ICRISAT, India soils: yesterday, today and tomorrow

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Associated red and black soils are common in the Deccan plateau and the Indian peninsula. The red soils are formed due to the progressive landscape reduction process and black soils due to the aggradation processes; and they are often spatially associated maintaining their typical characteristics over the years. These soils are subject to changes due to age-long management practices and the other factors like climate change. To maintain soil quality, it is essential to monitor changes in soil properties preferably using benchmark (BM) soil sites. One such example lies at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) farm in Patancheru, India where red (Patancheru) and black (Kasireddipalli) soils co-exist in close association under almost similar topographical condition, which also represents very commonly occurring spatially associated soils. The database generated over the years for these two dominant soils that are under cultural practices for the last 2–3 decades, helps us understand the relative changes in properties over a time scale. To do this exercise, we revisited the BM spots as the data on the original characterization of these soils since the development of the farm, are available, for comparative evaluation. We also attempted to make prediction of future changes in properties for these two important and representative black and red soils of the ICRISAT farm in Patancheru, India.

Keywords: Associated red and black soils, changes, ICRISAT farm, monitor, soil quality.

Introduction

SMITH and Powlson[1] adapted a definition of sustainable soil management as that meets the needs of the present without compromising the ability of future generations to meet their own needs from soil. Thus, soil management is sustainable when it does not alter the capacity of the soil to provide for future needs. Soil sustainability is threatened by management practices including over-cultivation, decreased or increased water abstraction, under or over-fertilization, non-judicious use of biocides, failure to maintain soil organic matter levels and clearing natural vegetation. Such management practices may lead to physical, chemical and biological degradation of the soil and thus threaten the sustainability of soil productivity. When soil management is not appropriate, soil sustainability is often threatened by a combination of physical, chemical and biological factors[1]. Climate change may further increase the threat to soil sustainability in poor countries because the cereal crop yields are predicted to decline in most tropical and sub-tropical regions under the future climatic scenarios[2], and in countries which have a low capacity to adapt[3]. The impact of climate change in soils of tropical parts of the Indian subcontinent, in particular and globally, in general, has attracted the attention of soil researchers in recent years as indicated by degradation in soil physical, chemical and biological properties[4–10].

Amidst neo-tectonics 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[10]. In India, a change of climate has been recorded from humid to semi-arid in rainfed areas only during the Holocene period[9,11]. It is observed that the red and black soils as two major soil types of India under SAT environments, are gradually converted from non-calcareous to calcareous with the concomitant development of exchangeable sodium percentage (ESP) in the subsoils, which indicates a climatically controlled natural degradation[8,11]. This type of degradation ultimately modifies the soil physical and chemical properties. Such modifications resulting through the regressive pedogenesis[12] restrict the entry of rain water, and reduces the storage and release of soil water[13]. The lack of soil water impairs the possibility of growing both rainy and winter crops in a year, in vast areas especially in black soils of SAT with mean annual rainfall (MAR) <1000 mm (ref. 14) and thus the black soils cease to be sustainable for growing agricultural crops under SAT environments[10,14]. Keeping this in view, we have developed this article on the associated red and black

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soils of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Farm in Patancheru focusing on the changes in soil quality through management interventions (anthropogenic activities) over time. An attempt is also made to predict on their quality in the future using available relevant datasets[4–8].

Geological setting of the ICRISAT, Patancheru farm

The ICRISAT farm, India is located between 17°25′N to 17°40′N lat. and 78°05′E to 78°20′E long. near Patancheru, India and covers an area of ~1400 ha. The geology of the area is comprised of the oldest rock formations of the earth's crust overlain by stratified deposits including the Quaternary alluvium. The rocks belong to the Pre-Cambrian and upper Cretaceous to lower Miocene periods. Coarse-grained granite, one of the major rock formations, is characterized by large feldspars and quartz grains of uniform size with flakes of biotite and muscovite micas. At places, the rocks are traversed by granitized basic materials which on weathering have given rise to calcareous veins and carbonate concretions. Gneissic formations are not so well marked in the area as is the coarse-grained granite. Dolomite dykes occur at places, and consist mainly of plagioclase feldspars and augite. In the south-west part of the farm, there is a thin capping of the Deccan basalt. The basalts occur as tongues confined mainly to the south-western portion of the area and the extension of the basaltic flow is about 30 m at the highest point near Shankarpalli. The basalt thins out gradually towards the granite area. Near Indrakun and Jolki, it is barely 1 m thick where the superimposition of basalt over granite was observed. At places intertrappean beds of some fluviatile or lacustrine deposits are seen[15].

Geomorphic history showed that the farm area forms a part of a peneplained surface of the ancient and stable Deccan peninsula which had undergone several cycles of erosion, deposition and uplift. Sporadic monolithic domes as *tors* are also present. The general elevation ranges from 500 to 620 m above mean sea level (msl). In the basaltic terrain, the highest point is 620 m and the lowest is 580 m above msl; the corresponding figures in the granitic area are 610 and 500 m above msl respectively. The farm is characterized by dendritic and parallel to sub-parallel drainage systems of different densities where streams are mostly seasonal and active during the rainy season. The NW part is drained by the Manjira river and the SW part by the Musi river. The drainage system is most intricate in the east of the farm where there are small and seasonal tanks. The drainage pattern is similar in the NW and tanks are larger although fewer. The climate is semi-arid characterized by mild to hot summers and mild winters. The semi-arid tropics (SAT) is essentially of two types, viz. dry SAT (semi-arid, dry: SAd) and moist SAT (semi-arid, moist: SAm). The ICRISAT farm is grouped as SAm (Table 1)[16,17]. Except during the south-west monsoon from June to October, the weather in this farm is dry. The month of May is the hottest (42–43°C) while December is warm (25.9°C). The mean annual rainfall ranges from 852 to 986 mm during four different time periods of which 80% falls from June to September. The pattern of rainfall is bimodal with weak rains during the winter (Figure 1). The variation of Patancheru climate reduces the length of growing period (LGP) from 60 to 90 days during 1980. Mean annual rainfall and rainy days have decreased over the last 41 years as evidenced by the climate shift.

Agricultural land use: A chronological account

Land use during 1975s

Nearly 94% of the area was intensively cultivated[15] mostly under dry land farming with traditional management (TM). A small area was irrigated. Commonly grown rainy-season crops included cereals, viz. sorghum (Jowar: *Sorghum bicolor*), maize (*Zea mays*) and pearl millet (*Pennisetum glaucum*); pulses, viz. pigeon pea (*Cajanus cajan*), mung bean (green gram: *Vigna radiata*) and black gram (black lentil: *Vigna mungo*); oilseeds, viz. groundnut (*Arachis hypogaea*) and safflower (*Carthamus tinctorius*); and a few other crops, viz. cotton (*Gossypium* sp.) and chillies (red pepper: *Capsicum annuam*). The post-rainy season crops were sorghum, safflower and sunflower. Rice and sugarcane were grown under irrigation. A small parcel of land was used for growing bananas, vegetables and grapes (Table 2).

Land use during 1980, 2001, 2010 and 2014

Black (Kasireddipalli) soils were cultivated for chickpea, pigeon pea, sorghum and safflower. Natural vegetations

Table 1. Different bioclimatic systems and their characteristics in Indian subcontinent

Bioclimatic systems	Mean annual rainfall mm	Length of growing period days
Arid (cold)	<550	<60
Arid (dry)	<550	<60
Semi-arid (dry)	550–850	60–90
Semi-arid (moist)	850–1000	90–120
Sub-humid (dry)	1000–1200	120–150
Sub-humid (moist)	1200–1500	150–180
Humid	1500–1800	180–210
Perhumid	>1800	>210

Source: Bhattacharyya *et al.*[16], Mandal *et al.*[17]; we considered SAT to cover the areas of arid and semiarid systems; besides, some drier sub humid systems also show typical characteristics of semiarid systems in terms of soil properties.

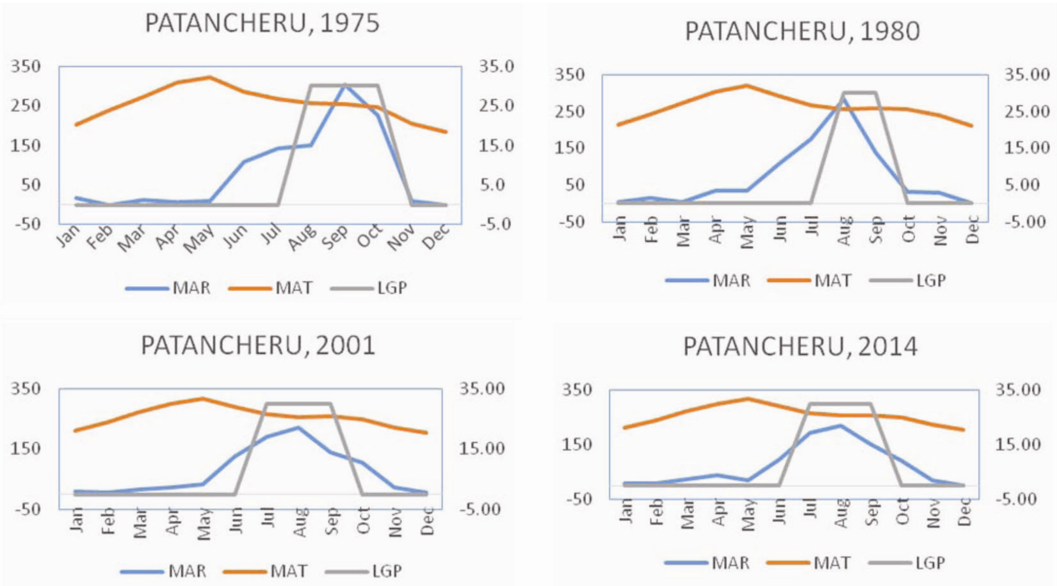

Figure 1. Water balance diagrams in four different time scales at Patancheru showing the length of growing period. MAR, mean annual rainfall; MAT, mean annual temperature.

