7 Formation and Management of Cracking Clay Soils (Vertisols) to Enhance Crop Productivity

Indian Experience

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CONTENTS

7.1 INTRODUCTION

Cracking clay soils (Vertisols and their intergrades) [Soil Survey Staff 2006] are important natural resources in a wide range of climatic zones, from humid tropical to arid dry areas of the world [Ahmad 1996]. The natural vegetation of these areas is dry deciduous forest. However, most of the soils are now under cultivation. Soils of these climates have a significant role in the agricultural resource inventory of countries such as Australia, India, the Caribbean Islands, and the United States [Ahmad 1996].

Traditionally, these soils were often difficult to cultivate, particularly for small farmers using handheld or animal-drawn implements. Subsoil porosity and aeration are generally poor and roots of annual crops do not penetrate deeply. Farmers faced with these difficulties allow these soils to lie fallow for one or more rainy seasons or cultivate them only the postrainy season [Pal et al. 2009a]. Vertisols and their intergrades have limitations that restrict their full potential to grow two crops in a year during the rainy season and winter [NBSS and LUP-ICRISAT 1991]. However, with the advent of technologies and the introduction of new crops in assured rainfall ecoregions, two crops are now grown on these soils [El-Swaify et al. 1985; Wani et al. 2003].

Rainfed agriculture is globally predominant (80%) and contributes 56% to the world's food basket. Current productivity of farmers' fields in the rainfed tropics are two- to four-fold lower than the achievable crop yields [Wani et al. 2003; 2009; Rockstroem et al. 2007].

In India, sorghum (*Sorghum* spp.), maize (*Zea mays*), and pearl millets (*Pennisetum glaucum*) are the main cereal crops under dryland farming. Pigeonpea (*Cajanus cajan*), mung bean (*Vigna radiate*), and chickpea (*Cicer arietinum*) are the main pulses, safflower (*Carthamus tinctorius*), soybean (*Glycine max*), and groundnut (*Arachis hypogaea*) are the main oilseed, and cotton (*Gossypium* spp.) is the main industrial crop. Growing sorghum in the soils of wetter climates has been a recent trend. Sugarcane (*Saccharam* spp.), paddy (*Oryza sativa*), wheat (*Triticum aestivum*), and cotton are grown under irrigation. Intercropping is very common under rainfed agricultural systems [Jodha 1980]. The major combinations are sorghum/pigeonpea, cotton/pigeonpea, and cotton/sorghum/pigeonpea. These kind of mixtures usually combine crops with different maturity lengths, drought-sensitive with drought-tolerant crops, cereals with legumes, and cash crops with food crops [Swindale 1989].

In Africa, Vertisols occupy an area of over 100 million hectare (Mha) of arable land. The landscape of African Vertisols is quite diverse and a relatively small portion of the total area of Vertisols is irrigated in Sudan. The most widely cultivated crop is cotton. Wheat is grown in northern Africa in rainfed conditions. In the Ethiopian Highlands, several food cereals, grain legumes, and oil seed crops are produced due to an adequate and predictable rainfall. The major forms of land use in African Vertisols, however, are small-scale, mixed rainfed and arable farming, and extensive rearing of livestock. In general, under rainfed conditions, crop yields and productivity are low [Ahmad 1996].

In Caribbean Vertisols, sugarcane is the dominant crop and grown in both rainfed and irrigated conditions. In Guyana, the soils are rejuvenated periodically by flood fallowing. In Jamaica, the crop is grown with full irrigation, and in Trinidad, under rainfed conditions, the cropping cycle is synchronized with the seasons. Rice is grown continuously throughout the year where irrigation is available [Ahmad 1996].

In Australia, Vertisols are extensively used for dryland agriculture in the east and south. Wheat, safflower, barley, and oats are winter crops, and sorghum, maize, cotton, soybean, sunflower, and millets are grown as summer crops. Under irrigated conditions, cotton, some grain and fodder crops, and rice are grown [Ahmad 1996].

More than half of Vertisols in the United States are confined to Texas, where mean annual precipitation ranges from 760 to 1150 mm [Puentes et al. 1988]. This precipitation is received mainly before or during the growing season and the favorable rainfall makes these soils productive. Wheat, oats, sorghum, and maize are important crops;

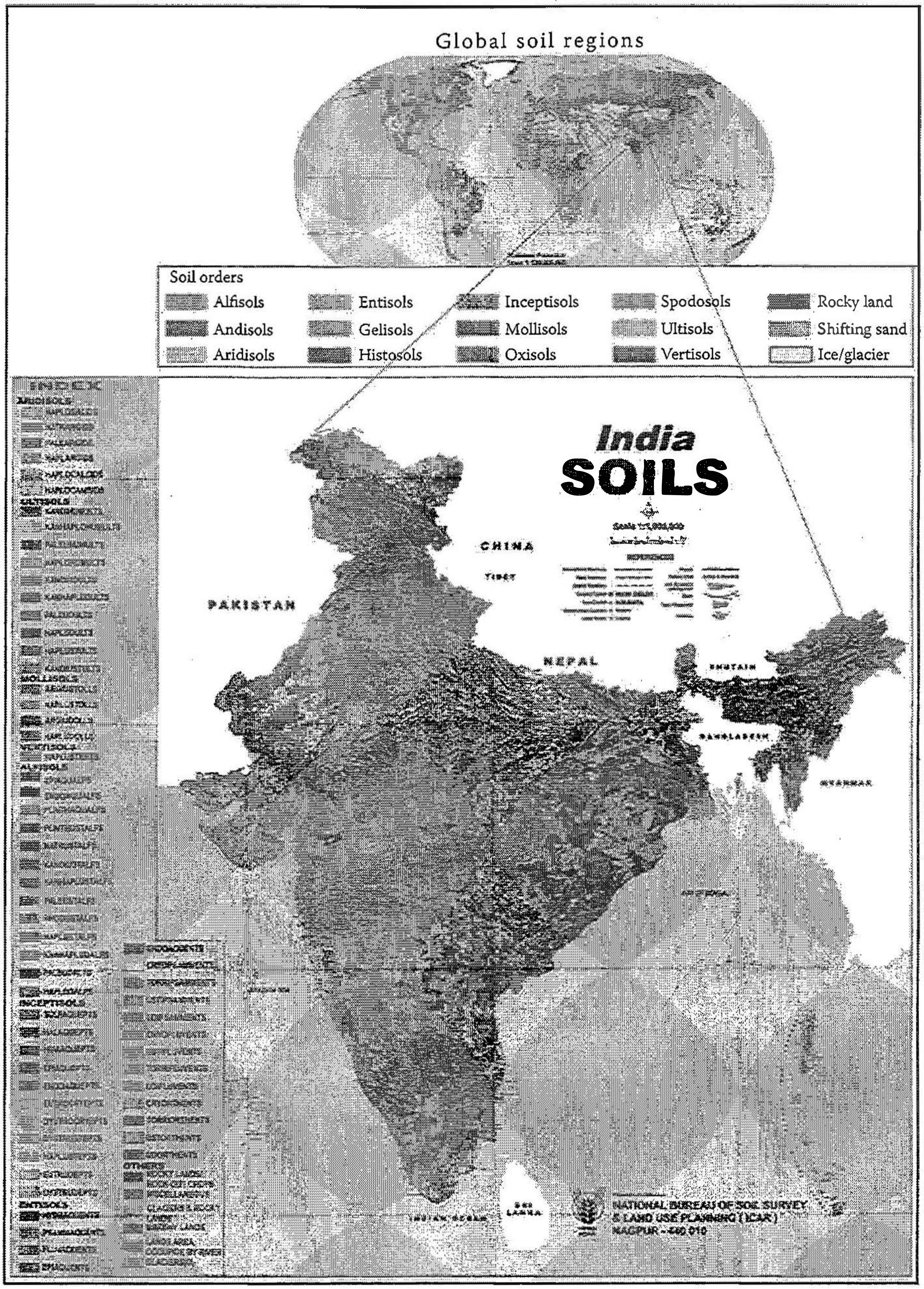

FIGURE 7.1 Global distribution of Vertisols indicating areal extent in India. (From staff of National Bureau of Soil Survey and Land Use Planning, 2002.)

other crops are cotton and hay. The land-use pattern in the upper coast area is more diverse with grain sorghum, soybean, rice, maize, and cotton. With limited irrigation, cotton and sorghum are the main crops grown [McKee and Hajek 1973].

