Chapter 6
Land and Soil Degradation and Remedial Measures

Abstract Most published research on soil degradation in general emphasizes the role of anthropogenic factors. Even among the natural soil degradation processes the regressive pedogenic processes that lead to the formation of $CaCO_3$ and concomitant development of subsoil sodicity and the adverse effects of palygorskite mineral on the soils of the semi-arid tropics (SAT), have received little global attention as the natural processes of chemical degradation of soils. Pedogenic calcium carbonate, soil sodicity and palygorskite mineral impair the hydraulic properties of the SAT soils, which reduce their crop productivity. This type of unfavourable soil health triggered by the tectonic-climate linked regressive pedogenic processes (formation of pedogenic calcium carbonate and development of sub soil sodicity) needs to be globally considered as the natural soil degradation process. The regressive pedogenic processes that are inherently connected to the development of natural soil degradation, expands the basic knowledge in pedology and thus it may have relevance in soils of other SAT areas of the world. Research efforts made in the Indian subcontinent explains the cause-effect relationship of the degradation and provides enough insights as to how the remedial measures are to be invented including the role of pedogenic $CaCO_3$ and geogenic Ca-zeolites as soil modifiers along with gypsum, in making naturally degraded soils resilient and healthy.

Keywords $CaCO_3$ formation · Regressive pedogenesis · Remedial measures · SAT soils · Subsoil sodicity

6.1 Introduction

Soil is an integral part of land and land degradation is believed to be an anthropogenic induced process. The soil degradation is a big threat in maintaining sustainable livelihood security of farmers as it reduces the agricultural crop productivity (ICAR-NAAS 2010). Both land and soil degradation is induced by natural and human-induced processes, which are considered as chemical, physical or a biological phenomenon. Most published research on soil degradation in general

D.K. Pal, *A Treatise of Indian and Tropical Soils*,
DOI 10.1007/978-3-319-49439-5_6

emphasizes the role of anthropogenic factors. One of the best examples is the development of saline and sodic soils in the north-west (NW) part of the IGP by introducing canal irrigation. The canal irrigation introduced during the end of the 19th century in the NW part of the IGP, is an important factor that affects the IGP soils. It was introduced to minimize the problem of aridity and to stabilize crop yields. Although it resulted in the expansion of the cultivable area in the IGP, the practice of irrigation during the dry climate without the provision of drainage led to soil salinization and alkalinisation within a few years, due to rise in the groundwater table containing high proportion of sodium relative to divalent cations and/or high residual alkalinity (Abrol 1982a). In addition, the application of groundwater with high sodicity for irrigation also increased sodic soils in the IGP (Abrol 1982b). Canal irrigation has caused similar salinity and sodicity problem also in shrink-swell and ferruginous soils of SAT environments. Even amidst such development of salinity and sodicity, recent research done in India during the last two decades has demonstrated the development of sodicity in soils in NW part of the IGP, shrink-swell soils of western and central India and ferruginous soils of southern India as the natural chemical soil degradation (Pal et al. 2016).

Physical degradation like water erosion is the most widespread form of soil degradation in India especially in the most affected RF soils of both HT and SAT climatic environments (ICAR-NAAS 2010). However, it has been demonstrated that the rate of top soil formation in Ultisols, Alfisols, Mollisols and Inceptisols of north eastern hills (NEH) (Bhattacharyya et al. 2007) and southern peninsular areas with clay enriched B-horizon is much higher than the soil loss by water erosion (Pal et al. 2014). Thus it is difficult to accept the higher rate of soil degradation in RF soils due to water erosion, and therefore demands a relook into the published literature.

In view of the background information, a proper identification of both natural and human-induced soil degradation in Indian soils is warranted. Such science backed exercise will help to identify the basic cause-effect relation of soil degradation in order to suggest the proper rehabilitation measures to make degraded soils resilient.

6.2 Natural Chemical Degradation of Soils in the Indian SAT, and Remedial Measures

Out of the 12 soil orders in Soil Taxonomy six diversified soil orders (Alfisols, Aridisols, Entisols, Inceptisols, Mollisols and Vertisols) do occur in the Indian semi-arid tropics (SAT) (Pal et al. 2000). In US Soil Taxonomy the SAT environments are identified at the suborder level within the ustic moisture regime. Although the ustic soil moister regime suggests the prevalence of dryness during a few months of the year, enough soil moisture is actually available for potentially growing crops in the rainy season (Soil Survey Staff 1975). The specific definition of ustic moisture regime is based on the mean annual soil temperature, and the duration of the period in which the control section of the profile remains moist or dry (Soil Survey Staff 1975). This definition means that the ustic moisture regime occurs in the tropical regions, with a monsoon climate that has at least one rainy season lasting three or more months in a year (Soil Survey Staff 1975).

Rain-fed agriculture with low productivity still prevails in the majority of the SAT soils. Although an increase in food production due to the implementation of improved soil, water and nutrient management practices is realized, many parts of the world continue to face food insecurity. Majority of the world's population ($\sim 60\%$) is facing food insecurity resides in South Asia and sub-Saharan Africa. Most of these areas are rain-fed and there are several challenges in improving the livelihoods of the rural poor. Ironically the rain-fed areas are mostly inhabited by poor rural communities. Moreover the rain-fed agriculture in the SAT area is fragile due to climatic variability in terms of spatial and temporal variation of rainfall. Besides, the rainfall is a short duration with high intensity phenomenon, which causes severe soil erosion, leading to physical, chemical and biological degradation of soils (Pal et al. 2000, 2012a, 2014; Srivastava et al. 2015).

The menace of degradation in SAT areas has made all scientists, agriculturists, environmentalists and policy makers anxious whether the soil resource base will be enough to feed the expected 8.2 billion world population by 2030 (www.unpopulation.org). In reality, soils are dynamic and are capable to supply nutrients, buffer acid-base reactions, absorb and degrade pathogens, detoxify and attenuate xenobiotic and inorganic compounds. Moreover, soils also possess the capacity of self-restoration through the process of soil formation. But soil formation is a slow process, and a substantial amount of soil can form only over a long geologic time. The misuse of soils and associated extreme climatic conditions can damage such self-regulating capacity and give way to regressive pedogenesis (Pal et al. 2013). This unfavourable pedogenesis might lead to the soil to regress from higher to lower usefulness and or drastically diminished productivity. Such an unfavourable endowment of soils is termed soil degradation (Lal et al. 1989).

6.3 Definition, Processes and Factors of Soil Degradation

Lal et al. (1989) defined soil degradation as diminution of soil quality (and thereby its current and potential productivity) and or a reduction in its ability to be a multi-purpose resource due to both natural and human-induced causes. The authors identified various processes that lead to soil degradation and they are accelerated erosion, increasing wetness and poor drainage, laterization, salinization, nutrient imbalance, decline in soil organic matter, and reduction in activity and species activity of soil fauna and flora. Processes of soil degradation are identified as chemical, physical and biological degradation of soils. The interactions among these factors affect the capacity of a soil for self-regulation and productivity (Lal et al. 1989).

