Clay Research, Vol. 31, No. 2, pp. 94-108 (2012)

Role of Calcium Carbonate Minerals in Improving Sustainability of Degraded Cracking Clay Soils (Sodic Haplusterts) by Improved Management: An Appraisal of Results from the Semi-Arid Zone of India

D.K. PAL*, S.P. WANI AND K.L. SAHRAWAT

Resilient Dry land Systems, International Crops Research Institute for the Semiarid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India

Abstract: *A long-term heritage experiment (LTHE) following the improved management (IM) system was initiated in 1976 on bench mark Vertisols (Kasireddipalli soils, Sodic Haplusterts with ESP > 5 but < 15 and saturated hydraulic conductivity, sHC < 10 mm hr^{-1}) under semi-arid tropics (SAT) environments at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) centre, Patancheru, India for increased productivity. It was undertaken to test the hypothesis that the IM system in combination with appropriate cropping practices can improve soil quality in comparison to the prevailing traditional management (TM) practices. The average grain yield of the IM system over thirty years was five times more than that in the TM system. Adaptation of the IM system improved physical, chemical and biological properties of soils to the extent that Sodic Haplusterts now qualify for Typic Haplusterts. Constant release of higher amount of Ca^{2+} ions during the dissolution of $CaCO_3$ (8.4 mg/100g soil/year in 1m profile) under the IM system, compared to slower rate of formation of $CaCO_3$ (0.10 mg/100g soil/year in 1m profile), provided soluble Ca^{2+} ions enough to replace unfavourable Na^{+} ions on the soil exchange sites. Higher exchangeable Ca/Mg ratio in soils under IM system improved the sHC for better storage and release of soil water during dry spell between rains. Adequate supply of soil water helped in better crop productivity and higher organic carbon (OC) sequestration. The improvement in Vertisols' sustainability suggests that the IM system is capable of mitigating the adverse effect of climate change, and the sustainability of the Typic Haplusterts may continue for another couple of centuries under SAT environments, and thus stands for its adaptation on a sufficiently large scale through national and international initiatives.*

***Key words* :** $CaCO_3$, Improved management, ICRISAT, Vertisols' sustainability, SAT, Climate change, Mitigation

Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs for land (W C E D, 1987). Smith and Powlson (2003) adapted this definition to derive a definition for

***Corresponding author :** e-mail: paldilip2001@yahoo.com

sustainable soil management. They defined soil management that meets the needs of the present without compromising the ability of future generations to meet their own needs from that soil. Thus, soil management is sustainable when it does not alter the capacity of the soil to provide for future needs. Soil sustainability can be threatened by a numerous management practices; including over-cultivation, decreased or increased water abstraction, under-fertilisation or over-fertilisation, careless use of biocides, failure to maintain soil organic matter levels and clearing natural vegetation. These may threaten sustainability in a number of ways; through physical and chemical processes (eg. by increasing soil erosion, salinisation, desertification), or biological processes (eg. by decreasing soil fertility). When soil management is poor, soil sustainability is often threatened by a combination of these factors at the same time (Smith and Powlson, 2003). Climate change may further increase the threat to soil sustainability in poorer countries because cereal crop yields are predicted to decline in most tropical and sub-tropical regions under future climates (Rosenzweig and Parry, 1994, Fischer *et al*., 2001), in countries which have a low capacity to adapt (IPCC, 2007). The impact of climate change in soils of tropical parts of Indian subcontinent in particular and in the world in general, in terms of impairment in their physical, chemical and biological properties has attracted the attention of soil researchers in recent years (Pal *et al*., 2009a, b).

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 conditions elsewhere (Pal *et al*., 2009b). In India, a change of climate has been recorded from humid to semi-arid in rainfed areas only during the Holocene period (Pal *et al*., 2001; 2009a). It is observed that the major soil types of India under SAT environments are becoming calcareous with the concomitant development of exchangeable sodium percentage (ESP) in the subsoil, which indicates a climatically controlled natural degradation (Pal *et al*., 2000). This type of degradation ultimately modifies the soil physical and chemical properties. Such modifications resulting from regressive pedogenesis (Johnson and Watson-Stegner, 1987) restrict the entry of rain water, and reduce the storage and release of soil water (Kadu *et al*., 2003). The lack of soil water impairs the possibility of growing both rainy and winter crops in a year, especially in vast areas under Vertisols of SAT with mean annual rainfall (MAR) <1000mm (Pal *et al*., 2011). This way not only the Vertisols with ESP>15 (Sodic Haplusterts) but also the soils with ESP >5 but <15 (Aridic Haplusterts) cease to be sustainable for growing agricultural crops under SAT environments (Pal *et al*., 2009b, 2011). Thus, the loss of soil sustainability may not be always due to the human-induced soil degradation process (Oldeman, 1994).