Table 2. Land use of ICRISAT farm and the surrounding areas during 1980s*

Land use			Area	
Rainfed	Irrigated	Others	Ha	%
–	–	Rocks and uncultivable waste land	4,450	6.0
–	–	Rocks and cultivable waste land	1,780	2.4
Sorghum, groundnut, safflower, pigeon pea, chickpea	Rice, vegetables	Grapevine	28,517	38.8
Sorghum, safflower, coriander, tobacco, cotton, chillies, pigeon pea and chickpea**	–	–	28,370	38.6
Sorghum, cotton, safflower, pigeon pea, chickpea, green gram, black gram	–	–	1,780	2.4
–	Rice, sugarcane	–	4,005	5.4
Sorghum, pulses	Salt-resistant paddy	–	1,780	2.4
–	Banana, chillies, vegetables and ground nut	–	2,225	3.1
–	–	Water bodies	630	0.9
Total			73,537	100.0

*Also see Figure 3; **Life-saving irrigation (also see Murthy and Swindale[15]).

were mostly *Accacia* sp. (Babul) and grasses. Red (Patancheru) soils were cultivated for rainfed sorghum, maize, and pulses. Natural vegetations consisted of neem (*Azadirachta indica*), karanj, (*Pongamia* sp.) and grasses. The land capability and irrigability subclasses of both these soils were assessed as IIIs and 3s respectively, suggesting their productivity potential as medium[18]. Kasireddipalli soils were cultivated for soybean with pigeon pea as intercropping under rainfed condition (*kharif* season). The site chosen for Patancheru soil during this period was inside the ICRISAT farm which was under permanent fallow (grass land) (Table 3). This was chosen to assess the datasets of the pristine Patancheru soils. Kasireddipalli soils were used for soybean–pigeon pea/maize/sunflower during this period with appropriate management techniques (Table 3). ICRISAT farm uses nearly 65% of the area for cultivation including the plantation crops. The black soils (total area in Farm ~786 ha) contribute ~64% and the red soils (total area ~604 ha) contribute 55% towards cultivation. A general view of the land parcels and land use in the farm are shown in Figures 2–4.

Soils of the farm

Detailed soil survey of the ICRISAT farm was carried out using the base map generated by interpretation of the aerial photographs during 1970s and was published

Table 3. Characteristics of high and traditional management systems in ICRISAT farm

Particulars	Kasireddipalli (Black soils)						Patancheru (Red soils)		
			2001		2010				
	1975	1980	HM[a]	TM[b]	HM	TM	1975	1980	2001
Production system	Rainfed system: cultivated for chickpea, pigeon pea, sorghum and safflower	Rainfed system: crops grown are sorghum, chickpea, pigeon pea	Rainfed *kharif* intercropping system with 6–7 months fallow. Soyabean + pigeon pea (4 : 1)	Rainfed *kharif* fallow; rabi cropping system of chickpea-sorghum (two year rotation) with 8 months fallow period	Rainfed *kharif* soyabean-pigeon pea/maize/safflower system	Rainfed *kharif* Chickpea-sorghum system	Rainfed system, mainly cultivated for sorghum and pulses	Rainfed system, crops grown are sorghum and pulses	Permanent fallow-grasslands since early 1990s. Natural vegetation consists of *yerragda*, *kasigada*, and *pelachettu*
Management	NA[c]	NA	Improved varieties for soybean (PK 432) and pigeon pea (Asha) 40 kg P_2O_5 ha^{-1} as single super phosphate Green manuring with *Glyricidia* loppings Occasional insecticides Basalin weedicide @ 2 L ha^{-1} Broad bed ridge (1.05 m) and furrow (0.5 m) system	Improved varieties for sorghum (M 35-1) and chick pea (Anagiri) FYM @10 t ha^{-1} in alternate years since 1994. No chemical fertilizers Occasional insecticides	N: 40 kg ha^{-1} P_2O_5: 40 kg ha^{-1} K : Nil No FYM	No fertilizers FYM @ 10 t ha^{-1}	NA	NA	
Yield	NA	NA	Soyabean: 469–2068 kg ha^{-1} Pigeon pea: 589–1452 kg ha^{-1}	Chickpea: 1160–1550 kg ha^{-1} Sorghum: 820–1739 kg ha^{-1}	Soyabean: 1800–2200 kg ha^{-1} Maize: 4500–5000 kg ha^{-1} Pigeon pea: 1200–1800 kg ha^{-1} Safflower: 2200–2500 kg ha^{-1}	Chickpea: 800 kg ha^{-1} Sorghum: 1200–1500 kg ha^{-1}	NA	NA	

[a]HM, high management; [b]TM, traditional management; [c]NA, not available (Sources: Murthy and Swindale[15]; Lal *et al.*[18]; Bhattacharyya *et al.*[8,19]).

later[15]. An aerial photomosaic of the farm (1 : 15000 scale) was developed to delineate the interpretative units. Actual mapping was done at 1 : 4000 scale (cadastral map) with cartographic details showing 14 soil series (Figure 3; Table 4). Among these 14 soils, Kasireddipalli and Patancheru soils occupy the dominant proportions which are nearly 40% and 18% of the farm area respectively. We selected these two soils for bringing out the changes over time using the soil data sets for four different time series. A brief discussion is given below.

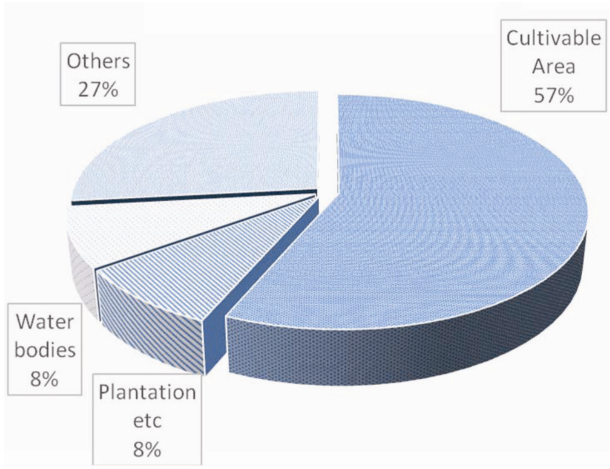

Figure 2. Land use in the ICRISAT farm during 2014.

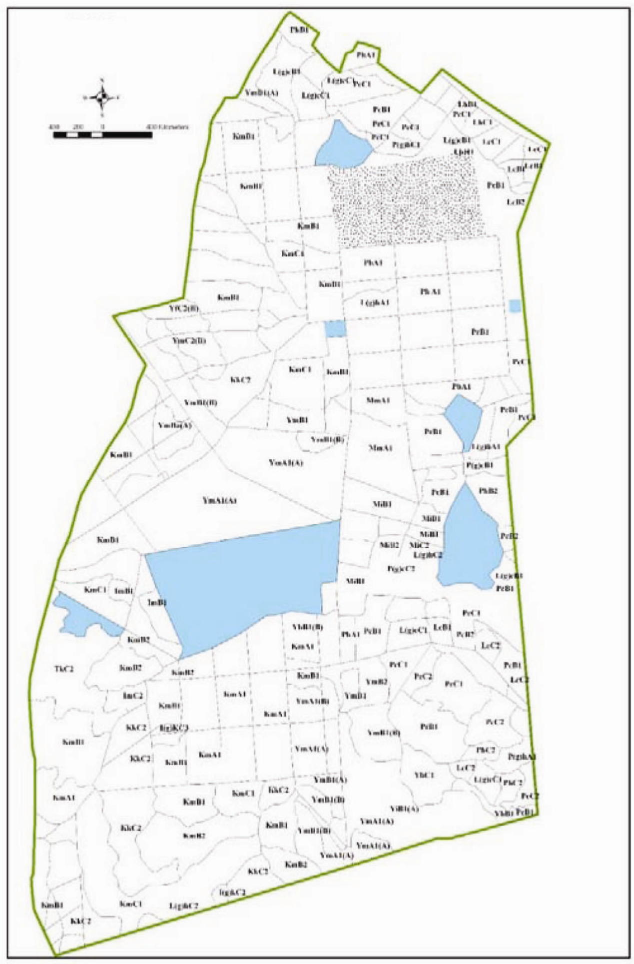

Figure 3. Soil map of the ICRISAT farm showing distribution of different soils (series) (also see Table 4).