Factors of soil degradation are both natural and human-induced in nature. These factors enhance degradation, leading to changes in properties of soils and the attributes for their life support (Lal et al. 1989). Some selected pedogenic processes such as laterization, hard setting, fragipan formation and clay-pan formation are hitherto considered as natural soil degradation processes as they lead to less desirable physical and chemical conditions of soils (Lal et al. 1989; Hall et al. 1982). But the majority of the information on soil degradation at national (Sehgal and Abrol 1992, 1994), regional (FAO 1994) or international level (Oldeman 1988; UNEP 1992) has focused only on degradation due to anthropogenic activities. Amidst such generalized statement a few recent reports on major soil types (Indo-Gangetic Plains or IGP, red ferruginous and deep black soils) confirm the development of sodicity and accumulation of relatively higher amounts of exchangeable Mg (EMP) than that of exchangeable Ca (ECP) in soils are also a natural process of soil degradation in semi-arid tropical (SAT) climatic conditions (Balpande et al. 1996; Pal et al. 2000, 2001, 2003a, b, 2006, 2012a, 2016; Vaidya and Pal 2002; Chandran et al. 2013).

6.4 Natural Chemical Soil Degradation: Neotectonic-Climate Linked and Mineral Induced

During the Quaternary especially in the last post-glacial period, the soils at many sites worldwide witnessed climatic fluctuations in response to the global climatic event, and the climatic changes were of frequent nature (Ritter 1996). Tectonic slopes and or faults determine the courses of large rivers (Singh et al. 2006) and play a significant role in the evolution of geomorphology and soils (Srivastava et al. 2015). The formation of the Western Ghats due to crustal movements also caused the change in climate from humid to semi-arid (Brunner 1970). FAO's (1994) endeavor to record land degradation in south Asia, the potential effects of global climatic change to cause soil degradation were not considered. But it was envisaged that if adverse changes occur in some areas, then these processes will certainly constitute a most serious form of human-induced degradation of natural resources. During the late Holocene period climate change from the humid to semi-arid did occur in major parts of the Indian subcontinent (Pal et al. 2009a, b, 2012a, 2014; Srivastava et al. 2015). Therefore, it is expected that the current aridic environment prevailing in many parts of the world including India might impair the physical and chemical properties of soils that may lead to reduced productivity of soils. Apart from the adverse effect of arid and semi-arid climates on soils' properties, the impairment of soil physical properties in presence of magnesium rich palygorskite minerals has also been observed (Pal et al. 2012a; Pal 2013). Thus a new research initiative is warranted to identify the changes in soil properties in the SAT due to climate change and Mg-minerals. Research database thereof can help in expanding our basic knowledge in pedology and provide opportunity to develop relevant database (Pal et al. 2009a). Such a database could be of immense value while adapting sustainable soil management and long-range resource management strategies for many developing nations in the arid and semi-arid regions of the world, especially in the Indian subcontinent, where arid and semi-arid environments cover more than 50% of the total geographical area (Pal et al. 2000). Considerable account on soil degradation due to anthropogenic activities (Sehgal and Abrol 1992, 1994; FAO 1994; Oldeman 1988; UNEP 1992) is available, which however fails to relate to an important issue of the natural chemical soil degradation that is causing reduction in soil productivity. Presently a precise account of factors of natural chemical degradation in major soil types of India is available, which forms a robust research database (Pal et al. 2012b, 2014; Srivastava et al. 2015; Bhattacharyya et al. 2004) to expand the current knowledge on natural soil degradation and to protect the livelihood of humankind.

6.5 Chemical Soil Degradation: Regressive Pedogenic Processes in the SAT

The SAT soils are calcareous, in general and the soils with mean annual rainfall (MAR) <800 mm are also sodic either in the subsoil or throughout the depth of soil profile (Pal et al. 2000, 2006). But it is to be noted that all calcareous soils are not sodic, but all sodic soils are calcareous (Pal et al. 2000). Calcareousness of soils is due to the presence of both pedogenic and non-pedogenic $CaCO_3$, but the pedogenic formation of $CaCO_3$ is not a favourable chemical reaction for soil health because this creates unfavourable physical conditions, caused by concomitant development of exchangeable sodium percent (ESP) (Pal et al. 2000; Balpande et al. 1996; Bhattacharyya et al. 2004). The presence of pedogenic $CaCO_3$ (PC) that is distinguished from the pedorelict $CaCO_3$ (NPC) by the soil thin section studies (Pal et al. 2000), is very common in major soil types of India (alluvial soils of the Indo-Gangetic plains, ferruginous soils and shrink-swell soils) (Fig. 6.1a, b; please refer to Fig. 3.6b). Water loss through evapo-transpiration is considered the primary mechanism in the precipitation of PC in the SAT environments, while temperature controls the water flow in the soil (Pal et al. 2000). Despite having low MAR (<500 mm) the development of sodicity is not common in the desert soil profiles (within ~100 cm soil depth) due to their sandy textural class, ensuring better leaching of bicarbonates; and thus PC is generally observed at greater depth (Pal et al. 2000). However, in the loamy and clayey textured soils, the leaching of bicarbonates is slow and thus both PC and sodicity develop in upper horizons (Pal et al. 2000). Such pedogenetic processes are well exhibited in the SAT ferruginous soils (Alfisols) of southern India. These Alfisols developed in humid tropical climate of pre-Pliocene geological period, have restricted leaching because of ~30%

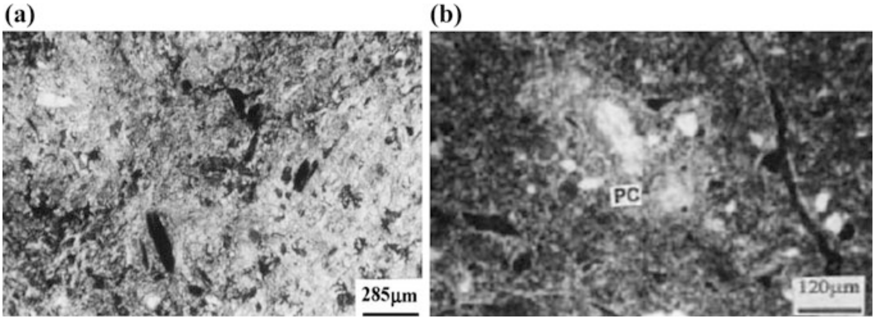

Fig. 6.1 Representative micromorphological features of pedogenic $CaCO_3$ (PC) in cross-polarized light **a** soils of the IGP (Natrustalfs), **b** Vertisols of central India (Adapted from Pal et al. 2009a)

clay, which are dominated by 2:1 expanding clay minerals. In these clayey and smectitic Alfisols, the formation of PC is observed due to the impact of the present day semi-arid climate, making these soils calcareous, unlike the ferruginous soils of humid tropical soils. The PCs in such soils with restricted leaching, are mainly concentrated as lubinites (please refer to Fig. 3.6b) that are formed only when the soil solution is supersaturated with $CaCO_3$ in the semi-arid environments (Wright 1988). This particular pedogenetic way of PC formation suggests that in addition to the climatic aridity, the texture has an important role in the accumulation of carbonates in soils (Wieder and Yaalon 1974).