These agricultural land-use scenarios clearly highlight that even though Vertisols make up a relatively homogeneous major soil group, they occur in a wide range of climatic environments throughout the world and show a considerable variability in their land uses and crop productivities [Coulombe et al. 1996; Syers et al. 2001].

In view of their shrink-swell properties and stickiness, Vertisols are recognized by a number of local regional and vernacular names [Dudal 1965; Dudal and Eswaran 1988]. In India alone, they are known by at least 13 different names [Murthy et al. 1982] that are related either to their characteristic dark color or some aspect of their difficult workability or both. Thus, these soils exhibit spatial and temporal variability in their properties and remain difficult land resources to manage successfully. This variability, however, needs to be fully comprehended while developing technologies improve their performance.

Soil is an open system within an ecosystem and it is strongly influenced by the external environment. Therefore, it becomes very necessary to understand the factors that cause the variability in their properties. A critical review of the recent developments

TABLE 7.1
Distribution of Vertisols in Different States of India under a Broad Bioclimatic System

States	Bio-Climate[a]	Area (Mha)(%)[b]
Uttar Pradesh	SAM, SHD	0.41 (0.12)
Rajasthan	AD	0.98 (0.30)
Gujarat	AD, SAD, SAM	1.88 (0.57)
Madhya Pradesh	SAM, SHD, SHM[c]	10.75 (3.27)
Maharashtra	SAD, SAM, SHD, SHM[c]	5.60 (1.70)
Andhra Pradesh	SAD, SAM, SHD	2.24 (0.68)
Karnataka	AD, SHD, SHM, H	2.80 (0.85)
Tamil Nadu	SAD, SAM, SHD, SHM, H	0.91 (0.28)
Puducherry and Karaikal	SHM	0.011 (0.003)
Jharkhand	SHM, SHD	0.11 (0.034)
Orissa	SHM, SHD, H	0.90 (0.28)
India		26.62 (8.10)

Source: Bhattacharyya, T. et al., NBSSLUP Publication 143, 2009.

[a] AD: arid dry, 100–500 mm MAR (mean annual rainfall); SAD: semiarid dry, 500–700 mm MAR; SAM: semiarid moist, 700–1000 mm MAR; SHD: subhumid dry, 1000–1200 mm MAR; SHM: subhumid moist, 1200–1600 mm MAR; H: humid, 1600–2500 mm MAR.

[b] Parentheses indicate percent of the total geographical area of the country.

[c] In addition, Vertisols occur in HT climate (>2500 mm MAR) in Madhya Pradesh and Maharashtra, but they are not mapable in 1:250,000 scale [Bhattacharyya et al. 1993, 2005, 2009; Pal et al. 2009b].

in Vertisols research is necessary, as agricultural productivity is firmly rooted in the physical, chemical, and biological properties of soils [van der Merwe et al. 2001]. As in several parts of the world, Vertisols occur in wide climatic zones in India (Figure 7.1). They are found in humid tropical (HT), humid (H), subhumid moist (SHM), subhumid dry (SHD), semiarid moist (SAM), semiarid dry (SAD), and arid dry (AD) climatic environments [Bhattacharyya et al. 1993, 2005, 2009; Pal et al. 2009a, 2009b] in eleven states of India (Table 7.1). These soils have attracted scientific attention since the nineteenth century [Leather 1898; Harrison and Sivan 1912], mainly from India where they were historically important agricultural soils for growing cotton. A review on an array of Vertisols in a climosequence of India and the modification of soil properties (if any) impairing or favoring the crop productivity appears to be an excellent model case study to address and understand the factors for the variability in Vertisols vis-à-vis their agricultural land uses and crop productivity. Development of such state-of-the-art information may guide stakeholders in better understanding the intricacies of Vertisols for their efficient use and management in varied climatic environments, not only in tropical India but in the other tropical parts of the world.

7.2 VERTISOLS IN A CLIMOSEQUENCE: THEIR FORMATION AND MODIFICATIONS IN THEIR PROPERTIES

7.2.1 Formation

The majority of Vertisols in India occur in the lower piedmont plains or valleys [Pal and Deshpande 1987], or in microdepressions [Bhattacharyya et al. 1993]. They are developed mainly in the alluvium of weathering Deccan basalt [Pal and Deshpande 1987; Bhattacharyya et al. 1993] mostly during the Holocene period [Pal et al. 2001, 2006].

Frequent climatic changes occurred during the Quaternary [Ritter 1996]. As a result, the soils of many places of the world witnessed climatic fluctuations, especially in the last postglacial period. Brunner [1970] reported evidence of tectonic movements during the Plio-Pleistocene transition, which caused the formation of different relief types and relief generation. With the formation of the Western Ghats during the Plio-Pleistocene crustal movement, the humid climate of the Miocene-Pliocene was replaced by the semiarid conditions that continue to prevail in central and southern Peninsular India. The Arabian Sea flanks the Western Ghats, which rise precipitously to an average height of 1200 m, the result of a heavy orographic rainfall all along the west coast. The leeside toward the east receives less than 1000 mm of rainfall and is typically rain-shadowed [Rajaguru and Korisetter 1987]. The current aridic environment prevailing in many parts of the world, including India [Eswaran and van den Berg 1992], may create adverse physical, chemical, and biological properties of soils [Pal et al. 2001]. A recent study [Pal et al. 2009b] indicates that the color of Vertisols in HT climates is dark brown (7.5YR 3/3) to dark-reddish (5YR 3/3) and yellowish brown (10YR 4/3), and dark (10YR 3/1) to dark-grayish brown (10YR 3/2) in soils of other climates (SHM, SHD, SAM, SAD, and AD). Structurally, they are small, weak wedge-shaped aggregates with pressure faces that break to weak, angular blocky structures in soils of HT climates. In soils of SHM, SHD, SAM, SAD, and AD climates, their structure is strong, medium subangular

TABLE 7.2
Properties of Vertisols in a Climosequence

Climosequence Properties	Humid Tropical (HT)	Subhumid Moist (SHM)	Subhumid Dry (SHD)	Semiarid Moist (SAM)	Semiarid Dry (SAD)	Arid Dry (AD)
Soil color	7 5YR 3/3 to 5YR 3/3	←------ ---- ----- -------10YR 3/1 to 10YR 3/2---------------- ---→				
Subsoil structure	Weak and small wedge shaped aggregates that break to weak subangular blocks with pressure faces	Strong, medium subangular blocky to strong, coarse angular blocky with pressure faces and slickensides that break into small angular peds				
Cracks	>0 5 cm wide, extend down to the zones of spheroids and wedge-shaped peds with smooth or slickensided surface				Deep cracks cut through Bss horizons	
Microfabric	Poro/grano/reticulate striated plasmic fabric indicating high shrink-swell activity		Stipple/ mosaic-speckled plasma indicating moderate shrink-swell activity	Mosaic/ crystallitic plasma indicating moderate shrink-swell activity	Mosaic/ stipple-speckled plasma indicating low shrink-swell activity	Crystallitic plasma indicating very low shrink-swell activity
Classification	Typic Haplusterts		Typic/aridic Haplusterts		Sodic Haplusterts and sodic Calciusterts	

Source Pal, D K , et al , *Quaternary International* 209, 6–21, 2009b blocky to strong, coarse angular blocky with pressure faces and slickensides that break into small angular peds (Table 7.2). In soils of HT, SHM, SHD, and SAM climates, cracks > 0.5 cm wide extend down to the zones of sphenoids and wide-shaped peds with smooth or slickensided surfaces, whereas cracks cut through the slickensided horizons (Bss) in soils of SAD and AD climates (Table 7.2, Figure 7.2).