Physical and chemical properties of Kasireddipalli (black) and Patancheru (red) soils during 1975

Black soils (*Kasireddipalli*). These soils were very deep, alkaline, calcareous, non-saline Vertisols showing

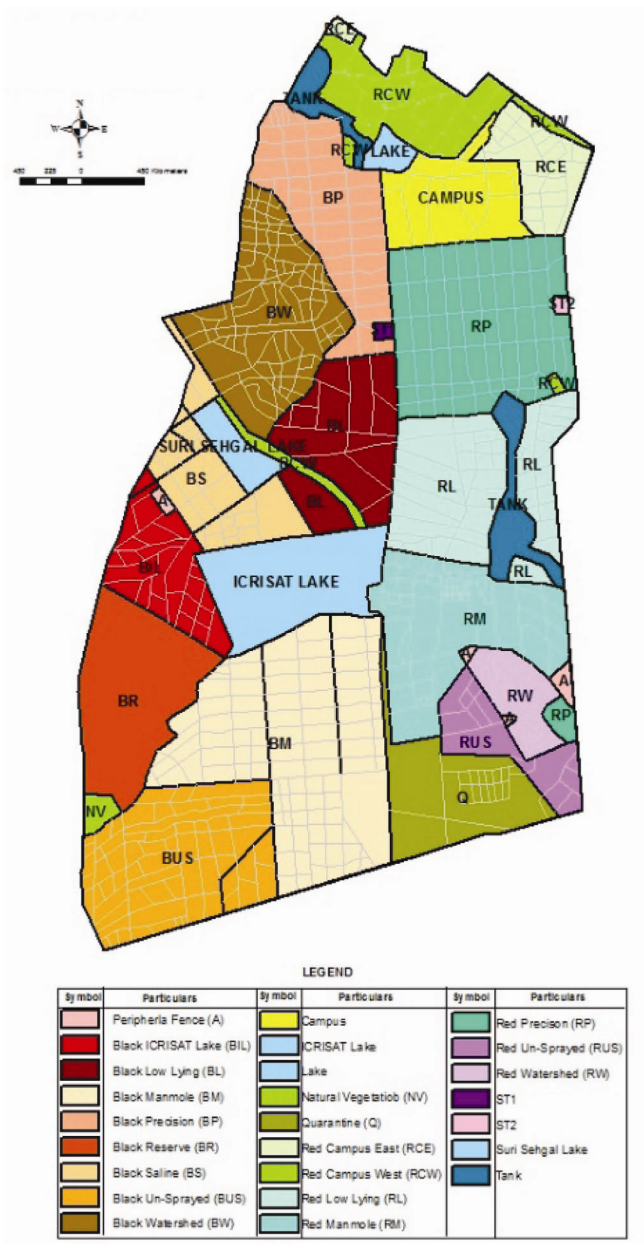

Figure 4. Simplified maps of the ICRISAT farm showing spatially associated red and black soils.

Table 4. Soils (series) of the ICRISAT farm

Soil series	Soil taxonomy: 1975's[a]	Soil taxonomy: 2015[b]	World reference base[c]	Mapping units	Area: Ha	Area: %
Icri	Fine, montmorillonitic, isohyperthermic Paralithic Vertic Ustropepts	Fine, smectitic, isohyperthermic Vertic Haplustepts	Vertic Cambisols	lkC2, l(g)kC2, l(g)kC3, lmBl, lmB2, ImC2	82.4	5.91
Kasireddipalli	Very fine, montmorillonitic, isohyperthermic Typic Pellusterts	Very fine, smectitic, isohyperthermic Typic Pellusterts	Eutric Vertisols	KkC2, KMAl, KMB1, KMB2, KMC1	552.3	39.6
Lingampalli	Fine-loamy, mixed, isohyperthermic Lithic Rhodustalfs	Fine-loamy, mixed, isohyperthermic Lithic Rhodustalfs	Eutric Alfisols	LcB1, LcB2, L(g)cB1, L(g)cB2, LcC1, L(g)cC1, LcC2, L(g)hA1, LhB1, LhC1, L(g)hC2	71.6	5.2
Manmool	Fine, mixed, isohyperthermic, Fluventic Ustropepts	Fine, smectitic, isohyperthermic Fluventic Haplustepts	Chromic Cambisols	MIB1, M1B2, MIC2, MmAl, MmB2	53.8	3.9
Patancheru	Clayey-skeletal, mixed, isohyperthermic Udic Rhodustalfs	Clayey-skeletal, mixed, isohyperthermic Udic Rhodustalfs	Chromic Luvisols	PbA1, PcB1, P(g)cB1, PcB2, P(g)cB2, PcC1, PcC2, P(g)cC2, PhA1, P(g)hA1, PhB1, PhB2, P(g)hC1, PhC2	247.7	17.8
Yamkunta	Fine, montmorillonitic, isohyperthermic Vertic Halaquepts	Fine, smectitic, isohyperthermic Vertic Halaquepts	Vertic Solonchaks	Yf(C2)B, YhB1, YhB1(B), YhC1, YiA1(A), YiB1(A), YmA1(A), YmA1(B), YmB1, YmB1(A), YmB1(B), YmB2, YmC2(B)	177.4	12.7
Others (buildings, etc.)					208.8	12.7

[a]Murthy and Swindale[15]; [b]Soil Survey Staff[42]; [c]World reference base[43]; [d]Mapping units (also see Figure 3)[15].

intersecting slickensides[19]. These are formed in basaltic alluvium in the valleys showing slow permeability. Kasireddipalli soils were cultivated for chickpea, pigeon pea, sorghum and safflower[15]. These soils contained ~1% organic carbon in the surface (0–25 cm) with almost 100% base saturation down the depth. Data on exchangeable sodium percent (ESP) showed that during 1975 these soils were non-sodic (ESP <15 in the control section) which was also reflected in their classification. As compared to the black soils formed in the states of Maharashtra, Gujarat and Madhya Pradesh, Kasireddipalli soils contain more sand (15–22%). Cation exchange capacity (CEC) (soils and clay) indicates smectites as the dominant clay mineral[20] (Table 5).

Red soils (Patancheru). These were reported to be non-calcareous, nearly neutral, non-saline showing the illuvial *Bt* horizons and are grouped as Alfisols[21]. These are developed in granitic rocks with more coarse fragments (17–63%, Table 5). Relative proportion of sand and silt is high when compared to the Kasireddipalli soils. Higher values of ESP in the lower horizons indicate the initiation of chemical degradation due to the formation of $CaCO_3$ as induced by the SAT climate[8,11]. However, the presence of $CaCO_3$ remained lacking until few decades[22]. It is observed that even with neutral pH range similar soils do contain free $CaCO_3$ (ref. 22). The CEC (soils and clay) indicates mixed mineralogy class for these soils[20] (Table 5).

Physical and chemical properties of Kasireddipalli (black) and Patancheru (red) soils during 1980

Black soils (Kasireddipalli). Organic carbon in surface layer decreased. The amount of $CaCO_3$ increased alongside an increase in subsoil sodicity as evidenced by relatively high ESP (13 within the control section but >15 beyond this depth). Other than sodium, relative proportion of extractable magnesium also increased in the subsurface layers (Table 6).

Red soils (Patancheru). After 5 years since 1975 these soils developed acidity as evidenced by relatively low pH. During 1975 the benchmark spot of the Patancheru soils were reported from outside ICRISAT farm area[15]. These soils were, however, examined later during 1980 in the ICRISAT farm. Other than relatively low pH, these soils were similar with some minor differences, viz. coarse fragments, base saturation (BS) and cation exchange capacity (CEC). Relatively higher value of exchange properties might be due to greater illuviation of clay particles. Although changes of exchangeable sodium percent (at ESP ~5) were not well pronounced, but an increase in extractable magnesium was noticed. Low amount of Na along with moderate exchangeable Mg and clay smectite[23] generally cause dispersion of clay particles, which results in reduced drainage[20] (Table 6).

Physical and chemical properties of Kasireddipalli (black) and Patancheru (red) soils during 2001

Black soils (Kasireddipalli). Organic carbon remained stable nearly at around 1%, indicating a near-equilibrium value[24]. The level of $CaCO_3$ marginally increased down the depth. Interestingly, the ESP decreased, although the range remained well above the limit of concern to group these soils as sodic soils (Sodic Haplusterts)[25] (Table 4). During 2001, we studied black soils under both high management (HM) (Figure 5) and traditional management (TM) systems (Table 7). These soils under TM showed lower pH in the surface, low organic carbon, higher $CaCO_3$ and ESP, as compared to those under HM system (Tables 3 and 7).

Patancheru soils. Patancheru soils reported during 1975 and 1980 were sampled from agricultural fields. For the first time during 2001, we visited the pristine ICRISAT farm dominated by the red soils (Patancheru) (Table 3). These are under grass and maintained as a protected area. Termite activity is common to a depth of 65 cm. The first 4–5 cm depth of soil consists of earthworm casts (70–80% volume basis). A few calcareous nodules are present which effervesce with hydrochloric acid (HCl), although the soil matrix appears non-calcareous. These nodules are softer and brighter than the calcareous nodules commonly found in the black soils. These soils developed calcareousness with 0.4–0.9% $CaCO_3$. Such calcareousness induces subsoil sodicity in SAT environment[11], which is observed in increased ESP values in these soils also. The SOC content was high[8] due to the maintenance of grass cover under protection (Table 7).

Physical and chemical properties of Kasireddipalli (black) soils during 2010

Black soils (Kasireddipalli). These soils lost some amount of SOC and showed a value near 0.5–0.6% in the surface. Decrease in $CaCO_3$ content was observed due to its dissolution and the released Ca ions helped in bringing down the ESP in plots under both high and traditional management system (HM and TM) (Table 8). It seems that the cropping and crop management practices in both these soils reduced the rate of formation of pedogenic $CaCO_3$ and the subsoil sodicity[26]. This scenario of soil resilience suggests how important it is to keep soil and land under vegetative cover to mitigate the adversity of the SAT climate[19].

Discussion

Our discussion is based on soils studied that are similar within the range of characteristics[27] to compare the changes in physical and chemical properties of soils over 2 to 3 decades time.

