tamil Nadu	97	3.422	1.152	4.575	0.642	0.055	18.157	0.234
Kerala	35	3.121	0.434	3.555	0.499	0.051	19.564	0.312
Puducherry & Karaikal	10	2.251	0.052	2.303	0.323	0.133	7.519	0.371
Eastern Zone	218	4.300	1.084	5.384	0.755	0.022	46.446	0.138
Bihar and Jharkhand	79	3.517	0.853	4.369	0.613	0.038	26.321	0.566
Odisha	98	3.766	0.818	4.585	0.643	0.035	28.182	0.240
Sikkim	69	3.246	0.988	4.234	0.594	0.071	14.043	0.317
West Bengal	74	3.442	0.862	4.304	0.604	0.041	24.618	0.267
North Eastern Zone	207	4.448	0.884	5.333	0.748	0.020	51.130	0.089
Arunachal Pradesh	58	2.990	1.070	4.060	0.570	0.077	12.993	0.424
Assam	82	3.920	0.486	4.407	0.618	0.026	38.543	0.327
Nagaland	50	2.991	0.921	3.912	0.549	0.063	15.784	0.429
Manipur	47	3.087	0.763	3.850	0.540	0.056	17.725	0.313
Mizoram	53	2.820	1.150	3.970	0.557	0.081	12.305	0.054
Tripura	42	2.852	0.886	3.738	0.524	0.111	9.005	0.293
Meghalaya	33	3.077	0.420	3.497	0.490	0.062	16.152	0.099
Islands	42	3.063	0.675	3.738	0.524	0.062	16.217	0.175
Andaman and Nicobar	36	3.160	0.424	3.584	0.503	0.069	14.458	0.190
Lakshadweep	6	0.870	0.921	1.791	0.251	0.056	1.770	0.786

S=taxa richness in each taxonomy category; $H^{/}$=Shannon's diversity index; D = O'Neill dominant index; H_{max}=maximum diversity; H_{maxr}=maximum relative diversity; Ds= Simpson's index; 1/D= Inverse Simpson's index; E=Smith's evenness index

Iba'n˜ez *et al.* (1998) studied pedodiversity for each continent of the world using the soil data from the FAO soil map and biodiversity indices. The FAO soil classification system differs from the U.S. Soil Taxonomy used in the State Soil Geographic Database (STATSGO). However, taxa in FAO might be considered equivalent (in detail) to the order or suborder categories in the U.S. Soil Taxonomy. The map scales of FAO and STATSGO are also different. Nevertheless, the scale effects are not strongly reflected in estimating diversity indices of taxa areas of higher taxonomic categories. The taxa richness and Shannon's diversity indices calculated for the order (7 and 1.471) and suborder (23 and 2.122) categories are 7 and 1.471, respectively for Indian soil orders and 23 and 2.122 for soil suborders (Tables 4 and 5).

Pedodiversity indices ($H^{/}$), maximum (H_{max}), and maximum relative diversity (H_{maxr}) for each taxonomic category in different zones and states in India were estimated (Tables 4 to 8) for different categories. The pedodiversity indices in each region follow an increasing trend for $H^{/}$. The pedodiversity ($H^{/}$) index follows the sequence of India>North>South> West> Central> Islands>Eastern>North Eastern Zones (Figure 6a). The taxa evenness (E) follows the trends as North Eastern Zones > Islands > South > India> Central> North>East > West Zones (Figure 6b). The diversity index would reach its maximum value if all taxa had an equal area abundance (complete evenness; maximum E=1).

Fig.6. Zone-wise (a) soil diversity index ($H^{/}$) and (b) Smith's soil evenness index (E) in India (Source: Revised from Bhattacharyya 2016).

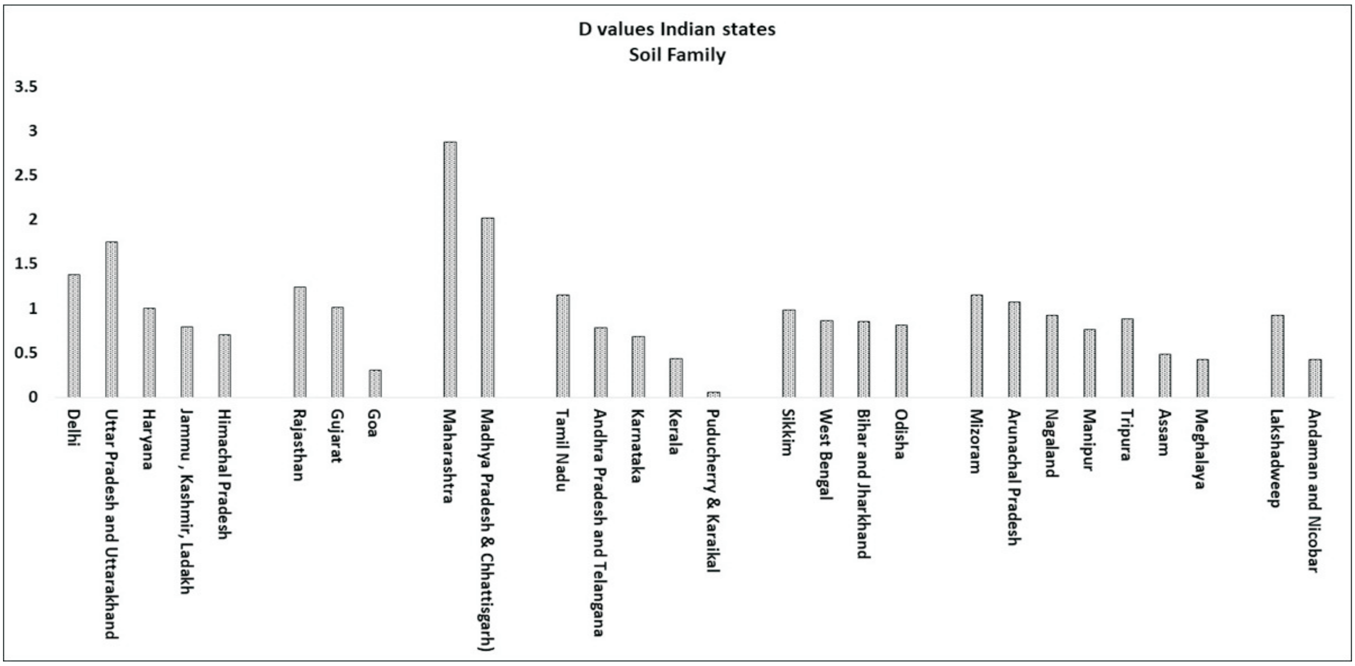

Fig.7. D values of Indian soil for soil families in different states (Mean difference between the calculated diversity index and its maximum value)