The Vertisols in the ICRISAT heritage watersheds at Patancheru ($17^0$36 N, 78^0 16 E, 545 m altitude) belong to Kasireddipalli series and was initially classified as Typic Pellusterts (Murthy *et al*., 1982) but is revised to Sodic Haplusterts recently in view of their very low sHC (< 10 mm hr^{-1}) that causes decline in crop yield more than 50% as compared to Typic Haplusterts of SAT environments (Pal *et al*., 2003, 2006). The area receives 800 mm average annual rainfall; the average minimum temperature is 19^0 C and maximum temperature is 32^0C.

In SAT agro-ecosystems, the primary constraint for productivity is water. The study on the sustainability of Vertisols through adoption of integrated catchment management was started at the ICRISAT, Patancheru, Andhra Pradesh, India, since 1976. Two long term catchment heritage experiments (adjacent to each other) were studied with two systems (improved and traditional) with objectives to validate the hypothesis that improved management (IM) system of Vertisol not only enhances crop productivity, but also favours organic carbon (OC) sequestration and enhances soil quality (Wani *et al*., 2003, 2007).

Description of Long-Term Heritage Experiments (LTHEs)

Improved system (IM): An integrated watershed management system with a broad-bed and furrow (BBF) landform treatment (El-Swaify *et al*., 1985) was followed. The beds were 1.05 m wide with a 0.45 m furrow prepared at 0.4-0.6 % gradient using a bullock-drawn bed-marker mounted on a tropicultor (El-Swaify *et al*., 1985). The land was refreshed soon after harvesting of the post-rainy season crop and after unseasonal rains the beds were formed again at the same place. Field traffic was confined to the furrows. Excess rainfall drained along the furrows and discharged into grassed waterways. Improved high-yielding varieties were dry-sown on a bed with a spacing of 1.5× 0.15 m for pigeon pea (*Cajanus cajan)* ICP1-6, 0.9 x 0.1 m for sorghum (*Sorghum bicolour*) CSH 9, and 0.75× 0.20 m for maize (*Zea mays*) DH 103 at a depth of 50-70 mm during the period 8-15 June each year. Sixty kg N ha^{-1} and 20 kg phosphorus (P_2O_5) ha^{-1} as urea and di-ammonium phosphate (DAP), respectively, were applied in rows with a seed and fertilizer drill. Generally, monsoon rains arrives on or after 15 June at Patancheru.

From 1976 to 1988 the field was treated as a single plot. A two-year rotation was followed with sorghum intercropped with pigeon pea (2:1 proportion) and maize during the rainy season followed by chickpea (*Cicer arietinum*) (Annigeri) in the post-rainy season. The field was divided from 1989 to 1998 in two plots and a two-year rotation with sorghum ICSV 745 intercropped with green gram (*Vigna radiata*) PS 16 in the rainy season followed by sorghum M 35-1 in the post-rainy season. The plots were treated as mirror images. Weed control was carried out by mechanical weeding once, using the tropicultor, and two hand weeding. Appropriate pest and disease management protocols were followed as required. Sorghum was harvested by cutting the plants at 150 mm from ground level, leaving the stubbles in the field. The stalks were dried and the plant dry matter weight was recorded. Pigeon pea was harvested at the end of February. In each plot from two replicates, an area of 12 m^2 from each replicate was used for recording yield parameters. Immediately after the harvest of pigeon pea, the land was cultivated and once in two years ploughed and left fallow. When summer rains occurred, the beds were reshaped for sowing of the next rainy season crops.

Traditional system(TM): The land was left as cultivated bare fallow from 1976 to 1988 during the rainy seasons and sorghum was grown as sole crop in the post- rainy seasons. From 1989 the field was divided in to two plots, with a two-year rotation of bare fallow/sorghum (M 35-1) followed by bare fallow/chickpea (Annigeri) in the next year. The two plots were treated as mirror images. Seeds were sown with a local seed drill on a flat surface when seedbed moisture was adequate. No inorganic fertilizers were applied to the crop, but 10 t ha^{-1} of farm yard manure (FYM) was broadcast each alternate year before land preparation. Sorghum was intercultivated once, and then hand weeded. The land was ploughed every two years; harrowing was done with a blade harrow to control weeds. Dry matter yields were recorded each year.

