Chapter 9
Importance of Pedology of Indian Tropical Soils in Their Edaphology

Abstract Many consider that the soils of the tropical soils are acidic, infertile, and that they do not support a reasonable sustained agricultural production. Recent research in agricultural production in tropical Asia and Latin America indicate that universal infertility of tropical soils is a myth. In India, during the green revolution period, a renaissance was initiated by the National Agricultural Research Systems (NARS) in a modest way by managing the tropical soils properly for their restoration and preservation. It is clear now that the substrate quality of Indian tropical soils is good enough to support the agricultural land uses, horticultural, spices and cash crops, in making India self-sufficient in food production. The substrate quality is maintained by progressive pedogenic processes (pedology) in tropical Indian soils, which are inherently linked to many edaphological issues. Recent advances in pedology of the Indian tropical soils have demonstrated their considerable potential and also amply established the basic necessity of pedological research, in better understanding some queer edaphological aspects of Indian tropical soils (Vertisols, RF soils and IGP soils), which are affected by the climate change during the Holocene period. Thus edaphology is inherently based on deep fundamental understandings of soils and thus basic pedological research in tropical soils needs to be encouraged vigorously to link some of their major unresolved edaphological aspects to develop improved management practices as guiding principles to improve and maintain soil health through adequate national recommended practices in other tropical parts of the world.

Keywords Indian tropical soils · Dissolution of myth · Soil substrate quality · Basic pedological research · Edaphology

9.1 Introduction

It is often believed that the soils of the tropics are acidic, infertile, and that they do not support a reasonable sustained agricultural production. However, recent research in agricultural production in tropical Asia and Latin America (FAO 1986)

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indicate that universal infertility of tropical soils is a myth (Sanchez and Logan 1992). A renaissance is currently taking place in soil science (Hartemink and McBratney 2008). In India, during the green revolution period, such renaissance was initiated by the National Agricultural Research Systems, NARS in a modest way. This strategy commenced to manage the tropical soils properly for their restoration and preservation. It is thus important to highlight the substrate quality of Indian tropical soils, which have been efficiently supporting the agricultural land uses, horticultural, spices and cash crops, in making India self-sufficient in food production (Bhattacharyya et al. 2014a; Pal et al. 2012a, 2015). The substrate quality is maintained by progressive pedogenic processes (pedology) in tropical Indian soils, which are inherently linked to many edaphological issues. Recent advances in pedology of the Indian tropical soils (Pal et al. 2012a, 2014; Srivastava et al. 2015) have demonstrated their considerable potential and also amply established the basic necessity of pedological research especially in terms of pedogenetic processes, in better understanding some queer edaphological aspects of Indian tropical soils (Vertisols, RF soils and IGP soils), which are affected by the climate change during the Holocene period. It is thus important to highlight some selected edaphological issues where linking pedology and edaphology has helped to better understand the Indian tropical soils.

9.2 Impact of Spatially Associated Non-sodic (Aridic Haplusterts) and Sodic (Sodic Haplusterts) Vertisols on Crop Performance

Natural chemical soil degradation is common in SAT soils of India. In Vertisols of the Purna Valley of Maharashtra, central India (total area ~0.6 M ha), natural degradation in terms of PC formation and development of subsoil sodicity is triggered by the semi-arid climate, with an MAR (mean annual rainfall) of 875 mm, a tropustic moisture regime and a hyperthermic temperature regime (Balpande et al. 1996; Pal et al. 2000a). Due to these pedogenetic processes, these soils have developed severe drainage problems, but in the Pedhi Watershed, in the adjacent east upland of the Purna valley (area ~45,000 ha), Vertisols do not have any problem of subsoil sodicity but have drainage problems. The area, however, has a higher MAR (975 mm) than the Purna valley and has similar moisture and temperature regimes to the Purna Valley. Vertisols are the dominant soil type in the watershed, but as a result of micro-topographic variation (0.5–5 m; please refer to Fig. 2.6), Sodic Haplusterts occur on micro-high (MH) positions and at a distance of approximately 6 km, whereas Aridic Haplusterts occur on micro-low (ML) positions (Vaidya and Pal 2002). Following typical managements as detailed elsewhere (Kadu et al. 2003) farmers get better yield of cotton (0.6–1.6 t/ha of seed + lint) in Aridic Haplusterts with ESP <5 than in Aridic Haplusterts (ESP >5, <15; 0.6–1.0 t/ha) and Sodic Haplusterts (ESP ≥ 15; 0.2–0.8 t/ha yield;

Table 9.1 Range in values of PC, ESP, sHC and yield of cotton in Vertisols of Vidarbha, Central India

District, Vidarbha Region, Maharashtra, Central India	Soil classification	PC (%)[a]	ESP[b]	sHC[c] ($mm\ h^{-1}$) weighted mean in the profile (1 m)	Cotton yield ($t\ ha^{-1}$) (seed + lint)
Nagpur (MAR—1011 mm)	Typic Haplusterts/Typic calciusterts	3–6	0.5–11	4–18	0.9–1.8
Amravati (MAR—975 mm)	(a) Aridic Haplusterts	3–7	0.8–4	2–19	0.6–1.6
	(b) Sodic Haplusterts	3–13	16–24	0.6–9.0	0.2–0.8
Akola (MAR—877 mm)	(a) Aridic Haplusterts	3–4	7–14	3–4	0.6–1.0
	(b) Sodic Haplusterts	3–4	19–20	1–2	0.6

[a]*PC* pedogenic $CaCO_3$, [b]*ESP* exchangeable sodium percentage (sodicity), [c]sHC saturated hydraulic conductivity (Adapted from Kadu et al. 2003)

Table 9.1). Due to comparatively poor crop productivity of the Aridic Haplusterts with the Sodic Haplusterts with an ESP >5 but <15 (having no soil modifiers; Pal et al. 2006), Aridic Haplusterts were classified as Sodic Haplusterts (Balpande et al. 1996; Pal et al. 2006). Such a close association of Aridic and Sodic Haplusterts under similar topographical conditions in a relatively small watershed is a unique example in pedological parlance, but such occurrence of Vertisols poses a challenge for land resource managers in comprehending the differences in the chemical environment between the Aridic Haplusterts with ESP <5 and the Aridic Haplusterts with ESP >5 but <15. Thus, for optimized use and management of the latter type of Aridic Haplusterts, the proposed modifications in their subgroup-level classification (as per US Soil Taxonomy) are mandatory (Pal et al. 2006, 2012a).