O'Neil's dominant index was estimated to assess the deviation of the estimated Shannon diversity index (H') from the maximum diversity (H_{max}) (O'Neil *et al.* 1988). The difference (D) between the calculated diversity index and its maximum value is another way to illustrate the evenness of taxa or to detect the dominant taxa. West Bengal (East Zone) registered minimum dominant index for soil order; however, for soil family, Puducherry & Karaikal registered minimum dominant index. It suggests that taxa abundance in this region is more evenly distributed. The diversity index ($H^{/}$) implies taxa richness and evenness; in other words, the higher the richness and evenness, the higher the diversity (Guo *et al.* 2003). Thus, the southern and eastern zones showed the highest diversity indices (shown in bold in Tables 4 to 8), except in the family category, where the northeastern zone also showed higher diversity values because the number of soil families is more. The southern zone is generally more diverse than the National Average; the northern zone is less diverse. Figure 7 shows the difference (D) between the calculated diversity index and its maximum value for different states in India at the soil family level.

Pedodiversity and aerial coverage of soil categories

The diversity index of different taxonomic categories versus the area of different zones showed a positive linear trend between areas and pedodiversity (Bhattacharyya 2016), which is similar to the results of pedodiversity for the world (Iba'n˜ez *et al.* 1998; MacBratney *et al.* 2000). A strong species-area relationship either in biodiversity (Kilburn 1966) or pedodiversity (Beckett and Bie 1978) was reported, and this relationship can be commonly formulated as S=cAz (S, taxa richness; A, area; c and z are constants). The formula is well known in ecology as the power law (Borde-de-Agua *et al.* 2002). In the work of Iba'n˜ez *et al.* (1998), there was no species-area relationship using the FAO small-scale soil map (1:5,000,000). It is, therefore, essential to test whether taxa richness is area-dependent in a large-scale soil map. If taxa richness is area-dependent, the diversity index calculated should be related to the area factor (Bhattacharyya 2016).

It is observed that for Indian soils, diversity values are scale-dependent and increase from soil order to family. Eastern Zone showed more diversity in suborder and great group and subgroup levels; for order and family levels, southern zones are more diverse. Earlier, significantly ($p<0.01$) higher diversity indices were reported in the soils of relatively moist bioclimate as compared to drier ones (Velmourougane *et al.* 2014a). Besides, higher microbial biomass carbon indicating more diversity was found in the soil subgroup *viz* Typic Haplustert compared to other subgroups of the same soil order (Vertisol). Interestingly, the areal extent of Typic Haplustert is much higher than other subgroups in the southern, western, and central zones, which signifies a close species (soil subgroups)–area relationship reported by others (Beckett and Bie 1978; Iba'n˜ez *et al.* 1998; MacBratney *et al.* 2000).

A comparison of pedodiversity between the zones should be based on equal land areas, as is followed in biodiversity studies. A relation between the areal coverage of each taxonomic category for all the states and union territories with the Pedodiversity index (PDI) (H') was developed. For brevity, only the graph at the soil family level in different states in India is shown (Figure 8). Karnataka shows the highest H' with some exceptions. It is observed that the southern zone and undivided Andhra Pradesh state showed maximum pedodiversity as evidenced by the Shannon diversity index.

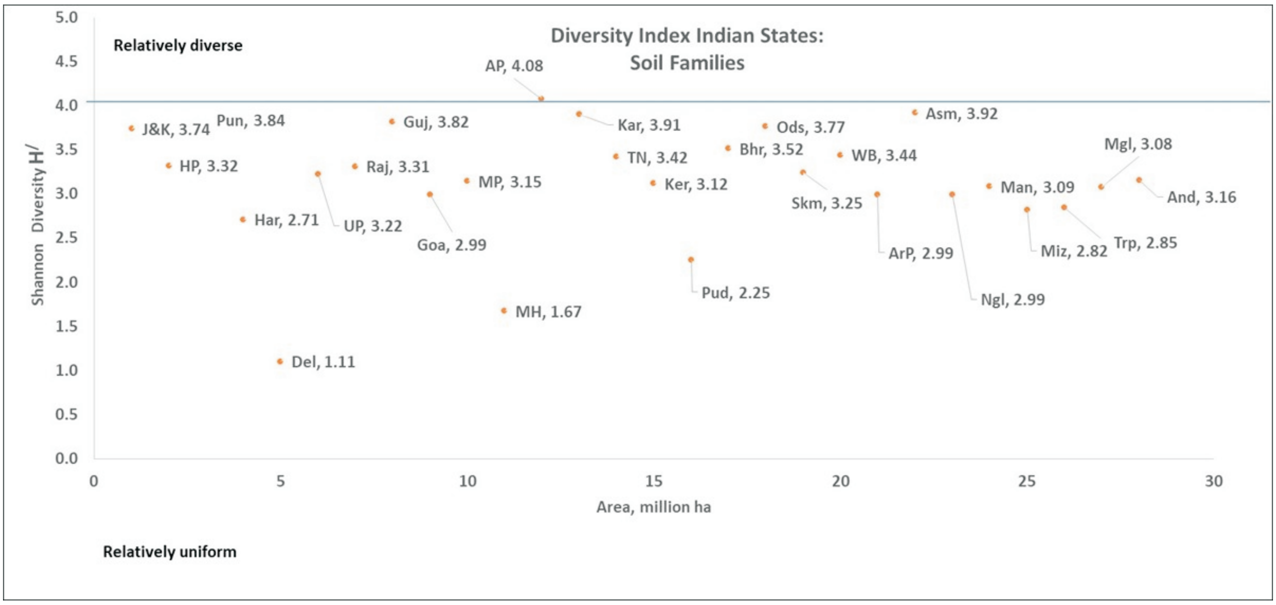

Fig. 8. Pedodiversity index (PDI) (H') and area relationship at soil family level in different states in India (maximum values are shown by the horizontal bar).[Jammu, Kashmir & Ladakh (J&K), Himachal Pradesh (HP), Punjab (Pun), Haryana (Har), Delhi (Del), Uttar Pradesh (including Uttarakhand) (UP), Rajasthan (Raj), Gujarat (Guj), Goa, Madhya Pradesh (including Chhattisgarh) (MP), Maharashtra (MH), Andhra Pradesh (including Telangana) (AP), Karnataka (Kar), Tamil Nadu (TN), Kerala (Ker), Puducherry & Karaikal (Pud), Bihar (including Jharkhand) (Bhr), Odisha (Ods), Sikkim (Skm), West Bengal WB), Arunachal Pradesh (ArP), Assam (Asm), Nagaland (Ngl), Manipur (Man), Mizoram (Miz), Tripura (Trp), Meghalaya (Mgl), Andaman and Nicobar (And)].