With the lowering of mean annual rainfall (MAR), the soils are more alkaline, calcareous, and sodic due to a progressive increase in pedogenic $CaCO_3$ (PC) content in HT to AD climates (Figure 7.2). This demonstrates the fact that the aridity in the climate is the prime factor in the formation of calcareous sodic soils (showing the presence of calcium carbonate and exchangeable sodium percentage, ESP ≥ 5), as evidenced by the formation of typic Haplusterts in HT, typic/udic Haplusterts in SHM, SHD, and SAM, and sodic Haplusterts and sodic Calciusterts [Soil Survey Staff 2006] in SAD and AD climates, respectively (Table 7.2, Figure 7.2).

Smectite clay minerals are ephemeral in the HT climate and they transform to kaolin [Pal et al. 1989; Bhattacharyya et al. 1993]. Thus, it is difficult to understand the formation of Vertisols in HT climates. Ca-zeolites in these soils provide sufficient bases to prevent the complete transformation of smectite to kaolin. The presence of smectites and zeolites make the formation of Vertisols possible in lower physiographic positions, even under HT climates. The formation and persistence of slightly acidic to acidic Vertisols, not only in western and central India [Bhattacharyya et al. 1993, 1999, 2005] but elsewhere [Ahmad 1983], can only be possible in the presence of soil modifiers (Ca-zeolites, gypsum) that maintain the base saturation of these soils well above 50% [Pal et al. 2003c, 2006].

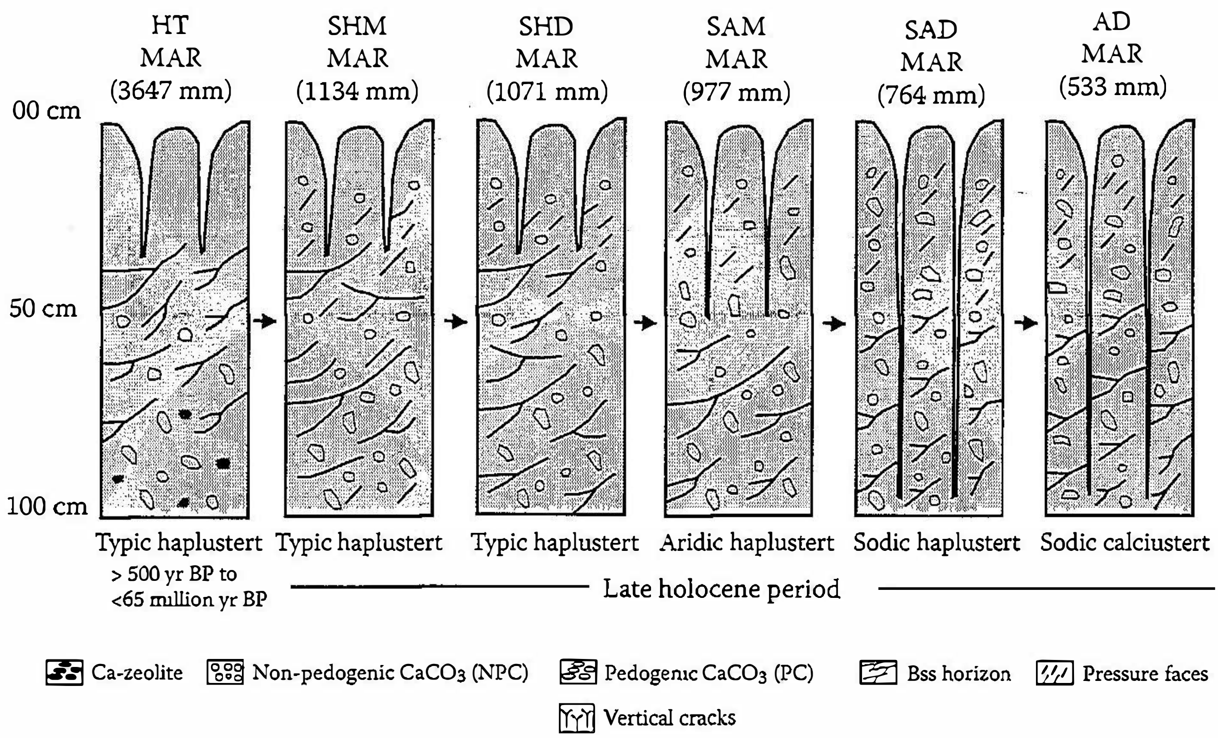

FIGURE 7.2 Successive stages of pedogenic evolution of Vertisols in a climosequence from humid to arid climate. (Based on data from Pal, D.K. et al., *Quaternary International* 209, 6–21, 2009b.)

In arid climatic environments, the weathering of primary minerals contributes very little toward the formation of smectite and it has been demonstrated that the formation of PC at the expense of nonpedogenic $CaCO_3$ (NPC) is the prime chemical reaction that triggers the increase in pH, exchangeable Mg^{+2}, and Na^+ on the exchange complex [Pal et al. 2000, 2009b; Srivastava et al. 2002]. The fine clay smectite of these soils is fairly well crystallized, but is also partially hydroxy-interlayered [Pal et al. 2009c]. Hydroxy-interlayering in smectite can occur in an acidic environment at a pH well below 8.3 [Jackson 1964]. The Vertisols of subhumid, semiarid, and arid climates are calcareous and some are sodic. Thus, hydroxy-interlayering does not appear to be a contemporary pedogenic process in the prevailing dry climatic conditions. The crystallinity of smectite is, however, preserved in the nonleaching environments of the subhumid to dry climates. This suggests that smectite in Vertisols must have formed in an earlier more humid climate and been deposited in the lower Piedmont Plains, valleys, or in microdepressions where the majority of Vertisols of India occur. These Vertisols are thus developed during the drier climate of the Holocene [Pal et al. 2009b].

7.3 MODIFICATION IN SOIL PROPERTIES VIS-A-VIS THE PEDOGENIC THRESHOLD

The soils of the SHM and SHD do not generally contain PC in the first 50 cm of the profile (Figure 7.2) and have better drainage (saturated hydraulic conductivity, sHC > 20 mm hr^{-1}, Table 7.3). The subsoils of the Vertisols in SAM, SAD, and AD climates, due to the accelerated rate of formation and accumulation of PC, are becoming sodic, impairing their sHC even in the presence of soil modifiers like Ca-zeolites (Table 7.3) [Pal et al. 2006, 2009b]. The initial impairment of the percolative moisture regime in the subsoils (caused either by exchangeable Mg (EMP), or exchangeable Na (ESP), or both) results eventually in a system where gains exceed losses. This self-terminating process [Yaalon 1983] leads to the development of aridic to sodic Haplusterts and, subsequently, to sodic Calciusterts [Pal et al. 2009b].

