4 Tectonics–Climate-linked Natural Soil Degradation and its Impact in Rainfed Agriculture: Indian Experience

D.K. Pal,* T. Bhattacharyya, P. Chandran and S.K. Ray**
Division of Soil Resource Studies, National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Amravati Road, Nagpur 440 010, India;
*emails: *dkpal@nbsslup.ernet.in; **tapas11156@yahoo.com*

Introduction

Soil is the most basic of all resources and the primary substrate for growing crops. It is also non-renewable over the human timescale. This basic fact made all scientists, agriculturists, environmentalists and policy makers anxious about whether soil resources will remain capable to feed, clothe and shelter the expected 8.2 billion inhabitants of the world by the year 2030 (www.unpopulation.org). The available land resources are gradually diminishing because, on a global scale, land resources and population are unevenly distributed. Soils, being most dynamic, are able to supply nutrients, buffer acid and base reactions, destroy and absorb pathogens, detoxify and attenuate xenobiotic and inorganic compounds and have the capacity for self-restoration through soil formation. However, soil formation is a slow process, and a substantial amount of soil can form only over a geologic timescale. Soil misuses and extremes of condition can upset these self-regulating attributes and cause a soil to regress from a higher to a lower type of usefulness and/or drastically diminish its productivity (Lal *et al.*, 1989). This unfavourable endowment of soils has been termed 'soil degradation'.

Definition, Processes and Factors of Soil Degradation

Definition

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 man-induced causes.' However, such an explanation remains undefined since it is not related to a quantitative value of crop yield beyond which soils can be considered as degraded. Sodicity tolerance ratings of crops in loamy-textured soils of the Indo-Gangetic Plains (IGP) indicated that a 50% reduction in relative yield was observed when exchangeable sodium percentage (ESP) in soils was above 50 for rice and around 40 for wheat (Abrol and Fireman, 1977). In shrink–swell soils (vertisols), an optimum yield of cotton can be obtained when soils are non-sodic (ESP <5) and have saturated hydraulic conductivity (sHC) ≥20 mm/h. About 50% reduction in yield occurs when soils are sodic (ESP >5) and exhibit sHC <10 mm/h. However, the Ca-zeolitic sodic haplusterts of Rajasthan and Gujarat states of India do support rainfed crops fairly well (Pal *et al.*, 2006a) because of their favourable sHC

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

(>10 mm/h). Therefore, fixing a lower limit of sodicity (Pal *et al.*, 2006a) at ESP >40 for soils of the IGP (Abrol and Fireman, 1977), at ESP >5 but <15 for Indian vertisols (Kadu *et al.*, 2003), at ESP 6 for Australian soils or at ESP >15 for all soil types (Soil Survey Staff, 1999) appears to be irrelevant to the performance of crops in highly sodic vertisols with soil modifiers, especially Ca-zeolites (Pal *et al.*, 2006a). In view of the pedogenetic processes that ultimately impair the hydraulic properties of soils of dry climates mediated through dispersibility, the most important factor of soil degradation, Pal *et al.* (2006a) advocated a value of sHC <10 mm/h (as weighted mean in 0–100 cm depth of soil) to define sodic soils instead of any ESP.

Processes

Processes that lead to soil degradation include 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 (Lal *et al.*, 1989). Processes of soil degradation have been identified as chemical, physical and biological actions and interactions that would affect the capacity of a soil for self-regulation and its productivity.

Factors

Factors causing soil degradation are both natural and man-induced agents and catalysts that induce the processes leading to changes in properties of soils and the attributes for their life support (Lal *et al.*, 1989). Although some pedogenic processes, such as laterization, hardsetting, fragipan formation and clay-pan formation, are hitherto considered as natural soil degradation processes as they lead to less-desirable physical and chemical conditions, causing degradation of soils (Hall *et al.*, 1982; Lal *et al.*, 1989), the majority of the information on soil degradation, whether at national (Sehgal and Abrol, 1992, 1994), regional (FAO, 1994) or international level (Oldeman, 1988; UNEP, 1992), centres around only human-induced degradation. However, a few recent studies in the Indian subcontinent at the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India showed that the development of sodicity is also a natural process of soil degradation in arid and semi-arid climatic conditions (Balpande *et al.*, 1996; Pal *et al.*, 2000, 2001, 2003a,b,c, 2006a; Vaidya and Pal, 2002).

Climate, Neotectonic and Soil Degradation

In response to the global climatic event during the Quaternary, the soils of many places of the world witnessed climatic fluctuations, especially in the last post-glacial period. Frequent climatic changes occurred during the Quaternary (Ritter, 1996). Tectonic slopes/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.*, 1994; Kumar *et al.*, 1996; Singh *et al.*, 1998; Pal *et al.*, 2003c, 2006b). Crustal movements also caused the change in climate from humid to semi-arid, as experienced with the formation of the Western Ghats (Brunner, 1970). In the FAO's (1994) endeavour to record land degradation in South Asia, the potential effects of global climatic change to cause degradation in soils were not considered. It was, however, envisaged that if adverse changes occur in some areas, then these will certainly constitute a most serious form of human-induced degradation of natural resources. It is quite likely, however, that 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 environments that may reduce the productivity of soils. Thus a new research initiative to follow the changes in soil properties by identifying the 'pedogenic threshold' due to tectonic-induced climate change can help us in expanding our basic knowledge in pedology and also in creating a relevant database. Such a database, although not sufficient, could be of high importance in any attempt to adapt sustainable soil management and long-range resource management strategies for many developing nations belonging to the arid and semi-arid parts of the world.

Maintenance of the agricultural productivity in arid and semi-arid lands of the world would ever remain a great challenge, including in the Indian subcontinent, where arid and semi-arid environments cover more than 50% of the total geographical area (Pal *et al.*, 2000). There is no dearth of literature on soil degradation due to anthropogenic activities (Oldeman, 1988; Sehgal and Abrol, 1992, 1994; UNEP, 1992; FAO, 1994). This chapter, however, presents a few case studies to indicate the severe consequences of the natural degradation triggered by tectonic and climatic events. Such information will expand the present knowledge on soil degradation, which is necessary to protect the livelihood of humankind.

Natural Soil Degradation in Major Soil Types of India

Degradation in ferruginous soils

Ferruginous soils are tropical soils. They occur in the geographic tropics, i.e. in that region of the earth lying between the Tropic of Cancer and the Tropic of Capricorn. The tropics comprise approximately 40% of the land surface of the earth. Thus more than one-third of the soils of the world are tropical soils (Eswaran *et al.*, 1992). Ferruginous soils are the group of soils variously termed as 'red', 'brown', 'yellow', 'laterite', 'lateritic', 'ferralitic' and 'latosols', because they lack precise definition (Rengasamy *et al.*, 1978), and in India, these soils occupy about 70 million ha, covering about 21% of the total geographical area (Sehgal, 1998).

The present-day climate is too dry to have caused the iron accumulation in ferruginous soils of peninsular India. The laterization process must have taken place during the earlier humid tropical climate. Brunner (1970) reported evidence for tectonic movements during the Pliocene–Pleistocene transition which caused the formation of different relief types and relief generation. With the formation of the Western Ghats during the Plio-Pleistocene crustral movements, the humid climate of the Miocene–Pliocene was replaced by the semi-arid conditions which continue to prevail to date in the area. The Arabian Sea currently confronts the Western Ghats, which rise precipitously across to an average height of 1200 m. The result is an orographic rainfall, being heavy all along the west coast. The lee-side towards the east receives less than 1000 mm rainfall and is typically rain-shadowed (Rajaguru and Korisettar, 1987). Occurrence of numerous ferruginous soils capping the detached plateau at an average elevation of about 1100 m above mean sea level with an annual rainfall of more than 5000 mm (Anonymous, 1984) along the Western Ghats suggests that an extensive peneplained surface with a general southerly slope and moderate relief existed earlier in this area (Sahasrabudhe and Deshmukh, 1981). In some parts of southern India, laterite mounds and laterite plateau remnants are scattered over the landscape (Rengasamy *et al.*, 1978; Subramanian and Mani, 1981). In central India, thin to thick (0.25–3 m) laterite cappings cover various rock types, ranging in the age from Archean to Gondwanas (Pascoe, 1965; Sahasrabudhe and Deshmukh, 1981; Subramanian and Mani, 1981). Extensive, massive granitic tors in gneissic terrain bear the evidence of exhumation (Pal *et al.*, 1989) during an arid period following prolonged deep weathering in the humid tropical climate that prevailed from the Upper Cretaceous (Subramanian and Mani, 1981) until the Plio-Pleistocene. The Plio-Pleistocene was a transition period when the climate became drier with the rising of the Western Ghats (Brunner, 1970). As a result, the upper layers of the ferruginous soils (alfisols) formed in the preceding tropical humid climate were truncated by multiple arid erosional cycles (Rengasamy *et al.*, 1978; Chandran *et al.*, 2000; Srivastava *et al.*, 2001). Due to truncation of the upper layers of the alfisols, the clay contents presently show an upward increase from the C to the B horizons (Fig. 4.1a). The clay fractions are dominated by both kaolin and smectite (Pal *et al.*, 1989; Chandran *et al.*, 2000; Srivastava *et al.*, 2001) and bear the evidence of transformation of smectite to kaolin (Pal *et al.*, 1989). The present-day warm semi-arid climatic conditions are not considered severe enough for transformation of smectite to kaolin, and the neutral to alkaline reaction of these soils does not favour the transformation of 2:1 layer minerals to kaolin but favours the formation of pedogenic $CaCO_3$ (PC) (Fig. 4.1b). The adverse aridic climatic conditions induce the precipitation of $CaCO_3$, thereby depriving the soils of Ca^{2+} ions in exchange complex, with a con-