In India, in the states which are part of the Himalayas (Jammu & Kashmir including Ladakh, Himachal Pradesh, and northeastern states), a positive relation is registered to relate pedodiversity with an area of the states (Figure 9). This contrasts sharply with the pedodiversity in the states representing the Indo-Gangetic Plains (Uttar Pradesh, Bihar, Odisha, and West Bengal). The O'Neil's D values (discussed later) showed that it is at the great group and subgroup levels the extent is dominated by one or few taxa.

Table 9. The similarity between soil endemism, diversity, and pedodiversity

Original concepts	Soil equivalent	Remarks	References
Endemism	Soil endemism	Taxa richness of soils; soil taxa restricted to a geographical area (*isolating mechanism* of soils)	(Guo et al.2003); (Amundson et al. 2003); (Bockheim2005)
	Edaphic endemism	Soil type strongly related to a specific soil taxon and not found elsewhere (sandy soils on dunes, nutrient-poor soils, soils on high carbonates)	(Whittaker 1954); (Bockheim 2005)
	Neoendemism	Soils of recent origin (Entisols); Azonal soils (Absence of well -developed profile in soils; *weak soil endemism*)	(Bockheim 2005)
	Paleoendemism	*Zonal soils* (matured soils developed under good soil drainage over a long period under the influence of climate and vegetation) *Intrazonal soils* (more or less well -developed with the dominant influence of parent material and relief)	(Bockheim 2005)
Biodiversity	Pedodiversity	Soil types and their variation	(McBratney 1992); (Bhattacharyya 2021a, b)

It seems that the scale of soil mapping may be fixed considering the dominance of the soil category since survey at larger scales is expensive and time-consuming. For example, in plain areas of the Ganga alluvium (IGP), great groups' and subgroups' dominance may be more significant. Therefore, soil survey and classification may be restricted at that level of soil taxonomy. For hilly areas with many topographical variations, soil families would be necessary to find out pedodiversity appropriately. This is why the pedodiversity index in the hilly states shows an upward relation with the area (Figure 9). This requires analyzing datasets at taxonomic category to fix the scale of soil survey and mapping for land use planning.

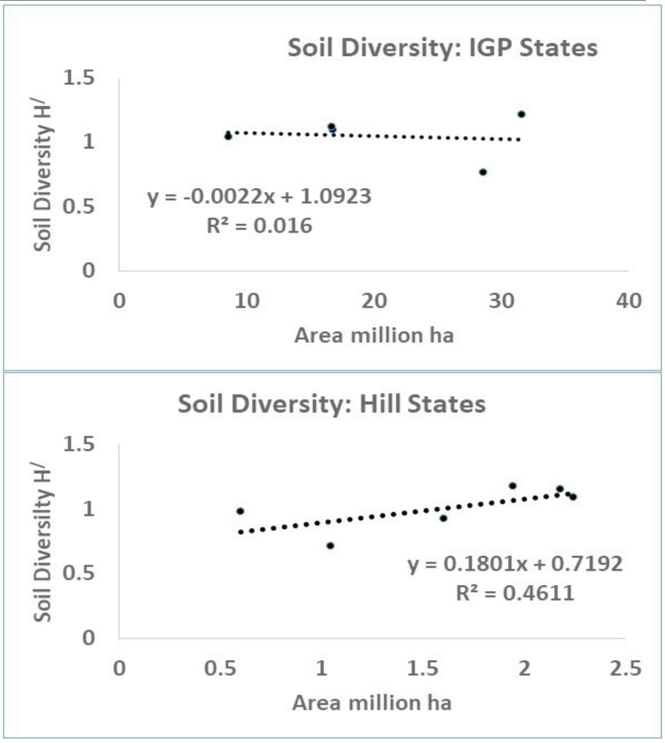

Fig. 9. Soil diversity index (H') and area relationship in different states (Indo-Gangetic Plains, IGP, and hilly states) in India

Taxa similarity: geographical regions and taxonomy category for Indian soils

The results of a similarity analysis of taxa between the regions are presented in the figure 10. The distance at the top of the figure indicates the level of similarity: 1.0 means that the taxa in two (or more) regions studied are precisely the same, and 0.0 indicates that the taxa in the regions are completely different. For Indian soils, the results indicate that the taxa in different zones are midway between entirely different and completely similar (Figure 10). The general pattern of taxa similarity between the regions is that taxa in the north and west zones are most similar, while taxa in the east and the north are slightly different. Taxa similarity between the zones decreases with change in taxonomic levels from order to family (Figure 10a). In Figure 10b, taxa similarity between different states shows Haryana, Maharashtra (M.H.), Karnataka, TN (Tamil Nadu), West Bengal, Assam, and Arunachal Pradesh have < 0.5 on the dissimilarity scale suggesting these states have distinctly different taxa in terms of soil family.