Vertisols have considerable amounts of water-dispersible clay (WDC) [Pal et al. 2006, 2009b], which increases with depth. This proves that an adequate dispersion of clay smectite is possible in a slightly acidic to moderately alkaline pH under a very low electrolyte concentration (ECe ≤ 1 me L^{-1}) [Pal et al. 2006, 2009b]. This ensures a conducive pH condition higher than the zero point of charge required for full dispersion of clay [Eswaran and Sys 1979]. Thus, the movement of deflocculated fine clay smectite and its subsequent accumulation in the Bss horizons is possible in noncalcareous as well as calcareous Vertisols. The depth distribution of EMP and ESP and soluble Na^+ ions in the majority of Vertisols of India [Pal et al. 2003c, 2006, 2009b] indicates clearly that the precipitation of $CaCO_3$ as PC enhances the pH and also the relative abundance of Na^+ ions, both in soil exchange and soil solution. The Na^+ ions, in turn, cause the dispersion of smectites to translocate down the depth of soils. Thus the formation of PC and clay illuviation are two concurrent and contemporary pedogenic events that provide an appropriate soil environment to bring the pedogenic threshold during the dry climates of the Holocene until a further change in climate sets in [Pal et al. 2003a, 2009b].

TABLE 7.3
Hydraulic Properties of Vertisols as Influenced by ESP in the Presence and Absence of Ca-Zeolites

Horizon	Depth cm	Clay %	Fine Clay %	sHC mm hr^{-1}	sHC mm hr^{-1} weighted mean[a]	CEC cmol(p+)kg^{-1}	ESP	Base Saturation %	Saturation Extract Residual Sodium Carbonate (RSC) me/L
				Zeolitic: Kheri soils: Subhumid moist: Typic Haplusterts					
Ap	0–14	51.1	27.3	23	23.0	48.0	0.8	98	–0.06
Bw1	14–32	53.7	32.2	32		48.0	0.8	90	1.31
Bw2	32–61	46.3	31.0	22		53.5	0.9	85	1.55
Bss1	61–82	53.6	28.7	21		49.3	0.8	109	1.99
Bss2	82–112	46.6	33.7	16		49.3	1.2	83	1.33
Bss3	112–133	44.6	27.0	10		49.3	0.8	85	0.22
Bss4	133–156	47.7	34.8	20		52.1	1.1	80	0.65
				Nonzeolitic: Paral soils: Semiarid dry: Sodic Haplusterts					
Ap	0–9	55.3	22.6	17	4.0	54.4	1.4	84	0.07
Bw1	9–35	58.9	30.7	5		56.5	4.1	79	0.94
Bss1	35–69	56.9	29.5	2		47.8	8.1	92	5.89
Bss2	69–105	62.6	35.6	3		51.8	14.2	97	6.95
Bss3	105–132	61.8	37.6	1		52.5	16.7	91	ND[b]
Bss4	132–150	56.3	37.6	1		43.3	21.0	100	ND

TABLE 7.3 (Continued)
Hydraulic Properties of Vertisols as Influenced by ESP in the Presence and Absence of Ca-Zeolites

Horizon	Depth cm	Clay %	Fine Clay %	sHC mm hr^{-1}	sHC mm hr^{-1} weighted mean[a]	CEC cmol(p+)kg^{-1}	ESP	Base Saturation %	Saturation Extract Residual Sodium Carbonate (RSC) me/L
Zeolitic: Jhalipura soils: Semiarid dry: Typic Haplusterts									
Ap	0–12	45.0	25.1	8	10.0	36.5	3 6	98	−1 16
Bw1	12–31	47 6	27 9	15		36 5	2.5	108	0.70
Bw2	31–48	52.4	31.4	7		40.2	1.5	105	0 60
Bss1	48–74	49 2	31.4	6		37.0	1.6	110	−1.58
Bss2	74–110	50.0	31.2	13		36.5	1.6	106	1.11
Bss3	110–148	50.9	32.6	14		37.0	1.9	109	0.05
Bss4	148–165	50.4	29.1	3		38.0	4 2	112	1.04
Zeolitic: Vasmat soils: Semiarid moist (irrigated): Sodic Haplusterts									
Ap	0–20	64 0	46 2	18	13.0	47.6	4 2	107	0.59
Bw1	20–42	66.9	45 8	17		45.3	10.4	119	2 24
Bw2	42–68	66.3	48.0	5		46.7	18.8	94	0 95
Bss1	68–102	66.4	46 4	10		45.9	13 7	105	0.99
BC/Bss	102–131	59.1	37 5	13		47.8	12.1	103	0.44
Bss2	131–150	70.9	44.3	12		51.3	8.0	109	0.60

Source: Pal, D.K., et al. Developing a model on the formation and resilience of naturally degraded black soils of the Peninsular India as a decision support system for land use planning. NRDMS, DST Project Report, Nagpur, India, 2003c

[a] Weighted mean of 0–100 cm ; [b] ND = not determined.

The dominant presence of poro/parallel/grano/reticulate-striated plasmic fabric indicates high shrink-swell activity of smectites in soils of HT and SHM climates [Pal et al. 2009b]. On the other hand, the dominant presence of stipple/mosaic-speckled plasma in soils of SHD, mosaic/crystallitic plasma in soils of SAM, mosaic/stipple-speckled plasma in soils of SAD, and crystallitic plasmic in soils of AD climates suggests that shrink-swell magnitude is much less in the soils of drier climates compared to HT and SHM climates, as manifested in poor plasma separation. Thus, weak swelling is sufficient for the development of sphenoids and/or slickensides, but not adequate to cause a strong plasma separation [Pal et al. 2006, 2009b].

The sHC decreases rapidly with depth in all soils, but the decrease is sharper in both zeolitic and nonzeolitic soils of SAD and AD climates (Table 7.3), because of their subsoil sodicity [Pal et al. 2006, 2009b]. The decreased sHC restricts both vertical and lateral movement of water in the soils. During the very hot summer months, this would result in much less water in the subsoils of SAD and AD climates. This is evident from the deep cracks cutting through the Bss horizons (Figure 7.2). The lack of adequate soil water during the shrink-swell cycles restricts the swelling of smectite and results in weaker plasma separation. The subsoils of SAM, SAD, and AD remain under a smaller amount of water as compared to those of HT, SHM, and SHD climates [Pal et al. 2006, 2009b]. These polygenetic soils with very low water-supplying capacity to plants would lose further crop productivity in the event of more climatic adversities [Pal et al. 1989, 2001, 2009b]. Such situations shall remain a challenge for resource-poor farmers growing more than one crop in a year (Figure 7.3).