Results of the LTHEs

The updated results from the LTHEs (Fig.1) indicate that the moving average grain yield under the IM system over 30 years has been 5.1t ha^{-1} yr^{-1}. And this yield is nearly five-fold higher than under the TM system, which has an average yield of about 1.1t ha^{-1} yr^{-1}. The annual gain in yield in the IM system was 82 kg ha^{-1} as compared to 23 kg ha^{-1} in the TM system (Table 1). Enhanced crop productivity in the IM system increased its carrying capacity as compared to that in the TM system (21 persons ha^{-1} in the IM versus 4.6 persons ha^{-1} in the TM system) (Wani *et al*., 2009). The yield of deep-rooted crops on Vertisols under rain-fed conditions depends primarily on the amount of rain stored in the profile, and its release during crop growth. The IM system thus shows increased rainwater use efficiency as compared to the TM system (65% versus 40%) (Table1). In addition, it shows reduced runoff (from 220 mm to 91 mm) and soil loss as a result of implementation of the IM (from 6.64 t ha^{-1} to 1.6 t ha^{-1}) (Table 1) (Wani *et al*., 2003). The favourable entry of rain water has been possible because of enhancement in sHC values > 10 mm hr^{-1}(weighted mean in 1m

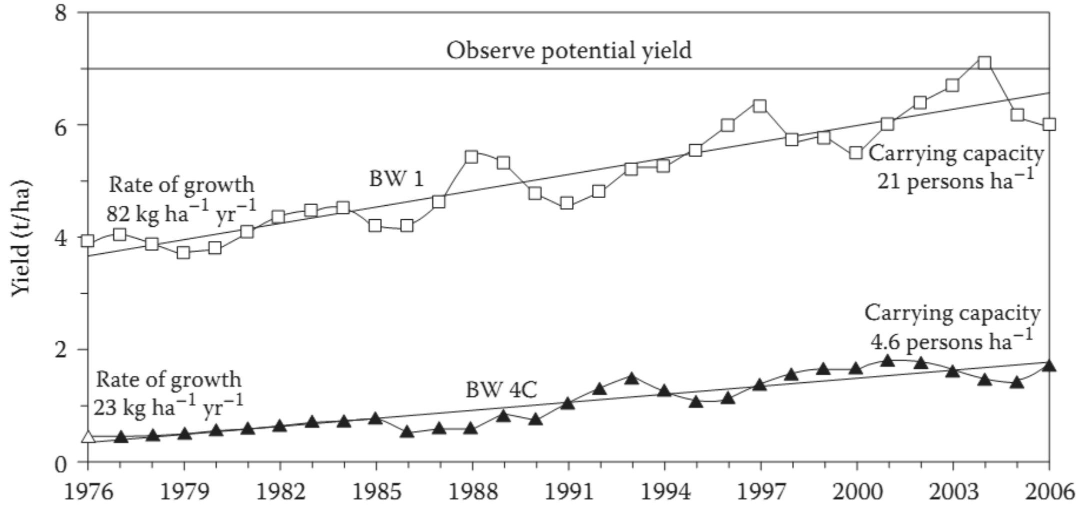


Fig. 1. *Three year moving average of sorghum and pigeonpea grain yields under IM and TM in Kasireddipalli soils at Patancheru, India. Adapted from Wani et al.(2007).*

Table 1. *Effect of 24 years of LTE on the grain yield, SOC and total Nitrogen, microbial biomass C (MBC), microbial biomass N (MBN), and P in Vertisols (Kasireddipalli series) **

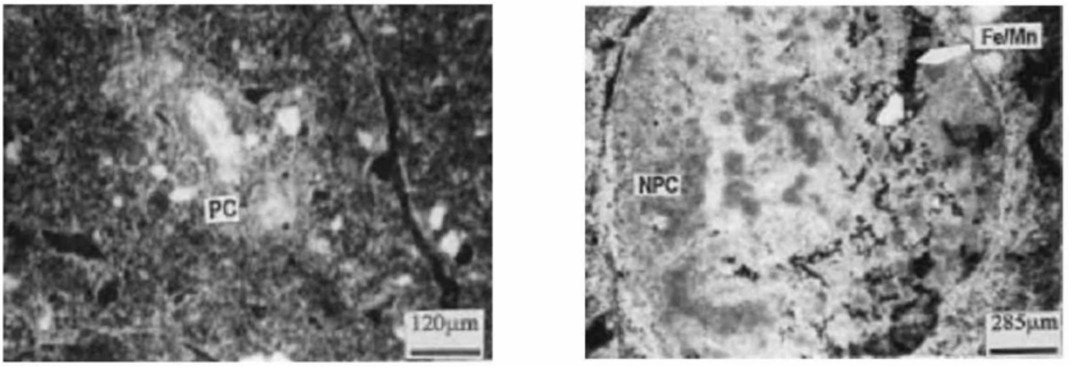
Grain yield/soil properties	Improved management (IM)	Traditional management (TM)
Grain yield	5.1 t ha^{-1} yr^{-1}	1.1 t ha^{-1} yr^{-1}
OC (t ha^{-1})	27.4 (0-60 cm depth)	21.4 (0-60 cm depth)
	19.4 (60-120 cm depth)	18.1 (60-120cm depth)
Total N (kg ha^{-1})	2684 (0-60 cm depth)	2276 (0-60 cm depth)
	1928 (60-120 cm depth)	1884 (60-120 cm depth)
MBC (kg C ha^{-1})	2676 (0-60 cm depth)	1462 (0-60 cm depth)
	2137 (60-120cm depth)	1088 (60-120 cm depth)
MBN(kg N ha^{-1})	86.4 (0-60 cm depth)	42.1 (0-60 cm depth)
	32.2 (60-120 cm depth)	25.8 (60-120 cm depth)