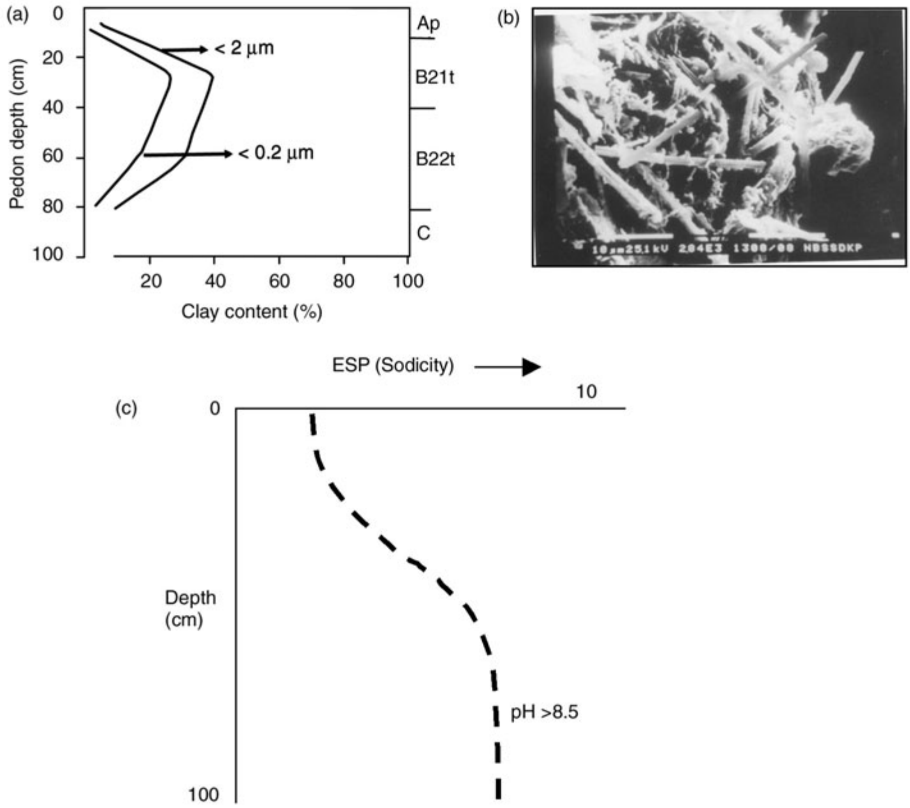

Fig. 4.1. (a) Clay distribution with pedon depth of representative ferruginous soils; (b) lubinites (pedogenic $CaCO_3$ (PC)) as evidence of supersaturation with $CaCO_3$ in arid climate in ferruginous soils; (c) concomitant development of sodicity with the formation of PC in subsoils of ferruginous soils (Source: Division of Soil Resource Studies, NBSS&LUP, Nagpur, India).

comitant chemical degradation in terms of development of sodicity in the subsoils (Fig. 4.1c). The rate of formation of $CaCO_3$ was estimated to be 0.2 mg/100g soil/year in 0–100 cm profile depth (Pal *et al.*, 2000).

Degradation in vertisols

The global distribution (except in Antarctica) of vertisols and vertic intergrades indicates that an area of 257 million ha are confined between 45° N and 45° S latitudes, of which India occupies nearly 30% area (Dudal, 1965). Vertisols occur in wider climatic zones of the world (Ahmad, 1996) and in India they belong to humid tropical (HT), subhumid moist (SHM), subhumid dry (SHD), semi-arid moist (SAM), semi-arid dry (SAD) and arid dry (AD) climatic environments (Fig. 4.2a) in the states of Madhya Pradesh, Maharashtra, Chhattisgarh, Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, Rajasthan and West Bengal (Kalbande *et al.*, 1992; Srivastava *et al.*, 2002; Kadu *et al.*, 2003; Pal *et al.*, 2003a, 2006a; Bhattacharyya *et al.*, 2005, 2006a,b, 2007a; Ray *et al.*, 2006). However, the occurrence of vertisols (Fig. 4.2a) in HT (Bhattacharyya *et al.*, 2005), SHM, SHD, SAM, SAD and AD climatic environments (Pal *et al.*, 2003a) in Deccan basalt area apparently suggests that the basaltic material has influenced soil formation in such a way that similar soils are formed under different climatic conditions (Mohr *et al.*, 1972).

A dominance of smectitic clay minerals causes appreciable shrink–swell phenomena, which

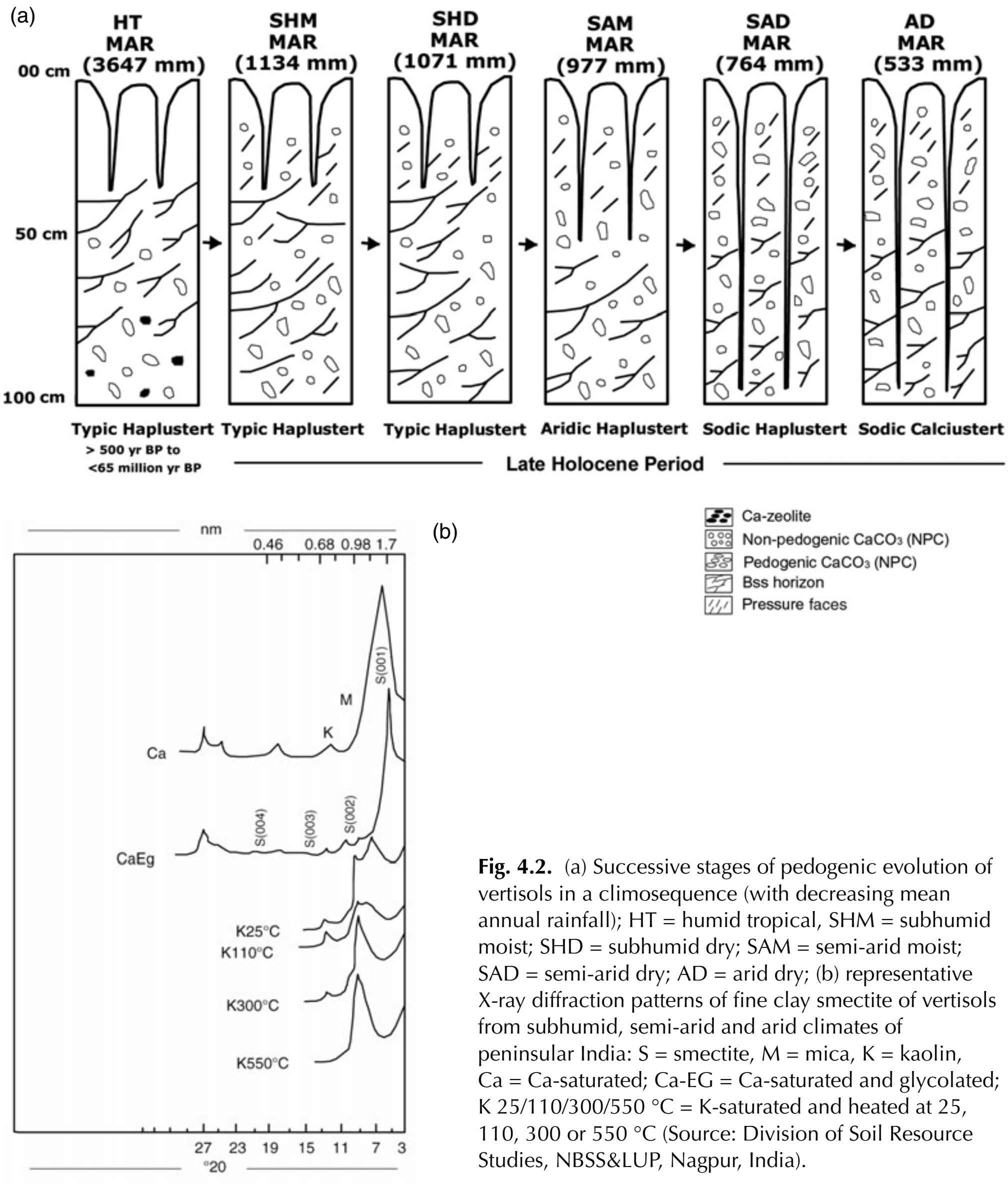

Fig. 4.2. (a) Successive stages of pedogenic evolution of vertisols in a climosequence (with decreasing mean annual rainfall); HT = humid tropical, SHM = subhumid moist; SHD = subhumid dry; SAM = semi-arid moist; SAD = semi-arid dry; AD = arid dry; (b) representative X-ray diffraction patterns of fine clay smectite of vertisols from subhumid, semi-arid and arid climates of peninsular India: S = smectite, M = mica, K = kaolin, Ca = Ca-saturated; Ca-EG = Ca-saturated and glycolated; K 25/110/300/550 °C = K-saturated and heated at 25, 110, 300 or 550 °C (Source: Division of Soil Resource Studies, NBSS&LUP, Nagpur, India).