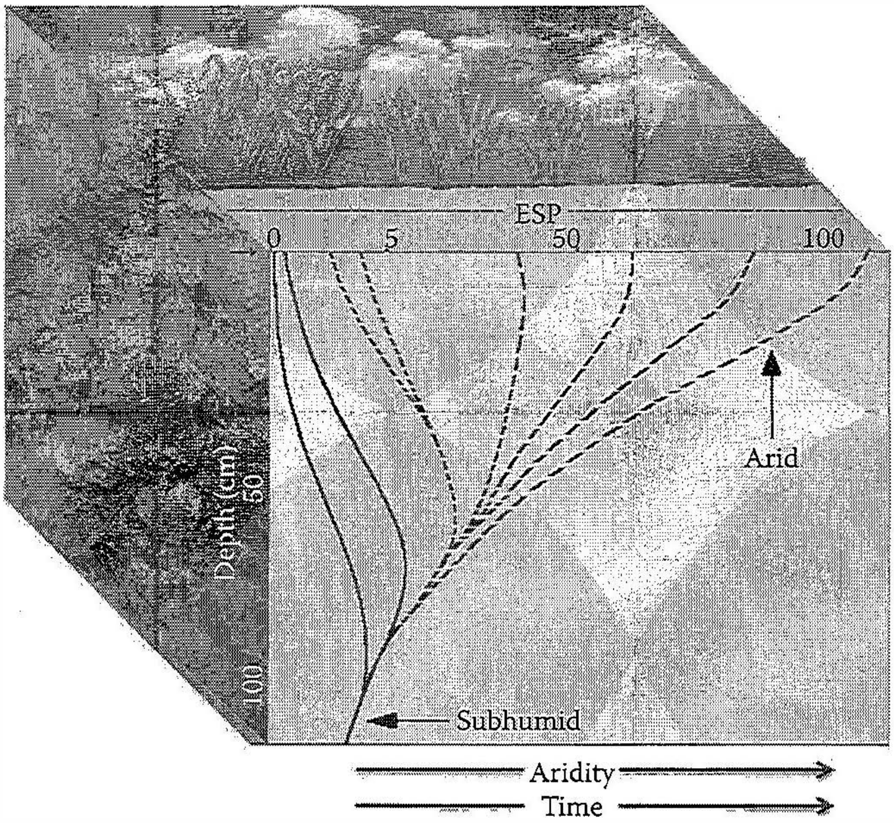

FIGURE 7.3 Projected view of the progressive development of soil sodicity from a wet to dry climate with time, a threat to resource-poor farmers.

7.4 PEDOGENIC THRESHOLD AND SOIL AND CROP PRODUCTIVITY

7.4.1 Pedogenic Threshold in Dry Climates

The pedogenic threshold in soils of dry climates during the Holocene has been realized as a natural soil degradation process induced by tectonic- and climate-linked events [Pal et al. 2003a, 2003b, 2009a, 2009b]. An example from benchmark Vertisols, with and without soil modifiers, representing a climosequence from SHM to AD climates (Table 7.4) indicates that dry climates during the late Holocene restricted further leaching and as a result, the formation of PC was favored [Pal et al. 2001]. The amount of PC in the first 1 m of the profile of soils of a representative climatic region indicates in general a progressive increase in the rate of formation of PC (from 0.39 to 2.12 mg per 100g soil per year) and ESP (from 1 to 28), and a decrease in sHC (from 33 to 2 mm hr^{-1}) (Table 7.4).

7.4.2 Loss in Crop Productivity Due to Pedogenic Thresholds

Vertisols have limitations that constrain their full potential to grow both rainy-season and winter crops (NBSS and LUP-ICRISAT 1991). This situation is observed at Nagpur, Amravati and the Akola districts of Maharashtra in central India. Vertisols of the western part of Amravati and the adjoining Akola district support either kharif/rabi (summer/winter) crops, whereas in the Nagpur district, both crops are grown with limited irrigation [Kadu et al. 2003]. The MAR in Akola, Amravati, and Nagpur is 877, 975, and 1127 mm, respectively. This indicates more aridity in Akola than in Amravati or Nagpur. Vertisols of these districts are deep-ploughed (30-cm soil depth) once every 2 to 3 years where a blade harrow is used each summer before the onset of monsoon season. The system is monoculture (cotton) with 4 months of fallow (February–May). Frequent blade harrowing is done after rains to produce the necessary tilth for sowing. Organic manures are added every 2 years. Improved cultivars are hand sown at a depth of about 5 cm on marker intersection points at appropriate times. The interrow spacing is 75–90 cm. Repeated intercultural operation is done to remove weeds, improve aeration, and to adsorb maximum moisture from receding rains, as well as to function as a dust mulch during the postrainy season. The first intercultural operation is carried out 20–25 days after sowing, which is followed by fertilizer application (N-P-K 18:18:10). Cotton yield (average of 5–6 years covering an area of about 200 ha in each village) was collected during the study by periodic contact with eight to ten farmers during 1991–2001. The variation in yield between years was about 40%. The maximum yield of cotton (1.8 t ha^{-1}) obtained by the farmers following the typical management was taken as the optimum yield [FAO 1983] to evaluate the soils [Kadu et al. 2003]. Under similar soil management by farmers in 29 Vertisol (pedons) areas, and also under similar soil moisture and temperature regimes, cotton yields were better in the soils of Nagpur than those of Amravati and Akola (Table 7.5). The subsoils in Amravati and Akola are becoming sodic due to accelerated rates of formation and accumulation of PC.

TABLE 7.4
Rate of Formation of PC and Concomitant Development of ESP in Vertisols of a Representative Climatic Region in India

Soil Series[a] (District, State)	$CaCO_3$ (%)[b]	Rate of Formation of PC[b]	Maximum ESP in 1-m Profile	sHC (mm hr^{-1})[b]
	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[c]	6[c]
	Semiarid Dry (MAR 842–583 mm)			
Jhalipura (Typic Haplusterts) (Kota, Rajasthan)	5.5	0.57	3.6[d]	10[d]
Teligi (Sodic Haplusterts) (Bellary, Karnataka)	9.6	0.94	17[d]	24[d]
Kovilpatti (Gypsic Haplusterts) (Thoothokudi, Tamil Nadu)	7.9	1.02	1[e]	33[e]
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 (Sodic Calciusterts) (Rajkot, Gujarat)	21.7	2.12	28[c]	17[c]

Source: Pal, D.K., et al., 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, 2003c.

Note: PC = pedogenic $CaCO_3$; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity; MAR = mean annual rainfall. [a]Soil Survey Staff [2003], [b]weighted mean in the first 1 m of the profile, [c]irrigated, [d]Ca-zeolitic, [e] gypsic.

TABLE 7.5
Range in Values of PC, ESP, sHC, and Yield of Cotton in Vertisols of Vidarbha, Maharashtra

District, Maharashtra, Central India	Soil Classification	PC (%)	ESP	sHC (mm hr^{-1}) Weighted Mean in the Profile (1 m)	Cotton Yield (tz ha^{-1}) (seed + lint)
Nagpur (MAR 1011 mm)	Typic Haplusterts/ Typic Calciusterts	3–6	0.5–11	4–18	1.0–1.8
Amravati	(a) Aridic Haplusterts	3–7	0.8–14	2–19	0.6–0.7
(MAR 975 mm)	(b) Sodic Haplusterts	3–13	16–24	0.6–9.0	0.3–0.8
Akola	(a) Aridic Haplusterts	3–4	16–44	3–4	1.0
(MAR 877 mm)	(b) Sodic Haplusterts	3–4	19–20	1–2	0.6

Source: Kadu, P.R.
Note: PC = pedogenic $CaCO_3$; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity.

This impairs their sHC and, hence, a significant positive correlation between cotton yield and sHC was observed [Kadu et al. 2003].