Table 5. Physical and chemical properties of Kasireddipalli (black) and Patancheru (red) soils (1975)

Horizon	Depth (cm)	Particle size distribution (% of < 2 mm): Sand (0.02–2)	Silt (0.02–0.002)	Clay (<0.002)	CF[a]	Organic carbon (%)	$CaCO_3$ (%)	pH (1 : 2.5 water)	BD[b] $Mg\ m^{-3}$	sHC[c] $cm\ hr^{-1}$	Water retention (%): 33 kPa	1500 kPa	EC[d] (1 : 2.5 water) dSm^{-1}	Extractable bases: Ca	Mg	Na	K	CEC[e]: Soil	clay	BS[f] (%)	ESP[g]
														←		$cmol(+)\ kg^{-1}$			→		
Kasireddipalli soils (Typic Pellusterts; Block no. BW/11 of ICRISAT farm)																					
Ap	0–25	22.5	19.6	57.9	19	0.96	1.4	8.1	1.36	1.19	38	31	2.2	39.6	13.9	1.2	1.2	57	98	99	2
A12	25–70	18.6	17.3	64.1	–	0.69	2.0	8.2	1.39	1.14	39	33	2.2	47.4	11.8	1.1	0.6	61	95	97	1
A13	70–143	15.9	18.1	66.0	9	0.60	2.4	8.0	1.40	1.30	41	34	0.2	40.5	12.0	1.4	0.7	55	83	100	2
A14	143–187	14.8	17.2	68.0	–	0.30	2.1	8.1	1.45	1.22	41	34	0.2	44.8	11.2	1.4	0.7	56	83	104	2
Patancheru soils (Udic Rhodustalfs)																					
Ap	0–5	79.3	6.4	14.3	17	0.55	NA[h]	6.0	1.51	4.66	21	12	0.1	2.6	0.5	Nil	0.4	4.8	34	74	Nil
B1	5–18	66.7	5.5	27.8	17	0.52	NA	6.9	1.48	3.23	28	18	0.1	3.8	0.9	Nil	0.5	8.2	29	64	Nil
B21t	18–36	41.6	6.8	51.6	36	0.63	NA	6.9	1.42	2.68	39	29	0.1	5.8	3.8	Nil	0.6	14.8	29	69	Nil
B22t	36–71	45.0	4.4	50.6	54	0.40	NA	6.8	1.46	2.94	36	27	0.1	7.9	3.1	Nil	0.6	14.1	28	82	Nil
B23t	71–112	54.1	7.4	38.5	50	0.10	NA	6.5	1.55	3.41	31	22	0.1	5.4	2.5	0.3	0.4	9.8	25	88	3
B3	112–140	70.6	4.1	25.3	63	0.18	NA	6.2	1.58	4.12	24	16	0.2	5.7	1.5	0.5	0.3	9.1	36	92	5

[a]Coarse fragments (>2 mm) (% of whole soils); [b]BD, bulk density; [c]sHC, saturated hydraulic conductivity; [d]EC, electrical conductivity; [e]CEC, cation exchange capacity; [f]BS, Base saturation (%); [g]ESP, exchangeable sodium percentage; [h]NA, not available (Note: BD, sHC, water retention capacity were not available in the original document; hence estimated following pedo-transfer functions, Tiwary *et al.*[34]; Patancheru soil bench mark was in village Patancheru (Source: Murthy and Swindale[15]).

Table 6. Physical and chemical properties of Kasireddipalli (black) and Patancheru (red) soils (1980)

Horizon	Depth (cm)	Particle size distribution (% of < 2 mm): Sand (0.02–2)	Silt (0.02–0.002)	Clay (< 0.002)	CF[a]	Organic carbon (%)	$CaCO_3$ (%)	BD[b] $Mg\ m^{-3}$	sHC[c] $cm\ hr^{-1}$	Water retention (%): 33 kPa	1500 kPa	pH (1 : 2.5 water)	EC[d] (1 : 2.5 water) dSm^{-1}	Extractable bases: Ca	Mg	Na	K	CEC[e]: Soil	Clay	BS[f]	ESP[g]
														←		cmol(+) kg^{-1}			→		
Kasireddipalli soils (Sodic Haplusterts; 23 July 1980, BW/7, ICRISAT farm) (17°35′N; 78°17′E)																					
Ap	0–20	23.5	22.8	53.7	6	0.73	5.3	1.51	0.01*	21	12	8.8	0.09	41.7	10.9	0.9	0.7	57	106	95	2
A	20–40	21.7	21.6	56.7	6	0.54	7.4	1.48	0.01	28	18	9.2	0.09	37.5	14.7	5.3	0.6	58	103	100	9
Bss1	40–60	19.5	22.1	58.4	6	0.47	7.0	1.42	0.01	39	29	9.4	0.09	38.4	13.0	2.9	0.6	56	96	98	5
Bss2	60–90	16.2	23.7	60.1	6	0.39	6.3	1.46	0.01	36	27	9.4	0.18	34.1	16.4	7.8	0.6	60	100	98	13
BC	90–130	11.6	21.0	67.4	7	0.28	6.2	1.55	0.01	31	22	9.4	0.45	30.2	18.4	12.8	0.6	63	93	98	20
C	130–180	12.9	20.4	66.7	9	0.25	7.5	1.58	0.01	24	16	9.4	0.54	26.2	19.1	14.2	0.6	62	92	97	23
Patancheru soils (Udic Rhodustalfs; 24 July 1980; RA 32, ICRISAT farm (17°35′N; 78°17′E)																					
Ap	0–10	73.0	9.1	17.9	4	0.84	NA[g]	1.45	5.29	20	13	5.3	NA	5.8	1.9	0.1	0.3	8.1	45	100	1
A	10–20	72.5	9.1	18.4	6	0.79	NA	1.47	5.11	21	13	5.4	NA	5.6	2.1	0.2	0.3	8.4	46	98	2
BA	20–30	58.5	9.3	32.5	10	0.85	NA	1.42	5.35	25	18	5.2	NA	10.8	2.9	0.2	0.2	14.1	45	100	1
Bt1	30–49	56.9	8.6	34.5	8	0.85	NA	1.42	5.31	26	19	5.2	NA	11.0	3.1	0.2	0.2	14.5	44	100	1
Bt2	49–102	53.1	7.4	39.5	37	0.48	NA	1.48	3.63	28	21	6.5	NA	14.3	3.4	0.3	0.2	18.2	43	100	2
BC	102–145	61.9	13.8	24.3	15	0.23	NA	1.55	5.99	22	15	4.8	NA	18.9	4.7	0.4	0.2	24.2	91	100	2

[a]Coarse fragments (>2 mm) (% of whole soils); [b]BD, bulk density; [c]sHC, saturated hydraulic conductivity; [d]EC, electrical conductivity; [e]CEC, cation exchange capacity; [f]BS, Base saturation (%); [g]ESP, exchangeable sodium percentage; [h]NA, not available (Note: BD, sHC, water retention capacity were not available in the original document; hence estimated following pedo-transfer functions, Tiwary *et al.*[34] for soils showing pH ~9.0 the pedo transfer functions do not work; the soils have very poor drainage, values assumed as 0.01 cm h^{-1}.) (Source: Lal *et al.*[18]).

Table 7. Physical and chemical properties of Kasireddipalli (black soils) and Patancheru (red soils) soils (high management) (2001)

Horizon	Depth (cm)	Particle size distribution (% of < 2 mm): Sand (0.02–2 mm)	Silt (0.02–0.002 mm)	Clay (<0.002 mm)	Fine clay (<0.0002 mm)	Organic carbon (%)	$CaCO_3$ (%)	BD[a] $Mg\ m^{-3}$	sHC[b] $cm\ hr^{-1}$	Water retention (%): 33 kPa	1500 kPa	pH (1 : 2.5 water)	EC[c] (1 : 2.5 water) dSm^{-1}	Extractable bases (← $cmol(+)\ kg^{-1}$ →): Ca	Mg	Na	K	CEC[d]: Soil	Clay	Base saturation (%)	ESP
Kasireddipalli soils (high management) (Sodic Haplusterts; BW/7, ICRISAT farm) (17°30′13″N; 78°16′07″E) (date of sampling: 18.12.2001)																					
Ap	0–12	21.5	26.4	52.1	28.8	1.0	4.2	1.5	1.7	35	29	7.5	0.14	36.5	12.5	1.0	0.5	50	97	100	2
Bw1	12–31	20.4	28.1	51.5	28.1	0.6	4.5	1.6	1.6	38	31	7.8	0.15	34.7	14.4	1.0	0.4	54	105	93	2
Bss1	31–54	16.7	29.1	54.2	34.0	0.4	6.2	1.6	1.0	38	31	7.8	0.22	31.9	19.0	1.8	0.4	56	103	95	3
Bss2	54–84	13.9	28.8	57.3	40.0	0.4	5.1	1.5	0.9	41	33	8.2	0.31	28.9	15.3	3.7	0.4	56	98	86	7
Bss3	84–118	10.9	32.6	56.5	26.0	0.5	8.6	1.6	0.7	45	37	8.1	0.23	38.7	10.2	4.2	0.7	62	109	87	7
Bss4	114–146	3.6	37.1	59.3	31.7	0.5	8.4	1.4	0.3	46	37	8.2	0.30	34.6	16.8	4.2	0.5	58	98	96	7
BC	146–157	9.9	30.1	60.0	41.5	0.3	7.4	1.4	0.3	35	9	8.2	0.62	24.4	22.8	5.1	0.7	55	92	96	9
Kasireddipalli soils (traditional management) (Sodic Haplusterts; BW/4C, ICRISAT farm) (17°30′28″N; 78°15′49″E) (date of sampling: 18.12.2001)																					
Ap	0–12	22.5	29.6	47.9	26.4	0.6	5.9	1.44	1.73	33	28	7.8	0.08	34.2	10.7	0.9	0.4	49	102	95	2
Bw1	12–30	18.7	29.9	51.4	29.7	0.4	6.2	1.48	1.64	35	29	7.8	0.16	34.9	12.7	1.9	0.3	52	101	96	4
Bss1	30–59	17.9	29.6	52.5	32.5	0.4	6.0	1.49	1.16	37	31	8.1	0.17	29.3	14.0	3.7	0.3	52	99	91	7
Bss2	59–101	16.6	27.8	55.6	36.4	0.4	6.4	1.52	0.84	40	32	8.3	0.10	26.2	14.4	6.8	0.3	53	96	89	13
Bss3	101–130	7.2	33.4	59.4	30.8	0.4	6.5	1.48	0.95	40	34	8.3	0.29	35.8	11.6	4.6	0.5	58	97	91	8
BCk	130–160	13.0	29.1	57.9	38.7	0.1	9.1	1.61	0.91	41	33	8.2	0.47	25.1	16.2	11.1	0.5	50	85	107	22
Patancheru soils (permanent fallow) (Udic Rhodustalfs; RUS 6B, ICRISAT farm, 17°28′36″N; 78°16′54″E) (date of sampling: 18.12.2001)																					
A1	0–4	66.7	15.4	17.9	12.5	3.1	0.6	1.35	3.63	24	15	6.4	0.17	4.2	3.8	0.8	1.2	10	36	12	8
A2	4–11	74.7	10.8	14.5	11.0	1.6	0.4	1.35	3.91	24	14	6.2	0.05	3.3	3.4	0.6	0.3	10	24	76	6
Bt1	11–38	50.6	5.3	44.1	37.3	1.0	0.6	1.60	3.92	31	23	6.1	0.03	8.3	3.3	0.7	0.3	11	26	111	6
Bt2	38–65	35.9	11.5	52.6	41.9	0.7	0.8	1.71	3.82	35	28	6.1	0.05	12.5	5.2	0.8	0.3	18	35	103	4
Bt3	65–79	34.8	12.0	53.2	40.9	0.6	0.8	1.70	3.91	39	30	6.0	0.06	12.4	5.9	0.7	0.4	26	40	92	3
BC	79–109	50.4	14.4	35.2	25.9	0.4	0.9	1.72	3.62	28	21	6.4	0.05	14.8	5.7	0.8	0.2	23	66	93	4
C	109–163	61.1	16.4	22.5	17.5	0.2	0.9	1.84	3.57	21	15	6.6	0.04	16.3	5.0	0.9	0.3	22	100	101	4