The formation of PC in SAT soils as soil inorganic carbon (SIC) hitherto is considered an undesirable natural endowment because it impairs the soil productivity (Pal et al. 2000; Srivastava et al. 2002) and enhances the pH and also the relative abundance of Na^+ ions on soil exchange sites and in the solution. The Na^+ ions in turn cause dispersion of the fine clay particles. The dispersed fine clays translocate in major soil types of India (Pal et al. 2012a, 2014; Srivastava et al. 2015) as the formation of PC creates a Na^+—enriched chemical environment conducive for the deflocculation of clay particles and their subsequent movement downward. The formation of PC and the clay illuviation are thus two concurrent and contemporary pedogenetic events, resulting in increase in relative proportion of sodium, causing increased sodium adsorption ratio (SAR) and ESP and pH values with depth (please refer to Fig. 2.3; Fig. 6.2a, b). These pedogenetic processes represent a pedogenic threshold during the dry climates of the Holocene (Pal et al. 2012b, 2014, 2016; Srivastava et al. 2015), and clearly suggest that the formation of PC is a basic natural chemical degradation process (Pal et al. 2000, 2016), induced by tectonics-climate linked events (Pal et al. 2003b, 2009a, b), which exhibits the regressive pedogenesis (Pal et al. 2013, 2016); and it also immobilizes soil carbon (C) in unavailable form.

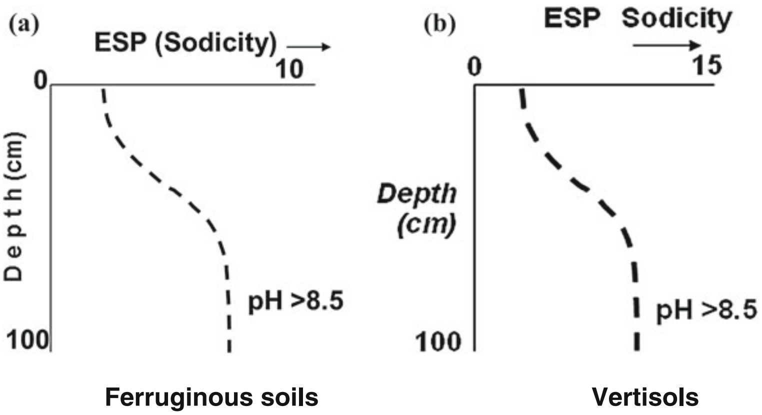

Fig. 6.2 Illuviation of Na-clay triggered by formation of PC, causing higher ESP and pH in the subsoils (Adapted from Pal et al. 2009a)

6.6 Clay Mineral (Palygorskite) Induced Natural Chemical Soil Degradation

Although the United States Salinity Laboratory (Richards 1954) grouped Ca^{2+} and Mg^{2+} ions together since both these ions improve the soil structure, Vertisols of dry climates of peninsular India have poor drainage due to clay dispersion caused by exchangeable magnesium (Vaidya and Pal 2002). Therefore, the saturation of Vertisols not only with Na^+ ions but also with Mg^{2+} ions blocks small pores in the soil (Pal et al. 2006). In other words, Mg^{2+} ions are less efficient than Ca^{2+} ions at flocculating soil colloids. The deflocculation of soil colloids is further enhanced even by low ESP (>5, <15), which reduces the saturated hydraulic conductivity (sHC) to <5 mm h^{-1}, causing a >50% reduction in cotton yield (Pal et al. 2012a, b). In presence or absence of soil modifiers, dispersion of clay colloids as deflocculated colloids and impairment of the sHC of Vertisols is generally an effect of ESP or exchangeable magnesium percent (EMP). In contrast, the sHC of zeolitic Vertisols of the Marathwada region of Maharashtra is reduced to < 10 mm h^{-1}, although the soils are non-sodic (Typic Haplusterts, Zade 2007), neutral to mildly alkaline pH, with ESP <5, and EMP increasing with depth. Interestingly, in some pedons, the EMP is greater than ECP at depths below 50 cm. These soils contain palygorskite mainly in the silt and clay fractions (Zade 2007). Palygorskite minerals are present in Typic Haplusterts and also in Sodic Haplusterts/Sodic Calciusterts in association with Typic Haplusterts in India (Zade 2007) and elsewhere (Heidari et al. 2008). Palygorskite is the most magnesium-rich of the common clay minerals (Singer 2002). Neaman et al. (1999) examined the influence of clay mineralogy on disaggregation in some palygorskite-, smectite-, and kaolinite-containing soils with ESP <5 of the Jordan and Betshe'an valley in Israel. This mineral is the most disaggregated of the clay minerals, and its fibre does not remain associated with or within aggregates in soils and suspensions even when the soils are saturated with Ca^{2+} ions. Thus the deflocculated clay size palygorskite particles move downward in the profile preferentially over smectite and eventually clog the soil pores (Neaman and Singer 2004). Therefore, Vertisols with palygorskite content with high EMP lead to the dispersion of the clay colloids that form a 3D mesh in the soil matrix. Clay dispersion induced by this mineral, ultimately causes drainage problems when such soils are irrigated, presenting a predicament for crop production. In view of their poor drainage conditions and loss of productivity, non-sodic Vertisols (Typic Haplusterts) with palygorskite minerals should be better considered as naturally-degraded soils. It is a unique situation but poorly drained soils caused by palygorskite also occur in other parts of the world, and therefore a new initiative to classify this group of soils is warranted (Pal et al. 2012a, 2016; Pal 2013).

6.7 Micro-topography: A Unique Factor of Natural Soil Degradation in SAT

The SAT soils that are calcareous have sodicity in the subsoil or throughout the soil profile. But the degree of sodicity varies in the soil scape. In the IGP and area representing ferruginous soils highly sodic soils are formed on the micro-low (ML), whereas non-sodic/less sodic soils are developed on the micro-high (MH) positions (Fig. 6.3a, b) (Pal et al. 2003b; Chandran et al. 2013). In contrast, sodic Vertisols (Sodic Haplusterts) are developed in MH and non-sodic/less sodic Vertisols (Typic Haplusterts) on ML positions (please refer to Fig. 2.5) (Vaidya and Pal 2002). This follows from this that the soils in a micro-topographical sequence have contrasting chemical characteristics. The soils at MH positions are less alkaline in the IGP and highly alkaline in SAT Vertisols areas, respectively. Pal et al. (2003b) explained the formation of sodic soils in the IGP and observed that the micro-lows are repeatedly flooded with surface water during brief high-intensity showers, and so the soils are subject to cycles of wetting and drying. This provides a steady supply of alkalis by hydrolysis of feldspars, leading to precipitation of calcium carbonate at high pH, and due to the illuviation of Na-clay sodicity develops in the subsoils. This initially impairs the hydraulic properties of the subsoils and eventually leads to the development of relatively high ESP in the subsoils. It follows then that the SAT climate and topography interact to facilitate greater penetration of bicarbonate-rich water in ML than in MH positions. The sHC of the soils at ML position is almost nil in the subsurface layers due to higher amount of clay smectite and ESP. The SAT climate of the area induced precipitation of carbonates which in turn has increased Na^{+} ion in the exchange complex (Pal et al. 2000). This chemical reaction is common in IGP, ferruginous and black soil regions of India wherein SAT climate induces the precipitation of calcium carbonates with a concomitant development of subsoil sodicity (Pal et al. 2000, 2003b, 2016; Balpande et al. 1996; Vaidya and Pal 2002; Chandran et al. 2013).