induce the formation of cracks and distinctive structural elements in the form of sphenoids and wedge-shaped peds with smooth or slicken-sided surfaces (Eswaran *et al.*, 1988). Smectites are ephemeral in HT climate and they transform to kaolin (Pal *et al.*, 1989; Bhattacharyya *et al.*, 1993). Thus it is difficult to reconcile the formation of vertisols in HT climate. However, the presence of smectites and Ca-zeolites made the formation of vertisols possible in a lower physiographic situation, even under HT climate (Bhattacharyya *et al.*, 1993, 1998). It is equally difficult to understand the formation of vertisols in SHM, SHD, SAM, SAD and AD climates, since a large amount of smectite clay is required for their formation. In these climatic environments, the weathering of primary minerals contributes very little towards the formation of smectites, and the formation of PC is the primary chemical reaction responsible for the increase in pH, exchangeable magnesium percentage and ESP (Pal *et al.*, 2003b, 2006a). Thus the formation of such vertisols reflects a positive entropy change (Srivastava *et al.*, 2002). X-ray diffraction analysis of fine clays indicates that smectites are fairly well crystallized, as evident from a regular series of higher-order reflections, though short and broad, and do not show any sign of transformation (Fig. 4.2b) except for hydroxy-interlayering (Srivastava *et al.*, 2002; Pal *et al.*, 2003a).

These soils have both non-pedogenic $CaCO_3$ (NPC) and PC (Fig. 4.3). The NPCs have sharp boundaries with the soil matrix and are coated with Fe–Mn oxides (Fig. 4.3a). Brewer (1976) stated that such forms are pedorelic features. Based on ^{14}C dates of carbonate nodules, Mermut and Dasog (1986) concluded that vertisols with Fe–Mn-coated $CaCO_3$ glaebules are older than those with white $CaCO_3$ glaebules, i.e. PC. The PCs are formed in soils of dry climates (Pal *et al.*, 2000). This suggests that NPCs were formed in a climate much wetter than the present, which ensured adequate soil water for reduction and oxidation of iron and manganese to form Fe–Mn coats. Thus the smectites must have formed in an earlier humid climate, its crystallinity being preserved in the non-leaching environment of the latter sub-humid to dry climates (Fig. 4.2b).

The ^{14}C age of soil organic carbon (OC) of these vertisols was estimated to be between 3390 and 10,187 years BP (Pal *et al.*, 2003a, 2006a). This suggests that the change from humid to drier climate occurred in peninsular India during the late Holocene (Pal *et al.*, 2001, 2003a, 2006a; Deotare, 2006). Vertisols of HT climate are dominated by Ca^{2+} ions in their exchange complex throughout the depth (Bhattacharyya *et al.*, 2005). However, in lower horizons of vertisols of subhumid to arid climates, the Mg^{2+} ions lead to dominate in the exchange complex (Pal *et al.*, 2003a). The soils

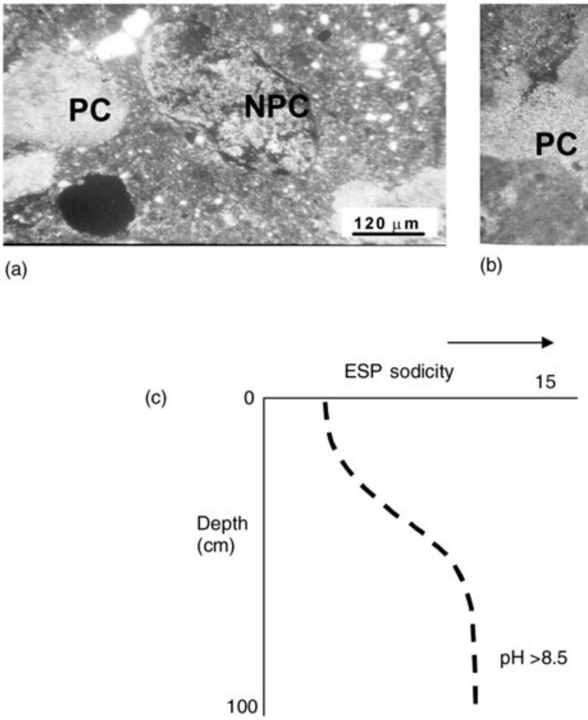

Fig. 4.3. (a) Pedogenic (PC) and non-pedogenic (NPC) $CaCO_3$ in vertisols; (b) the formation of PC at the expense of NPC; (c) concomitant development of sodicity with the formation of PC in subsoils of vertisols (Source: Division of Soil Resource Studies, NBSS&LUP, Nagpur, India).

of SAM, SAD and AD climates become more calcareous and sodic (ESP 5–15 with sHC <10 mm/h) (Pal *et al.*, 2006a) than those of SHM and SAM climates. The observations confirm the polygenesis in vertisols (Pal *et al.*, 2001) as the climate becomes drier during the Holocene. The formation of PC at the expense of NPC (Fig. 4.3b) is the prime chemical reaction responsible for increase in pH, the decrease in the Ca/Mg ratio of the exchange sites with depth and in the development of subsoil sodicity (Fig. 4.3c). It is the basic and natural process of soil degradation for the development of calcareous sodic soils (Pal *et al.*, 2000). The rate of formation of PC was estimated to be 0.25 mg/100g soil/year in the 0–100 cm of the profile depth (Pal *et al.*, 2000).

Earlier studies (Balpande *et al.*, 1996) on the factors and processes of soil degradation in vertisols of the Purna Valley of central India indicated that the semi-arid climate characterized by a mean annual rainfall (MAR) of 875 mm and a tropustic moisture regime causes the development of calcareous sodic soils. However, recent observations (Vaidya and Pal, 2002) indicated that in the adjacent east upland (Pedhi watershed) of the Purna Valley, vertisols have subsoil sodicity despite the fact that the area receives a higher MAR (975 mm) than the Purna Valley. Vertisols of the watershed occur on both micro-high (MH) and micro-low (ML) positions and the distance between MH and ML positions is approximately 6 km and the elevation difference is 0.5–5 m. The soils of the MH positions are strongly alkaline and those of the ML positions are mildly alkaline (Fig. 4.4a). Formation of sodic vertisols in MH positions alongside non-sodic vertisols in ML positions is a unique phenomenon. It develops because of microtopographic differences which modify distribution of water across the landscape and facilitate greater penetration of rainwater in ML positions. The degradation of soils in terms of the development of sodicity due to microtopographic differences in vertisols in the higher MAR zone of an overall semi-arid climate possibly indicates the subtle role of neotectonics in creating the MH and ML positions in the Purna Valley, which is an outcome of complex interplay/interaction of tectonic, climatic and other geological parameters (Ghatak *et al.*, 2005).

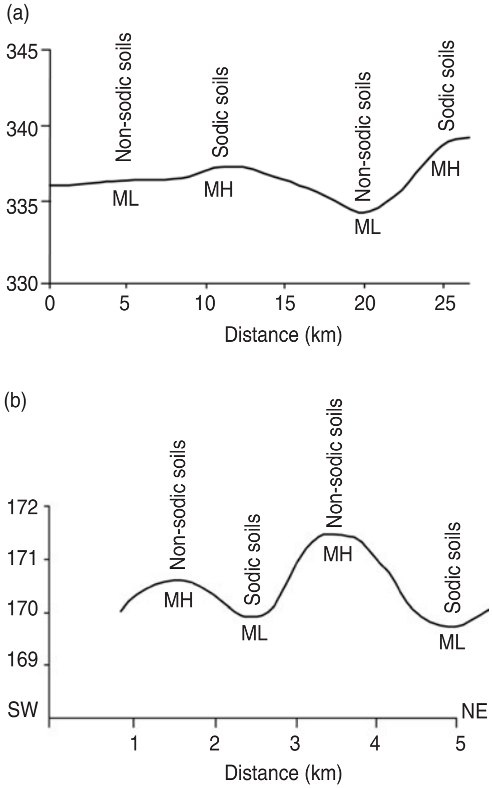

Fig. 4.4. Juxtaposition of the occurrence of sodic and non-sodic soils on micro-high (MH) and micro-low (ML) positions in (a) black soil region (BSR) and (b) the Indo-Gangetic Plains (IGP). Y-axis = elevation (msl).