7.4.3 Loss in Soil Productivity Due to Irrigation

Many productive cracking clay soils under rainfed conditions have been unrendered for agriculture through irrigation. Such a menacing situation is not only confined to irrigated (command) areas but also occurs in situations where river or well waters are used for irrigation [Nimkar et al. 1992; Pal et al. 2003c]. In 7 years of irrigation, nonzeolitic Vertisols at Chendkapur, Amravati district, Maharashtra have become more calcareous and ESP shows a four-fold increase as compared to nonirrigated soils. Likewise the ECe shows a two- to three-fold increase. In addition, soils have become highly alkaline and the sHC has been impaired (Table 7.6). On the other hand, some zeolitic Vertisols (at Vasmat, Hingoli district, Maharashtra) in SAD climates are being irrigated through canals to produce sugarcane for the past 2 decades. These soils lack salt-efflorescence on the surface and are not waterlogged at present. This apparently suggests that these soils are not degraded due to better drainage (please see sHC in Tables 7.3 and 7.6). However, values of pH, ECe, $CaCO_3$, and ESP of the same soil, with and without irrigation, indicate the development of sodicity in irrigated soils (Table 7.6). The presence of Ca-zeolites ensures a constant supply of soluble Ca^{2+} ions that help in maintaining sHC > 10 mm hr^{-1} (Table 7.6). Natural endowment with modifiers in soils is not uncommon in other parts of the world. No ill effects of high ESP (>15) in crop production in the Vertisols of Gezira in Sudan or in Tanzania
1996]; Vertisols of both the places showed high base saturation, mainly with Ca^{2+} ions. It appears that these soils might contain soil modifiers like zeolites,

TABLE 7.6
Comparative Soil Properties of Unirrigated and Irrigated Deep Black Soils (Haplusterts) of Maharashtra, India

Depth (cm)	pH (1:2 water)	ECe (dS m⁻¹)	$CaCO_3$ (<2 mm) %	SAR	ESP	sHC (mm hr⁻¹)
			Unirrigated Chendkapur Soils[a]			
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[a]			
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[b]			
0–18	8 4	0 94	21 5	–	4 0	26
18–45	8 2	2 50	17 7	–	4 6	34
45–77	8 2	2 64	17 4	–	5 5	35
77–108	8 7	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[b]			
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

Source [a]Nimkar, A M , et al , *Agropedology*, 2, 59–65, 1992, [b] Pal, D K , et al , 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, 2003c

Note ECe = electrical conductivity of the saturation extract, SAR = sodium adsorption ratio, ESP = exchangeable sodium percentage, sHC = saturated hydraulic conductivity as suggested by base saturation in excess of 100 [Bhattacharyya et al. 1999]. However, sustainability of crop productivity in dry climates, even in the presence of soil modifiers may not be possible because pedogenic thresholds in dry climates would make these soils more calcareous, sodic, and impermeable to water with time (Figure 7.3).

Many Vertisols in higher MAR regions (>1400 mm) are cultivated to rice with well-water irrigation, like growing sugarcane in both nonacidic and near-neutral Vertisols in India [Pal et al. 2003c]. Despite the probable presence of Ca-zeolites, such Vertisols (Kheri, Table 7.3) have accumulated HCO_3^- and CO_3^{--} ions in their soil solution, making residual sodium carbonate (RSC), ranging from 1 to 2 (Table 7.3). This practice caused the decline in wheat productivity and impaired sHC in the subsoils (sHC ≤ 20 mm hr^{-1}) (Table 7.3). Thus, Vertisols of SHM to AD climates need to be cultivated to crops that are possible under rainfed agricultural management even though the soils have modifiers. However, the beneficial effect of soil modifiers can be realized in HT climates through sustained productivity of rice and sugarcane in both slightly acidic to acidic Vertisols of the Caribbean that are highly base-saturated (>100%), even in the presence of very high organic carbon content (>>1%) [Ahmad 1996].

7.5 MANAGEMENT INTERVENTION IN VERTISOLS VIS-À-VIS ENHANCEMENT OF CROP PRODUCTIVITY

The loss and gain of Ca^{2+} ions during the formation of PC and dissolution of soil modifiers have a relevance both in soil exchange and soil solution for crop productivity by improving the hydraulic property of soils [Pal et al. 2006] besides their (Ca^{2+} ions) role as environmental sensors [Nayyar 2003]. The cultivation of sugarcane and rice has been successful because of the continuous supply of Ca^{2+} ions by the soil modifiers, even in HT climates. Sustainability of such agricultural land use is likely to remain as a viable management intervention for years, until the Vertisols become devoid of soil modifiers forever. However, despite their role in improving sHC, the use of irrigation, either with canal or well water, cannot help sustain the good crop yield because of the development of high pH, ECe, $CaCO_3$, and ESP in Vertisols in different climatic environments.

The presence of $CaCO_3$ (mainly the PC) in Vertisols has generally been considered of doubtful significance in replacing exchangeable Na^+ ions by Ca^{2+} ions of $CaCO_3$ at a pH around 8.0. However, it is generally affected by other factors such as the application of gypsum, followed by cropping. The beneficial effect of naturally endowed gypsum has been realized in the Vertisols of southern Peninsular India, even in SAD climates. Such gypsum-containing Vertisols have sHC > 30 mm hr^{-1} and ESP < 15 (Table 7.7), despite rapid formation of PC because of the much higher solubility of gypsum than Ca-zeolites [Pal et al. 2006]. Even after realizing the beneficial role of gypsum in the slightly to highly sodic soils of the Indo-Gangetic Plains (IGP) and Vertisols, in terms of better physical, chemical, and biological properties [Gupta and Abrol 1990; Rao and Ghai 1985], the use of gypsum as management intervention in Vertisols of the dry climates of western, central, and southern Peninsular India is not commonly practiced [Venkateswarlu 1984; Pal et al. 2009c], unlike in similar soils

TABLE 7.7
Physical and Chemical Properties of Vertisols Endowed with Gypsum in Semiarid Dry Parts of Tamil Nadu, India

Depth (cm)	pH (1:2 Water)	ECe (dS m^{-1})	$CaCO_3$ (<2 mm) %	ESP	sHC (mm hr^{-1})
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

Source: Pal, D.K., et al., 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, 2003c.

Note: ECe = electrical conductivity of the saturation extract; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity.

in Australia [McGarity et al. 1988]. In dry areas of Australia, the positive response to gypsum and gypsum deep tillage could be due to increased water storage in subsoils. This management intervention offers a cost-effective means of increasing crop productivity under rainfed agricultural systems [McGarity et al. 1988].

Under rain-fed 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 the crop growth [Kadu et al. 2003; Pal et al. 2006]. In the semiarid part of western and central India, rainfed cotton is grown under suboptimal conditions, with soil depth and moisture availability as the main limitations. Field experiments conducted in the Yavatmal district of Maharashtra (central India) [Venugopalan et al. 2004] on the comparison of soil properties of Vertisols of SAM climates under organic and nonorganic (conventional) cotton production systems indicate that the yield of cotton and component crops grown under the organic production system were higher than those of the nonorganic production system and, in general, the productivity was higher than the average productivity of the district. Even in a hot, semiarid climate, higher values of soil organic matter (SOC) (>0.6%) in the organic production system have been due to the sequestration of carbon (Table 7.8) as compared to conventional systems [Venugopalan et al. 2004]. The limits of SOC content of the typical soil association of smectitic and noncalcareous Mollisols–Alfisols–Vertisols of tropical India under various land uses indicate that the clay mineral type of soils could be one of the important factors influencing the build-up of SOC. Such agricultural management intervention can help the sequestration of SOC, even up to 1% [Bhattacharyya et al. 2005]. Due to improvement in SOC

TABLE 7.8
Comparison of Chemical Properties of Surface Soils (0–20 cm) under Organic and Conventional Production Systems (Based on 55 Soil Samples)

	Conventional Farming		Organic Farming	
Properties	**Range**	**Mean**	**Range**	**Mean**
pH (1:2 water)	7.7–8.4	8.0	7.1–8.1	7.7
OC (%)	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

Source: Venugopalan, M.V., et al., 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, 118–121. 2004.

and the subsequent dissolution of $CaCO_3$, the pH of soils under organic production systems remained below 8.1 (Table 7.8).