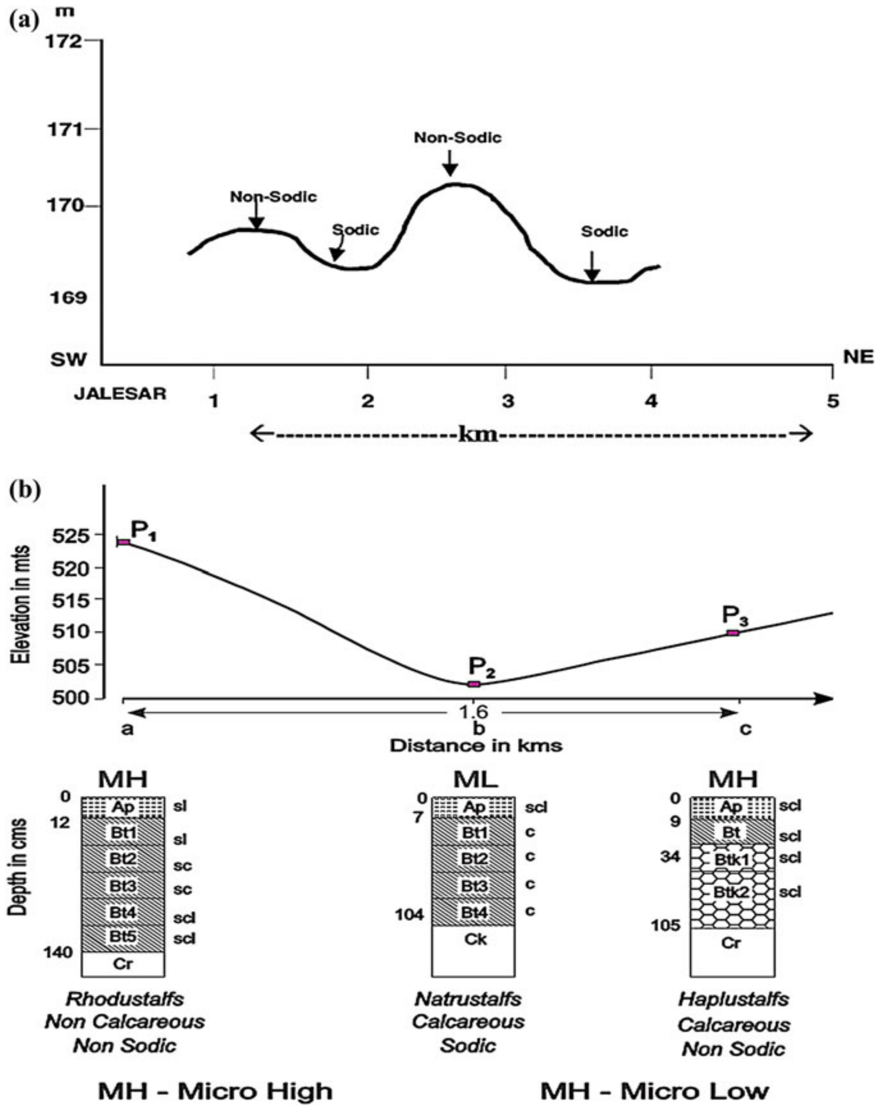

Fig. 6.3 **a** NE–SW profile in Ganga–Yamuna interfluve of the IGP showing non-sodic soils on MH and sodic soils on ML sites (Adapted from Pal et al. 2009a). **b** Schematic diagramme of the landscape representing the unique role of micro topography in the formation of non-sodic and sodic RF soils at MH and ML positions (Adapted from Chandran et al. 2013)

The formation of $CaCO_3$ enhances relatively more amount of Na^+ ions, which facilitates the illuviation of clay particles. Thus these two pedogenetic processes can be considered as the pedogenic processes occurring simultaneously as contemporary events in the drier climates in ML position. Similar micro-topographical situations in the formation of sodic and non-sodic soils on ML and MH positions respectively are observed in soils of the north-western parts of the IGP (Pal et al. 2003b) and also in ferruginous soils of southern India (Chandran et al. 2013). In contrast to this, in swell-shrink soils of central India a reverse situation was observed; sodic soils occur in MH and non-sodic soils as ML position. It is an example of unique situation in pedological parlance. It is observed that relatively higher amounts of PC and subsoil sodicity in MH Vertisols than in ML soils, suggesting that the formation of MH sodic soils is due to relatively more aridity on MH than the ML positions (Vaidya and Pal 2002). Thus the development of $CaCO_3$ and sodicity in the soils of ML and MH positions may be widespread in similar SAT areas of India. The rate of formation of PC for bench mark soils in Indian IGP, black (shrink-swell) soils and red ferruginous soils of SAT is estimated to be 129, 37.5 and 30 kg $CaCO_3$ ha^{-1} $year^{-1}$ respectively (Pal et al. 2000). At present the rate of formation of carbonates in ferruginous and black SAT soils is not alarming. But due care is needed while irrigating these soils especially those with clayey texture. In view of a high rate of $CaCO_3$ formation in the drier part (SAT) of the IGP soils, immediate remedial measures are required to make them resilient.