[a]BD, bulk density; [b]sHC, saturated hydraulic conductivity; [c]EC, electrical conductivity; [d]CEC, cation exchange capacity; [e]ESP, exchangeable sodium percentage (Source: Bhattacharyya *et al.*[4–7]).

Table 8. Physical and chemical properties of Kasireddipalli soils (2010)

Horizon	Depth (cm)	Particle size distribution (% of < 2 mm): Sand (0.02–2)	Silt (0.02–0.002)	Clay (<0.002)	Fine clay (<0.0002)	Organic carbon (%)	$CaCO_3$ (%)	BD[a] Mg m^{-3}	sHC[b] cm hr^{-1}	Water retention (%): 33 kPa	1500 kPa	pH (1 : 2.5 water)	EC[c] (1 : 2.5 water) dSm^{-1}	Extractable bases: Ca	Mg	Na	K (cmol(+) kg^{-1})	CEC[d]: Soil	Clay	Base saturation (%)	ESP
Kasireddipalli soils (high management) (Typic Haplusterts; BW/7, ICRISAT farm) (17°30′25.2″N; 78°15′9.33″E) (date of sampling: 20.02.2010)																					
Ap	0–8	23.3	29.6	47.1	19.9	0.65	4.37	1.44	1.59	31	26	8.0	0.21	35.9	8.6	1.1	0.3	43	90	108	3
Bw	8–18	22.6	25.6	51.8	26.2	0.58	4.21	1.44	1.47	34	28	8.1	0.09	38.7	8.2	0.8	0.3	49	95	98	2
Bss1	18–32	21.2	25.9	52.9	29.2	0.42	4.14	1.46	1.32	33	28	8.2	0.17	42.9	9.3	1.0	0.3	50	95	106	2
Bss2	32–44	20.4	25.0	54.6	39.7	0.34	4.88	1.47	1.18	34	29	8.2	0.19	40.9	11.4	1.1	0.3	49	89	110	2
Bss3	44–65	17.0	24.4	58.6	43.2	0.30	4.25	1.47	1.18	38	32	8.1	0.16	38.4	14.0	1.3	0.4	57	98	94	2
Bss4	65–87	14.3	24.9	60.8	42.9	0.27	4.14	1.47	0.98	40	33	8.2	0.25	35.5	15.1	1.3	0.4	55	90	95	2
Bss5	87–115	13.0	22.4	64.6	39.1	0.15	6.09	1.49	1.06	42	35	8.1	0.35	34.9	15.3	1.4	0.4	55	85	95	3
Kasireddipalli soils (traditional management) (Sodic Haplusterts; BW/4C, ICRISAT farm) (17°30′51″N; 78°16′26″E) (date of sampling: 20.02.2010)																					
Ap	0–10	23.7	26.6	49.7	25.0	0.58	5.06	1.45	1.03	34	28	8.3	0.26	32.9	11.0	1.2	0.5	49	98	94	3
Bw1	10–21	21.3	28.3	50.4	25.8	0.40	4.42	1.47	0.85	34	28	8.4	0.25	34.7	13.3	1.1	1.0	47	94	106	2
Bw2	21–31	20.4	26.7	52.9	37.1	0.38	5.29	1.47	0.65	36	30	8.5	0.27	33.2	15.2	1.0	1.1	52	99	97	2
Bss1	31–48	19.9	27.2	52.9	30.7	0.38	4.42	1.47	0.50	37	30	8.6	0.34	32.7	15.9	1.0	1.6	55	104	96	2
Bss2	48–91	17.4	28.3	54.3	48.5	0.36	4.71	1.47	0.14	39	32	8.8	0.47	26.6	19.6	1.1	3.3	55	101	92	2
Bss3	91–110	11.7	27.1	61.2	23.4	0.23	4.83	1.48	0.04	43	35	8.8	0.69	24.1	22.1	1.2	5.5	57	94	92	2
Bss4	110–135	13.2	24.2	62.6	16.7	0.11	4.14	1.50	0.02	44	36	8.8	1.31	24.0	22.8	1.3	6.5	61	97	90	2

[a]BD, bulk density; [b]sHC, saturated hydraulic conductivity; [c]EC, electrical conductivity; [d]CEC, cation exchange capacity; [e]ESP, exchangeable sodium percentage (Source: Bhattacharyya *et al.*[27]).

Chemical properties of soils

The soil reaction (water pH) which was alkaline in black soils and acidic to neutral in the red soils, decreased over time (Figure 6 *a*). During 1975, the soil EC was higher (Figure 6 *b*). Soil organic carbon in black soils (Kasireddipalli) decreased over time to reach a quasi-equilibrium value of 0.6% in the surface[24]. For red soils (Patancheru), the increased SOC during 2001 showed the status of organic carbon in the pristine red soils in the ICRISAT farm (Tables 7 and 9; Figure 6 *c*). This suggests that these red soils have a potential to sequester >1% SOC even in the semiarid climatic conditions. The major problem in the SAT is the formation of pedogenic $CaCO_3$ (refs 11, 28) which triggers other associated soil problems[19] that affect crop performance. Over time $CaCO_3$ formation is considerable and seems stabilized within 0–30 cm depth of black soils (Figure 6 *d*). Similar rise in $CaCO_3$ in red soils could have been observed if they were analysed for $CaCO_3$ in similar SAT soils of southern peninsula[22]. These carbonates coated by Fe–Mn mottles[28] may not effervesce in field with dilute HCl, but in laboratory with 100 mesh soil samples the presence of carbonates has been ascertained[29]. In earlier report on red soils (Patancheru) $CaCO_3$ was not reported[15,18], but pristine red soils (as collected for the present study) show the presence of climatically induced pedogenic $CaCO_3$ in SAT environment.

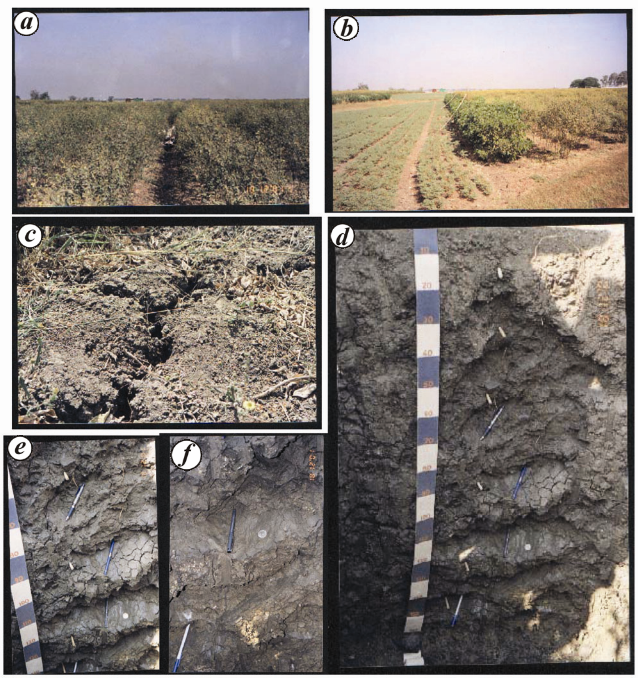

Figure 5. Landscape, landuse and soils in Kasireddipalli (black) soils under high management with: ***a***, soybean–pigeon pea crop rotation; ***a***, ***b***, standing crops; ***c***, wide and polygonal cracks; ***d***, typical soil profile (Sodic Haplusterts); ***e***, ***f***, Close-up view of the profile showing typical slickensides, a common feature in Vertisols (Source: Bhattacharyya *et al.*[4–7]).