* Adapted from Wani *et al*. (2003; 2007), Sahrawat *et al*. (2010) and Pal *et al.* (2011)

depth, WM) in soils of the IM system (Table 2). It is a fact that an optimum yield of deep-rooted crops (cotton) in Vertisols of SAT of central India can be obtained when the soils are non-sodic (ESP<5) with sHC ≥ 20 mm hr^{-1}, and 50% reduction in yield was observed in Vertisols with ESP>5 and sHC <10 mm hr^{-1} (Kadu *et al.*, 2003; Pal *et al.*, 2006).

Vertisols under IM and TM system have comparable clay (<2µm), and fine clay

(<0.2μm) content and CEC (WM, in the first 1 m depth), but the sHC value (WM) under the IM has increased by almost 2.5 times whereas ESP (WM) has decreased by about 2 times (Table 2). Soils contain both non-pedogenic (NPC) and pedogenic (PC) $CaCO_3$ (Fig. 2 a, b). The rate of formation of PC (Fig.. 2a) in Vertisols in general, was estimated to be 0.25 mg/ 100g soil /year in the first 1m profile depth (Pal *et al*., 2000) but the rate has enhanced with the decrease in MAR and rise in mean annual temperature (MAT) within the semi-arid dry (SAD) climatic environments and it can be more than 1.0 mg/100g soil /year (Pal *et al*., 2006). The $CaCO_3$ content (WM) of the IM system was 5.7% whereas it remained at 6.2% under the TM system. The depth distribution of $CaCO_3$ in soils under the IM system indicates a gradual increase and under the TM system its amount has remained almost same throughout the depth (Table 2). Under the IM system the root system of chickpea exude organic acids (malic or citric) (ICRISAT, 1988) and those of pigeon pea produces piscidic acid (Ae *et al*., 1990). The acids of these crops and their rootlets in soil through which rainwater passes, or other sources of CO_2, could have caused the increase in solubility of $CaCO_3$. The rate of dissolution of $CaCO_3$ under the IM system in the last 24 years is 21 mg yr^{-1} in the first 1 m of the profile, indicating a value much higher than its rate of formation in SAT environments. The proportion of Ca to C in $CaCO_3$ is more than 3.0, suggesting the availability of Ca ions in soil solution is higher (8.4 mg/100g soil/ year in 1m profile) than that of bicarbonate ions (2.52 mg/100g soil/year in 1m profile). The favourable amount of Ca^{2+} ions leads to an increase in exchangeable Ca/Mg ratio and a concomitant decrease in ESP



(a) (b)

Fig. 2. *Micromorphological features of $CaCO_3$ in Kasireddipalli soils, in cross-polarized light. (a) PC as diffuse nodules and as micrite crystals in the ground mass, (b) NPC showing dissolution. Adapted from Pal et al.(2003).*

(Table 2). The enrichment of Ca^{+2} ions both in soil solution and on the exchange complex improves sHC of Vertisols (Kadu *et al*., 2003). In Vertisols of the SAT regions, pedogenic relationships between SAT, PC, exchangeable Ca/Mg, ESP and sHC do exist (Kadu *et al*., 2003). Due to better entry of rain water and air in Vertisols under the IM system for the past 24 years, higher crop productivity was observed, and thus Vertisols sequestered more amount of OC in the first 0.3m depth of the profile than in the soil under the TM system. At present, soils under the IM system contain 0.53 % OC (WM) whereas soils under TM system contain 0.42% (Table 2). The rate of addition of OC for the last 24 years since 1977 has been 5 mg yr^{-1} in the first 1m of the Vertisols under the IM system. Increased OC sequestration in soils of the tropics induces dissolution of native $CaCO_3$ and its leaching (Bhattacharyya *et al*., 2001). The improvement in physical and chemical environments highlight the role of $CaCO_3$ that remains chemically inert in Vertisols (Pal *et al*., 2000) during its sequestration