A long-term heritage watershed experiment initiated in 1976 at the ICRISAT Centre, Patancheru, Andhra Pradesh, India under rainfed conditions to demonstrate how an improved system of catchment management (IM) in combination with an appropriate cropping system can sustain increased productivity and improve the soil quality of Vertisols [Wani et al. 2003, 2007], in comparison to the existing traditional farming (TM) system. The improved system followed soil and water conservation practices, where excess rainwater was removed in a controlled manner. The soil and water conservation practices consisted of improved, legume-based crop rotation and improved nutrient management. In the TM system, sorghum or chickpeas were grown in the postrainy season with organic fertilizers, and in the rainy-season, the field was maintained as a cultivated fallow.

The updated results from this experiment (Figure 7.4) indicate that the average grain yield of the improved cropping system over 30 years was 5.1 t ha^{-1} yr^{-1}, nearly a five-fold increase in the yield over the TM system with an average yield of about 1.1 t ha^{-1} yr^{-1}. The annual gain in yield in the IM system was 82 kg ha^{-1} yr^{-1} as compared to 23 kg ha^{-1} yr^{-1} in the TM system (Figure 7.4). The IM system thus has a higher carrying capacity (21 persons versus 4.6 persons ha^{-1} of the TM system) [Wani et al. 2009]. The IM system shows increased rainwater use efficiency (65% versus 40%), reduced runoff (from 220 mm to 91 mm) and soil loss (from 6.64 t ha^{-1} to 1.6 t ha^{-1}), along with increased crop productivity and carrying capacity of land [Wani et al. 2003]. All these benefits have, however, been possible in the improvement of the hydraulic properties of Vertisols under IM systems as compared to TM systems (Table 7.9). Vertisols under IM and TM system have comparable pH, clay, and fine clay content (weighted mean, WM, in the 0–100 cm), however, the sHC value (WM) of IM has increased by almost 2.5 times due to the reduction in ESP through the dissolution of $CaCO_3$ (Table 7.9). The $CaCO_3$ (WM) content of IM decreased from 6.2% under the TM system to 5.7% (WM). In the past 24 years, the rate of dissolution of $CaCO_3$ is 21 mg yr^{-1} in the first 100 cm of the profile. Under the IM system, the inclusion of pigeonpea, which produces piscidic acid in root exudates that solubilize iron-bound phosphorous (Fe-P) [Ae et al. 1990] and the rootlets in soil through which rainwater passes, or other sources of CO_2 could have caused the increase in solubility of PC and a slight increase in exchangeable Ca/Mg (Table 7.9). Increased SOC sequestration in soils of the tropics induced dissolution of native $CaCO_3$ and its leaching [Bhattacharyya et al. 2001]. The further importance of inorganic carbon in sequestering carbon in soils of dry regions is highlighted by Sahrawat [2003]. The improvement in soil properties through the IM system is also reflected in the classification of Vertisols. The Vertisols under the IM system qualify as typic Haplusterts, after being originally classified as sodic Haplusterts in the TM system (Table 7.9). The contribution of the dissolution of $CaCO_3$ to the improvement of soil quality of the Vertisols under the IM system validates the soil carbon transfer model [Bhattacharyya et al. 2004]. The IM system with better hydraulic properties has also helped the Vertisols to sequester more SOC since 1976. At present, soils under the IM system contain 0.53% SOC in the 0–100-cm soil depth, in comparison with soils under the TM system, which contain 0.42% (Table 7.9). The rate of addition of soil carbon for the past 24 years since 1977 has been around 5 mg yr^{-1} in the first 100 cm of the soil profile of the IM system (Table 7.9).

A study was conducted by ICRISAT and its partners to determine the carbon status of Vertisols at 21 benchmark sites covering arid, semiarid, and moist HT locations in India to identify carbon sequestrating systems [ICRISAT 2004]. The study indicates that after 20 years, the Vertisols sequestered more organic carbon than ferruginous Alfisols. The legume-based systems (high management) sequestered more carbon than the cereals and the horticultural systems, whereas grasslands sequestered more carbon than the annual crops [Bhattacharyya et al. 2007a,c; Sahrawat et al. 2005; Ramesh et al. 2007].

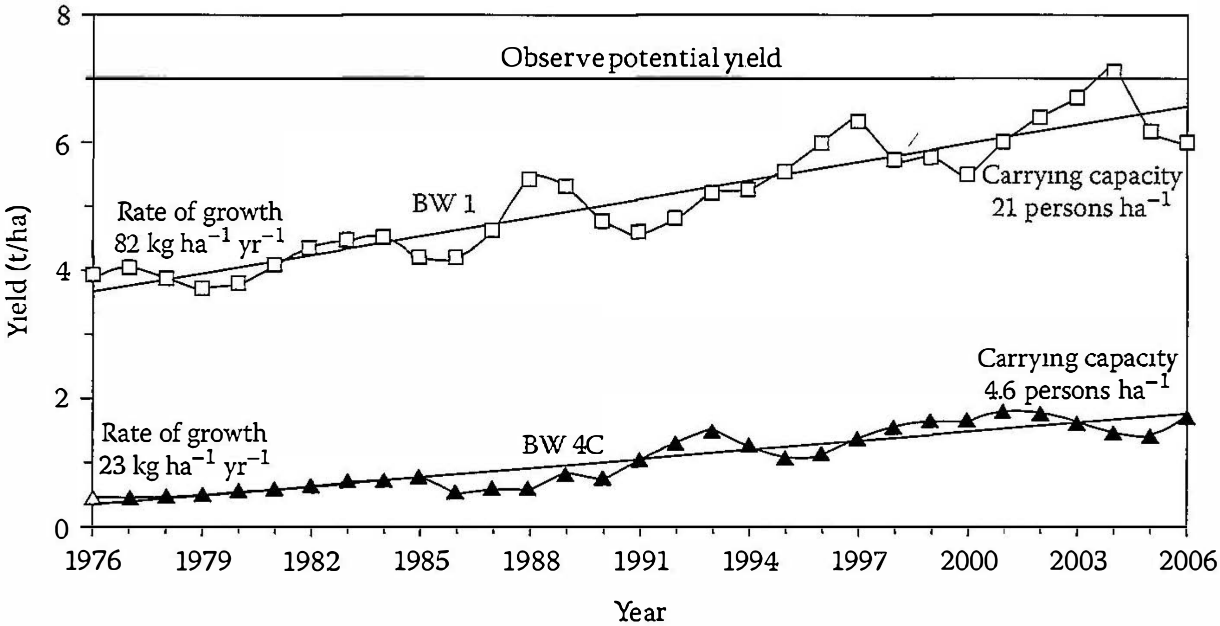

FIGURE 7.4 Three year moving average of sorghum and pigeonpea grain yields under improved (IM) and traditional management (TM) in a deep Vertisol catchment at Patancheru, India. (Based on data from Wani, S.P. et al., *International Journal of Environmental Studies* 64, 719–727, 2007.)