Degradation in soils of the Indo-Gangetic Plains (IGP)

The IGP came into existence through collision of the Indian and Chinese plates. The Indian plate is still moving at the rate of 2–5 cm/year towards the north, and forming the world's highest mountain range on its border. The north–south compression generated through the plate ensures that it is continually under stress and provides the basic source of accumulating strain in the fractured zones (Gaur, 1994). The fluvial deposits and landforms of the IGP have been influenced by the stresses directed towards the north and north-east (Parkash *et al.*, 2000). The major rivers of the Plain have changed their courses and, at present, are flowing in south-east and easterly directions with convexity towards the south-west, which is strikingly similar to the arcuate pattern of the major thrusts bordering the Plains (Parkash *et al.*, 2000). Thus, the IGP show a series of terraces, bars and meandering scars resulting in MH and ML areas in the apparently smooth topography (Mohindra *et al.*, 1992; Srivastava *et al.*, 1994; Kumar *et al.*, 1996; Singh *et al.*, 2006). Many observations in Punjab (Sehgal *et al.*, 1975), Haryana (Bhumbla *et al.*, 1973) and Uttar Pradesh (Agarwal and Mehrotra, 1953; Srivastava *et al.*, 1994; Kumar *et al.*, 1996) indicate that the sodic soils occupy these ML areas, 50–100 cm lower than the MH areas, which have less sodic soils (Fig. 4.4b). The post-glacial warm period, in which human civilization developed and flourished, represents a short epoch, which began 10,000 years BP. Within the present interglacial period too, thermal conditions have continued to change. It is believed that monsoons were much stronger in the early part of the interglacial period. Around 4500–3700 years BP, the rainfall in the Indus Valley was probably much more than double the amount received now, and thus both agriculture and forestry flourished (Randhawa, 1945; Prasad and Gadgil, 1986). The paleoclimatic record has been documented from the north-west and south-west parts of India (Singh *et al.*, 1972, 1974, 1990). Climatic variations have also been inferred from Holocene soils (Srivastava *et al.*, 1994, 1998; Singh *et al.*, 2006). During pedogenesis two major regional climatic cycles are recorded: relatively arid climates between 10,000 and 6500 years BP and 3800 years BP and a warm and humid climate punctuated between these aridic climates (Srivastava *et al.*, 1998; Pal *et al.*, 2006b).

Sodic soils interspersed with non-sodic or less sodic soils occur in both canal-irrigated and unirrigated areas of the semi-arid parts of the IGP. Therefore, the introduction of canal irrigation in the IGP is not the reason for development of the sodic soils. Pal *et al.* (2003c) demonstrated that the main soil-forming processes were clay illuviation, deposition of PC and concomitant development of subsoil sodicity in these soils. The ML areas are repeatedly flooded with surface water during brief high-intensity showers, so the soils are subject to cycles of wetting and drying. This provides a steady supply of alkalis by hydrolysis of feldspar, leading to precipitation of $CaCO_3$ at high pH and development of subsoil sodicity. This impairs the hydraulic conductivity of soils and eventually leads to the development of natrustalfs, with ESP increasing up the profile (Fig. 4.5). The semi-arid climate and topography interact to facilitate greater penetration of bicarbonate-rich water in ML than MH positions. Thin sections show deformational pedofeatures such as cross- and reticulate-striation of plasmic fabric, disruption of clay pedofeatures, carbonate nodules and elongation of voids as a result of tectonic activity during the Holocene (Pal *et al.*, 2003c, 2006b). There is also support from geodetic observations that an area under tectonic compression undergoes horizontal movements and slow changes of height. By creating ML and MH sites, the tectonic activity may also have been ultimately responsible for degrading soils in terms of the formation of more and less sodic soils (Fig. 4.4b) (Pal *et al.*, 2003c). The rate of formation of $CaCO_3$ in these soils was estimated to be 0.86 mg/100 g soil/year in the 0–100 cm profile (Pal *et al.*, 2000).

Pedogenic Threshold in Dry Climates and Loss in Soil Productivity

Pedogenic thresholds

Case studies presented here indicate that the soils are becoming calcareous and sodic. Formation of PC facilitates the illuviation of clay

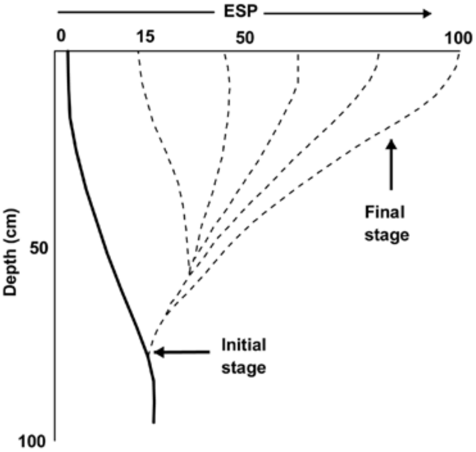

Fig. 4.5. Progressive development of sodicity in soils of the Indo-Gangetic Plains in a semi-arid environment.

particles and these two are concurrent, contemporary and active pedogenic processes. Thus it provides examples of pedogenic threshold in soils of semi-arid climate during the Holocene (Pal *et al.*, 2003b), which signifies the natural degradation process induced by neotectonic and climatic events (Fig. 4.6). An example from benchmark vertisols with and without soil modifiers (Ca-zeolites and gypsum) representing a climosequence from SHM to AD climate (Table 4.1) indicates that dry climate during the late Holocene restricted further leaching and as a result formation of PC was favoured (Pal *et al.*, 2001). The amount of PC in soils of a representative climatic region in the first 1 m of the profile (Table 4.1) indicates a general progressive increase in the rate of formation of PC (from 0.39 to 2.12 mg/100 g soil/year) and ESP (from 1 to 28) from sub-humid to arid climate (Table 4.1).

Loss in soil productivity

Inefficient cropping and water application in irrigation commands result in a rise in groundwater and soil salinity and sodicity problems. Over the years, these problems have been so severe that misgivings are being raised on the sustainability of irrigated agriculture in canal irrigation commands (Abrol and Chaudhary, 1988).

Loss due to irrigation

There are instances to indicate that productive black soils under rainfed conditions have been degraded to such an extent that they are now not usable for agriculture. Such a problem is not only confined to an irrigation command area but also occurs in areas where river or well waters are used for irrigation (Nimkar *et al.*, 1992; Pal *et al.*, 2003a). This dismal scenario in non-zeolitic and

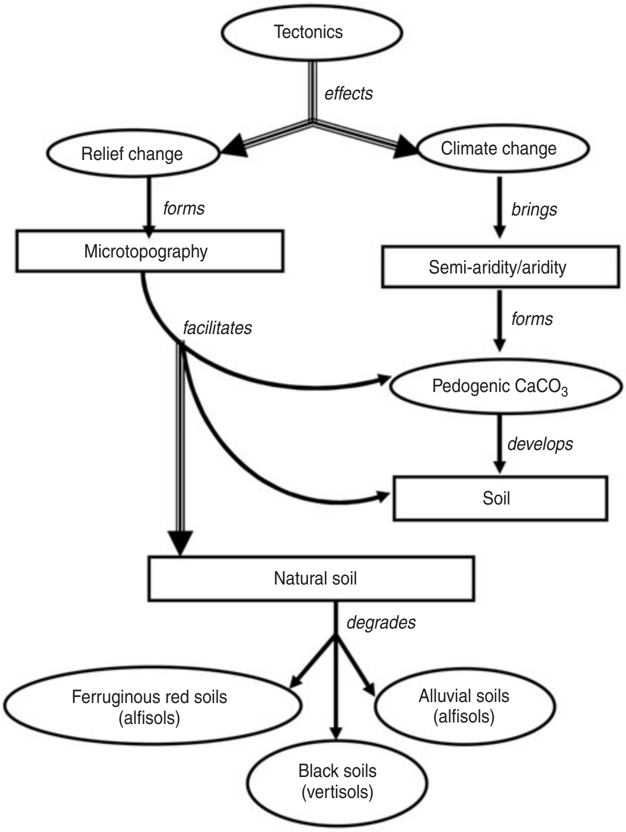

Fig. 4.6. Tectonics-induced natural soil degradation model.

Table 4.1. Rate of formation of PC and concomitant development of ESP in vertisols of a representative climatic region in India[a].