Table 2. *Modification of physical and chemical properties of Vertisols through improved management system at ICRISAT, Patancheru in 24 years since 1977.*

Horizon	Depth cm	Clay %	Clay (%), weighted of man 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	Ca CO_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	Exchan-geable Ca/Mg	Exchan-geable 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		8.5	0.4		6.4		53.5		1.8		13.0	
Bss3	101-130	59.4		30.8		2.0		8.5	0.4		6.5		57.8		3.1		8.0	
BCk	130-160	58.0		38.7		1.0		8.2	0.1		9.1		49.5		1.5		22.2	
Kasireddipalli Soil (Typic Haplusterts) under Improved Management (IM)[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	

[a]Adapted from Pal *et al*. (2003); [b]Adapted from Bhattacharyya *et al*. (2007)

(Sahrawat, 2003), but acts as a soil modifier during the adaptation of the IM system. The improvement in soil properties is also reflected in classification of Vertisols. The Kasireddipalli soils of the TM system (Sodic Haplusterts) now qualify for Typic Haplusterts under the IM system (Pal *et al.*, 2011).

It is observed that along with the increased crop productivity, OC, total N, and Olsen P also increased. Among the soil biological properties, microbial biomass carbon (MBC), and microbial biomass N (MBN) also increased in the improved physical and chemical environments of Vertisols under the IM system (Table 1).

Discussion

Amidst climate change from humid to semi-arid in Indian Peninsular region during the Holocene period, sequestration soil inorganic carbon (PC) in SAT environments (Fig. 2a) due to the dissolution of NPC (Fig. 2b) is the prime chemical reaction responsible for the increase in pH, the decrease in Ca/Mg ratio of exchange site with depth and the development of subsoil sodicity in Vertisols (Table 2)(Srivastava *et al.*, 2002). These modifications in soil chemical properties together impair the hydraulic properties of soils, which restrict the entry of air and rain water in subsoil region of the profile. Thus, Vertisols of the TM system with ESP>5 and <15, and sHC < 10 mm hr^{-1}, show poor crop productivity due to inadequate amount of soil water available during crop growth (Fig.1). Recently Kadu *et al*.(2003) made an attempt to identify bio-physical factors that limit the yield of deep-rooted crops (cotton) in 29 Vertisols, developed in the basaltic alluvium of sub-humid dry (SHD) to semi-arid dry (SAD) climate of Nagpur (SHD), Amravati (SAD) and Akola (SAD) districts of Vidarbha region of Maharashtra (adjacent state to Andhra Pradesh) in central Peninsular India. They have demonstrated that with the decrease in MAR and increase of MAT, the physical, chemical and biological properties of Vertisols of Amravati and Akola districts under SAD climates are degraded as soils lose OC and become more calcareous, alkaline and sodic due to accelerated formation of PC. As a result, the sHC of soils have decreased and impaired the cotton productivity (Table 3). The AWC (available water content) calculated on the basis of moisture content held between 33 and 1500kPa (Table 3), indicate that not only the Typic/Aridic Haplusterts but also the Sodic Haplusterts can hold sufficient water apparently for optimum crop growth. But a non-significant negative correlation between yield of cotton and AWC (Table 4) indicates that during the growth of crops this water is not released because of prevalence of Na^+ ions on exchange sites of Aridic Haplusterts and Sodic Haplusterts with ESP > 5. In fact, storage of soil water in the subsoils is governed by the movement of water in the profile. The sHC of Vertisols of SAT, decreases rapidly with depth, and the

Table 3. *Range in values of AWC, OC, PC, ESP, sHC and yield of cotton in Vertisols of Vidarbha, Central India*

District, Vidarbha Region, Maharashtra, Central India	Soil Classification	AWC(%)[1*]	OC (%)[2]	PC (%)[3*]	ESP[4*]	sHC[5*] ($mm\ hr^{-1}$) weighted mean in the profile (1 m)	Cotton yield ($t\ ha^{-1}$) (seed+lint)*
Nagpur (MAR – 1011 mm)	Typic Haplusterts/ Typic Calciusterts	14-20	0.74	3 – 6	0.5 – 11	4 – 18	0.9 – 1.8
Amravati (MAR – 975 mm)	(a) Aridic Haplusterts	10-20	0.54	3 – 7	0.8 – 4	2 – 19	0.6 – 1.6
	(b) Sodic Haplusterts	17-24	0.42	3 – 13	16 – 24	0.6 – 9.0	0.2- 0.8
Akola (MAR – 877 mm)	(a) Aridic Haplusterts	17	0.30	3.6	7 – 14	3 – 4	0.6-1.0
	(b) Sodic Haplusterts	18	0.20	4.0	19 – 20	1- 2	0.6