Extractable bases (Ca, Mg, Na, and K) in both black and red soils showed variations after 20 to 30 years in surface and subsurface (Figure 6 *e*–*j*). Extractable Mg increased in the lower depth of red and black soils (Figure 6 *f*). This is also reflected in reduced Ca/Mg ratio in soils (Figure 6 *g*). Concentration of extractable Mg down the depth of soil along with extractable Na, especially in red soils (Figure 6 *i*) indicates the initiation of subsurface sodicity which might affect the entire soil if management intervention is not adopted in SAT areas[11,19,26,28]. Cation exchange capacity is controlled by soil colloids (mostly clay) and organic matter. Since physical parameters like particle size separates (read clay) do not change over a period of short time of study (1975–2010), we presume the variation of CEC is due to organic matter, especially in Patancheru soils (pristine) (Figure 6 *k*, *l*).

Potassic fertilizers are not added in black soils at the ICRISAT farm. This is due to the presence of biotite mica as the inherent supplier of native K in these soils[30]. However, our datasets showed native K to decrease over a period of 25–35 years at ICRISAT (Figure 6 *j*). This is in accordance with the earlier observations on agronomic experiments on the Vertisols of central India where crop responded to K fertilizers after two years of cropping with hybrid cotton[30]. Therefore, the present available K status may not be sustainable over a long time because the contents of sand and silt biotites are low. This information helps dispel the myth that the Vertisols are rich in available K and that they may not warrant the application of K fertilizers. An analysis on the K stock of soils in the black soil region (BSR) held the same view[31] and thus warrants application for K fertilizer in ICRISAT soils. In contrast to black soils, the K available status of Patancheru soils still remains very high (exchangeable K is around 4% of the CEC even in subsoils) as compared to that in black soils (~1%) (Table 7). Thus crops do not respond to K fertilizer application in these soils of ICRISAT[32]. Because of the almost unweathered sand and silt biotites, K release increased with the increase in silt-sized mica. Thus, quite favourable K release rate from both silt and clay micas explains as to why crop response to fertilizer K is seldom obtained in many rainfed red soils (Alfisols) under SAT environments[32]. Base saturation reached equilibrium after 1980 or so in both the soils (Figure 6 *m*).

Physical properties of soils

It is observed that dynamic chemical properties of soils, viz. soil organic carbon and calcium carbonate influence physical properties of soils, which influence crop performance[11,16] and thus these properties along with climate (rainfall and temperature) are closely related to establish a cause–effect relationship (Figure 7). Due to the formation of pedogenic calcium carbonate relative proportion

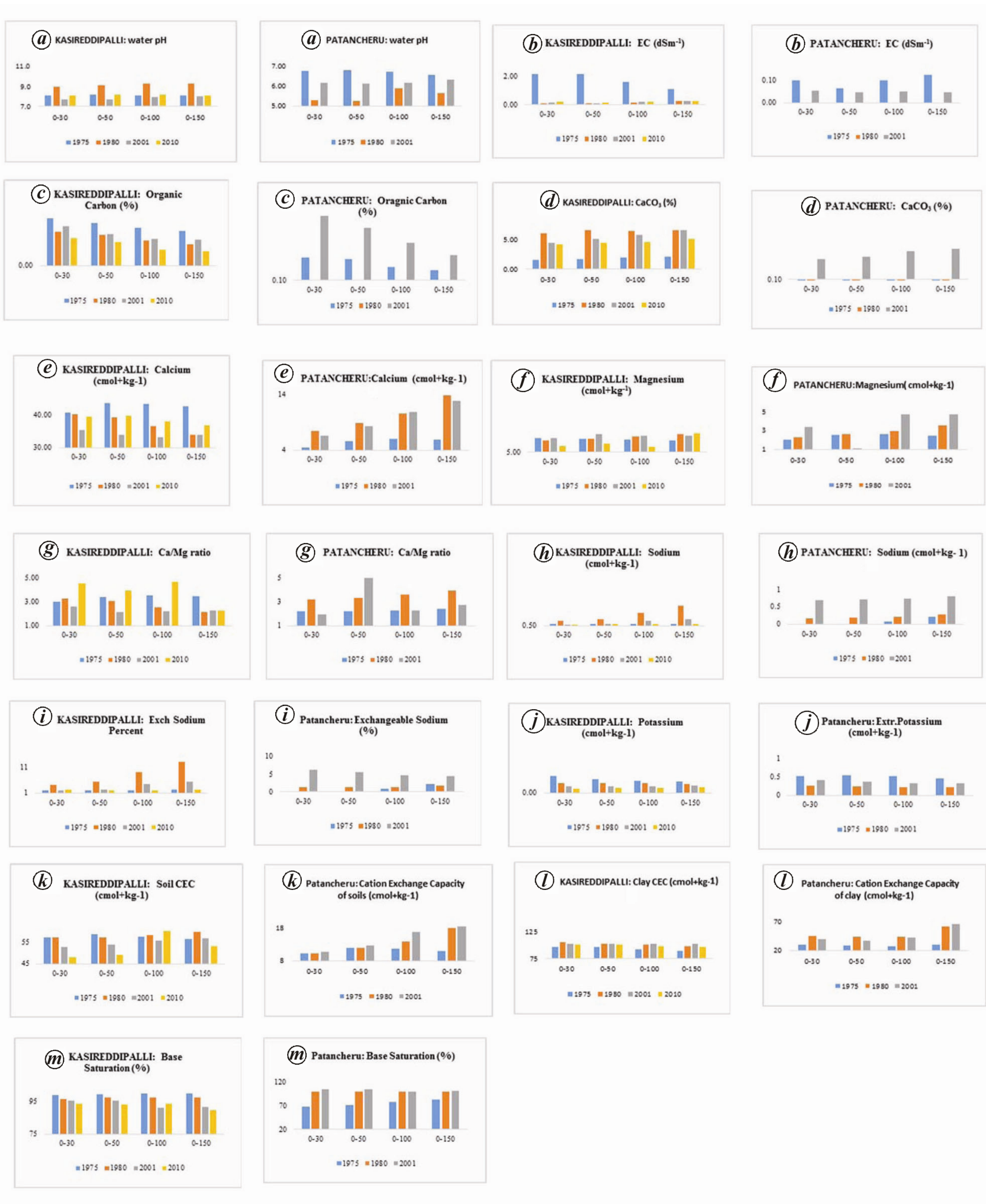

Figure 6. Changes in chemical properties over time in black (Kasireddipalli) and red (Patancheru) soils. ***a***, Water pH; ***b***, electrical conductivity; ***c***, organic carbon; ***d***, $CaCO_3$; ***e***, extractable calcium; ***f***, extractable magnesium; ***g***, extractable calcium/magnesium ratio; ***h***, extractable sodium; ***i***, exchangeable sodium percentage; ***j***, extractable potassium; ***k***, soil CEC; ***l***, clay CEC; ***m***, base saturation.

Table 9. Change in selected soil parameters of black (Kasireddipalli) and red (Patancheru) soils in ICRISAT farm

	Rate of change per year[a] (percentage change over 1975)			
	Kasireddipalli		Patancheru	
Soil parameters	0–30	0–150	0–30	0–150
Chemical parameters				
Organic carbon (%)	–1.19	–1.65	5.75	3.89
Calcium carbonate (%)	5.19	4.02	∞[b]	∞
Extractable calcium [cmol(+)kg^{-1}]	–0.09	–0.38	1.91	4.59
Extractable magnesium [cmol(+)kg^{-1}]	–1.013	0.941	8.86	16.47
Extractable sodium [cmol(+)kg^{-1}]	–0.54	–0.05	–0.46	0.52
Extractable potassium [cmol(+)kg^{-1}]	–2.08	–1.45	∞	11.10
Exchangeable sodium percentage	0.27	0.26	∞	3.86
Physical parameters				
Bulk density (Mg m^{-3})	0.99	0.98	0.27	0.51
Saturated hydraulic conductivity (cm^{-hr})	3.10	–0.63	0.74	0.34
Water retention % 33 kPa	–0.40	–0.66	–0.37	–0.45
Water retention % 1500 kPa	–0.32	–0.65	–0.28	–0.32

[a]Change over 36 years in Kasireddipalli and 26 years in Patancheru soils.
[b]During base year the values were zero making the change infinite.

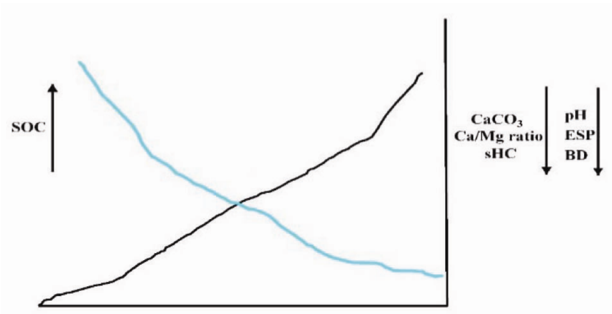

Figure 7. Schematic diagram showing relation between climate (rainfall), chemical (soil organic carbon, SOC; $CaCO_3$; soil reactions, pH; extractable calcium/magnesium ratio exchangeable sodium percentage (ESP); and physical parameters (bulk density, BD; saturated hydraulic conductivity, sHC) in soils.

of exchangeable sodium increased which concomitantly increased soil pH. When the soil pH reaches >8.5, fine clays are dispersed blocking the micro pores of soils. Under this condition and in extreme limit of high pH (>9.0), saturated hydraulic conductivity (sHC) (soil drainage) reaches its minimum which does not allow free passage of water movement, resulting in an extremely hostile pedo environment for soil microflora and fauna. Under these situations the soils become very hard showing high bulk density[27,33]. This is the reason why the pedo transfer functions (PTFs) developed for the black soils do not work for assessing saturated hydraulic conductivity in these soils with high pH[34] (Figure 8 *a*, *b*) (also see the footnotes in Tables 5 and 6). However, these PTFs are useful to assess bulk density (Figure 8 *b*). Earlier through soil data derived from regular soil survey activities and also using Roth*C* model a threshold limit of 850 mm mean annual rainfall was arrived at to show the initiation of the formation of pedogenic carbonates[26,27,35] (Figure 9). If the data for 1980 are ignored, the water retention at 33 and 1500 kPa was reduced over years (Figure 8 *c*, *d*).