6.8 Indices of Soil Degradation

Research results indicate that the impairment of soil physical properties due to high ESP/EMP, and the presence of palygorskite mineral, as judged by reduced sHC, explains the cause-effect relation for the development of natural soil chemical degradation in SAT. In reality, such an explanation for the soil degradation remains elusive until it is related to crop performance and yield. Also, the critical limits of these indices have not been established. Sodicity tolerance ratings of crops in loamy-textured soils of the IGP indicated that a 50% reduction in relative yield of rice and wheat was observed when soil ESP was above 50 and ~40, respectively (Abrol and Fireman 1977). In shrink–swell soils (Vertisols), an optimum yield of cotton will be possible when soils are non-sodic ($ESP < 5$) and have $sHC > 20$ mm h^{-1}. About 50% reduction in yield occurs when soils are sodic ($ESP > 5$) showing low sHC (<10 mm h^{-1}). However, the Ca-rich zeolitic black soils (Sodic Haplusterts) of Rajasthan and Gujarat support rainfed crops fairly well (Pal et al. 2006, 2009c) due to favourable soil drainage ($sHC > 10$ mm h^{-1}). Therefore, fixing a lower limit of sodicity (Pal et al. 2006) at $ESP > 40$ for soils of the IGP (Abrol and Fireman 1977), at ESP >5 but <15 for Indian Vertisols (Balpande et al. 1996; Kadu et al. 2003), at ESP 6 for Australian soils or at ESP >15 for all soil types (Soil Survey Staff 1999) does not seem relevant for Vertisols (Pal et al. 2006). In view of the impairment of the hydraulic properties of soils in SAT a value of $sHC < 10$ mm h^{-1} (as weighted mean in 0–100 cm depth of soil) was advocated to define sodic soils instead of using an ESP or SAR (Pal et al. 2006). Hence, the deciding feature of soil classification must be the native vegetation because it indicates the nature of the land much more explicitly and authoritatively than any other arbitrary definition or nomenclature (Pal et al. 2000).

6.9 Rehabilitation of Degraded Soils

Research results obtained on the loss of Ca^{2+} ions from the soil system due to the formation of PC and concomitant development of sodicity indicate that SAT soils are prone to chemical degradation that creates strikingly different soil properties as compared to a normal soil. Therefore maintenance of required balance between exchangeable and water soluble Ca^{2+} ions in soil systems is of fundamental importance and thus poses a challenge for land resource managers to make these degraded soils resilient.

6.9.1 Difficulties in Identification and Reclamation of Sodic Soils

Sodic soils in the north-western (NW) parts of the IGP show salt-efflorescence in the surface as an evidence of soil sodicity, and this soil characteristic is mappable using remote sensing. Such maps for the shrink-swell soils (Vertisols and intergrades) are not available due to general lack of salt-efflorescence in the soil surface. Another difficulty remains in the identification of sodicity in shrink-swell soils as they do not qualify as salt-affected soils as per the United States Salinity Laboratory criteria even when these soils have poor hydraulic properties of (<10 mm h^{-1}) at an ESP > 5 but < 15. The Central Soil Salinity Research Institute (ICAR), Karnal developed reclamation technology, which advises the use of mined gypsum, followed by paddy as the first crop (Abrol and Fireman 1977). The success of this technology however depends upon on the proper identification of nature of sodicity in all major soil types and also on the quantum of subsidy received by land holders (offered by the different Govt. and non-Govt. organization) of such problem soils for the procurement of the raw gypsum.

6.9.2 An Alternative Management to Reclaim Sodic Soils

Non-zeolitic and non- gypsiferrous Vertisols (Sodic Haplusterts) in SAT show poor sHC (<10 mm h^{-1}) even at ESP $\geq 5 < 15$, and have poor crop productivity, and are impoverished in organic carbon (OC) but are rich in $CaCO_3$. In the long-term experiment such soils show enough resilience under improved management (IM) system of the ICRISAT (International Crops Research Institute for Semi-Arid Tropics) (Wani et al. 2003) that does not include any amendment like gypsum and FYM. Soil productivity is enhanced and the average grain yield of the IM system over thirty years was five times more than that in the traditional management (TM) system. Adaptation of the IM system improved physical, chemical and biological properties of soils to the extent that a poorly drained black soil (Sodic

Haplusterts) can now qualify for well-drained soil (Typic Haplusterts). A continuous release of higher amount of Ca^{2+} ions during the dissolution of $CaCO_3$ (8.4 mg/100 g soil/year in 1 m deep profile) under the IM system, compared to slower rate of formation of $CaCO_3$ (0.10 mg/100 g soil/year in 1 m profile), provide enough soluble Ca^{2+} ions to replace unfavourable Na^+ ions on the soil exchange sites. Higher exchangeable Ca/Mg ratio in soils under IM system improved the sHC for better storage and release of soil water during dry spell between rains. Adequate supply of soil water helped in better crop productivity and also in higher OC sequestration. Such remarkable improvement in Vertisols' sustainability suggests that the IM system can mitigate the adverse effect of climate change (Pal et al. 2012b, c). The IM management protocol though very slow as compared to gypsum-aided one, is however a cost-effective and farmer–friendly. This technology is recommendable for a large scale impact on agricultural productivity (Wani et al. 2007). The above research results open up an interesting area of soil research that is to realize the benefit of the presence of $CaCO_3$ as a hidden treasure during the reclamation of sodic soils even with the addition of gypsum as practised in NW part of the IGP (Pal et al. 2009a, 2016). This has been detailed through C transfer mode (Bhattacharyya et al. 2004) which was reported to work better in the drier part of the IGP (Pal et al. 2009a).

6.9.3 Linking Calcium Carbonates to Resilience of the IGP Sodic Soils

Sodic soils (Natrustalfs) after following the reclamation protocol, show improvements in their morphological, physical and chemical properties so much that these soils can now reclassified as well-drained and OC-rich normal Alfisols (Haplustalfs). At present gypsum as amendment is added in relatively less amount than estimated by 'Gypsum Requirement' of highly sodic soils with ESP ~90–100 (Natrustalfs). But even with the low amount of added gypsum, sodic soils are reclaimed to show their resilience. Thus the success of this reclamation protocol cannot be fully credited to gypsum added because it does not enrich soil solution by the required amount of Ca^{2+} ions to replace Na ions on the soil exchange sites. Therefore, the Ca requirement to replace all exchangeable Na^+ ions is aided by Ca^{2+} ions available through the rapid dissolution of the native pedogenic $CaCO_3$ (PC) during the growing of the rice crop under submerged conditions. The rate of dissolution of PC during 30 months' cultural practice with gypsum in Natrustalfs is estimated to be 254 mg/100 g soil in the top 1 m of the profile. This indicates a much higher rate of dissolution (~100 mg/100 g soil/year) (Pal et al. 2009a) than its rate of formation (0.86 mg/100 g soil/year) in the top 1 m soil depth (Pal et al. 2000). It is worth mentioning here that the current theories favouring blue-green algae as a biological amendment to bring about sodic soil reclamation are untenable because of its inability to mobilize Ca from native $CaCO_3$ and thus are not comparable with an effective chemical amendment such as gypsum (Rao and Burns 1991).