AWC= available water content (weighted mean in 1m depth of soil), [2]OC= organic carbon (weighted mean in 1m depth of soil), [3]PC=pedogenic $CaCO_3$ (weighted mean in 1m depth of soil), [4]ESP=exchangeable sodium percentage (sodicity)(maximum value in 1m depth of soil), [5]sHC= saturated hydraulic conductivity (weighted mean in 1m depth of soil). * minimum and maximum average values. Adapted from Kadu *et al*. (2003).

decrease is sharper in Aridic/Sodic Haplusterts with ESP >5 (Pal *et al*., 2009a). This is observed by a significant positive relation between ESP and AWC, also by a significant negative correlation between yield and ESP (Table 4). A significant positive correlation between yield and exchangeable Ca/Mg (Table 4) indicates that a dominance of Ca^{2+} ions in the exchange sites of Vertisols is required to improve the hydraulic properties for a favourable yield of crop. The development of subsoil sodicity (ESP ≥ 5) replaces Ca^{2+} ions in the exchange complex, causes reduction in yield of cotton in Aridic /Sodic Haplusterts (ESP ≥ 5). A significant negative correlation between ESP and exchangeable Ca/Mg (Table 4) indicates impoverishment of soils with Ca^{2+} ions during the sodification process. This process causes the depletion of Ca^{2+} ions from the soil solution in the form of $CaCO_3$ with the concomitant increase of ESP with pedon depth (Balpande *et al*., 1996; Vaidya and Pal, 2002). Thus, these soils show the presence of PC (Pal *et al*., 2000; Srivastava *et al*., 2002; Vaidya and Pal, 2002). This chemical process is evident from the positive correlation between ESP and carbonate clay (PC) (Table 4). A significant positive correlation between yield of cotton and carbonate clay (Table 4) indicates that like ESP, the formation of PC is also a yield-reducing factor and a more important soil parameter than total $CaCO_3$ (PC+NPC) in soils (Sys *et al.*, 1993; NBSS&LUP, 1994). Due to an accelerated rate of formation of PC in dry climates, the hydraulic properties of Vertisols are impaired and thus, a significant negative correlation exits between ESP and sHC (Kadu *et al.*, 2003; Pal *et al.*, 2006). All the processes operating in soils of dry climates also influence the sHC of the Vertisols and thus, a significant positive correlation exits between yield of cotton and sHC (Table 4). Thus, Kadu *et al*. (2003) in view of pedogenetic processes that ultimately impair the hydraulic properties of soils advocated the evaluation of Vertisols (without any soil modifiers like Ca-zeolites and gypsum, Pal *et al*., 2006) for deep-rooted crops on the basis of sHC alone.

The results of LTHE on Kasireddipalli soils (Sodic Haplusterts) under the IM system involving legumes, BBF land and water management protocols, use of inorganic fertilizers, indicate that physical, chemical and biological properties of Kasireddipalli soils can be improved to a great extent and can also convert the naturally degraded Vertisols in to resilient ones. This fact is evident from their much higher crop productivity and carrying capacity as compared to Vertisols (Sodic Haplusterts) of the LTHE under the TM system with crop rotation involving rainy season bare fallow and addition of organic fertilizers like FYM. Release of good amount Ca^{2+} ions during the dissolution of $CaCO_3$ (8.4 mg/100g soil/year in 1m

Table 4. *Co-efficient of correlation among various soil attributes and yield of cotton* [1]

No.	Parameter Y	Parameter X Based on 29 Vertisols	r
1	Yield of cotton (q ha^{-1})	AWC (%) WM [b]	-0.10
2	Yield of cotton (q ha^{-1})	ESP max [a]	- 0.74*
3	Yield of cotton (q ha^{-1})	sHC WM [b]	0.76*
4	Yield of cotton (q ha^{-1})	carbonate clay [c]	-0.64*
5	Yield of cotton (q ha^{-1})	Exch. Ca/Mg WM [b]	0.50*
6	ESP max [a]	AWC (%) WM [b]	0.30*
7	ESP max [a]	Exch. Ca/Mg WM [b]	-0.55*
8	ESP max[a]	clay carbonate [c]	0.83*