Soils for tomorrow

It is difficult to assess soil properties for monitoring their changes over time. This is due to many reasons such as reaching the exact spot of sampling due to changes in land use pattern, economics and expertise. It was for this reason that we need to develop an information system on soils, landscape, climate and related earth parameters which directly and/or indirectly influence these parameters[27]. Developing such robust system requires a host of datasets which are lacking on many occasions. Use of pedotransfer functions helps in this regard as has already been demonstrated while developing soil information system for the Indo-Gangetic plains and the black soil regions of India[34]. Such exercise not only helps monitoring soil parameters, but also permits the trend of changes in the dynamic properties of soils through appropriate data interpretation[36], soil carbon and crop modelling[35,37,38]. We made an effort to understand the nature of the SAT soils as it would exist in years to come. Judging by the rate of changes in chemical and physical soil parameters (Table 9) and also on the basis of available trend of data in the semi-arid tropics[27,35,37–39], we attempted to project changes in soil properties in case the present land use and management interventions are continued (business as usual, BAU) and also, if appropriate, management interventions are adopted[40] (Figure 10).

It is quite likely that soil organic C level in black soils will further decrease until management interventions are

Figure 8. Changes in physical properties over time in black (Kasireddipalli) and red (Patancheru) soils: ***a***, saturated hydraulic conductivity; ***b***, bulk density; ***c***, water retention (%) at 33 kPa; ***d***, water retention (%) at 1500 kPa.

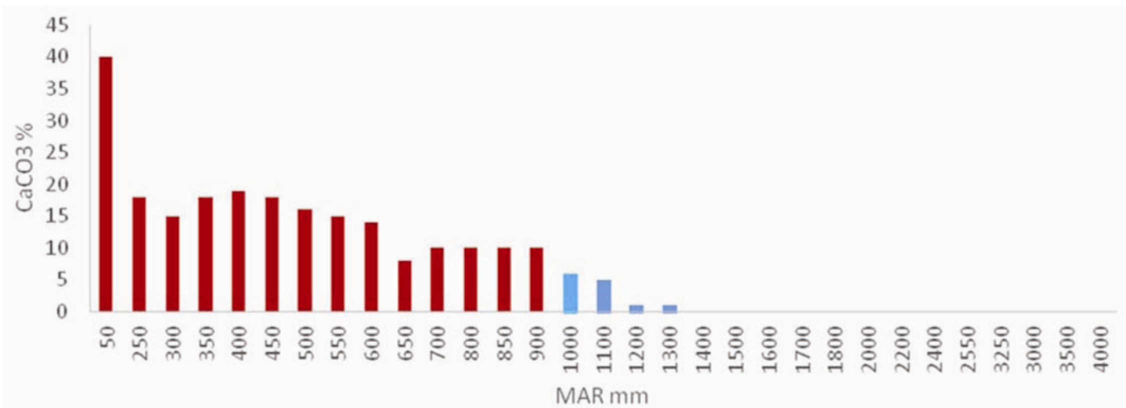

Figure 9. Distribution of rainfall and $CaCO_3$ content in soils (0–150 cm depth). The red colours show the initiation of secondary carbonate formation with the concomitant soil degradation[11,26,44].

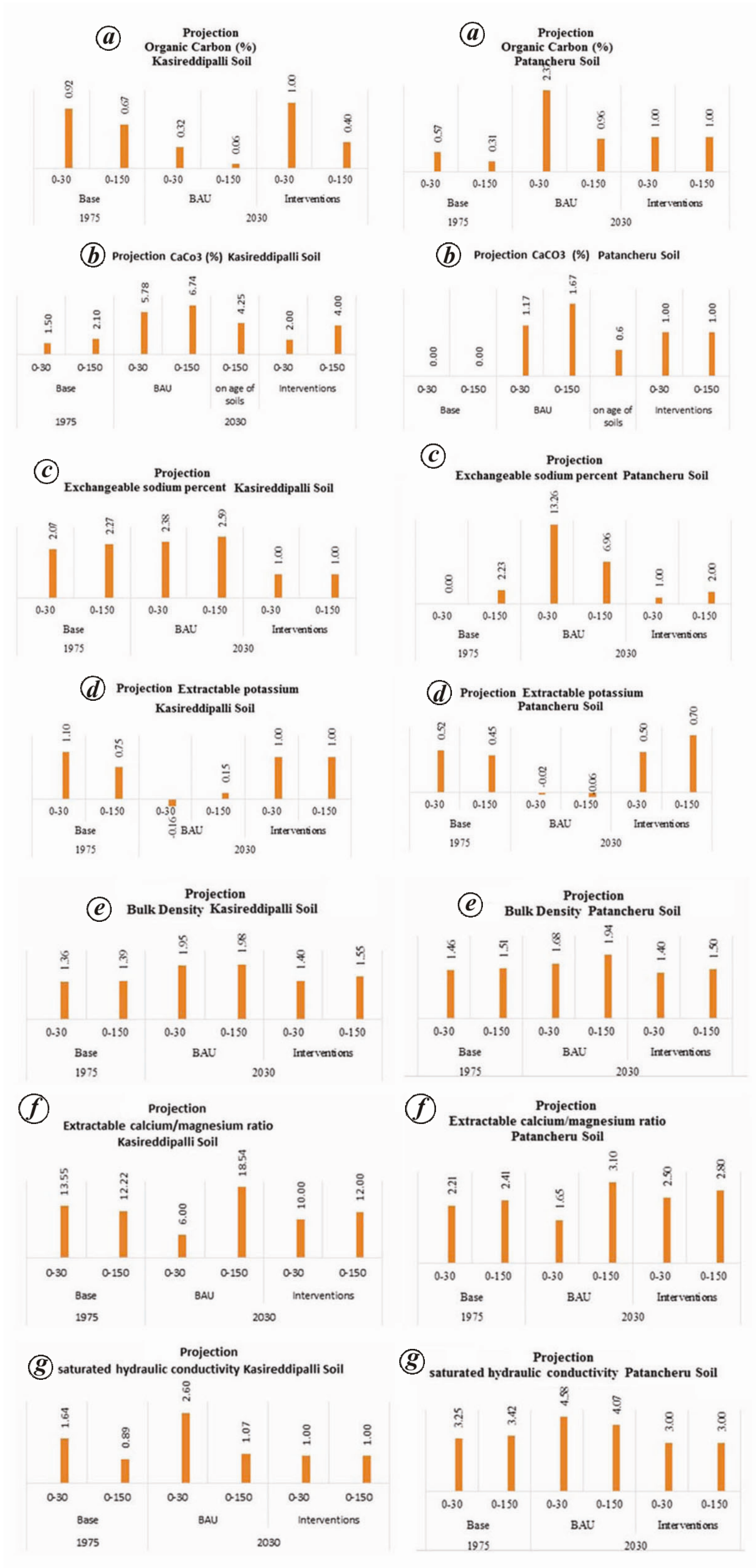

Figure 10. Projected changes in selected parameters in Kasireddipalli and Patancheru soils of ICRISAT farm during 2030. The values of different parameters obtained during 1975 were considered as base year to predict the changes under business as usual (BAU) presuming the same management practices are continued and also under different types of interventions which include addition of recommended doses of fertilizers along with organics (Source: Bhattacharyya *et al.*[45,46]). ***a***, Organic carbon; ***b***, $CaCO_3$ (%) (also on the basis of age of soils assuming calcium carbonate formation @ 1.48 mg 100 g m^{-1} soil yr^{-1} in 0–100 cm soil depth (Pal *et al.*[39]); ***c***, extractable sodium percentage; ***d***, extractable potassium; ***e***, bulk density (mg kg^{-1}); ***f***, extractable calcium/magnesium ratio; ***g***, saturated hydraulic conductivity (cm hr^{-1}).