6.9.4 Calcium Carbonates as Soil Modifier in Ensuring Soil Sustainability of SAT Soils

After becoming non-sodic in nature through cultural practices, both IGP soils (Haplustalfs) and Vertisols (Haplusterts) still remained with substantial stock of $CaCO_3$ (SIC) in the first 1.5 m depth, which has potential to improve the drainage, establishment of vegetation, and also sequestration of OC in soils (Pal et al. 2012c). The continuance of agronomic practices of the NARS (National Agricultural Research Systems) and ICRISAT can provide the most important Ca^{2+} ions both in solution and exchange sites of soil. These resilient soils still contain nearly 2–7% $CaCO_3$. In view of the rate of its dissolution ($\sim$100 mg/100 g soil/year for IGP soils, and 21 mg/100 g soil/year for Vertisols, Pal et al. 2012a, c), it is envisaged that under improved management in the SAT environment, total dissolution of $CaCO_3$ would take a time of couple of centuries. Such chemical environment enriched with Ca^{2+} ions would not allow both Haplustalfs and Haplusterts to transform to any other soil order so long $CaCO_3$ would continue to act as a soil modifier (Pal et al. 2012a). Positive role of $CaCO_3$ in both reclamation and sequestration of OC in SAT soils may benefit maintaining the soil health of the farmlands if additional financial support through national and international initiatives including the incentives or transferable C credits under CDM is made available (Pal et al. 2015, 2016) to stake holders of sodic soils.

6.10 Nature and Extent of Degradation in RF Soils: A Critique

Water erosion is the most widespread form of soil degradation in the Indian sub-continent. It is estimated that the erosion affects $\sim$73.3 m ha area spreading in all agro-climatic zones. The extent and severity of soil degradation are related to the intensity of the rainfall, slope of the land, and the types of soil and land use. Soils under HT climate of NEH and southern peninsular areas are most affected by water erosion, and the highest area under this category of degradation is in Nagaland (87%), followed by Meghalaya (78%), Arunachal Pradesh (73%), Assam (66%), Manipur (53%), Tripura (38%), Sikkim (37%) and Kerala (15%) (ICAR-NAAS 2010).

It is worth mentioning here that the above estimates were based on an assumption that soil erosion <10 t ha^{-1} year^{-1} (using the empirical Universal Soil Loss Equation, USLE to estimate spatial variations of soil loss factors like R, K, L, S, C and P factors) generally does not significantly affect soil productivity; and the soils with loss <10 t ha^{-1} year^{-1} were not considered degraded (ICAR-NAAS 2010). Such assumption on soil loss appears to be far from real situation in soils under HT climate, because of the dominance of Ultisols, Alfisols, Mollisols, and Inceptisols with clay enriched B horizons in NEH areas, Kerala, Goa, Maharashtra, Madhya Pradesh, Karnataka and Andaman and Nicobar Islands (please refer to Table 3.1). In the event of such amount of soil loss persistence of these soil orders with clay enriched B horizons would not have been a reality. Moreover, formation and persistence of such soil orders are possible when landscape attains the stability.

The major pedogenetic processes that are operative to give rise to these soil orders, are evident through the addition of C by litter falls and its accumulation as soil organic matter under adequate vegetation and climate, translocation of clay particles (to form clay enriched B horizons) and transformation of 1.4 minerals to kaolin (detailed in Chap. 3). The rate of soil formation varies from <0.25 mm year^{-1} in dry and cold environments to >1.5 mm year^{-1} in humid and warm environments (Kassam et al. 1992).

If the rate of soil formation is taken as 2.0 mm year^{-1} for soils of HT climate, the amount of top soil formation would be around 29 t ha^{-1} year^{-1} (as shown for soils of Tripura in NEH, Bhattacharyya et al. 2007). This gain in soil clearly suggests that the rate of soil loss by water erosion from Ultisols, Alfisols, Mollisols and Inceptisols is minimal (Bhattacharyya et al. 2007). The pedogenetic processes in soils of HT climate ensures the positive balance of soil formation, and thus mature soils (like Ultisols, Alfisols, Mollisols and clay enriched Inceptisols) on a stable landscape under HT climate is a reality. In contrast, in RF soils (mainly Entisols) on higher slopes (ridges, scarps and terraces) under low vegetation with only shrubs and bushes, soil development is greatly hampered by the severe soil loss due to water erosion. Soil loss is also evident in other soils that have less vegetative cover. Besides proper mechanical conservation measures, such soils areas may be suitable for forestry, horticultural and plantation crops to build resilience in them (Bhattacharyya et al. 1998, 2007).

As per report of ICAR-NAAS (2010), the RF soils of Indian states under SAT environments also suffer soil loss due to erosion, and the loss is maximum in Karnataka (49%) followed by Andhra Pradesh (40%) and Tamil Nadu (20%), considering soil loss >10 t ha^{-1} year^{-1} as the threshold for soil degradation. It is to be noted that the RF soils of SAT dominantly belong to Alfisols, and the other soil orders are Inceptisols, Entisols and Mollisols (please refer to Table 3.1). If the rate of soil formation in dry environments is considered at <0.25 mm year^{-1} (Kassam et al. 1992), SAT Alfisols would gain soil at least 3.67 t ha^{-1} year^{-1}. This value is close to soil loss as evident from the results of short-term hydrological studies on small agricultural watershed on Alfisols at the ICRISAT Center, Patancheru, India, which indicate an average soil loss from SAT Alfisols under traditional system is around 3.84 t ha^{-1} year^{-1} (Pathak et al. 1987). On the other hand, the results from long-term study reported an annual soil loss of 4.62 t ha^{-1} (Pathak et al. 2013). Soil loss from both the ICRISAT experiments is much less than the soil loss value assumed by ICAR-NAAS (2010).

The higher soil loss on the SAT Alfisols under traditional management was attributed to crusting, sealing and low structural stability (Pathak et al. 1987, 2013). But many SAT Alfisols have clay enriched B horizons with substantial amount of smectite clay mineral in the subsoils (please refer to Fig. 3.2b) (Pal et al. 1989; Chandran et al. 2009), which causes moderate shrink-swell properties (coefficient of linear extensibility, COLE >0.06, Pal et al. 2014). Additionally, these Alfisols have reduced saturated hydraulic conductivity in the subsoils (Pathak et al. 2013). Such physical and mineralogical characteristics in the subsoil restrict vertical movement of water in the soil profile, resulting in greater soil loss from the SAT Alfisols through overland lateral flow of water. Vertical movement of water will be further restricted in SAT Alfisols that have subsoil sodicity due to the formation of pedogenic $CaCO_3$ (Pal et al. 2013).

In order to reduce unwarranted soil loss and also to improve the sustainability of the SAT Alfisols, improved system of management developed by the ICRISAT (Pathak et al. 1987) may help. ICRISAT's improved system (improved water management, land development and soil conservation practices combined with appropriate cropping systems, Pathak et al. 1987) minimized soil loss to nearly 1 t ha^{-1} $year^{-1}$ and simultaneously increased crop productivity compared to traditional system. These research results aptly suggest that a threshold value of soil loss by water erosion as a sign of degradation, must be based on experimental results rather than assuming an arbitrary value of >10 t ha^{-1} $year^{-1}$ (ICAR-NAAS 2010).