9.3 Linear Distance of Cyclic Horizons in Vertisols and Its Relevance to Agronomic Practices

It is well known that Vertisols develop deep, wide shrinkage cracks in the summer, which close as the soil rewets. In the sub-surface regions where sphenoids and/or slickensides are formed, the difference between horizontal stress and vertical stress is quite large when swell. The cyclic horizons repeat in the subsoil, the size of which depends on the length of cycle. One-half of the linear distance (LD) of the cycle is a measurement of the lateral dimension of a cyclic horizon (Johnson 1963). For evaluating the subsoil variability and determine LD, trenches of at least 10 m long with depths of 2 m or more are required (Bhattacharjee et al. 1977; William et al. 1996). Such field examination is time consuming, laborious and expensive.

A large area of Vertisols is used for pastures, and cracks developed therein may be wide enough to cause dangerous footing for animals (Buol et al. 1978). Agronomic uses of Vertisols vary widely, depending on the climate. Field moisture conditions, drainage conditions and patterns of vegetation indicate that the maximum oscillation between wet and dry conditions manifests in micro-depressions that retain moisture for longer periods and in microknolls, which dry out faster. Vertisols are capable of tilting large trees, and surprisingly, few if any commercial forests are cultivated on Vertisols (Buol et al. 1978). In addition, highways, buildings, fences, pipelines, and utility lines are moved and distorted by the shrinking and swelling of these soils. Prior knowledge about the highs and lows of the cyclic pedons may help the stakeholders plan their programmes and avoid mishaps. In view of the need for a method to determine LD, a mathematical equation has been proposed to measure the LD of the cyclic horizons, taking into account the depth of occurrence of slickensides (Bhattacharyya et al. 1999). A standard parabolic equation represented by ($y^2 = 4ax$) was considered, where *a* is the focus of the parabola. The concept of cyclic horizons of Vertisols in terms of this parabolic pattern (Fig. 9.1) centres around two basic assumptions. The first assumption is that the depth of the first occurrence of slickensides (*b*) coincides with the focus of the parabola. The second assumption is that *b* remains constant within a cyclic horizon.

To calculate LD using the equation ($LD = MN = 2KN = 4[a\ \ (a + b)]^{1/2}$) (Fig. 9.1), the values of *a* and b are needed. In the field, the value of *b*

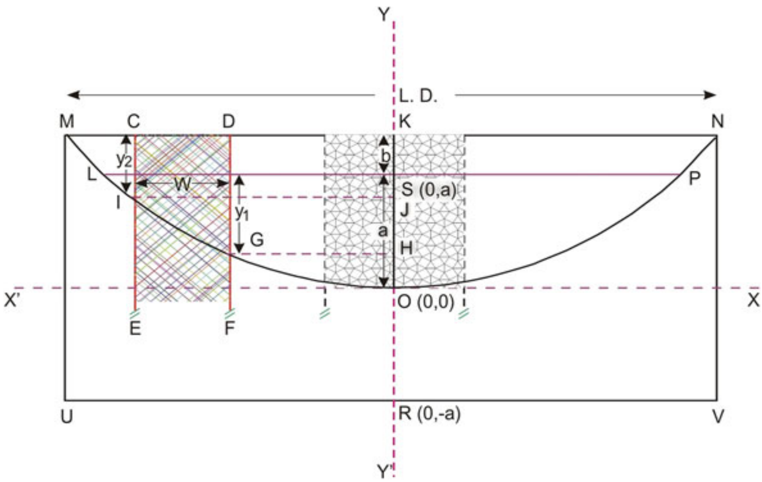

Fig. 9.1 The parabolic path of cyclic pedon where PL, S, UV, O, and KR are latus rectum, focus, directrix, vertex and axis of the parabola (KN = KM, OS = OR, KN = NV, KM = MU, $OJ - OH = y_1 - y_2 = HJ$, $OJ + OH = y_1 + y_2$, OJ. OH = y_1, $\mathbf{y_2}$) (Adapted from Bhattacharyya et al. 1999)

(the depth of the first occurrence of slickensides) is obtained; however, the value of *a* can be obtained only by examining the profile exactly in the centre of the cyclic horizon. This value is difficult to acquire because from the surface the cyclic horizons in the subsurface cannot be identified, especially where micro-knolls and micro- depressions are obliterated. When the profile is examined away from the centre of the cyclic horizon, the value of *a* cannot be obtained, and calculation of LD becomes difficult. To circumvent this difficulty, Bhattacharyya et al. (1999) proposed the following equation.

LD (cm) = $200/Y\,(2500 + bY)^{1/2}$, where $Y = y_1 + y_2 - 2\,(y_1\,y_2)^{1/2}$ and y_1 and y_2 are the vertical distances (cm) from the first occurrence of slickensides to the intersecting points of the cyclic pedon such that $y_1 > y_2$ and b is the depth of the first occurrence of slickensides. It is always possible to find the values of y_1 and y_2, if the profile is examined on either side of the centre of the cyclic horizon (Fig. 9.1). This equation can eliminate some of the need for fieldwork to determine the LD with the help of three variables, namely y_1 (the length of the slickensided zone on the right-hand side of the profile wall from the depth of the occurrence of slickensides), y_2 (the length of the surface and the slickensided zone on the left-hand side of the profile wall) and b (the depth of the occurrence of slickensides). These values can be obtained with ease by soil survey and mapping. The accuracy of the equation proposed by Bhattacharyya et al. (1999) is between 81 and 86% in Vertisols in arid to semi-arid climates. The equation provides a new method of locating micro-depressions and micro-knolls in an effort to better manage Vertisols for agricultural and non-agricultural purposes.

9.4 Smectite as the First Weathered Product of the Deccan Basalt and Its Contribution in Growing Vegetation on Weathered Basalt and in Very Shallow Cracking Clay Soil

Dominated by dark ferromagnesian minerals, gabbros and basalts are more easily weathered than granites and other light-coloured rocks. Low charge dioctahedral smectite (DOS) is the first weathering product of the Deccan basalt. Therefore, the DOS rich alluvium of the weathering Deccan basalt is principally responsible for the formation of deep black soils in the Peninsular India (Pal and Deshpande 1987; Pal et al. 2009a). In the Deccan basalt litho logs, boulders of different sizes adjoin each other (Fig. 9.2a) and exhibit spheroidal weathering (Fig. 9.2b). These boulders have concentric rings similar to onions (Fig. 9.2c) that easily come away under gentle pressure from fingers. The boulders also contain DOS (Fig. 9.2d) similar to that of Vertisols (Pal and Deshpande 1987). Smectites do possess an excellent capacity to hold moisture and nutrients; thus, they help several tree species to anchor on weathered basalt (Fig. 9.2e), even on steep slopes (>40%). The long-term preservation of tree species under national forest management in Maharashtra and