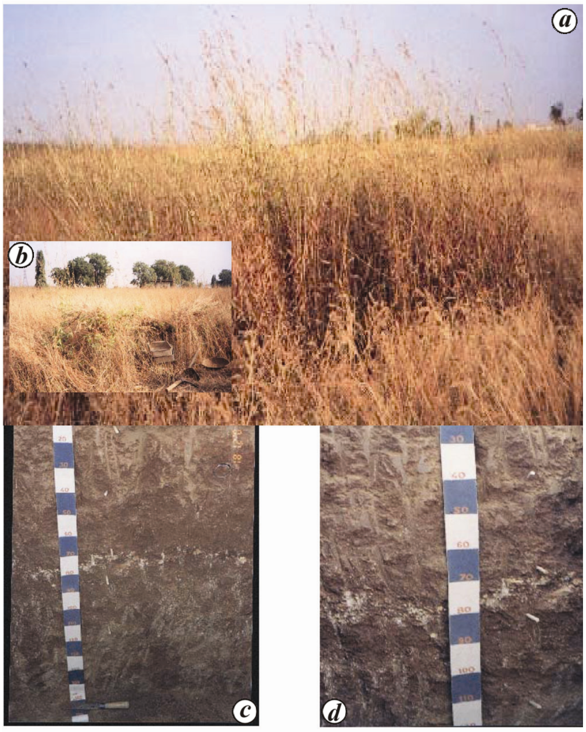

Figure 11. Landscape, landuse and site in Patancheru soils under permanent fallow with: ***a***, grass and other vegetations; ***b***, Patancheru site with grass and other perennial vegetations; ***c***, Typical Patancheru soil profile (Typic Rhodustalfs); ***d***, Close-up view of the profile showing lot of Fe/Mn concretions in the sub soil layers (Bhattacharyya *et al.*[4–7]).

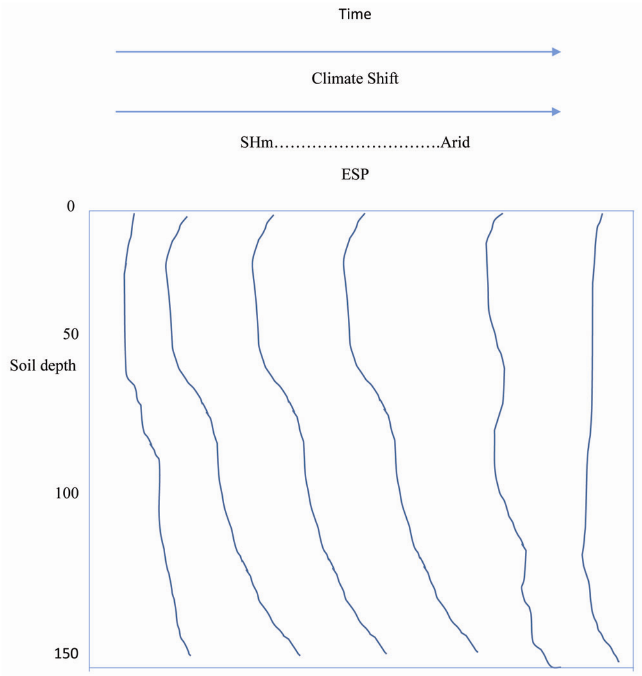

Figure 12. Progressive development of subsoil sodicity as evidenced by increasingly more sodium concentration (ESP) engulfing the entire profile from down top ward with time with the shift in climate from sub humid moist to arid ecosystem (SHm: sub humid moist) (on the basis of …. No. of datasets representing benchmark soils of the IGP and BSR[27]).

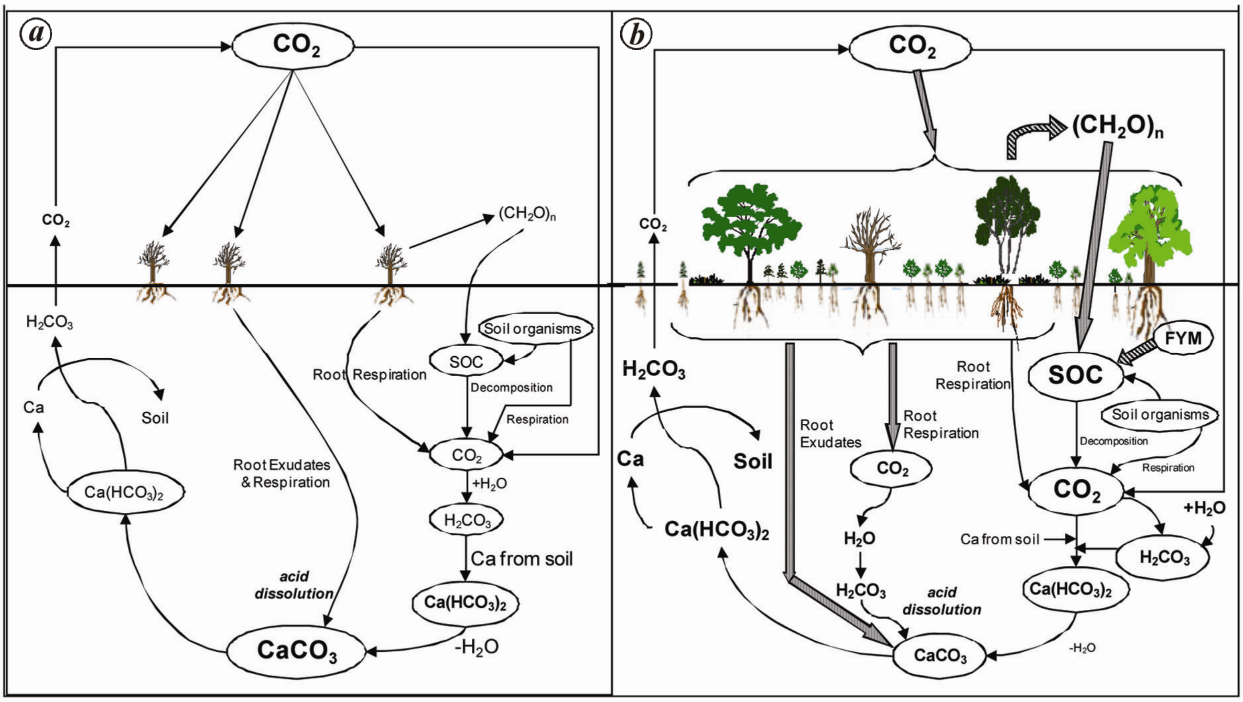

Figure 13. Carbon transfer model showing effect of management intervention in semi-arid and arid bioclimatic systems of (***a***) chemically degraded land, and (***b***) areas showing management intervention (size of circle and letters indicate relative proportion of individual component)[26].

not adopted to add mineral fertilizers and organic matter on a continuing basis (Figures 10 *a*). Modelling and results from the long-term experiments predict that soil organic carbon can be increased if recommended dose of fertilizers (RDFs) along with farm yard manure (FYM) (10 t ha^{-1}) are applied[35,37,38,41]. For Patancheru soils, BAU indicates an increase of SOC as the site is pristine. This area is under perennial grass, which cites an effective land use practice to sequester OC in SAT soils (Figure 11).

In spite of the projected increase in $CaCO_3$, ESP showed a decreasing trend (Figure 10 *b*, *c*). Although SOC, SIC, BD and other properties are inter-related (Figure 7), this shows that the management interactions, especially addition of farm yard manure, has a positive influence in offsetting the ill effect of the increased sodium in soil exchange complex (Figure 10 *c*). As mentioned earlier, exchangeable K is getting depleted and requires attention in both black and red soils of Patancheru (Figure 10 *d*). Increase in bulk density is a cause of concern in both these types of soils (Figure 10 *e*). Interestingly, the trends in hydraulic conductivity appeared positive (Figure 10 *f*). It might be due to the addition of FYM and also due to enhanced soluble and exchange Ca^{+2} ions available through the dissolution of $CaCO_3$ by the acidic crop root exudates.

The projections under BAU was derived on the basis of available trend during the past 26–36 years (Figure 10; Tables 5–8). However, the values shown under interventions in these figures emanate from the experience gathered in red and black soil research over the years[19,20,23,26,40]. Our observations suggest a progressive development of subsoil sodicity due to increase in pedogenic carbonates (PCs) under SAT environment with time when anthropogenic activities in terms of sustainable management interventions to raise agricultural crops are not made (Figure 12). We presume that if appropriate management techniques are not adopted, the soils will lose their productivity as shown also through the carbon transfer model[26] (Figure 13).

Black soils in sub humid ecosystems contain less $CaCO_3$ and maintain higher Ca/Mg (exchangeable) ratio (>2) than those in dry areas like Kasireddipalli. We predict that if appropriate management techniques are adopted, the Ca/Mg ratio (Figure 10 *f*) could be 2 or higher[28,39]. Higher Ca/Mg ratio helps black soils in the wetter climate to maintain good physical conditions and in better productivity than the SAT black soils. The threshold ratio of Ca/Mg (≥ 2) could thus be a useful soil health parameter for the SAT soils. Other than PC, non-pedogenic carbonates get dissolved in wetter climate to release Ca^{2+} ions to modify soil properties and enhance available soil water content during the cropping seasons. Pedogenic carbonates are thus a *curse* but the non-pedogenic counterparts are *boon* for the farmers[19]. To control formations of PCs, therefore, no parcel of land should be kept fallow in SAT regions[19,26].

Conclusion

Predicting behaviour of natural resources like soils has always been a difficult proposition. This is more so amidst the changing situations in resource management (anthropogenic activities), natural calamities including climate change. Such effort requires data on soils for the past, and present; fortunately the soil information system developed over the years for the semi-arid tropics permits us to comment on soil qualities. Sustainable management interventions for red and black soils of the ICRISAT, India for the last few decades have made possible both the soil types resilient. Resilience of these soils was possible because of increased soluble Ca ions both in soil solution and on the exchange sites through the continuous dissolution of $CaCO_3$ during the crop stand under the improved management systems. Even after decades of management interventions that created favourable Ca ions environment, red soils (Alfisols) remain as Alfisols and less sodic black soils (Sodic Haplusterts) have become non-sodic soils (Typic Haplusterts), suggesting the positive effect of appropriate recommendations and the management protocols. Moreover such example of soil resilience strongly demonstrates that initially degraded soils of the SAT could be made the vibrant crop production areas for another couple of centuries.

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doi: 10.18520/cs/v110/i9/1652-1670