Development of acidity in soils is indeed a sign of chemical degradation. Acid soils develop under HT climatic environment with a loss of soil fertility. While estimating the area degraded by acidity, soils with strong ($pH < 4.5$) and moderate acidity (pH 4.5–5.5) only were considered. With this assumption, about 6.98 m ha area is affected by soil acidity, which is about 9.4% of the total geographical area of the country (ICAR-NAAS 2010). Soils of HT climate in the states of Kerala, Goa, Karnataka, Tamil Nadu, Maharashtra and NEH areas are strong to moderately acidic Alfisols, Ultisols and Mollisols (please refer to Table 3.2); and their further weathering in HT climate would finally close at Ultisols with considerable amount of layer silicate minerals (Pal et al. 2012a, 2014). Such OC rich acid soils do respond to management interventions and support luxuriant forest vegetation, horticultural, cereal crops, tea, coffee and spices (Sehgal 1998). In view of such reality, it would not be prudent to class them as chemically degraded soils.

It is to be noted that at present the extent of degradation (soil loss and soil acidity) of RF soils (especially Ultisols, Alfisols, Mollisols and Inceptisols with clay enriched B horizons) is not at an alarming stage, which is in contrast to what so far has been projected by assuming arbitrary values for soil loss. But they require improved management (IM) practices developed by researchers to upgrade and maintain their nutrient status and make efficient use of soil water to sustain crop productivity at an enhanced level. The IM system package available includes improved seeds, NPK fertilizers, micronutrients, FYM and use of gypsum (for sodic soils), use of legumes in the cropping sequence (Wani et al. 2003), lime (Datta 2013), and improved water management, land development and the implementation of the soil conservation practices for acidic Alfisols, Ultisols and Inceptisols (Datta 2013) and SAT Alfisols (Pathak et al. 1987, 2009, 2013).

References

Abrol IP (1982a) Reclamation of waste lands and world food prospects. In: Whither soil research, panel discussion papers, 12th International Congress Soil Science, New Delhi, pp 317–337

Abrol IP (1982b) Reclamation and management of salt-affected soils. In: Review of soil research in India. Part 11, 12th International Congress Soil Science, New Delhi, pp 635–654

Abrol IP, Fireman M (1977) Alkali and Saline soils; identification and improvement for crop production. Bulletin No. 4. Central Soil Salinity Research Institute, Karnal, India

Balpande SS, Deshpande SB, Pal DK (1996) Factors and processes of soil degradation in Vertisols of the Purna valley, Maharashtra, India. Land Degrad Dev 7:313–324

Bhattacharyya T, Mukhopadhyay S, Baruah U, Chamuah GS (1998) Need for soil study to determine degradation and landscape stability. Curr Sci 74:42–47

Bhattacharyya T, Pal DK, Chandran P, Mandal C, Ray SK, Gupta RK, Gajbhiye KS (2004) Managing Soil carbon stocks in the Indo-Gangetic Plains, India, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi—110 012, India, p 44

Bhattacharyya T, Babu R, Sarkar D, Mandal C, Dhyani BL, Nagar AP (2007) Soil loss and crop productivity model in humid tropical India. Curr Sci 93:1397–1403

Brunner H (1970) Pleisitozane klimaschwankengen im Bereich den ostlichen Mysore-Plateaus (Sudindien). Geologie 19:72–82

Chandran P, Ray SK, Durge SL, Raja P, Nimkar AM, Bhattacharyya T, Pal DK (2009) Scope of horticultural land-use system in enhancing carbon sequestration in ferruginous soils of the semi-arid tropics. Curr Sci 97:1039–1046

Chandran P, Ray SK, Bhattacharyya T, Tiwari P, Sarkar D, Pal DK, Mandal C, Nimkar A, Maurya UK, Anantwar SG, Karthikeyan K, Dongare VT (2013) Calcareousness and subsoil sodicity in ferruginous Alfisols of southern India: an evidence of climate shift. Clay Res 32:114–126

Datta M (2013) Soils of north-eastern region and their management for rain-fed crops. In: Bhattacharyya T, Pal DK, Sarkar D, Wani SP (eds) Climate change and agriculture. Studium Press, New Delhi, pp 19–50

FAO (Food and Agriculture Organization of the United Nations) (1994) Land degradation in South Asia: its severity, causes and effects upon the people. World Soil Resources Reports 78, FAO, Rome, Italy

Hall GF, Daniels RB, Foss JE (1982) Rates of soil formation and renewal in the USA. In: Schmidt BL (ed) Determinants of soil loss tolerance. ASA Publication No. 45. American Society of Agronomy, Madison, Wisconsin, USA, pp 23–29

Heidari A, Mahmoodi Sh, Roozitalab MH, Mermut AR (2008) Diversity of clay minerals in the Vertisols of three different climatic regions in western Iran. J Agric Sci Technol 10:269–284

ICAR-NAAS (Indian Council of Agricultural Research- National Academy of Agricultural Sciences) (2010) Degraded and waste lands of India—status and spatial distribution. ICAR-NAAS. Published by the Indian Council of Agricultural Research, New Delhi, 56 pp

Kadu PR, Vaidya PH, Balpande SS, Satyavathi PLA, Pal DK (2003) Use of hydraulic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semi-arid parts of central India. Soil Use Manage 19:208–216

Kassam AH, van Velthuizen GW, Fischer GW, Shah MM (1992) Agro-ecological land resource assessment for agricultural development planning: a case study of Kenya resources data base and land productivity. Land and Water Development Division, Food and Agriculture Organisation of the United Nations and International Institute for Applied System Analysis, Rome

Lal R, Hall GF, Miller FP (1989) Soil degradation. I. Basic processes. Land Degrad Rehabil 1:51–69

Neaman A, Singer A (2004) The effects of palygorskite on chemical and physico–chemical properties of soils: a review. Geoderma 123:297–303

Neaman A, Singer A, Stahr K (1999) Clay mineralogy as affecting disaggregation in some palygorskite-containing soils of the Jordan and Bet-She'an Valleys. Aust J Soil Res 37:913–928

Oldeman LR (ed) (1988) Global assessment of soil degradation (GLASOD). Guidelines for general assessment of status of human-induced soil degradation. ISRIC, Wageningen, the Netherlands

Pal DK (2013) Soil modifiers: their advantages and challenges. Clay Res 32:91–101

Pal DK, Deshpande SB, Venugopal KR, Kalbande AR (1989) Formation of di and trioctahedral smectite as an evidence for paleoclimatic changes in southern and central Peninsular India. Geoderma 45:175–184

Pal DK, Dasog GS, Vadivelu S, Ahuja RL, Bhattacharyya T (2000) Secondary calcium carbonate in soils of arid and semi-arid regions of India. In: Lal R et al (eds) Global climate change and pedogenic carbonates. Lewis Publishers, FL, USA, pp 149–185

Pal DK, Balpande SS, Srivastava P (2001) Polygenetic vertisols of the Purna Valley of central India. Catena 43:231–249

Pal DK, Srivastava P, Bhattacharyya T (2003a) Clay illuviation in calcareous soils of the semi-arid part of the Indo-Gangetic Plains, India. Geoderma 115:177–192