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

profile) under the IM system compared to immobilization of Ca^{2+} ions during formation of $CaCO_3$ (0.10 mg/100g soil/year in 1m profile) caused the improvement of sHC for storage and release of soil water during dry spell between rains in the growing season. Adequate supply of soil water helped in better crop productivity, and higher OC sequestration, indicating that soil chemistry is seldom visible in maintaining soils' sustainability (Buol, 1995). Improvement in sHC in the subsoil through the IM system helping in storage and release of soil water during crop growth suggests that it may also work successfully even in calcareous Vertisols with ESP < 5 (Typic Haplusterts), wherein sHC also decreases rapidly with depth (Balpande *et al.*, 1996; Pal *et al.*, 2003, 2006). The resilience of Sodic Haplusterts through the management interventions under the IM system of ICRISAT clearly suggests that the IM system is capable of mitigating the adverse effect of climate change of the Indian Peninsula. Thus, the IM system can be considered as good (IPCC, 1997, Paustian et al., 1997) or recommended (Lal, 2010) practices. The sustainability of IM system would, however, depend upon the maintenance of Vertisols' sustainability as Typic Haplusterts with time in SAT environments. The continuance of agronomic practices of the IM system can supply the most important Ca^{2+} ions both in solution and exchange sites of soil and such chemical environment would not allow Typic Haplusterts (still containing 5.7% $CaCO_3$, Table 2) to transform to any other soil order so long $CaCO_3$ (both PC and NPC) would continue to act as a soil modifier (Pal *et al.*, 2011). For complete dissolution of 5.7% $CaCO_3$ 'at the rate of' 21mg/100g soil/year, the IM system would require for more than 250 years. Thus, Typic Haplusterts are expected to be sustainable for another couple of centuries.

Despite this fact that the IM system is a cost-effective and win-win technology to improve the crop productivity in Vertisols under SAT environment, its full potential has neither been realised nor has been adapted on a sufficiently large scale to have substantial impact (Wani et al., 2007). A fresh initiative is warranted for the implementation of the IM technology to make Sodic Haplusterts resilient and sustainable by providing incentives, technological know-how, required resources and policy support to the farmers through transferable C credits under CDM of the Kyoto Protocol as C sequestration is one the important mitigation strategies to cope with the impacts of climate change (Lal, 2004). Trading C credits is a good incentive in improving the quality of soil and environments, and restoring the degraded ecosystem in addition to enhancing farm income (Lal, 2005).

Conclusions

SAT induced naturally degraded Vertisols of the Holocene period (with ESP>5, but <15 and sHC < 10 mm hr^{-})

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

References

Ae, N., Arihara, J., Okade, K., Yoshihara, T., C. and Johansen, C. 1990. Phosphorus uptake by pigeonpea and its role in cropping systems of the Indian subcontinent. *Science,* **248:**477-480.

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 and Development,* **7**:313-324.

Bhattacharyya, T., Pal, D. K., Velayutham, M., Chandran, P. and Mandal, C.2001. Soil organic and inorganic carbon stocks in the management of black cotton soils of Maharashtra. *Clay Research,* **20:**21-29.

Bhattacharyya, T., Chandran, P., Ray, S. K., et al. 2007. *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. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and New Delhi, India: Indian Council of Agricultural Research (ICAR). 236pp.

Buol, S. W., 1995. Sustainability of soil use. *Annual Review of Ecology and Systematics,* **26**:25-44.

El-Swaify, S. A., Pathak, P., Rego, T. J. and Singh, S. 1985. Soil management for optimized productivity under rain-fed conditions in the semi-arid tropics. *Advances in Soil Science***, 1**:1-63.

Fischer, G., Shah, M., van Velthuizen, H. and Nachtergaele, F. O. 2001. Executive Summary Report: *Global Agro-ecological Assessment for Agriculture in the 21st Century.* International Institute for Applied Systems Analysis. Laxenburg, Austria.

ICRISAT, 1988. Phosphorus in Indian Vertisols: Summary Proceedings of a Workshop, August 1988, ICRISAT Center, Patancheru, A.P.502324, India. pp.23-26.

I P C C. 1997. IPCC (revised 1996) *Guidelines for National Greenhouse Gas Inventories*. Workbook, Paris, Intergovernmental Panel on Climate Change.

I P C C. 2007. Climate Change 2001: The Scientific Basis. Cambridge University Press. UK, pp. 944.

Johnson, D. L.and Watson-Stegner, D. 1987. Evolution model of pedogenesis. *Soil Science*, **143**:349-366.

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 and Management*, **19**:208-216.

Lal, R., 2004. Soil carbon sequestration in India. *Climatic Change*, **65**:277-296.

Lal, R., 2005. Carbon sequestration and climate change with specific reference to India. In: *Proceedings of International Conference on Soil, Water and Environmental Quality- Issues and Strategies*. January 28-February 1, 2005, New Delhi, Indian Society of Soil Science, New Delhi.