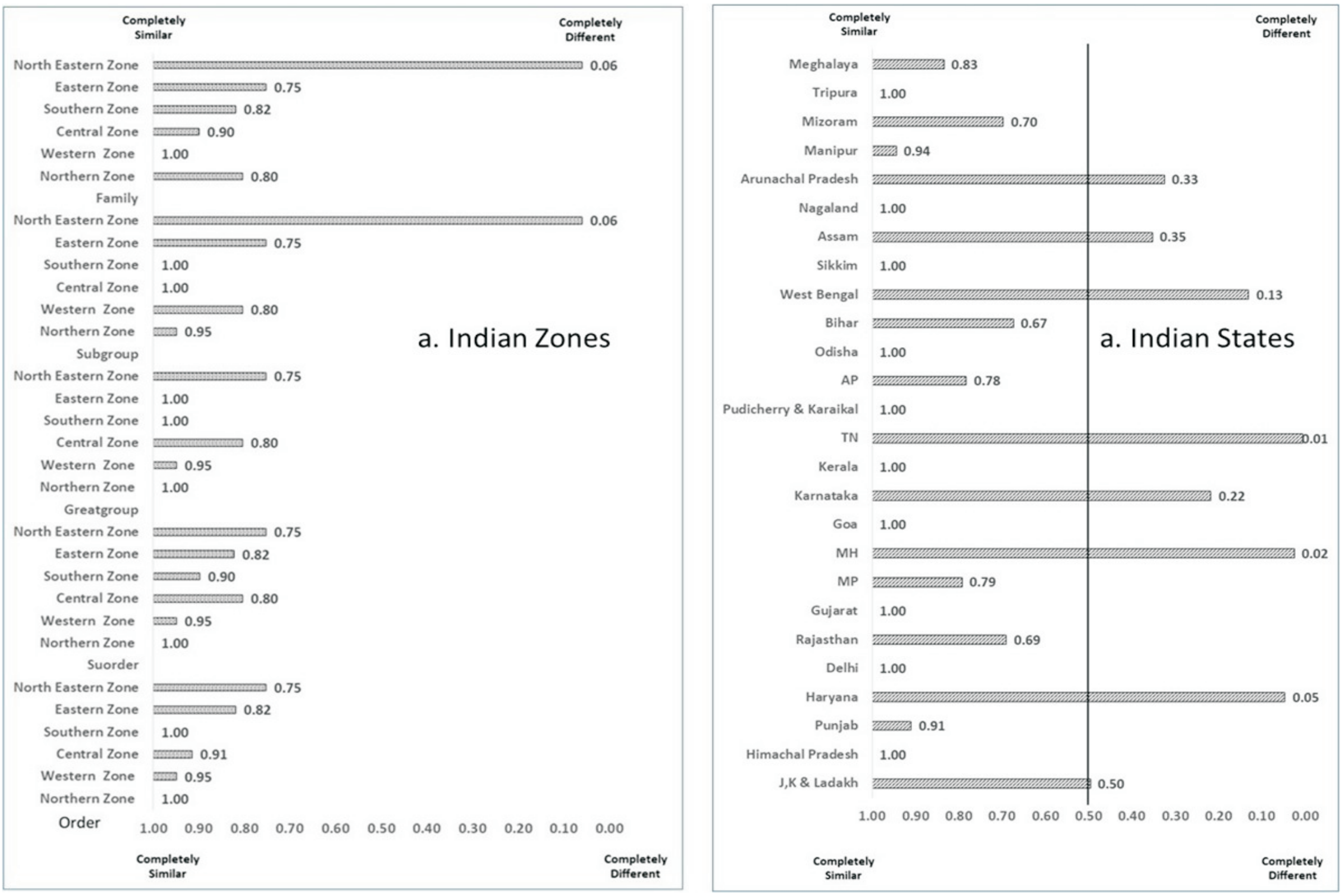

Fig. 10. Taxa similarity between the (a) geographical regions and (b) states (only soil family) for each taxonomy category for Indian soils.

The analysis indicates that taxonomic similarity at the higher categories is driven by geographic/climatic proximity, as are the rules for fixing soil order. However, at the lower taxonomic levels, soil dissimilarity is the norm, and even geographical proximity exerts little effect on similarity indices. The trend towards endemism (discussed later) at the family level is of considerable interest in conservation or preservation efforts. It likely reflects, controls, or is in some ways related to the regional distribution of plant species (Guo *et al.* 2003).

Mapping of pedodiversity

Pedodiversity at various categoric levels of soil taxonomy has been mapped in different scales for Indian soils. Pedodiversity estimated for Indian soils in terms of different parameters, as shown in the methods, has been mapped at zonal and state levels. For brevity, only a few maps on the Shannon diversity index (H/) and Smith's evenness E are presented here for different zones and states.

Mapping pedodiversity in different zones in India

Pedodiversity and related parameters (Tables 4 to 8) were mapped using different zones of India as mapping units. Western (W.Z.), southern (S.Z.), and northeastern zones (NEZ) indicate more pedodiversity (H': 1.15 and more) at the order level. At suborder and great group levels, NEZ and S.Z., along with eastern zone. The eastern zone indicates more pedodiversity due to more taxa richness owing to climatic, geologic, and climatic variations. At the subgroup level, E.Z., with 13% area, shows >3.25 values of H' suggesting more variations in this zone with soils of mostly Inceptisols and Alfisols orders. However, S.Z. and NEZ also cover a sizeable area (27%) with 3.00 to 3.25 values of H' and continue to maintain pedodiversity from order to subgroup level. S.Z. is considered as a soil gallery of India due to variations in geological formations with a typical tropical climate. At the family level, the south zone again shows maximum diversity with H' values of > 4.50, covering 19% area in India. However, E.Z. and NEZ also show appreciable pedodiversity with H' values ranging from 4.25 to 4.50, covering 21% area of India (Figure 11a).