Pal DK, Srivastava P, Durge SL, Bhattacharyya T (2003b) Role of micro topography in the formation of sodic soils in the semi-arid part of the Indo-Gangetic Plains, India. Catena 51:3–31

Pal DK, Bhattacharyya T, Ray SK, Chandran P, Srivastava P, Durge SL, Bhuse SR (2006) Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded vertisols of the Peninsular India in redefining the sodic soils. Geoderma 136:210–228

Pal DK, Bhattacharyya T, Chandran P, Ray SK (2009a) Tectonics-climate linked natural soil degradation and its impact in rainfed agriculture: Indian experience. In: Wani SP et al (eds) Rainfed agriculture: unlocking the potential. CAB International Publishing, Oxfordshire, pp 54–72

Pal DK, Mandal DK, Bhattacharyya T, Mandal C, Sarkar D (2009b) Revisiting the agro-ecological zones for crop evaluation. Indian J Genet 69:315–318

Pal DK, Bhattacharyya T, Chandran P, Ray SK, Satyavathi PLA, Durge SL, Raja P, Maurya UK (2009c) Vertisols (cracking clay soils) in a climosequence of Peninsular India: evidence for holocene climate changes. Quatern Int 209:6–21

Pal DK, Wani SP, Sahrawat KL (2012a) Vertisols of tropical Indian environments: pedology and edaphology. Geoderma 189–190:28–49

Pal DK, Bhattacharyya T, Wani SP (2012b) Formation and management of cracking clay soils (vertisols) to enhance crop productivity: Indian experience. In: Lal R, Stewart BA (eds) World soil resources. Francis and Taylor, pp 317–343

Pal DK, Wani SP, Sahrawat KL (2012c) Role of calcium carbonate minerals in improving sustainability of degraded cracking clay soils (Sodic Haplusterts) by improved management: an appraisal of results from the semi-arid zones of India. Clay Res 31:94–108

Pal DK, Sarkar D, Bhattacharyya T, Datta SC, Chandran P, Ray SK (2013) Impact of climate change in soils of semi-arid tropics (SAT). In: Bhattacharyya et al (ed) Climate change and agriculture. Studium Press, New Delhi, pp 113–121

Pal DK, Wani SP, Sahrawat KL, Srivastava P (2014) Red ferruginous soils of tropical Indian environments: a review of the pedogenic processes and its implications for edaphology. Catena 121:260–278. doi:10.1016/j.catena2014.05.023

Pal DK, Wani SP, Sahrawat KL (2015) Carbon sequestration in Indian soils: present status and the potential. Proc Natl Acad Sci Biol Sci (NASB) India, 85:337–358. doi:10.1007/s40011-014-0351-6

Pal DK, Bhattacharyya T, Sahrawat KL, Wani SP (2016) Natural chemical degradation of soils in the Indian semi-arid tropics and remedial measures. Curr Sci 110:1675–1682

Pathak P, Singh S, Sudi R (1987) Soil and water management alternatives for increased productivity on SAT Alfisols. Soil conservation and productivity. In: Proceedings IV international conference on soil conservation, Maracay-Venezuela, 3–9 Nov 3–9 1985, pp 533–550

Pathak P, Sahrawat KL, Wani SP, Sachan RC, Sudi R (2009) Opportunities for water harvesting and supplemental irrigation for improving rainfed agriculture in semiarid areas. In: Wani SP, Rockström J, Oweis T (eds) Rainfed agriculture: unlocking the potential. CABI International, Oxfordshire, pp 197–221

Pathak P, Sudi R, Wani SP, Sahrawat KL (2013) Hydrological behaviour of Alfisols and Vertisols in the semi-arid zone: implications for soil and water management. Agric Water Manage 118:12–21

Rao DLN, Burns RG (1991) The influence of blue-green algae on the biological amelioration of alkali soils. Biol Fertil Soils 11:306–312

Richards LA (ed) (1954) Diagnosis and improvement of saline and alkali soils. USDA Agriculture Handbook 60. USDA, Washington, DC, USA

Ritter DF (1996) Is quaternary geology ready for the future? Geomorphology 16:273–276

Sehgal JL (1998) Red and lateritic soils: an overview. In: Sehgal J, Blum WE, Gajbhiye KS (eds) Red and lateritic soils. Managing red and lateritic soils for sustainable agriculture 1. Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi, pp 3–10

Sehgal JL, Abrol IP (1992) Land degradation status: India. Desertification Control Bull 21:24–31

Sehgal JL, Abrol IP (1994) Soil degradation in India: status and impact. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi

Singh S, Parkash B, Rao MS, Arora M, Bhosle B (2006) Geomorphology, pedology and sedimentology of the Deoha/Ganga-Ghaghara Interfluve, Upper Gangetic Plains (Himalayan Foreland Basin)—extensional tectonic implications. Catena 67:183–203

Singer A (2002) Palygorskite and sepiolite. In: Dixon JB, Schulze DG (eds) Soil mineralogy with environmental applications, SSSA Book Series, vol 7., Soil science society of AmericaMadison, WI, pp 555–583

Soil Survey Staff (1975) Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. United States Department of Agriculture Handbook No. 436. U.S. Government Printing Office, Washington, DC

Soil Survey Staff (1999) Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. United States Department of Agriculture, Natural Resource Conservation Service, Agriculture Handbook No. 436, U.S. Government Printing Office, Washington, DC

Srivastava P, Bhattacharyya T, Pal DK (2002) Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (Vertisols) of India. Clays Clay Miner 50:111–126

Srivastava P, Pal DK, Aruche KM, Wani SP, Sahrawat KL (2015) Soils of the Indo-Gangetic plains: a pedogenic response to landscape stability, climatic variability and anthropogenic activity during the holocene. Earth Sci Rev 140:54–71. doi:10.1016/j.earscirev.2014.10.010

UNEP (1992) World atlas of desertification. Edward Arnold, London

Vaidya PH, Pal DK (2002) Micro topography as a factor in the degradation of vertisols in central India. Land Degrad Dev 13:429–445

Wani SP, Pathak P, Jangawad LS, Eswaran H, Singh P (2003) Improved management of vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. Soil Use Manag 19:217–222

Wani SP, Sahrawat KL, Sreedevi TK, Bhattacharyya T, Srinivas Rao Ch (2007) Carbon sequestration in the semi-arid tropics for improving livelihoods. Int J Environ Stud 64:719–727

Wieder M, Yaalon DH (1974) Effect of matrix composition on carbonate nodule crystallization. Geoderma 43:95–121

Wright VP (1988) Pleokarsts and paleosols as indicators of paleoclimate and porosity evolution: a case study from the carboniferous of South Wales. In: James NP, Choquette PW (eds) Springer, New York, pp 329–341

Zade SP (2007) Pedogenic studies of some deep shrink-swell soils of Marathwada region of Maharashtra to develop a viable land use plan. Ph.D Thesis, Dr. P D K V, Akola, Maharashtra, India