Soil series (soil taxonomy) (district, state)	$CaCO_3$ (%) weighted mean in the first 1 m of the profile	Rate of formation of PC in the first 1 m of the profile mg/100 g soil/year	Maximum ESP in the first 1 m of the profile	sHC (mm/h) weighted mean in the first 1 m of the profile
Subhumid moist (MAR 1209 mm) Nabibagh (typic haplusterts) (Bhopal, Madhya Pradesh)	3.7	0.39	~ 1	20
Subhumid dry (MAR 1011 mm)				
Linga (typic haplusterts) (Nagpur, Maharashtra)	7.8	0.76	1	23
Bhatumbra (udic haplusterts) (Bidar, Karnataka)	10.1	0.90	4[b]	6
Semi-arid dry (MAR 842–583 mm)				
Jhalipura (typic haplusterts) (Kota, Rajasthan)	5.5	0.57	3.6[c]	01
Teligi (sodic haplusterts) (Bellary, Karnataka)	9.6	0.94	17[c]	24
Kovilpatti (gypsic haplusterts) (Thoothokudi, Tamil Nadu)	7.9	1.02	1[d]	33
Sollapuram (sodic haplusterts) (Anantapur, Andhra Pradesh)	17.5	1.32	18	2
Paral (sodic haplusterts) (Akola, Maharashtra)	10.4	1.48	14	4
Arid dry (MAR 533 mm)				
Sokhda (calcic haplusterts) (Rajkot, Gujarat)	21.7	2.12	28[b]	17

PC = pedogenic $CaCO_3$; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivitiy; MAR = mean annual rainfall.
[a] Data from Pal et al. (2003a); [b] Irrigated; [c] Ca-zeolitic; [d] Gypsic.

zeolitic (Ca-rich) vertisols can be comprehended through the following examples.

Scenario 1 – continuous use of the Purna river water of high salinity with low sodium hazards (C3-S1) (Richards, 1954) in non-zeolitic vertisols of Maharashtra (central India) has hastened the sodification process. In 7 years of irrigation, soils have become more calcareous by formation of 371 mg of $CaCO_3$ per 100 g of soil per year in the first 100 cm of the profile. Values of exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) show a fourfold increase as compared with non-irrigated soils. Likewise, ionic composition and electrical conductivity of the saturation extract (ECe) show a two- to threefold increase. In addition, soils have become highly alkaline, and the sHC has further been impaired (Table 4.2). Such soils suffer waterlogging and salt-efflorescence appears on their surface.

Table 4.2. Comparative soil properties of unirrigated and irrigated deep black soils (haplusterts) of Maharashtra, India[a].

Depth (cm)	pH (1:2 water)	ECe (dS/m)	$CaCO_3$ (<2 mm) %	SAR	ESP	sHC (mm/h)
Unirrigated Chendkapur soils[b]						
0–17	8.3	2.3	6.1	3.5	3.8	3.2
17–44	8.4	1.5	6.9	2.9	3.4	2.7
44–67	8.5	1.9	8.3	3.1	3.6	2.3
67–100	8.6	2.4	12.6	3.4	3.9	2.0
100–130	8.6	1.9	13.9	3.6	4.2	1.3
Irrigated Chendkapur soils[b]						
0–15	8.9	5.7	10.4	18.2	17.8	3.1
15–43	8.9	6.5	10.9	20.7	18.2	3.2
43–59	8.8	5.2	11.8	18.7	15.3	3.2
59–93	8.6	3.4	12.3	11.6	11.6	0.9
93–129	8.6	3.2	12.7	7.9	7.0	0.9
Unirrigated Vasmat soils[c]						
0–18	3.2	0.94	21.5	–	4.0	26
18–45	3.2	2.50	17.7	–	4.6	34
45–77	0.9	2.64	17.4	–	5.5	35
77–108	0.9	1.85	15.8	–	6.0	33
108–142	9.2	0.67	17.2	–	5.5	13
142–166	9.2	0.32	17.2	–	3.9	12
Irrigated Vasmat soils[c]						
0–20	9.0	0.77	16.0	–	4.2	18
20–42	9.2	1.01	17.0	–	10.4	17
42–68	9.3	0.99	17.0	–	18.8	5
68–102	9.0	1.25	15.0	–	13.7	10
102–131	9.0	1.09	25.3	–	12.1	13
131–150+	9.0	1.02	16.1	–	8.0	12

[a]ECe = electrical conductivity of the saturation extract; SAR = sodium adsorption ratio; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity. [b]Data from Nimkar *et al.* (1992). [c]Data from Pal *et al.* (2003a).

Scenario 2 – there are Ca-zeolitic deep black soils in the semi-arid parts of Maharashtra (western India) that are being cultivated for sugarcane under canal irrigation for the last two decades. However, these soils lack salt-efflorescence on their surface and are not water-logged at present. This may apparently suggest that these soils are not degraded. However, data for pH, ECe, $CaCO_3$ and ESP of unirrigated and irrigated black soils clearly indicate the development of soil sodicity in the latter soils (Table 4.2). The presence of Ca-zeolites, which ensure continuous supply of soluble Ca^{2+} ions, has prevented the decline of sHC from >10 mm/h to <10 mm/h (Pal *et al.*, 2006a). However, with time these soils will also become more calcareous, sodic and impermeable to water (Pal *et al.*, 2003a), which would impair their productivity.

Loss due to aridity

The following two examples would highlight how the lowering in MAR causes loss of soil productivity even in the presence of a soil modifier like gypsum.

Scenario 1 – deep black soils (vertisols) have limitations that constrain their full potential to grow both rainy-season and winter crops (NBSS&LUP–ICRISAT, 1991), as also reported from Nagpur, Amravati and Akola districts of Maharashtra state of central India. Either rainy-season crops or winter crops are grown in vertisols of the western part of Amravati district and adjoining Akola district, whereas they are grown in those of Nagpur district with limited irrigation (NBSS&LUP–ICRISAT, 1991). The mean monthly temperature is highest in Akola throughout the year by 0.5–1.5 °C. The MAR in

Akola, Amravati and Nagpur is 877 mm, 975 mm and 1127 mm, respectively. This indicates more aridity in Akola than in Amravati or Nagpur. Despite this fact, vertisols of these districts indicate similar soil moisture (typic tropustic) and temperature (hyperthermic) regimes (Balpande *et al.*, 1996). Under similar soil management by farmers in 29 vertisol areas, and also under similar soil moisture and temperature regimes, yields of cotton were better in soils of Nagpur than in those of Amravati and Akola (Table 4.3). The subsoils in the western part of Amravati and Akola districts are becoming sodic due to accelerated rate of formation and accumulation of PC (Kadu *et al.*, 2003). This impairs their sHC, and hence a significant positive correlation between yield of cotton and sHC has been observed (Kadu *et al.*, 2003).

Scenario 2 – under a rainfed situation, continuous efforts to grow deep-rooted crops like cotton, pigeonpea and sorghum in gypsum-containing vertisols of the semi-arid dry part of southern India indicates no development of sodicity in the profile. The soils have sHC >30 mm/h despite the rapid formation of PC (Table 4.4), unlike in zeolitic vertisols of the semi-arid climate. This may be attributed to much higher solubility of gypsum (30 me/l) than Ca-zeolites (<0.1 me/l) in distilled water (Pal *et al.*, 2006a). The gypsum in such soils acts as antagonistic to the formation of more soluble salts in the soil because it prevents clay dispersion. This favourable natural endowment has helped in making subsurface drainage in some such soils successful in removing the excess soluble salts (Danfors *et al.*, 1988) for sustaining crop production. The sustainability of crop productivity in these soils would, however, depend on the amount of gypsum in the soils. In its absence, these soils would become sodic and impermeable to both air and water. At present, despite having adequate sHC, these soils produce ~2 t/ha of cotton owing to erratically distributed MAR of 660 mm. These are the soils of the arid climates wherein irrigation may be of great help for some time in enhancing the crop productivity.

Management Interventions for Naturally Degraded Soils

The presence of $CaCO_3$ in sodic soils has generally been considered of doubtful significance in replacing exchangeable Na^+ ions by Ca^{2+} ions of $CaCO_3$ at a pH of around 8.4. However, it is greatly affected by other factors (Gupta and Abrol, 1990) such as application of gypsum followed by cropping in highly sodic

Table 4.3. Range in values of PC, ESP, sHC and yield of cotton in vertisols of Vidarbha, Maharashtra, central India[a].

District	Soil classification	PC (%)	ESP	sHC (mm/h) weighted mean in the profile (first 1 m)	Cotton yield (t/ha) (seed + lint)
Nagpur (MAR – 1011 mm)	Typic haplusterts/typic calciusterts (7/1 pedons)	3–6	0.5–11	4–18	1.0–1.8
Amravati (MAR – 975 mm)	Aridic haplusterts (11 pedons)	3–7	0.8–14	2–19	0.6–1.7
	Sodic haplusterts (8 pedons)	3–13	16–24	0.6–9.0	0.3–0.8
Akola (MAR – 877 mm)	Aridic haplusterts (1 pedon)	3–4	16–44	3–4	1.0
	Sodic haplusterts (1 pedon)	3–4	19–20	1–2	0.6

[a] Data from Division of Soil Resource Studies, NBSS&LUP, Nagpur, India. PC = pedogenic $CaCO_3$; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity.

Table 4.4. Physical and chemical properties of vertisols modified by the presence of gypsum in semi-arid dry parts of Tamil Nadu, India[a].

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

[a] Data from Pal *et al.* (2003a). ECe = electrical conductivity of the saturation extract; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity.

soils (natrustalfs) of the IGP, and the application of gypsum increased the urease and dehydrogenase activity, the measures of biological activity, by about threefold (Rao and Ghai, 1985). Growing trees for more than a decade reclaimed the soil and improved the biological activity (Rao and Ghai, 1985). The reclamation was effected through more CO_2 production and mobilization of $CaCO_3$. The $CaCO_3$ content during the corresponding 12-year period decreased by 1%, 1.5% and nearly 2% with cereal cropping, grasses and agroforestry, respectively (Gupta and Abrol, 1990).