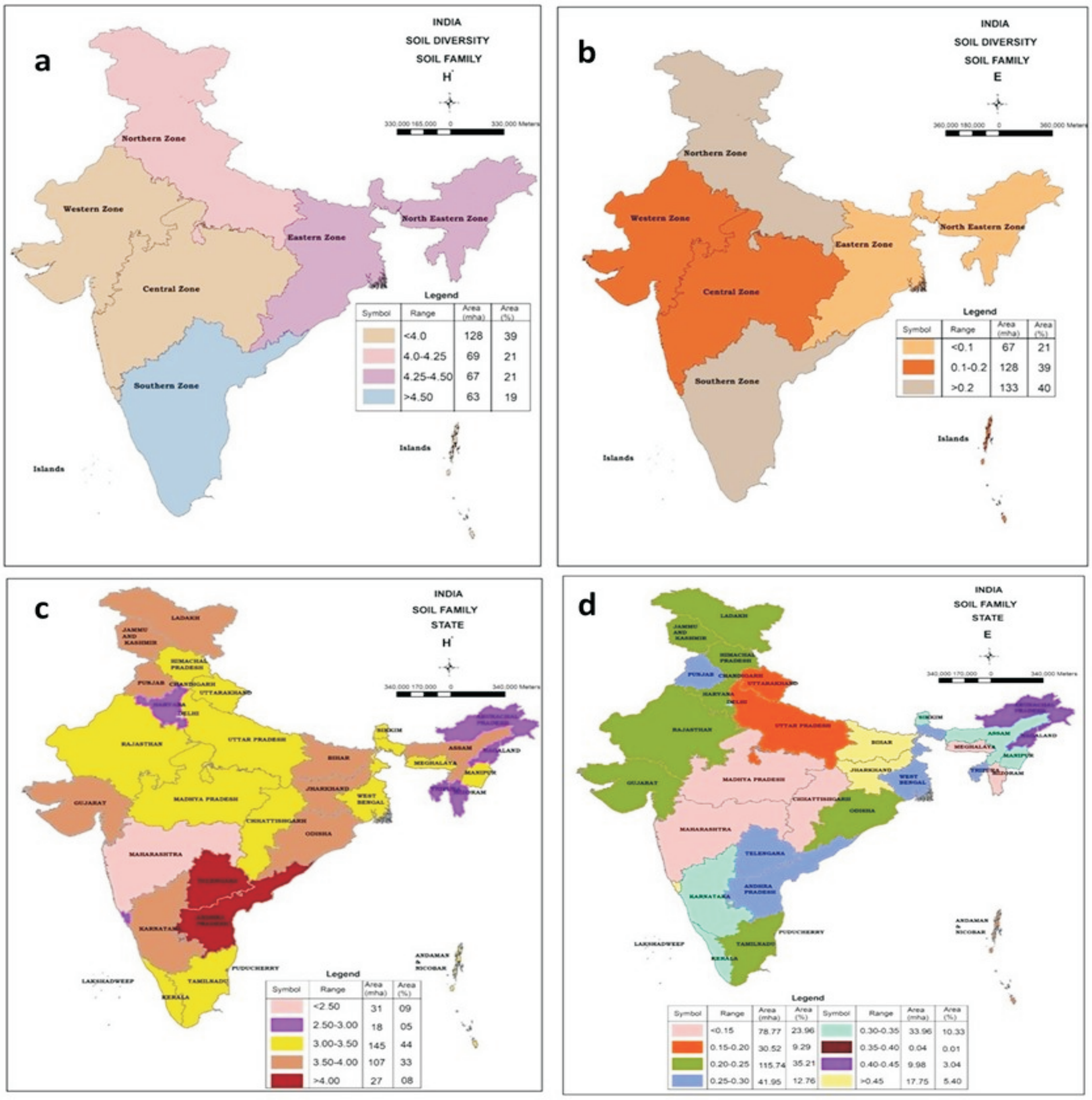

Fig. 11. Soil Diversity (H') and Evenness (E) in different zones (a, b) and states (c, d) in India at the family level of soil taxonomy.

Smith's evenness (E) is maximum in S.Z. and NEZ (>0.40), covering 40% area at the order level. The suborder level, only NEZ and Islands show relatively high evenness. At the great group level, NEZ showed more evenness (E> 1.75), covering 8% area . More evenness indicating more diversity is common in NEZ due to variations in climate, vegetation, and topography. Interestingly at higher categories like family, N.Z. and S.Z. showed more evenness (E > 0.2) (Figure 11b).

Mapping Pedodiversity in different states in India

Pedodiversity and related parameters (Tables 4 to 8) were mapped using different states of India as mapping units. For brevity, pedodiversity only for the soil family level is shown and discussed (Figure 11). Only two states, Andhra Pradesh and Telangana showed the highest pedodiversity ($H^{/}$) (>4.0) (Figure 11c). Most of the states fall in pedodiversity ($H^{/}$) values of 3.0 to 4.0 suggesting a fairly across the country when the datasets are arrayed at the family level of soil classification. The lower evenness of taxa indicates that some are relatively rare while others have a large area abundance. Smith's evenness (E) is low (<0.15) (Figure 11d) in Maharashtra, Madhya Pradesh, Chhattisgarh, Meghalaya, and Mizoram. Conversely, Goa, Bihar, and Jharkhand show higher E values (>0.45), suggesting an almost even distribution of soil taxa at the family level. This is important in terms of soil endemism, as discussed earlier.

Pedodiversity and biodiversity

Soil is a complex biomaterial on the planet. More than 90% of the planet's genetic biodiversity is resident in soils, but less than 1% of the microorganisms have been cultured and studied. The enormous gene reserve in soils may be exploited by industry and pharmaceutics with the help of soil microbiologists. Future projects may be oriented accordingly. With the advent of more sophisticated instruments, soil biologists may reveal the mystery of the structure-function relation of microbial communities. A greater understanding of the functional bridges with the available knowledge of basic sciences should find someplace in the agenda of future research in soil science (Rao 2006).

Biological information (Velmourougane *et al.* 2014a, b) was an essential component of the soil information system a soil database. Biodiversity can be the mechanism behind the performance of an ecosystem, particularly in communities of aboveground organisms. In soils below ground, however, the functioning of biodiversity is not well understood. The relationship between two interrelated aspects of natural diversity, namely pedodiversity and biodiversity, may be viewed in the image of a Mobius strip (Figure 12).

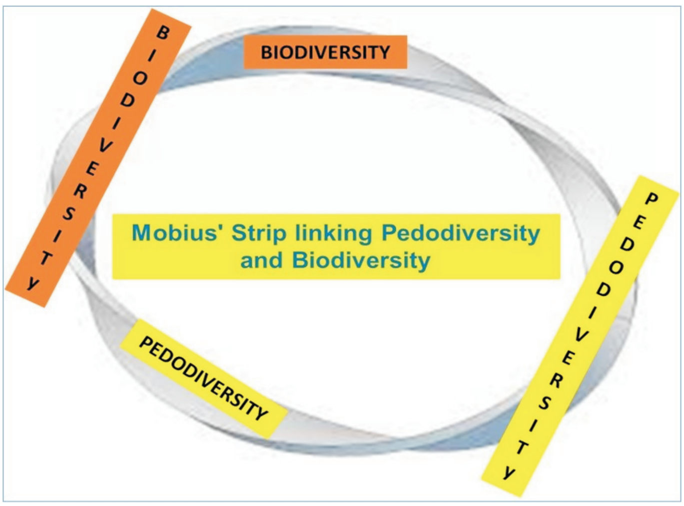

Fig. 12. Pedodiversity and biodiversity: a Mobius strip relation (Source: Bhattacharyya and Patil 2022b).

A Mobius strip is a curious and intriguing object that can be created with a strip having two surfaces. Once created, it will give an illusion of having only one continuous surface. The concept of diversity has been widely used in ecological studies in connection with biodiversity (Sugihara 1981; Magurran 1988). However, discussion to include the abiotic stresses from soils on the ecosystems has found very little attention. Inorganic carbon sequestration and soil/land degradation causing poor crop performance, especially in the drier climates due to abiotic stresses in the Indian context, have been discussed elsewhere (Bhattacharyya 2021a, b, 2022a). This brings a paradigm shift to catch the imagination of other experts in other parts of the globe to use Indian case studies as a model for tropical soils to study pedodiversity (Ibáñez *et al.* 1995).

Soil and pedodiversity are linked so are their contribution to the critical aspects of heritage, such as biological and cultural (preservation of biodiversity, ancient and traditional sustainable practices), soil monitoring (monitoring programmes of benchmark soils), prehistoric and paleontological (archive of artefacts and remnants of extinct species), bio-geosphere (archive of past environments), and geological (pedodiversity is a part of the concept of geo-diversity) (Ibáñez *et al.* 2012). Figure 13 shows the relationship between soil and pedodiversity and their heritage *vis-à-vis* ecosystem services (Bhattacharyya 2021a). The relationships between pedodiversity and the diversities of other natural bodies are shown in the figure 14.