Lal, R., 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bio Science* **60**:708-721.

Murthy, R. S., Hirekerur, L. R., Deshpande, S. B. and Venkat Rao, B. V. (Eds.). 1982. *Benchmark Soils of India*. National Bureau of Soil Survey and land Use Planning (ICAR), Nagpur, India.

NBSS&LUP, 1994. Proceedings of National Meeting on Soil-Site Suitability Criteria for Different Crops. Feb 7-8, Nagpur India. p. 20.

Oldeman, L. R., 1994. In: (D. J. Greenland and J. Szabolcs, Eds), *Soil Resilience and Sustainable Land Use*, CAB International, Wallingford, pp. 99-118.

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: C.R. Lal, J. M. Kimble, H. Eswaran and B.A. Stewart, Eds), *Global Climate Change and Pedogenic Carbonates*, Lewis Publishers, Boca Raton, Fl, pp.149-185.

Pal, D. K., Balpande, S. S., 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. 2003. *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, NBSSLUP (ICAR), Nagpur, 144p.

Pal, D. K., Bhattacharyya, T., Ray, S. K., Chandran, P., Srivastava, P., Durge, S. L. and Bhuse, S. R. 2006. Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic soils. *Geoderma*, **136**:210-228.

Pal, D. K., Bhattacharyya, T., Chandran, P., Ray, S. K., Satyavathi, P. L. A., Durge, S. L., Raja, P. and Maurya, U. K. 2009a.Vertisols (cracking clay soils) in a climosequence of Peninsular India : Evidence for Holocene climate changes. *Quaternary International* **209**:6-21.

Pal, D. K., Bhattacharyya, T., Chandran, P. and Ray, S. K. 2009b. Tectonics-climate-linked natural soil degradation and its impact in rainfed agriculture: Indian experience. In: (S.P. Wani, J. Rockstrom, and T. Oweis, Eds), *Rainfed Agriculture: Unlocking the Potential*, CABI International, Oxfordshire, U.K., pp.54-72.

Pal, D. K., Bhattacharyya, T. and Wani, S. P. 2011. Formation and management of cracking clay soils (Vertisols) to enhance crop productivity: Indian Experience. In: (R. Lal and B.A. Stewart, Eds), *World Soil Resources*, Francis and Taylor, pp.317-343.

Paustian, K., Andren, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., Tiessen, H., van Noordwijk, M. and Woomer, P. L. 1997. Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management*, **13:**229-244.

Rosenzweig., C., Parry, M., 1994 Potential impact of climate change on world food supply. *Nature*, **367**:133-138.

Sahrawat, K. L. 2003. Importance of inorganic carbon in sequestering carbon in soils of dry regions. *Current Science*, **84**:864-865.

Sahrawat, K. L., Wani, S. P., Pathak, P. and Rego, T. J. 2010. Managing natural resources of watersheds in the semi-arid tropics for improved soil and water quality: A review. *Agricultural Water Management*, **97:**375-381.

Smith, P., Powlson, D. S., 2003. Sustainability of soil management practices-a global perspective. In: (L. K. Abbott and D. V. Murphy, Eds), Soil Biological Fertility, Kluwer Academic, Dordrecht, pp.241-254.

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.

Sys, C., van Ranst, E., Debaeveye, Ir J. and Beernaert, F. 1993. Land evaluation, Part 3: *Crop Requirements. International Training Centre for Post Graduate Soil Scientists,* University of Ghent, Belgium.

Vaidya, P. H. and Pal, D. K. 2002. Microtopography as a factor in the degradation of Vertisols in central India. *Land Degradation and Development* , **13**:429-445.

Wani, S. P., Pathak, P., Jangawad, L. S., Eswaran, H. and Singh, P. 2003. Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management*, **19:**217-222.

Wani, S. P., Sahrawat, K. L., Sreedevi, T. K., Bhattacharyya, T. And Srinivas, Rao. 2007. Carbon sequestration in the semi-arid tropics for improving livelihoods. *International Journal of Environmental Studies*, **64**:719-727.

Wani, S. P., Sreedevi, T. K., Marimuthu, S., Kesave Rao, A. V. R. and Vineela, C. 2009. Harnessing potential of *Jatropha* and *Pongamia* plantations for improving livelihoods and rehabilitating degraded lands. In: *Proceedings of 6th International Biofuels Conference*, March 4-5, 2009, Winrock International, New Delhi, pp.256-273.

W C E D (World Commission on Environment and Development). 1987. *Our Common Future.* Oxford University Press, Oxford, UK, pp. 383.

(Received July, 2012; Accepted October, 2012)