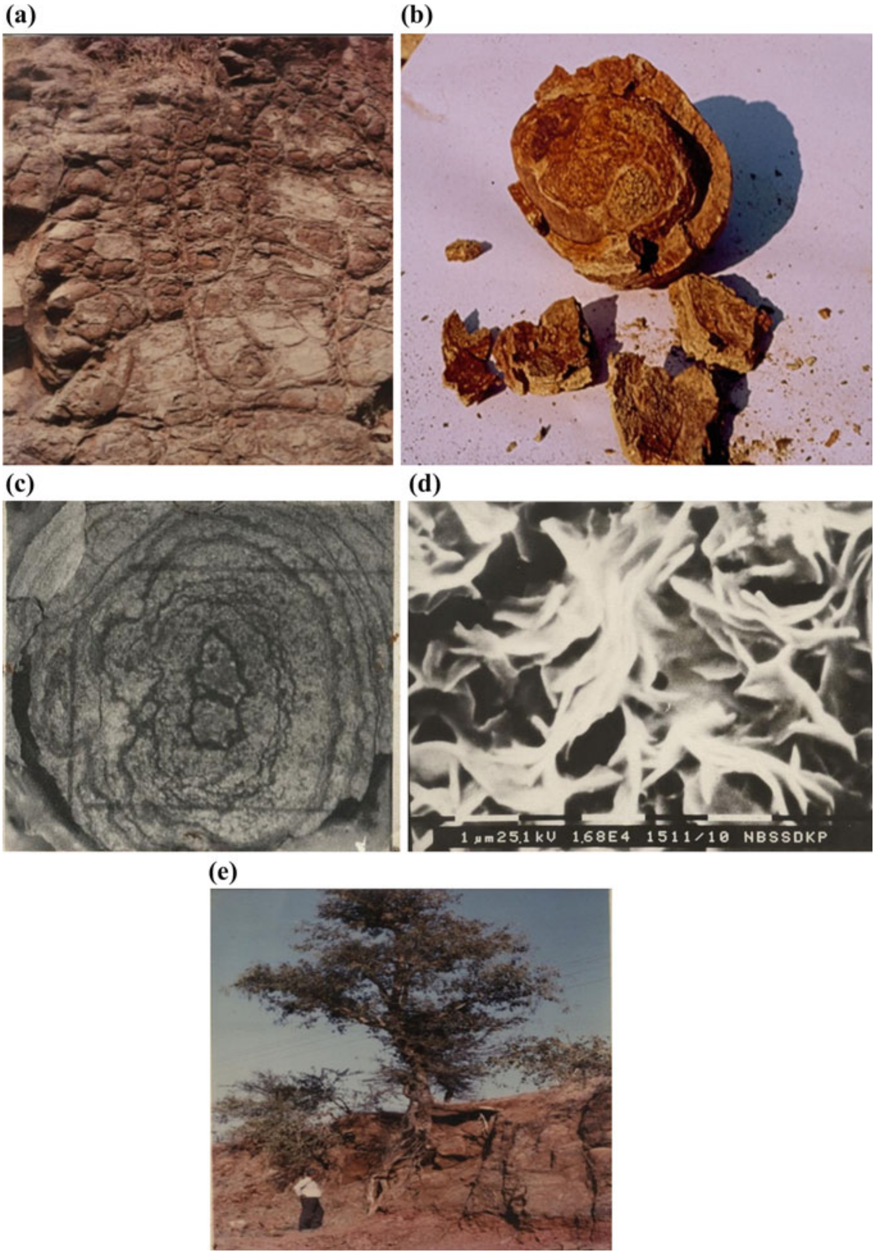

Fig. 9.2 Deccan basalt litholog showing spheroidal weathering (**a**), onion like peeling in basalt boulders (**b**), thin section of basalt boulder showing concentric weathering rinds (**c**), SEM *photograph* of clay sized dioctahedral smectite as its first weathering product (**d**) and smectite providing moisture and nutrient to tree species for anchoring on weathered basalt, even on steep slopes (>40%) (Adapted from Pal et al. 2000b and Pal and Deshpande 1987) *Photographs* (**a**–**e**), courtesy of DKP

Madhya Pradesh of western and central Peninsular India has become possible under favourable MAR conditions in HT, SHM, SHD, and SAM climates. In SAD and AD climates, care is needed at the initial stage of establishment of tree species. The largest Deccan basalt area with the greatest forest cover lies in the state of Madhya Pradesh, in central India; it is followed by Maharashtra, in western India. Smectite mineral has been very helpful in preserving and sustaining the spectacular natural forest vegetation (Bhattacharyya et al. 2005). The mineral also helps to maintain and preserve the forests in lower-MAR areas; however, initial care needed during the establishment of tree species. Thus, the natural abundance of smectite in the Deccan basalt areas of lower MAR can also prove useful in establishing agri-horticultural crops even on shallow soils (Entisols; depth <50 cm) strewn with small and weathered basalt rocks.

9.5 Sustainability of Rice Production in Zeolitic Vertisols

Vertisol use is not confined to a single production system. In India, major combinations of rainfed crops under semi-arid climatic environments are sorghum/pigeon pea, cotton/pigeon pea and cotton/sorghum/pigeon pea. Mixed cropping usually combines crops with different maturity lengths, drought-sensitive with drought-tolerant crops, cereals with legumes, and cash crops with food crops (Swindale 1989). In semi-arid western India (<1000 mm MAR), sugarcane and rice are grown under irrigated conditions, whereas rice is grown under rainfed conditions in areas of sub humid moist climatic conditions of central India (with MAR >1400 mm)(Pal et al. 2003a). The saturated hydraulic conductivity (sHC) decreases rapidly with depth in Vertisols, but the decrease is sharper in non zeolitic Sodic Haplusterts; and the weighted mean of sHC in 0–100 cm depth is <10 mm h^{-1}. In non-zeolitic Typic Haplusterts, the sHC is > 10 mm h^{-1}. But in zeolitic Typic Haplusterts (Kheri soils at Jabalpur, Tomar et al. 1996 and Sakka soils at Dindori, Madhya Pradesh, Pal et al. 2003a) sHC is >20 mm h^{-1}, and these soils are cultivated to rice as rainfed crop in areas with > 1400 mm MAR. Interestingly, zeolitic Sodic Haplusterts (Teligi soils in Bellary, Karnataka, Pal et al. 2013a) in areas with <700 mm MAR also have sHC >20 mm h^{-1}; and rice is cultivated in these soils under canal irrigation. The enhanced sHC (>20 mm h^{-1}) in such Vertisols due to the presence of zeolite, appears to be just adequate for the period of submergence required for the rice crop, and post-rainy season crops are successfully grown with good yields. Morphological examination of such soils showed no sign of gleyed horizons and soil moisture regime does not reach aquic conditions. Such situations are unique in nature and pose a great challenge to the soil mappers to classify them according to the US Soil Taxonomy, as they have good productive potential despite being sodic in nature. Sustainability of rice cropping system in such soils will, however, depend on rate of dissolution of Ca-zeolite on a timescale, and a new research initiative on this topic is warranted.