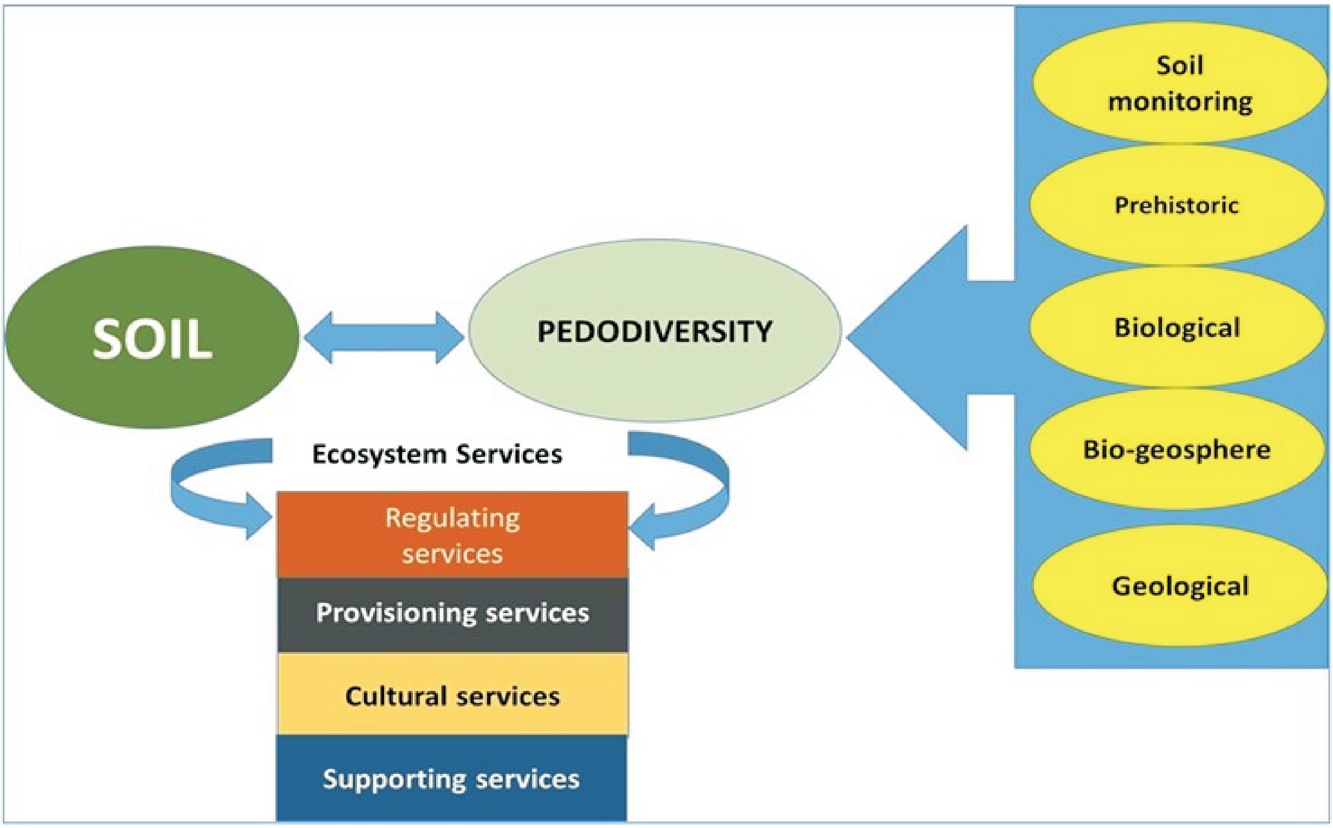

Fig.13. Role of soil and pedodiversity in providing ecosystem services (Source: Bhattacharyya and Patil 2022). Also see: Bhattacharyya 2021b).