TABLE 7.9
Modification of Physical and Chemical Properties of Vertisols through the Improved Management System at ICRISAT, Patancheru in the 24 Years since 1977

Horizon	Depth cm	Clay %	Clay (%), Weighted Mean in 0–100 cm	Fine Clay %	Fine Clay (%), Weighted Mean in 0–100 cm	sHC mm hr^{-1}	sHC mm hr^{-1}, Weighted Mean in 0–100 cm	pH H_2O (1:2)	Organic Carbon %	Organic Carbon (%) Weighted Mean in 0–100 cm	$CaCO_3$ %	$CaCO_3$ (%), Weighted Mean in 0–100 cm	CEC cmol(p+) kg^{-1}	CEC (cmol(p+) kg^{-1}), Weighted Mean in 0–100 cm	Exchangeable Ca/Mg	Exchangeable Ca/Mg, Weighted Mean in 0–100 cm	ESP	ESP Weighted Mean in 0–100 cm
Kasireddipalli Soil (Sodic Haplusterts) under Traditional Management (TM)[a]																		
Ap	0–12	48.0	53.0	26.4	33.0	7.0	4.0	7.8	0.6	0.42	6.0	6.2	48.7	52.2	3.2	2.2	2.0	8.3
Bw1	12–30	51.4		29.7		6.0		7.8	0.4		6.2		52.1		2.8		4.0	
Bss1	30–59	52.5		32.5		6.0		8.1	0.4		6.0		52.2		2.1		7.1	
Bss2	59–101	55.6		36.4		2.0		8.3	0.4		6.4		53.5		1.8		13.0	
Bss3	101–130	59.4		30.8		2.0		8.3	0.4		6.5		57.8		3.1		8.0	
BCk	130–160	58.0		38.7		1.0		8.2	0.1		9.1		49.5		1.5		22.2	

Kasireddipalli Soil (Typic Haplusterts) under Improved Management (IM)[b]

Ap	0–12	52.1	54.7	28.8	32.8	17.0	11.0	7.5	1.0	0.53	4.2	5.7	50.4	56.0	2 9	2.4	2.0	4.5
Bw1	12–31	51.5		28.1		16.0		7.8	0.6		4.5		54.3		2.4		2 0	
Bss1	31–54	54.2		34.0		10.0		7.8	0.4		6 2		55.6		1.7		3.0	
Bss2	54–84	57.3		40 0		9.0		8 2	0 4		5.1		56.4		1.9		7.0	
Bss3	84–118	56 5		26 0		7.0		8 1	0.5		8 6		61 6		3 8		7.0	
Bss4	118–146	59.3		31 7		3.0		8.2	0.5		8.4		58.2		2.1		7.0	
BC	146–157	60 0		41.5		--		8.2	0.3		7.4		55.2		1 1		9 0	

Source: [a] Pal, D K , et al., 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, 2003c; [b] Bhattacharyya, T., et al. *Physical and chemical properties of selected benchmark spots for carbon sequestration studies in semi-arid tropics of India Global Theme on Agro-ecosystems Report No.* 35, 2007c, Andhra Pradesh, India, ICRISAT and ICAR

Despite an overall benefit of IM systems in enhancing the crop productivity and improving the soil quality of Vertisols of semiarid tropics under rainfed conditions, its widespread adoption at the farmers' level is still fraught with crop failure due to capricious rainfall patterns and socioeconomic constraints [Myers and Pathak 2001].

7.6 CONCLUDING REMARKS

Vertisols are a relatively homogeneous soil group. They occur in a wide range of climatic conditions and exhibit remarkable variability in their properties, either in the presence or absence of soil modifiers (mainly Ca-bearing minerals like Ca-zeolites and gypsum). This review has created a window of updated knowledge that should assist the stakeholders of cracking clay soils (Vertisols and their intergrades) in better understanding the efficient use and management of their soils in the varied climatic environments of the world.

Sustaining the productivity of rice and sugarcane in Vertisols endowed with soil modifiers is possible for a considerable period in HT climates. However, the pedogenic threshold (signifying the natural degradation process), in both zeolitic and nonzeolitic Vertisols of drier climates (SHM, SHD, SAM, SAD, and AD) is causing the decline in productivity of cereals, cash crops (cotton), and legumes. The rate of formation of $CaCO_3$ and the concomitant development of subsoil sodicity in the Vertisols of India provide a realistic scenario as to how the dry climatic conditions pose a threat to agriculture (Figure 7.3), as it demands extra resources for raising crops (especially the winter crops) from resource-poor farmers [Pal et al. 2009a].

Research initiatives on the significance of PC and soil modifiers in the management of the Vertisols of dry climates at the NBSS and LUP (ICAR), Nagpur, India [Srivastava et al. 2002; Pal et al. 2006, 2009a, 2009b, 2009c] 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 solubility of PC can be enhanced by establishing crops through the IM system of ICRISAT, with inclusion of legumes and improved soil water and crop management options. The extra soluble Ca^{2+} ions would lower the equilibrium pH and ESP and make Vertisols more permeable to both air and water. The favorable soil water status would cause the enhancement of crop productivity. Soil modifiers may facilitate further improvement in water statuses in soils to release adequate amounts of water for crops. Vertisols of dry climates can thus show a natural resilience [Pal et al. 2009a].

Rainfed agriculture is predominant (80%) globally; however, current productivity levels are hovering around 1 to 1.5 t/ha^{-1} yr^{-1}. Unlike the holistic approach taken for irrigated agriculture in Green Revolution areas in India, subsistence rainfed agriculture has so far been dealt with by compartments, such as soil conservation, water management, improved cultivars, and fertilizer application. The full potential of the technologies has not been realized, nor have these technologies been adapted on a sufficiently large scale to have a substantial impact [Wani et al. 2007]. In view of stagnating food grain production in the IGP areas, the maintenance of national buffer stock has become more dependent on the contributions by the few states of the northwestern part of the IGP that represent high crop productivity regions [Dhillon et al. 2010]. The total area of the IGP is 43.7 Mha, which produces 50% of the total food grain to feed 40% of the Indian population [Abrol and Gupta 1998; Pal et al. 2009d]. On the other hand, cracking clay soils (Vertisols and their intergrades) are less intensively cultivated as compared to the IGP areas [Bhattacharyya et al. 2007b], even though they occupy a nearly 66-Mha area [Bhattacharyya et al. 2009]. Therefore, areas dominated by cracking clay soils deserve immediate national attention so as to avoid the pitfalls encountered in the high productivity regions of the IGP [Bhattacharyya et al. 2007b; Dhillon et al. 2010]. Adaptation of the IM system may make Vertisols of dry climate more resilient and capable of producing more food grains required for the populous Indian subcontinent.

ACRONYMS

AD	arid hot
ECe	electrical conductivity of the saturation extract
EMP	exchangeable magnesium percentage
ESP	exchangeable sodium percentage
HT	humid tropical
ICAR	Indian Council of Agricultural Research
IGP	Indo-Gangetic Plains
IM	improved management
MAR	mean annual rainfall
NBSS and LUP	National Bureau of Soil Survey and Land Use Planning
NPC	nonpedogenic calcium carbonate
PC	pedogenic calcium carbonate
SAD	semiarid dry
SAM	semiarid moist
sHC	saturated hydraulic conductivity
SHD	subhumid dry
SHM	subhumid moist
SOC	soil organic carbon
TM	traditional management
WDC	water dispersible clay
WM	weighted mean

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