9.6 Holocene Climate Change, Natural Soil Degradation, Modified Vertisols and Their Evaluation

During the Quaternary Period, frequent climatic changes occurred (Ritter 1996). Due to climate change, soils worldwide were subjected to climatic fluctuations, especially in the last post-glacial period. Brunner (1970) reported evidence for tectonic movements during the Plio-Pleistocene transition, which caused the formation of various relief types. With the formation of the Western Ghats during the Plio-Pleistocene crustal movements, the humid climate of the Miocene-Pliocene was replaced by the semi-arid conditions that still prevail in central and southern peninsular India. The Arabian Sea flanks the Western Ghats, which rise precipitously to an average height of 1200 m, the result of a heavy orographic rainfall all along the west coast. The lee-side towards the coast receives less than 1000 mm of rainfall and is typically rain shadowed (Rajaguru and Korisetter 1987). The current aridic environment prevailing in many parts of the world (including India; Eswaran and van den Berg 1992) may create adverse physical and chemical soil environments, representing a regressive pedogenesis (Pal et al. 2013b). This is evident from the occurrence of more alkaline, calcareous and sodic shrink-swell soils (Sodic Haplusterts/Calciusterts) of Peninsular India due to a progressive increase in the PC content from HT to AD climates (Pal et al. 2009a; please refer to Fig. 2.12b), as aridity of the climate is the main factor in the formation of calcareous sodic soils (Pal et al. 2000a). The subsoils (SAM Aridic Haplusterts, SAD Sodic Haplusterts and AD Sodic Calciusterts) remain under less water than those of Typic Haplusterts in HT, SHM and SAM climates. As a result, the Vertisols in drier regions of India have relatively more PC and ESP, reduced sHC, (Please refer to Table 2.4) and poor micro-structure (please refer to Fig. 2.11c), as well as deep cracks cutting through the slickensided zones (please refer to Fig. 2.2). Thus, these modified Vertisols qualify as polygenetic soils (Pal et al. 2009a). Deep-rooted crops on Aridic Haplusterts (ESP >5, <15) and Sodic Haplusterts show poor productivity (Table 9.1). Recently, Kadu et al. (2003) and Deshmukh et al. (2014) attempted to identify bio-physical factors that limit the yield of deep-rooted crops (cotton) in 32 Vertisols (developed in the basaltic-alluvium) of the Nagpur, Amravati and Akola districts in the Vidarbha region in central India. Under rain-fed conditions, the yield of deep-rooted crops on Vertisols depends primarily on the amount of rain stored at depth in the soil profile and the extent to which this soil water is released between the rains during crop growth. Both the retention and release of soil water are governed by the nature and content of clay minerals, and also by the nature of the exchangeable cations. The AWC (available water content), calculated based on moisture content, varied between 33 and 1500 kPa (Table 9.2), indicating that not only the Typic/Aridic Haplusterts but also the Sodic Calciusterts can hold sufficient water; however, a non-significant negative correlation between cotton yield and AWC (Table 9.2) indicates that this water is not available during the growth of crops. The Na^+ ions on exchange sites of Aridic Haplusterts and Sodic Haplusterts/Calciusterts with ESP >5 thus amounts to over estimation

(Gardner et al. 1984). In fact, moisture remains at 100 kPa for Typic Haplusterts and Aridic Haplusterts (ESP <5) after the cessation of rains during June to September, while it is held at 300 kPa for Sodic Haplusterts (Pal et al. 2012a; Deshmukh et al. 2014) as the movement of water is governed by sHC, which decreases rapidly with depth, and the decrease is sharper in Aridic/Sodic Haplusterts (ESP >5, Pal et al. 2009a). This conclusion is supported by a significant positive relationship between ESP and AWC, and a significant negative correlation between yield and ESP (Table 9.2). A significant positive correlation between yield and exchangeable Ca/Mg (Table 9.2) indicates that a dominance of Ca^{2+} ions in the exchange sites of Vertisols is required to improve the hydraulic properties for a favourable growth and final yield of crops. The development of subsoil sodicity (ESP ≥5) replaces Ca^{2+}ions in the exchange complex, causing a reduction in the yield of cotton in Aridic/Sodic Haplusterts (ESP ≥5). A significant negative correlation between ESP and exchangeable Ca/Mg (Table 9.2) indicates an impoverishment of soils with Ca^{2+} ions during sodification by the illuviation of Na-rich clays. This pedogenetic process depletes Ca^{2+}ions from the soil solution in the form of $CaCO_3$, with the concomitant increase of ESP with pedon depth. Thus, these soils contain PC (Pal et al. 2000a), and carbonate clay, which, on a fine earth basis, increases with depth (please refer to Table 2.4). This chemical process is evident from the positive correlation between ESP and carbonate clay (Table 9.2). A significant positive correlation between the yield of cotton and carbonate clay (Table 9.2) indicates that, like ESP, PC formation also causes a yield reduction and is a more important soil parameter than total soil $CaCO_3$ (NBSS&LUP 1994;

Table 9.2 Co-efficient of correlation among various soil attributes and yield of cotton[a]

No.	Parameter Y	Parameter X	r
Based on 165 soil horizons samples of 29 Vertisols			
1	sHC (mm h^{-1})	Exch. Ca/Mg	0.51*
2	sHC (mm h^{-1})	ESP[b]	−0.56*
3	ESP	AWC (%)	0.40*
4	ESP	Exch. Ca/Mg	−0.40*
Based on 29 Vertisols			
5	Yield of cotton (q ha^{-1})	AWC (%) WM[c]	−0.10
6	Yield of cotton (q ha^{-1})	ESP max[a]	−0.74*
7	Yield of cotton (q ha^{-1})	sHC WM[b]	0.76*
8	Yield of cotton (q ha^{-1})	Carbonate clay[d]	−0.64*
10	Yield of cotton (q ha^{-1})	Exch. Ca/Mg WM[c]	0.50*
11	ESP max[a]	AWC (%) WM[c]	0.30*
12	ESP max[a]	Exch. Ca/Mg WM[c]	−0.55*
13	ESP max[a]	Carbonate clay[d]	0.83*