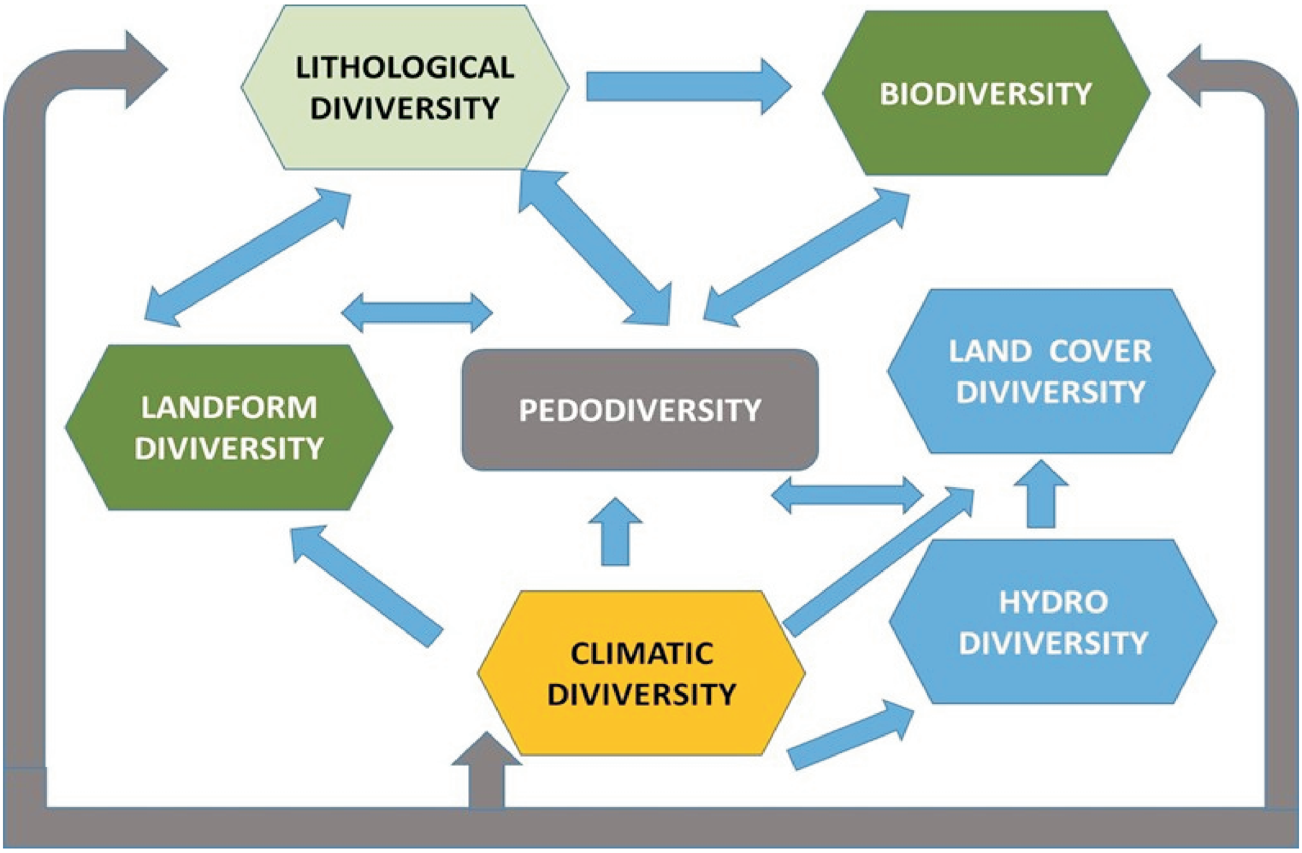

Fig. 14. Relationships between pedodiversity and biodiversity with other forms of diversity in nature (Source: Bhattacharyya and Patil 2022). (Adapted from Ibáñez *et al.* 2012).

The diversity index (H') increased from 0.48 (Delhi) to 1.70 (Karnataka) for soil orders and Lakshadweep (0.87) to Andhra Pradesh and Telangana (4.08) for soil family level (Figure 15). Shannon diversity index (H$^{/}$) is more (>1.20) in the soils found for the southern states like Karnataka, A.P. and Telangana and the central states like M.P. and Chhattisgarh. Comparatively, the soils in the northern states show lower H$^{/}$ values than the southern states (Figure 15). The values increase from order to soil family level. The central zone generally registers low H$^{/}$ values indicating lower Pedodiversity in this zone. The Simpson's index (Ds) values (Figure 15) showed that at the great group and subgroup levels, the extent is dominated by one or few taxa. Smith's E index (E) gradually decreased at the level of the soil family (Figure 15). The soil orders in India are relatively more equitably distributed in their extent compared to other taxa. Soil families show exactly opposite tendencies. In this form, as diversity increased, Ds values got smaller. The inverse of Simpson's index (Ds) generated Simpson's 1/D index. Thus, the larger the value of 1/D, the more was pedodiversity (Tables 4 to 8).

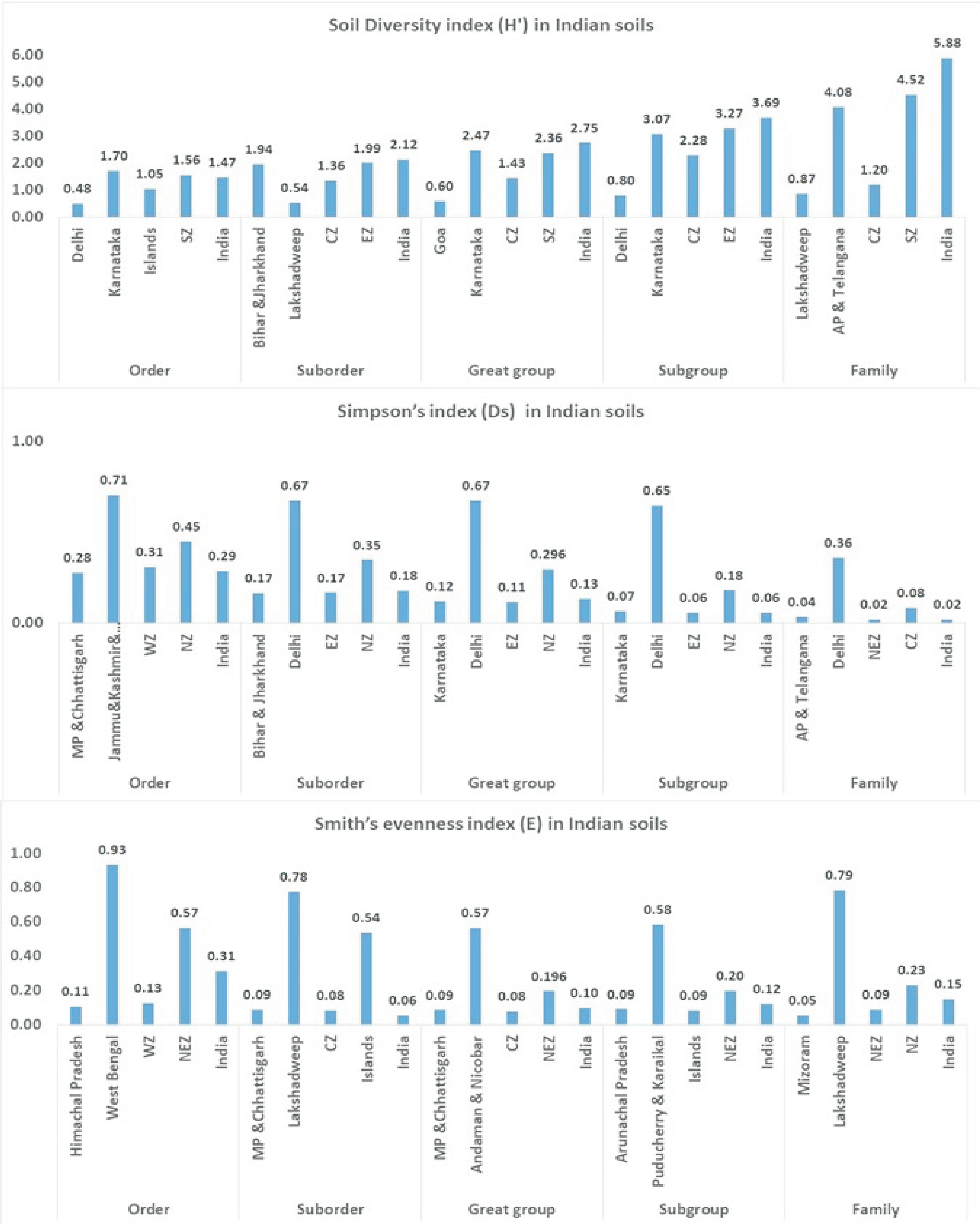

Fig.15. Range of soil diversity index (H'), Simpson's index (Ds), and Smith's evenness index (E) at different soil taxonomic categories for states in India.

The data generated through soil surveys vary in different parts of the country depending on topography and ease to access. This leads to variations in the exact number of their aerial extent, which leads to artefacts in the soil survey process. There are different opinions about accepting diversity, usually used in biological specimens and not in other earth science disciplines. Bio-geographical and pedological concepts might, therefore, be considered closely-linked subjects (Bockheim 2005).