Changes in chemical properties were also observed in natrustalfs of the IGP where gypsum and rice cropping were followed for the reclamation of these soils (Sharma and Bhargava, 1981). After 30 months, there was an increase in exchangeable Ca^{2+} and Mg^{2+}, a decrease in ESP, pH, SAR, ECe, and soluble carbonates and bicarbonates, and also in native $CaCO_3$ to a considerable depth (Table 4.5). After 30 months of cultural practice, the dissolution of $CaCO_3$ (<2 mm) was 254 mg/100 g soil in the top 100 cm of the profile. Such reclamation technology also enhanced the OC content by about 64% as compared with original sodic soils. In addition, plantation of forest species not only improves the physical conditions of sodic soils but also helps in increasing OC content considerably (Swarup *et al.*, 2000).

Under rainfed conditions, the yield of deep-rooted crops in vertisols depends primarily on the amount of rain stored in the profile, and the extent to which this soil water is released during crop growth. In the semi-arid part of central India, rainfed cotton is grown under suboptimal conditions, with soil depth and moisture availability as the main limitations. Field experiments conducted in Yavatmal district of Maharashtra (central India) (Venugopalan *et al.*, 2004) on the comparison of soil properties of vertisols under organic and non-organic (conventional) cotton production systems indicate that the yields of cotton and component crops grown under the organic production system were higher than those of the non-organic production system and in general the productivity was higher than the average productivity of the district. Despite a hot, semi-arid tropical climate, higher values of OC (>0.6%) in the organic production system have been due to sequestration of carbon (Table 4.6) as compared with conventional system. Owing to improvement of OC and the subsequent dissolution of $CaCO_3$, the pH of soils under the organic production system remained below 8.1 (Table 4.6). In addition, the organic production system improved the availability of zinc (Table 4.6). It appears that adoption of the organic production system offers a viable alternative land use plan that not only enhances the OC content but also improves physical and chemical properties, arresting the formation of PC. The realization of the beneficial effects of modifiers like Ca-zeolites and gypsum in vertisols of dry climates in terms of improvement of their hydraulic properties (Pal *et al.*, 2006a) strongly suggests that application of such modifiers at the soil surface can restore the productivity of naturally degraded soils. There is evidence to this effect in the literature (Gupta and Abrol, 1990; Pal *et al.*, 2000).

Table 4.5. Chemical properties of untreated and gypsum-treated sodic soils[a].

Depth (cm)	pH (1:2 water)	ECe (dS/m)	$CaCO_3$ (<2 mm) (%)	SAR	ESP
Untreated soils					
0–13	10.3	8.3	1.0	90	79
13–29	10.4	8.9	2.1	93	97
29–59	10.0	4.8	1.8	88	45
59–89	9.6	2.5	1.0	93	32
89–116	9.6	2.5	1.2	74	15
116–160	9.6	–	4.6	8	13
Gypsum-treated soils					
0–14	8.6	1.2	0.8	12	6
14–31	9.1	1.4	1.2	31	16
31–62	9.4	2.0	1.0	55	8
62–88	9.4	2.0	0.9	61	17
88–121	9.5	2.0	2.7	75	14
121–165	9.6	2.3	6.9	56	14

[a] Data from Sharma and Bhargava (1981). ECe = electrical conductivity of the saturation extract; SAR = sodium adsorption ratio; ESP = exchangeable sodium percentage.

Table 4.6. Comparison of chemical properties of surface soils (0–20 cm) under organic and conventional production systems (based on 55 soil samples)[a].

	Conventional		Organic	
Properties	Range	Mean	Range	Mean
pH (1:2 water)	7.7–8.4	8.0	7.1–8.1	7.7
Organic carbon (%)	0.20–0.80	0.54	0.30–1.70	0.76
$CaCO_3$ (%)	2.4–12.2	6.2	1.1–12.5	5.3
Zn (mg/kg)	0.38–1.1	0.66	0.39–3.14	0.90
Soluble HCO_3 (me/l)	1.25–3.75	2.35	0.50–7.5	1.85

[a] Data from Venugopalan *et al.* (2004).

The above examples are a few specific management interventions in vogue in India to restore the productivity of degraded soils. Soil carbon dynamics as a robust parameter offers a unique opportunity in assessing the sustainability of the various cropping systems that are followed in India. The NBSS&LUP (ICAR), through organized research initiatives, sponsored by national and international organizations, developed a data set of soil OC and soil inorganic carbon for two important crop production zones, namely the IGP and the black soil region in the semi-arid tropics (SAT). The soil carbon data sets generated during 1980–2005 indicate that the agricultural practices in the IGP and black soil regions of SAT did not reduce SOC (soil organic carbon) content. The inorganic soil carbon estimated through the $CaCO_3$ deposition in these soils, however, increased over the 25-year period and thus forewarns of soil degradation (Bhattacharyya *et al.*, 2006a, 2007b,c).

Perspective

Amidst neotectonics and the global warming phenomenon, rising temperature and shrinking annual rainfall with erratic distribution pose perpetual threats for soils not only for the Indian subcontinent but also for soils of similar climatic and geologic conditions elsewhere. The rate of formation of $CaCO_3$ and concomitant development of subsoil sodicity in the soils of India provides a very realistic scenario as to how the semi-arid climatic conditions pose a threat to agriculture in a country with an unfavourable natural endowment, as it demands extra

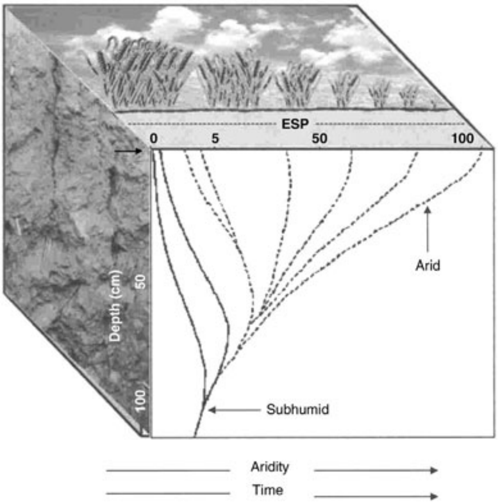

Fig. 4.7. A projected view of the progressive development of soil sodicity from wet to dry climates with time – a threat to Indian rainfed agriculture.

resources for raising crops (especially the winter crops) by the resource-poor farmers in the naturally degraded soils (Fig. 4.7). Thus, in the absence of national and international attention to combat this menace, soil degradation, through its impact on agricultural productivity, livelihood and environment, could lead to political and social instability. In addition, agricultural development would enhance the rate of deforestation, unwise use of marginal lands, accelerated run-off and soil erosion (Lal and Stewart, 1990).

The magnitude of degradation may not be very high in ferruginous soils at present, but it may create havoc in shrink–swell soils (vertisols and vertic intergrades) because of the huge amount of smectite clays. Perception of the natural degradation process may continue to be deceptive in shrink–swell and ferruginous soils as they lack evidence of salt-efflorescence on their surface (Pal *et al.*, 2000). However, the degradation process is proceeding at a much faster rate in soils of the IGP as compared with the other two soil types. Therefore, attempts to increase and stabilize yields in these soils, especially in soils without soil modifiers, by extension of canal irrigation may prove to be highly disastrous. This suggests that while managing natural resources for increasing soil productivity a new research initiative is required to comprehend and record the factors and processes of soil degradation whether natural or human induced, so that a precise cause–effect relationship is established. Such a relationship would form the mandatory requirement to develop methods to restore the productivity of already degraded soils and also to prevent the development of similar problem areas in the future.

Research initiatives on the significance of PC and soil modifiers like Ca-zeolites and gypsum in the management of naturally degraded soils, undertaken by the Central Soil Salinity Research Institute, Karnal, India (Abrol and Fireman, 1977) and NBSS&LUP (Srivastava *et al.*, 2002; Pal *et al.*, 2006a) suggest that for sustained performance of crops in soils of dry climates, the replenishment of Ca^{2+} ions both in the soil solution and in the exchange complex appears to be a viable technological intervention. The presence of $CaCO_3$ is of no significance and displacement of exchangeable Na^+ ions by Ca^{2+} ions from $CaCO_3$ is not feasible in soils with pH >8.0. If there are rootlets in the soil through which the rainwater passes, or other sources of CO_2 production and accumulation, there will be a corresponding increase in solubility of PC and a lowering of equilibrium pH. This situation can be further enhanced in the presence of Ca-zeolites and gypsum during the cultivation of crops (Pal *et al.*, 2000, 2006a). This way, such soils can be made resilient, where not only the movement of water but also the release of water during crop growth can be enhanced.