AWC available water content; *ESP* exchangeable sodium percentage; *sHC*, saturated hydraulic conductivity
*Significant at 1% level
[a]Adapted from Kadu et al. (2003); [b]Maximum in pedon; [c] weighted mean; [d] fine earth basis

Sys et al. 1993). An accelerated rate of PC formation in dry climates impairs the hydraulic properties of Vertisols, and a significant negative correlation exists between ESP and sHC (Table 9.2). The processes operating in the soils of dry climates also influence the sHC of the Vertisols. A significant positive correlation exists between the yield of cotton and sHC. In view of the pedogenic relationship among SAT environments, PC formation, exchangeable Ca/Mg, ESP and sHC, all of which ultimately impair the drainage of Vertisols, the evaluation of Vertisols for deep-rooted crops based on sHC alone may help in planning and management of soils, not only of Vertisols in the Indian SAT areas, but also of Vertisols under similar climatic conditions elsewhere (Kadu et al. 2003; Pal et al. 2012a).

9.7 Soil Modifiers (Zeolites, Gypsum and $CaCO_3$) in Mitigating the Adverse Holocene Climate Change and Making Sodic Vertisols Resilient

Since the beginning of the 1990 the presence of soil modifiers such as gypsum, calcium carbonate and zeolites, is being adequately reported in soils by the researchers of the ICAR-NBSS & LUP, Nagpur (Pal 2013). It is necessary to follow the unique role of soil modifiers in changing the pedo-chemical environment of soils, which is essential for better soil use and management, in fine-tuning the exiting soil classification scheme and also the management practices to enhance and sustain the productivity of Indian tropical soils (Pal 2013).

9.7.1 Ca-Zeolites

During the last 3 decades, zeolite minerals have been recognized with increasing regularity as common constituents of Cenozoic volcanogenic sedimentary rocks and altered pyroclastic rocks (Ming and Mumpton 1989). Zeolites have also been reported as secondary minerals in the Deccan flood basalt of the Western Ghats in the state of Maharashtra, India (Sabale and Vishwakarma 1996). Among the commonly occurring species of zeolites, heulandites (Fig. 9.3a) have a wide occurrence both in time and space (Sabale and Vishwakarma 1996). Zeolites have the ability to hydrate and dehydrate reversibly and to exchange some of their constituent cations. Consequently, they can influence the pedochemical environment during the formation of soils. The significance of zeolites has recently been realized in the formation and persistence of slightly acidic to acidic Vertisols (Typic Haplusterts) in HT climatic environments, not only in central and western India (Bhattacharyya et al. 2005), but elsewhere (Ahmad 1983). The formation and persistence of Vertisols on the Deccan basalts in HT climate with other associated soils (Mollisols and Alfisols) due to the presence of Ca-zeolites is a unique example

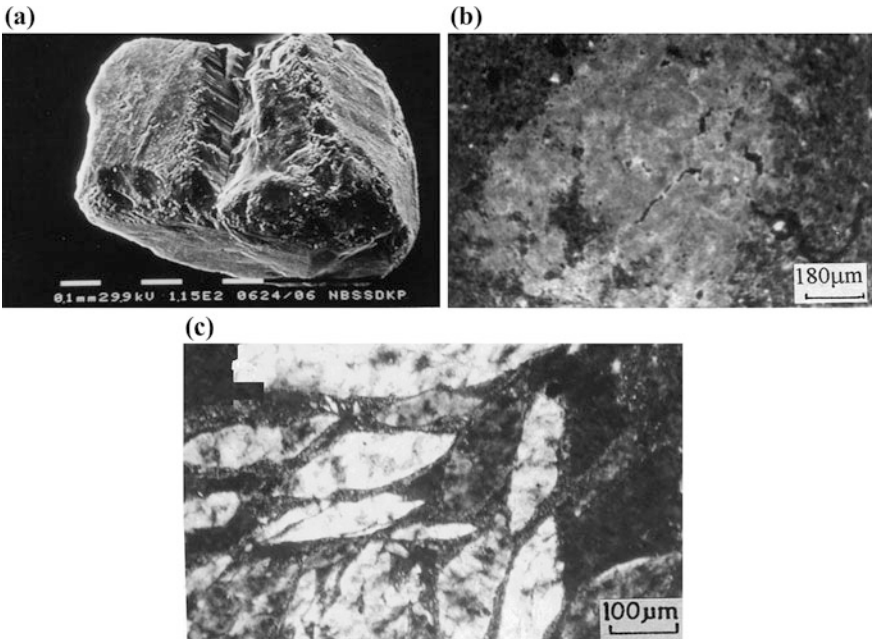

Fig. 9.3 Scanning electron microscope photographs of **a** unweathered heulandite of shrink-swell soils, and photomicrographs of **b** pedogenic calcium carbonate of shrink-swell soils, **c** lenticular gypsum crystal of shrink-swell soils (Adapted from Pal et al. 2000b)

in an open system such as soil. This highlights the inadequacy of the existing models to explain the formation of Indian tropical soils and also the role of zeolites in preventing the loss of soil productivity and maintaining soil health (as elaborated in Chap. 5).

Many productive Vertisols under rain-fed conditions have been rendered unproductive for agriculture under irrigated conditions in the longer-term. However, some zeolitic Vertisols of the SAD parts of western India have been irrigated through canals for the last twenty years to produce sugarcane. These soils lack salt-efflorescence on the surface and are not waterlogged at present, suggesting that these soils are not degraded due to their better drainage. However, these soils are now Sodic Haplusterts in view of their pH, ECe and ESP values, but they have sHC >10 mm h^{-1} (weighted mean in the 0–100 cm, Table 9.3). A constant supply of Ca^{2+} ions from Ca-zeolites in these soils most likely helps maintain a better drainage system. Because of such natural endowment with a soil modifier, no ill effects of high ESP (>15) in crop production in the Vertisols of Gezira in Sudan (El Abedine et al. 1969; Robinson 1971) and in Tanzania (Ahmad 1996) were observed. In addition, some Vertisols of the AD climate of western India produce deeply rooted crops such as cotton under rain fed conditions comparable to those of the Typic Haplusterts of the SAM climate of central India (Pal et al. 2009b). The sHC (weighted mean, 0–100 cm) of these soils is >10 mm h^{-1} (Table 9.3), despite

Table 9.3 Adverse effect of irrigation on zeolitic Typic Haplusterts during sugarcane cultivation