Soil Endemism: Rare, Unique, and Endangered Soils in India

Like plant/tree species threat to survive on the earth, soil species (family or series Soil Survey Staff 2014) indicate considerable soil endemism in the world. Endemism has been classified into three types such as (a) edaphic endemism (a particular type of soil strongly related to a specific soil taxon and not found elsewhere, (for example, sandy soils on dunes, nutrient-poor soils, soils on high carbonates; brown forest soils or Mollisols in a particular climatic condition), (b) neoendemism (soils of new or recent origin, for example, Entisols), and (c) paleo endemism (related to ancient time; Paleosols, Bhattacharyya 2021a) (Bockheim 2005). The trend towards endemism at the series and family levels of soil classification is of significant interest in conservation or preservation efforts. Since bio-geographical concepts and pedological concepts might be considered as a closely-linked subject (Bockheim 2005) (Table 9).

Due to the combined influence of different soil forming factors, soil characteristics are preserved within the soil since it can memorize various changes in soil properties during soil formation (Bhattacharyya 2014). Soil memory is, therefore, essential to maintain the history of soil formation to provide ecosystem services in the form of cultural heritage (Bhattacharyya 2021a). Individual trees or patches of trees leave their imprint on a microsite for repeated generations, which precludes competition from other plant species (Phillips and Marion 2004). Similarly, the concept of pedological memory seems to be in place and might help understand the fate of soil to protect itself for its existence.

Soil endemism reflects, controls, and perhaps relates to the regional distribution of the plant species. There is a jinx of the Mobius strip relation between soil pedodiversity and biodiversity (Bhattacharyya and Patil 2022b). These are complex relations in nature and need to be addressed regionally and globally for our survival. It is a key consideration in conservation and preservation planning and has yet to find importance in Indian soil science research. A future soil research programme might include this aspect. This has more relevance while mapping degraded soils on a large scale to indicate the soils under threat (Bhattacharyya 2021a).

Endemic soils are restricted to a particular geographic area based on a unique combination of soil-forming factors that may operate from the landscape to the eco-region scale. To validate those soils endemic, soil families occurring in different states but having a similar combination of soil-forming factors were compared using the available information (Bhattacharyya 2021a).

For rare or uncommon soils (families), the available literature suggests a few guidelines (Amundson *et al.* 2003). For Indian soils, it has been modified judging by the total geographical area of India soils should occupy < 500 ha, soils should exist only in one state, and soils should occur only in one state occupying a total area of < 5000 ha. Amundson *et al.* (2003) defined endangered soils as those rare or rare-unique soils, that have lost more than 50% of their area to various land disturbances. The quantitative definition of these three classes (rare, unique and rare-unique) is the first approximation for evaluating soil distribution in India. There is no accepted standard for defining soil rarity in the literature except for Amundson *et al.* (2003). The present analysis is focussed on pedodiversity by political boundary as opposed to ecosystem boundaries. It helps planners prioritize areas for land resource management (Dobson *et al.* 1997; Bhattacharyya 2021a). Ecosystem boundaries, for example, agro-eco sub-regions (AESRs) (Mandal *et al.* 2014, Bhattacharyya 2021a, b), can also be examined for soil rarity using the soil information system and the ecosystem services soils provide in the Indian context (Bhattacharyya 2021b). Endangered soils are those rare or rare-unique soil families that have lost more than 50% of their area to various land disturbances (Amundson *et* *al.* 2003). In the present study, endangered soils were not estimated.

Soil rarity is locally influenced by parent material (volcanic ash, clay, secondary silica) and topography (*e.g.,* closed basins) to suggest its inclusion in intra-zonal soils. The intra-zonal soils possess, in general, the characteristics which mark them as distinct and different from zonal soils. Zonal soils are fully matured soils that have developed under the conditions of good soil drainage over a long period. In the present study, Hapludolls, Hapludalfs, Haplustepts, Eutrochrepts Ustipsamments, Udipsamments, Ustochrepts (primarily as Lithic subgroup), and Endoaqueps represent most of the rare soils. The absence of a well-developed soil profile due to parent material or relief qualifies soils as azonal and shows neoendemism (Bockheim 2005). Zonal and intrazonal soils generally are endemic, and azonal soils are neoendemic. The concept of endemism is thus vital for detecting rare, unique, or endangered soils (Bockheim 2005). Nearly 52% of soil in India is (Figure 16). Other soils include different types, spread in various states, to an appreciable extent.

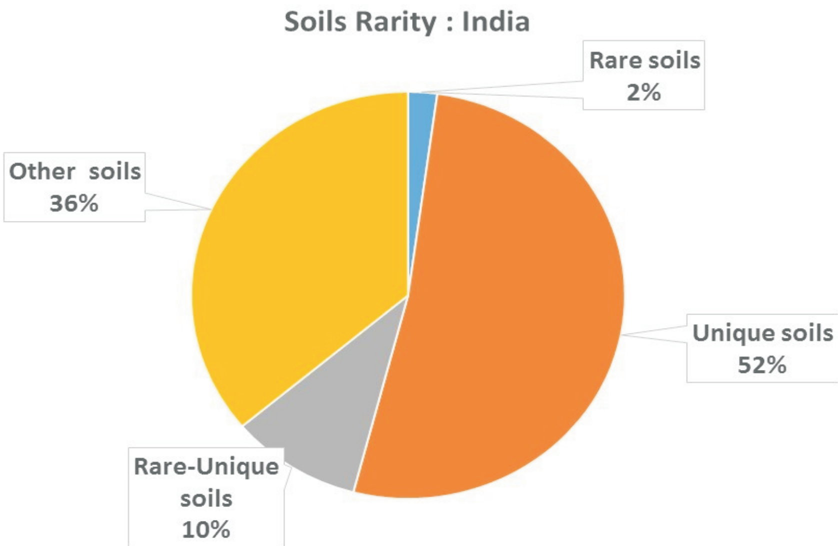

Fig. 16. Soil diversity and rarity for Indian soils (soil family).

Conclusion

In India, pedodiversity and its quantitative approaches are few and far between. Quantified values of pedodiversity can be used to preserve or even reconstruct the history of soil formation. Just as biologists argue that organisms need to be, soil scientists opined that soil conservation would maintain organisms and other unique soil materials for posterity to sustain biodiversity and ecological balance. This suggests a close relation between pedodiversity and biodiversity, as shown by the diversity index estimation (Shannon index) using data and soil groups. Therefore, it is imperative to understand the diversity of soils and the importance of quantification for its use in agriculture and non-agriculture purposes. The present paper paves the way for younger generations to understand the value of soils and their role in ecosystem services through quantitative approaches.

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