References

Abrol, I.P. and Chaudhury, T.N. (1988) Impact of irrigation on productivity of shrink-swell soils. In: Hirekerur, L.R., Pal, D.K., Sehgal, J.L. and Deshpande, S.B. (eds) *Classification, Management and Use Potential of Shrink-Swell Soils,* INWOSS, 24–28 October 1988. National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India; and Oxford and IBH Publishing Co., New Delhi, India, pp. 7–14.

Abrol, I.P. and Fireman, M. (1977) *Alkali and Saline Soils; Identification and Improvement for Crop Production*. Bulletin No. 4. Central Soil Salinity Research Institute, Karnal, India.

Agarwal, R.R. and Mehrotra, C.LO. (1953) *Soil Survey and Soil Work in Uttar Pradesh*, Vol. III. Department of Agriculture, Uttar Pradesh, India.

Ahmad, N. (1996) Occurrence and distribution of vertisols. In: Ahmad, N. and Mermut, A. (eds) *Vertisols and Technologies for their Management*. Elsevier, Amsterdam, the Netherlands, pp. 1–41.

Anonymous (1984) *Western Ghats Region, Maharashtra Subregional Plan*. Regional Planning Division, Town and Country Planning Organization, Ministry of Works and Housing, Government of India.

Balpande, S.S., Deshpande, S.B. and Pal, D.K. (1996) Factors and processes of soil degradation in vertisols of the Purna Valley, Maharashtra, India. *Land Degradation & Development* 7, 313–324.

Bhattacharyya, T., Pal, D.K. and Deshpande, S.B. (1993) Genesis and transformation of minerals in the formation of red (alfisols) and black (inceptisols and vertisols) soils on Deccan basalt in the Western Ghats, India. *Journal of Soil Science* 44, 159–171.

Bhattacharyya, T., Pal, D.K. and Srivastava, P. (1998) Role of zeolites in persistence of high altitude ferruginous alfisols of the humid tropical Western Ghats, India. *Geoderma* 90, 263–276.

Bhattacharyya, T., Pal, D.K., Chandran, P. and Ray, S.K. (2005) Land use, clay mineral type and organic carbon content in two mollisols–alfisols–vertisols catenary sequences of tropical India. *Clay Research* 24, 105–122.

Bhattacharyya, T., Chandran, P., Ray, S.K., Mandal, C., Pal, D.K., Venugopalan, M.V., Durge, S.L., Srivastava, P., Dubey, P.N., Kamble, G.K., Sharma, R.P., Wani, S.P., Rego, T.J., Ramesh, V. and Manna, M.C. (2006a) Estimation of carbon stocks in red and black soils of selected benchmark spots in semi-arid tropics of India. *Global Theme on Agroecosystems Report No. 28*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 402 324, Andhra Pradesh, India.

Bhattacharyya, T., Chandran, P., Ray, S.K., Mandal, C., Pal, D.K., Venugopalan, M.V., Durge, S.L., Srivastava, P., Dubey, P.N., Kamble, G.K., Sharma, R.P., Wani, S.P., Rego, T.J., Ramesh, V. and Manna, M.C. (2006b). Morphological properties of red and black soils of selected benchmark spots in semi-arid tropics of India. *Global Theme on Agroecosystems, Report No. 21*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Bhattacharyya, T., Pal, D.K., Chandran, P., Ray, S.K., Durge, S.L., Mandal, C., Telpande, B. and Wani, S.P. (2007a) Available 'K' reserve of two major crop growing regions (alluvial and shrink-swell soils) in India. *Indian Journal of Fertilizers* 3, 41–52.

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K., Williams, S., Killian, K., Coleman, K., Falloon, P. and Powlson, D.S. (2007b) Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. *Agriculture Ecosystems and Environment* 122, 84–94.

Bhattacharyya, T., Pal, D.K., Easter, M., Williams, S., Paustian, K., Milne, E., Chandran, P., Ray, S.K., Mandal, C., Coleman, K., Falloon, P., Powlson, D.S. and Gajbhiye, K.S. (2007c) Evaluating the Century C model using long-term fertilizer trials in the Indo-Gangetic Plains, India. *Agriculture Ecosystems and Environment* 122, 73–83.

Bhumbla, D.R., Abrol, I.P., Bhargava, G.P. and Singla, S.K. (1973) *Soils of the Experimental Farm, Karnal*. Central Soil Salinity Research Institute, Karnal, Haryana, India.

Brewer, R. (1976) *Fabric and Mineral Analysis of Soils*. Robert E. Krieger Publishing Co., Huntington, New York, USA.

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

Chandran, P., Ray, S.K., Bhattacharyya, T., Krishnan, P. and Pal, D.K. (2000) Clay minerals in two ferruginous soils of southern India. *Clay Research* 19, 77–85.

Danfors, E., Ramanathan, G. and Kandaswamy, P. (1988) Swelling clays of vertisols in PAP Command area and drainage problems. In: Hirekerur, L.R., Pal, D.K., Sehgal, J.L. and Deshpande, S.B. (eds) *Proceedings of the International Workshop on Swell–Shrink Soils*. Oxford and IBH Publishing Co., New Delhi, India, pp. 15–19.

Deotare, B.C. (2006) Late Holocene climatic change: archaeological evidence from the Purna Basin, Maharashtra. *Journal of the Geological Society of India* 68, 517–526.

Dudal, R. (1965) Dark clay soils of tropical and subtropical regions. FAO Agriculture Development Paper 83, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Eswaran, H. and van den Berg, E. (1992) Impact of building of atmospheric CO_2 on length of growing season in the Indian sub-continent. *Pedologie* 42, 289–296.

Eswaran, H., Kimble, J. and Cook, T. (1988) Properties, genesis and classification of vertisols. In: Hirekerur, L.R., Pal, D.K., Sehgal, J.L. and Deshpande, S.B. (eds) *Classification, Management and Use Potential of Swell–Shrink Soils,* INWOSS, 24–28 October 1988. National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India; and Oxford and IBH Publishing Co., New Delhi, India, pp. 1–22.

Eswaran, H., Kimble, J., Cook, T. and Beinroth, F.H. (1992) Soil diversity in the tropics: implications for agricultural development. SSSA Special Publication No. 29. Soil Science Society of America, Inc., and American Society of Agronomy, Inc. Madison, Wisconsin, USA.

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.

Gaur, V.K. (1994) Evaluation of seismic hazard in India towards minimizing earthquake risk. *Current Science* 67, 324–329.

Ghatak, S., Ghatak, M., Roy, A. and Chakrabarti, A. (2005) A preliminary overview of tectonic-climatic feedback in Purna Basin at south Satpura foothills: future research needs. IGCP-476, Extended Abstract Volume Paper, Geological Survey of India, Central Region, Nagpur, India, pp. 21–26.

Gupta, R.K. and Abrol, I.P. (1990) Salt-affected soils: their reclamation and management for crop production. In: Stewart, B.A. (ed.), *Advances in Soil Science*, Vol. II. Springer-Verlag, Berlin, Germany, pp. 223–288.

Hall, G.F., Daniels, R.B. and Foss, J.E. (1982) Rates of soil formation and renewal in the USA. In: Schmidt, B.L. (ed.) *Determinants of Soil Loss Tolerance*. ASA Publication No. 45. American Society of Agronomy, Madison, Wisconsin, USA, pp. 23–29.

Kadu, P.R., Vaidya, P.H., Balpande, S.S., Satyavathi, P.L.A. and Pal, D.K. (2003) Use of hydraulic conductivity to evaluate the suitability of vertisols for deep rooted crops in semi-arid parts of Central India. *Soil Use & Management* 19, 208–216.

Kalbande, A.R., Pal, D.K. and Deshpande, S.B. (1992) b-Fabric of some benchmark vertisols of India in relation to their mineralogy. *Journal of Soil Science* 43, 375–385.

Kumar, S., Parkash, B., Manchanda, M.L., Singhvi, A.K. and Srivastava, P. (1996) Holocene landform and soil evolution of the western Gangetic Plains: implications of neotectonics and climate. *Zeitschrift fur Geomorphologie N.F.*, Supplement, 103, 283–312.

Lal, R. and Stewart, B.A. (1990) Soil degradation: a global threat. In: Lal, R. and Stewart, B.A. (eds) *Advances in Soil Science*, Vol. II. Springer-Verlag, Berlin, pp. 13–17.

Lal, R., Hall, G.F. and Miller, F.P. (1989) Soil degradation. I. Basic processes. *Land Degradation and Rehabilitation* 1, 51–69.

Mermut, A.R. and Dasog, G.S. (1986) Nature and micromorphology of carbonate glaebules in some vertisols of India. *Soil Science Society of America Journal* 50, 382–391.

Mohindra, R., Parkash, B. and Prasad, J. (1992) Historical geomorphology and pedology of the Gandak Megafan, Middle Gangetic Plain, India. *Earth Surface Process Landforms* 17, 643–662.

Mohr, E.C.J., Van Baren, F.A. and Van Schuylenborgh, J. (1972) *Tropical Soils – a Comprehensive Study of their Genesis*. Mouton-Ichtiarbaru – Van Hoeve, The Hague, the Netherlands.