Depth (cm)	pH (1:2)	ECe (dS m^{-1})	$CaCO_3$ (<2 mm) %	ESP	sHC[a] (mm h^{-1})	Base saturation (%)	Available K (kg ha^{-1})
0–20	9.0	0.77	16.0	4.2	18	107	686
20–42	9.2	1.01	17.0	10.4	17	119	343
42–68	9.3	0.99	17.0	18.8	5	94	343
68–102	9.0	1.25	15.0	13.7	10	105	343
102–131	9.0	1.09	25.3	12.1	13	103	343
131–150	9.0	1.02	16.1	8.0	12	109	421

Adapted from Pal et al. (2003a)

ECe electrical conductivity of the saturation extract; *ESP* exchangeable sodium percentage; *sHC* saturated hydraulic conductivity

[a]13 mm h^{-1} is the weighted mean sHC in 0–100 cm depth of soil

being Sodic Calciusterts (Pal et al. 2009a). However, the sustainability of crop productivity in the dry climate depends on the solubility and supply of Ca^{2+}ions from zeolites such that it is sufficient to overcome the ill effects of the pedogenic threshold of dry climates (Pal et al. 2003b, 2009a). Such situations are unique in nature and pose a great challenge to soil mappers to classify them as per the US Soil Taxonomy when they are sodic in nature but have good productive potential.

9.7.2 Gypsum

Arid and semi-arid environments trigger natural soil degradation processes in terms of the precipitation of $CaCO_3$ and the concomitant development of sodicity (Pal et al. 2000a). Despite this possibility, selected Vertisols of the SAD climate in southern India are non-sodic and support the growth of crops such as cotton, pigeon pea and sorghum. The development of sodicity has been prevented by the presence of gypsum in these soils (Fig. 9.3b), but the soils are calcareous in nature (Table 9.4). The soils have a sHC >30 mm h^{-1} (Table 9.4) despite the rapid formation of PC, unlike in the zeolitic Vertisols of the SAD climate (Pal et al. 2009a). This can be attributed to the greater solubility of gypsum (30 me/L) than that of Ca-zeolites (< 0.1 me/L) in distilled water (Pal et al. 2006). The gypsum in such soils is antagonistic to the formation of more soluble salts in soils, as it prevents clay dispersion. Although the sustainability of crop productivity in these soils depends on the gypsum stock, the present poor productivity of cotton (approximately 2 t ha^{-1}) may be enhanced by irrigation because the gypsum present would prevent water logging and maintain better drainage (Pal et al. 2009c).

Table 9.4 Physical and chemical properties of Vertisols modified by gypsum in SAT parts of Tamil Nadu

Depth (cm)	pH (1:2 water)	ECe (dS/m)	$CaCO_3$ (<2 mm) (%)	ESP	sHC (mm/h)
0–6	8.0	0.2	5.4	0.5	19
6–20	8.0	0.3	4.3	0.9	22
20–41	8.0	0.5	5.3	0.6	44
41–74	8.0	0.4	7.9	0.9	30
74–104	7.9	0.2	12.5	1.1	37
104–128	7.9	0.6	12.8	1.4	34
128–140	7.4	2.7	15.6	1.8	32
140+	7.5	–	17.4	0.3	48

Adapted from Pal et al. (2003a). *ESP* exchangeable sodium percentage, *ECe* electrical conductivity of the saturation extract, *sHC* saturated hydraulic conductivity

9.7.3 $CaCO_3$

The subsoil sodicity impairs the hydraulic properties of the Vertisols of SAT environments, and this leads to the formation of sodic soils with ESP decreasing with depth. These soils are impoverished in organic carbon but have become enriched with $CaCO_3$ (Fig. 9.3c) with poor sHC (Table 9.5) (Pal et al. 2009a). However, such soils show enough resilience under the improved management (IM) (catchment management followed by adopting legume-based crop rotation, improved nutrient management and without any chemical amendments) system of ICRISAT, implemented in Patancheru, India. Through the implementation of such practices, a substantial increase in soil organic carbon (SOC) stock was observed (Wani et al. 2003). The resilience of such soils has been maintained by implementing IM practices in Vertisols. The increase in SOC is, however, related to chemical changes after the specified management interventions. In Vertisols (Sodic Haplusterts, Pal et al. 2012c) after 30 years of IM, the weighted mean (WM) of sHC in the first 100 cm of the profile increased by almost 2.5 times due to the reduction of ESP through the dissolution of $CaCO_3$ (Table 9.5), making the soils more permeable to air and water. In the last 24 years (since 1977), the rate of dissolution of $CaCO_3$ has been 21 mg year^{-1} in the first 100 cm of the profile. Dissolved Ca^{2+} ions improve the Ca/Mg ratio on the exchange complex of soils under IM compared with those under traditional management (Table 9.5) (Pal et al. 2012b).

The changes in soil properties, as stated above, suggest that $CaCO_3$ is dissolved through the cations of acidic root exudates and carbonic acid that formed due to evolved CO_2 from the root respiration in an aqueous solution, resulting in the formation of Ca $(HCO_3)_2$. The soluble Ca $(HCO_3)_2$, therefore, helps restore both the soluble and exchangeable Ca ions in the soils. The ESP decreases and the soil structure improve; as a result, the hydraulic properties of soils are improved (Table 9.5). This improvement in soil properties highlights the role of $CaCO_3$,

Table 9.5 Modification of physical and chemical properties of Vertisols through improved management system at ICRISAT, Patancheru in 24 years since 1977

Horizon	Depth cm	Clay %	Clay (%), weighted mean in 0–100 cm	Fine clay %	Fine clay (%), weighted mean in 0–100 cm	sHC mm h^{-1}	sHC mm h^{-1}, weighted mean in 0–100 cm	pH H_2O (1:2)	Organic carbon %	Organic carbon (%) weighted mean in 0–100 cm	$CaCO_3$ %	$CaCO_3$ (%), weighted mean in 0–100 cm	CEC cmol (p+) kg^{-1}	CEC (cmol(p+) kg^{-1}), weighted mean in 0–100 cm	Exchangeable Ca/Mg	Exchangeable Ca/Mg, weighted mean in 0–100 cm	ESP	ESP weighted mean in 0–100 cm
Kasireddipalli soil (Sodic Haplusterts) under traditional management (TM)																		
Ap	0–12	48.0	53.0	26.4	33.0	7.0	4.0	7.8	0.6	0.42	6.0	6.2	48.7	52.2	3.2	2.2	2.0	8.3
Bw1	12–30	51.4		29.7		6.0		7.8	0.4		6.2		52.1		2.8		4.0	
Bss1	30–59	52.5		32.5		6.0		8.1	0.4		6.0		52.2		2.1		7.1	
Bss2	59–101	55.6		36.4		2.0		8.5	0.4		6.4		53.5		1.8		13.0	
Bss3	101–130	59.4		30.8		2.0		8.5	0.4		6.5		57.8		3.1		8.0	
BCk	130–160	58.0		38.7		1.0		8.2	0.1		9.1		49.5		1.5		22.2	
Kasireddipalli soil (Typic Haplusterts) under improved management (IM)																		
Ap	0–12	52.1	54.7	28.8	32.8	17.0	11.0	7.5	1.0	0.53	4.2	5.7	50.4	56.0	2.9	2.4	2.0	4.5
Bw1	12–31	51.5		28.1		16.0		7.8	0.6		4.5		54.3		2.4		2.0	
Bss1	31–54	54.2		34.0		10.0		7.8	0.4		6.2		55.6		1.7		3.0	
Bss2	54–84	57.3		40.0		9.0		8.2	0.4		5.1		56.4		1.9		7.0	
Bss3	84–118	56.5		26.0		7.0		8.1	0.5		8.6		61.6		3.8		7.0	
Bss4	118–146	59.3		31.7		3.0		8.2	0.5		8.4		58.2		2.1		7.0	
BC	146–157	60.0		41.5		–		8.2	0.3		7.4		55.2		1.1		9.0	

Adapted from Pal et al. (2003a, 2012a, b, c) which remains chemically inert (Pal et al. 2000a) during its sequestration (Sahrawat 2003) but acts as a soil modifier during the amelioration of degraded soils. The improvements in soil properties are also reflected in the classification of Vertisols. The original Kasireddipalli soils (Sodic Haplusterts) now qualify as Typic Haplusterts (Table 9.5) (Pal et al. 2012b).

SAT induced naturally degraded Vertisols of the Holocene period (with ESP >5, but <15 and sHC <10 mm h^{-1}) (Table 9.5) like Kasireddipalli and similar soils (Sodic Haplusterts, without soil modifiers like Ca zeolites and gypsum) occurring elsewhere show poor crop productivity. The IM system of ICRISAT when adapted in such soils can make Sodic Haplusterts resilient by converting them to Typic Haplusterts. In view of constant supply of soluble Ca^{2+} ions through the dissolution of $CaCO_3$, sustainability of still calcareous Typic Haplusterts can be maintained for couple of centuries under SAT environments. Therefore, the IM system can be considered as a good/recommended/no regrets strategy as it has potential to mitigate the adverse effect of climate change. It may thus possibly lessen the emphasis of genetically modified crops for Sodic Haplusterts of the SAT, and is ready for its wide adaptation through national and international initiatives (Pal et al. 2012b).

9.8 Acidity, Al Toxicity and Lime Requirement in RF Soils of HT Climates: A Critique

Indeed, soil acidity is a major constraint to crop production because of the significant contribution of Al_3^{+} ions to exchangeable acidity in HT soils. To ward off the adverse effect of acidity, liming is generally recommended for strong to moderately acid soils of tropical India. But crop response to liming is not observed (Kadrekar 1979) in some moderately acidic Alfisols of the Western Ghats due to the presence of Ca-zeolites in these soils (Pal et al. 2012a). Aluminium toxicity to plants is a constraint in Oxisols, Ultisols and Dystropepts; and this is also associated with an overall low nutrient reserves (Sanchez and Logan 1992). Ultisols and Dystropepts of Kerala, Goa, Tamil Nadu, Karnataka and NEH are strongly to moderately acidic, and liming is often recommended to correct soil acidity and improve nutrient availability (ICAR-NAAS 2010).

Liming is done in order to bring exchangeable aluminium level in the soil to <1 mg kg^{-1} (Sanchez 1976) for maintaining sustained productivity because it improves the general nutrient availability (Nayak et al. 1996a, b; Sen et al. 1997). It is to be noted that reports on Al toxicity to crops in Indian acidic soils are scarce. The KCl extractable aluminium is used for liming tropical acidic pH soils (Oates and Kamprath 1983). It is intriguing that despite equally strongly acidic, Ultisols and Dystropepts of NEH, Ultisols of Kerala, and Alfisols of Goa indicate varying KCl exchange acidity. It is less than 1 cmol (p+)$kg^{-1}$for the Ultisols of Kerala and Meghalaya, and Alfisols of Goa whereas in the Ultisols of Arunachal Pradesh, Assam, Mizoram, Nagaland, Tripura and Dystrochrepts of Manipur, it ranges from 3 to 6 cmol (p+) kg^{-1} (please refer to Table 3.2). Thus, lime requirement (LR) of these acidic soils varies widely. Lime requirement is around 1 t lime ha^{-1} for Ultisols of Meghalaya, and for Dystrochrepts and Ultisols of other states of NEH, it ranges from 4 to 12 t ha^{-1}(please refer to Table 3.2). Such a low LR (<1 t ha^{-1}) may be expected for zeolitic soils as soil solution would remain adequately high in soluble Ca-ions from dissolution of Ca-zeolite but for the gibbsite containing Ultisols (Kerala, Meghalaya) and Alfisols (Goa), the reason for low KCl exchangeable acidity and LR, it is not understood yet. Therefore, fresh research on the role of zeolites and gibbsite in modifying the LR of acid soils needs to be initiated to make recommendations for LR on the basis of KCl exchangeable acidity. It is interesting to note that highly acidic pH Ultisols of Kerala, Karnataka, Tamil Nadu and NEH and moderately acidic Alfisols of Goa, Karnataka and Tamil Nadu have very high $BaCl_2$-TEA extractable acidity in contrast to that they have low to very low 1N KCl exchangeable acidity (please refer to Table 3.2). This indicates that Al_3^+ ions released during the humid tropical weathering do not remain in soil solutions but are trapped as Al $(OH)_2^+$ ion in the interlayers of 2:1 minerals to form hydroxy interlayered minerals (Bhattacharyya et al. 2006). Both smectites and vermiculites act as sinks for aluminium and thus protect the biota from Al toxicity. It is evidenced when surface horizons (0–30 cm) of such Ultisols release large quantities of Al_3^+, Fe_3^+ and H^+ on extraction with $BaCl_2$-TEA (Pal et al. 2014). In the event of their availability in soil solutions these cations might have created very high acidity as well as Al-toxicity in soils to render them problematic for agricultural use.