NBSS&LUP–ICRISAT (National Bureau of Soil Survey and Land Use Planning–International Crops Research Institute for the Semi-arid Tropics) (1991) *The Suitabilities of Vertisols and Associated Soils for Improved Cropping Systems in Central India*. NBSS&LUP, Nagpur, India and ICRISAT, Patancheru 502 324, Andhra Pradesh, India.

Nimkar, A.M., Deshpande, S.B. and Babrekar, P.G. (1992) Evaluation of salinity problem in swell-shrink soils of a part of the Purna Valley, Maharashtra. *Agropedology* 2, 59–65.

Oldeman, L.R. (ed.) (1988) *Global Assessment of Soil Degradation (GLASOD)*. Guidelines for general assessment of status of human-induced soil degradation. ISRIC, Wageningen, the Netherlands.

Pal, D.K., Deshpande, S.B., Venugopal, K.R. and Kalbande, A.R. (1989) Formation of di- and trioctahedral smectite as an evidence for paleoclimatic changes in southern and central Peninsular India. *Geoderma* 45, 175–184.

Pal, D.K., Dasog, G.S., Vadivelu, S., Ahuja, R.L. and Bhattacharyya, T. (2000) Secondary calcium carbonate in soils of arid and semi-arid regions of India. In: Lal, R., Kimble, J.M., Eswaran, H. and Stewart, B.A. (eds) *Global Climate Change and Pedogenic Carbonates*. Lewis Publishers, Boca Raton, Florida, USA, pp. 149–185.

Pal, D.K., Balpande, S.S. and Srivastava, P. (2001) Polygenetic vertisols of the Purna Valley of central India. *Catena* 43, 231–249.

Pal, D.K., Bhattacharyya, T., Ray, S.K. and Bhuse, S.R. (2003a) Developing a model on the formation and resilience of naturally degraded black soils of the peninsular India as a decision support system for better land use planning. NRDMS, DST Project Report. Nagpur, India.

Pal, D.K., Srivastava, P. and Bhattacharyya, T. (2003b) Clay illuviation in calcareous soils of the semi-arid part of the Indo-Gangetic Plains, India. *Geoderma* 115, 177–192.

Pal, D.K., Srivastava, P., Durge, S.L. and Bhattacharyya, T. (2003c) Role of microtopography in the formation of sodic soils in the semi-arid part of the Indo-Gangetic Plains, India. *Catena* 51, 3–31.

Pal, D.K., Bhattacharyya, T., Ray, S.K., Chandran, P., Srivastava, P., Durge, S.L. and Bhuse, S.R. (2006a) 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, D.K., Bhattacharyya, T., Srivastava, P., Chandran, P. and Ray, S.K. (2006b) Soils of the Indo-Gangetic Plains, India: their historical perspective and management. Presented at the 18th World Congress of Soil Science, 9–15 July 2006, Philadelphia, USA.

Parkash, B., Kumar, S., Rao, M.S., Giri, S.C., Kumar, C.S., Gupta, S. and Srivastava, P. (2000) Holocene tectonic movements and stress field in the Western Gangetic Plains. *Current Science* 79, 438–449.

Pascoe, E.H. (1965) *A Manual of the Geology of India and Burma*. Managers of Publication, Delhi, India.

Prasad, C.R. and Gadgil, S. (1986) Climatic change – a global perspective. *Science Age* 4, 35–40.

Rajaguru, S.N. and Korisettar, R. (1987) Quaternary geomorphic environment and culture succession in Western India. *Indian Journal of Earth Sciences* 14, 349–361.

Randhawa, M.S. (1945) Progressive dessication of northern India in historical times. *Journal of Bombay National Historical Society* 45, 558–565.

Rao, D.L.N. and Ghai, S.K. (1985) Urease and dehydrogenase activity of alkali and reclaimed soils. *Australian Journal of Soil Research* 23, 661–665.

Ray, S.K., Bhattacharyya, T., Chandran, P., Sahoo, A.K., Sarkar, D., Durge, S.L., Raja, P., Maurya, UK and Pal, D.K. (2006) On the formation of cracking clay soils (vertisols) in West Bengal. *Clay Research* 25, 141–152.

Rengasamy, P., Sarma, V.A.K., Murthy, R.S. and Murti, G.S.R.K. (1978) Mineralogy, genesis and classification of ferruginous soils of the eastern Mysore Plateau, India. *Journal of Soil Science* 29, 431–445.

Richards, L.A. (ed.) (1954) *Diagnosis and Improvement of Saline and Alkali Soils. USDA Agriculture Handbook 60*. USDA, Washington, DC, USA.

Ritter, D.F. (1996) Is Quaternary geology ready for the future? *Geomorphology* 16, 273–276.

Sahasrabudhe, Y.S. and Deshmukh, S.S. (1981) Laterites of the Maharashtra State. In: *Proceedings of the International Seminar on Laterization Processes*. A.A. Balkema, Rotterdam, the Netherlands, pp. 209–220.

Sehgal, J.L. (1998) Red and lateritic soils: an overview. In: Sehgal, J., Blum, W.E. and Gajbhiye, K.S. (eds) *Managing Red and Lateritic Soils for Sustainable Agriculture*, Vol. I. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India.

Sehgal, J.L. and Abrol, I.P. (1992) Land degradation status: India. *Desertification Control Bulletin* 21, 24–31.

Sehgal, J.L. and Abrol, I.P. (1994) *Soil Degradation in India: Status and Impact*. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India.

Sehgal, J.L., Hall, G.P. and Bhargava, G.P. (1975) An appraisal of the problems in classifying saline-sodic soils of the Indo-Gangetic plains in NW India. *Geoderma* 14, 75–91.

Sharma, R.C. and Bhargava, G.P. (1981) Morphogenic changes in an alkali (sodic) soil pedon during amelioration through gypsum application. *Journal of the Indian Society of Soil Science* 29, 274–277.

Singh, G., Joshi, R.D. and Singh, A.B. (1972) Stratigraphic and radiocarbon evidence for the age and development of the three salt lake deposits in Rajasthan, India. *Quaternary Research* 2, 496–505.

Singh, G., Joshi, R.D., Chopra, S.K. and Singh, A.B. (1974) Late Quaternary history of vegetation and climate of Rajasthan desert, India. *Philosophical Transactions of the Royal Society of London* 267, 467–501.

Singh, G., Wasson, R.J. and Agarwal, D.P. (1990) Vegetation and seasonal climate changes since the last full glacial in the Thar desert, NW India. *Review of Paleobotany and Palynology* 64, 351–358.

Singh, L.P., Parkash, B. and Singhvi, A.K. (1998) Evolution of the Lower Gangetic Plain landforms and soils in West Bengal, India. *Catena* 33, 75–104.

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

Soil Survey Staff (1999) *Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Agricultural Handbook, Vol. 436. USDA, Washington, DC, USA.

Srivastava, P., Parkash, B., Sehgal, J.L. and Kumar, S. (1994) Role of neotectonics and climate in development of the Holocene geomorphology and soils of the Gangetic Plains between Ramganga and Rapti rivers. *Sedimentary Geology* 94, 129–151.

Srivastava, P., Parkash, B. and Pal, D.K. (1998) Clay minerals in soils as evidence of Holocene climatic change, central Indo-Gangetic Plains, north-central India. *Quaternary Research* 50, 230–239.

Srivastava, P., Chandran, P., Ray, S.K. and Bhattacharyya, T. (2001) Evidence of chemical degradation in tropical ferruginous soils of southern India. *Clay Research* 20, 31–41.

Srivastava, P., Bhattacharyya, T. and Pal, D.K. (2002) Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (vertisols) of India. *Clays and Clay Minerals* 50, 111–126.

Subramanian, K.S. and Mani, G. (1981) Genetic and geomorphic aspects of laterites on high and low landform in parts of Tamil Nadu, India. In: *Proceedings of the International Seminar on Laterization Processes*. A.A. Balkema, Rotterdam, the Netherlands, pp. 236–245.

Swarup, A., Manna, M.C. and Singh, G.B. (2000) Impact of landuse and management practices on organic carbon dynamics in soils of India. In: Lal, R., Kimble, J.M., Eswaran, H. and Stewart, A. (eds) *Global Climate Change and Tropical Ecosystems*. Lewis Publishers, Boca Raton, Florida, USA, pp. 261–281.

UNEP (1992) *World Atlas of Desertification*. Edward Arnold, London, UK.

Vaidya, P.H. and Pal, D.K. (2002) Microtopography as a factor in the degradation of vertisols in central India. *Land Degradation & Development* 13, 429–445.

Venugopalan, M.V., Chandran, P., Pal, D.K., Challa, O. and Durge, S.L. (2004) Effect of organic and conventional cotton production systems on soil properties: a case study in Yavatmal district, Maharashtra. *International Symposium on Strategies for Sustainable Cotton Production – a Global Vision*, Vol. II, *Crop Production*. 22–25 November 2004, University of Agricultural Sciences, Dharwad, Karnataka, India, pp. 118–121.