9.9 Present Soil Health Status Due to Anthropogenic Activities in IGP Soils

It is crucial to understand the impact of climatic transition to aridification during 4th and 3rd millennium BC on cultivation over the IGP. Prior to the transition, rainfall in the Indus Valley was probably more than double the amount received now. Such a high rainfall facilitated the flourishing of both agriculture and forestry (Randhawa 1945). The aridification set in these times possibly caused the end of the great Harrapan civilization. The onset of climatic aridity started inducing regressive pedogenetic processes in the IGP soils, which made soils calcareous and sodic and also impaired their percolative moisture regime (Pal et al. 2000a). At present, the IGP covers approximately 1/3 cultivable area of India and produces nearly 50% of the country's food grains for its population. Most of the land in the IGP has been cultivated using traditional mixed cropping methods until the middle of the 19th century. During the last 3–4 decades the agriculturists of the IGP have successfully increased food grain production by introducing high-input technologies to meet the demands of the exponentially growing population. The strategies and measures adopted to achieve this success included, among others, (i) the spread of high-yielding varieties, (ii) expansion of irrigated area, (iii) increased use of fertilizers, (iv) use of plant protection chemicals, (v) strengthening of marketing infrastructure, and (vi) introduction of subsidies (Abrol et al. 2002). The production of grains was, however, not uniform across the IGP regions because of the spatial variation in land-resource characteristics and socio-economy in the region. These management interventions for 'money economy' have resulted in (i) widespread degradation, (ii) depletion of natural resources, (iii) declining water level, (iv) loss in soil fertility, (v) nutrient imbalance/deficiency, (vi) drainage congestion and (vii) loss in soil carbon (Abrol and Gupta 1998; Bhandari et al. 2002; Gupta 2003). Thus the sustainability ratings of some soil series of the IGP for the rice-wheat cropping system indicate many soil constraints, including low soil organic carbon (SOC) (Bhattacharyya et al. 2004).

The ICAR-NBSS&LUP reassessed the SOC stock of the IGP in 2005, and observed that there has been more than 30% increase in SOC in 0–150 cm depth over the value assessed in 1980. The SIC stock increased in some soils but decreased in sodic soils after their reclamation (Table 9.6) (Pal et al. 2015). The observed increase in SIC stock in the wetter part ((Table 9.6) could possibly be due to the accumulation of carbonates and bicarbonates from tube well water used for irrigation in the dry season (Pal et al. 2010). Despite the fact that the IGP soils of hot arid (HA), semi-arid dry (SAD), semi-arid moist (SAM), and sub-humid dry (SHD) climates may show deficiency in organic carbon due to high rate of decomposition, such decline in soil organic carbon did happen when the National Agricultural Research Systems' (NARS) recommendations for improved seeds, NPK fertilizers, micronutrients, FYM, and the inclusion of legumes in cropping sequence was not implemented in farmers' fields (Pal et al. 2015). This fact becomes clear when Indian tropical soils under various agricultural land uses under

Table 9.6 Changes in carbon stock (Tg = 10^{12} g) over years in the selected benchmark spots of the IGP (0–150 cm)

Bioclimatic systems	Soil series	SOC stock (Tg/10^5 ha)			SIC stock (Tg/10^5 ha)		
		1980	2005	SOC change over 1980 (%)	1980	2005	SIC change over 1980 (%)
Semi arid	Phaguwala	3.66	5.48	68	13.10	26.14	9
	Ghabdan	2.63	7.04	167	18.95	7.71	−59
	Zarifa	4.13	5.38	30	22.36	16.98	−24
	Viran	4.13	5.50	395	0	58.13	100
	Fatehpur	1.11	8.55	111	51.03	5.37	−89
	Sakit	4.05	5.84	31	0	10.15	100
	Dhadde	4.47					
Sub-humid	Bhanra	1.81	5.34	197	0	0.58	100
	Jagjitpur	2.52	8.76	248	2.52	8.86	251
	Haldi	8.55	6.28	−26	0	2.84	100
Humid	Hanrgram	6.93	11.0	59	0	3.68	100
	Madhpur	3.99	4.97	25	4.03	15.98	296
	Sasanga	5.25	8.42	61	0.88	4.45	405

Adapted from Bhattacharyya et al. (2007)

both short and long–long term experiments showed their potentiality to sequester OC under both arable and submerged conditions and they still show potential to sequester OC even in humid climates (Pal et al. 2015).

It is interesting to note that when the management interventions of the NARS have resulted in depletion of soil organic carbon in erstwhile Mollisols (e.g. Haldi soils, unit 26, Fig. 4.1; Table 9.6), the SIC stocks (as $CaCO_3$) in the arid and semi-arid IGP soils seem to be useful during the establishment of vegetation effected by appropriate ameliorative methods. During amelioration, the plant roots dissolve the immobile $CaCO_3$ and ultimately trigger the process of Ca release in the soil and thus $CaCO_3$ acts as a natural ameliorant for sodic soils (Bhattacharyya et al. 2004). It was observed that the rate of dissolution of $CaCO_3$ in Typic Natrustalfs was much higher than its rate of formation (details are available in Chap. 6) (Pal et al. 2000a, 2009c). This is important that $CaCO_3$ as SIC is more than double of the SOC stock in the first 150 cm depth, which helps improve the drainage, establishment of vegetation, and sequestration of OC in soils (Bhattacharyya et al. 2004) and would not allow Haplustalfs to transform to any other soil order so long $CaCO_3$ continues to serve as a soil modifier (Pal et al. 2012b).

In addition to the impairment of drainage by sodicity, some of the non-sodic soils are also marked by low hydraulic conductivity (sHC <10 mm/h) (Pal 2012). Impairment of hydraulic conductivity in such soils is attributed to an increase in bulk density (BD) in the subsoils (Pal 2012; Bhattacharyya et al. 2014b; Chandran et al. 2014; Tiwary et al. 2014). The increase in BD in subsoils is due to compaction caused by modern agricultural implements used to meet the high demand of rice, wheat and potato crops. This situation however, may help to maintain the yield of rice in rainy season and also in sequestering more soil organic carbon under sub-merged condition (Sahrawat 2004; Sahrawat et al. 2005). However, the yield of the subsequent crop, such as wheat, is either plateauing or declining (Dhillon et al. 2010). A comparison of the 1980 and 2005 soil data indicate an overall increase in SOC stock in these soils under agricultural land use despite the increase in soil inorganic carbon (SIC) (Bhattacharyya et al. 2007; Pal et al. 2009d). The soil degradation in terms of development of sodicity, increase in SIC and BD, despite the positive balance of OC sequestration, is a matter of concern. In view of the vast area of the IGP, new research initiatives are needed for development of the historical soil-climate-crop databank. Such a databank will not only help in fine-tuning the existing NARS management interventions, but also make the future projections on the sustainability of the cropping system in the IGP (Dhillon et al. 2010).

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