Impact of management levels and land-use changes on soil properties in rice–wheat cropping system of the Indo-Gangetic Plains

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Five benchmark soils, namely Fatehpur (Punjab) and Haldi (Uttarakhand) non-sodic soils, Zarifa Viran (Haryana), Sakit and Itwa sodic soils (Uttar Pradesh) representing Trans, Upper, Middle and Central Indo-Gangetic Plains (IGP) were revisited for studying the morphological, physical and chemical properties of soils at low and high management levels to monitor changes in soil properties due to the impact of land-use as well as management levels. The results indicate an increase in bulk density (BD) below the plough layer, and build up of organic carbon (OC) and decline in pH in surface layers of Zarifa Viran, Sakit and Itwa sodic soils under high management. The concentration of carbonates and bicarbonates in sodic soils decreased due to adaptation of rice–wheat system. The build-up of OC and decrease of pH in surface soils under rice–wheat system enhanced the soil health. Increase in BD in subsurface soils, however, is a cause of concern for sustaining rice–wheat cropping system. Soil management interventions such as tillage, conservation agriculture and alternate cropping system have been suggested for improved soil health and productivity.

Keywords: Benchmark soil, bulk density, land-use changes, rice–wheat system, soil properties.

Introduction

Land-use is a synthesis of physical, chemical and biological systems and processes on the one hand, and human/societal processes and behaviour on the other. Monitoring of such systems includes the diagnosis and prognosis of land-use changes in a holistic manner at various levels. In the Indo-Gangetic Plains (IGP), agriculture is the major land-use. In the northern parts of the IGP, during the past 3–4 decades (after the green revolution era), there is a great shift from wheat–maize and wheat–cotton to rice–wheat cropping systems. Rice–wheat is the main cropping system in IGP of northwestern India, because of high economic returns from high-yielding varieties of these crops and high management level[1]. In Punjab, the areas under rice and wheat cultivation are 2.6 and 3.4 m ha respectively. Studies showed that continuous rotation of cereal–cereal (rice–wheat) cropping system has resulted in decrease in organic carbon (OC) content[2]. There are also reports of positive impact on soil

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organic carbon (SOC)[3,4]. Cultivation of rice on light textured soils in recent flood plains resulted in lowering of water table[5,6], creations of hardpan in sub-soils, increase in SOC[7,8] and increase in selenium toxicity which adversely affects human as well as animal health[9,10]. Soil erosion through seasonal streams (Choes), low water-holding capacity in steeply sloping lands in the foothills of the Siwaliks and sandy soils of Choes and recent/active plains[11,12] and low land holding of the farmers, are other major problems of the area. Consequently, growth in the agriculture sector has slowed down. These studies[11,12] were mostly confined to static (one time) period without considering the impact of temporal changes of the cropping system on soil properties and/or soil quality parameters.

Keeping the above facts in view, study of five benchmark (BM) soils at high and low management levels in diversified agro-ecological sub-regions (AESRs) was undertaken at two time intervals, viz. 1979 and 2010. Some of these BM soils represent the areas under highly intensified agricultural land-use system, which had undergone drastic changes with respect to the cropping system. Other soils represent traditional rice–wheat cropping areas, which have not undergone changes in cropping system. The third set belongs to salt-affected soils, which produced high yields of these crops after reclamation. As such, it is an ideal case study to gain knowledge about the impact of the dynamics of cropping systems on soil properties that are important for plant growth and soil health under different site-specific conditions.

Materials and methods

General characteristics of the study area

The study area covers northern parts of the IGP, from Punjab in the north to Uttar Pradesh in the east. The area lies between 29°30′–31°28′N lat. and 73°55′–84°37′E long.

Physiography and relief

The IGP is basically a riverine plain which is composed of featureless landform on a broad scale. These alluvial deposits of main rivers, viz. Ravi, Beas, Sutlej, Ghagghar, Yamuna and Ganges belong to the Pleistocene and Recent periods and consist mainly of sand, silt and clay[13,14]. The IGP is subdivided into piedmonts, terai, old flood plains and recent/active flood plains, the monotony of which is broken at micro level by river bluffs, levees and dead arms of the river channels.

The northeastern area forms a part of the Siwalik system (lower Himalayas). The Siwalik deposits consist of alluvial detritus derived from sub-aerial wastes of the middle and upper Himalayas, swept down by rivers and streams. Information about the exact age of these deposits is lacking. Geologists argue that these were deposited during the Pleistocene and Holocene[13]. The piedmont plains formed by deposition of numerous seasonal streams merge with the alluvial plains of the rivers in the south-eastern parts of the Siwaliks. All streams join the main rivers of IGP.

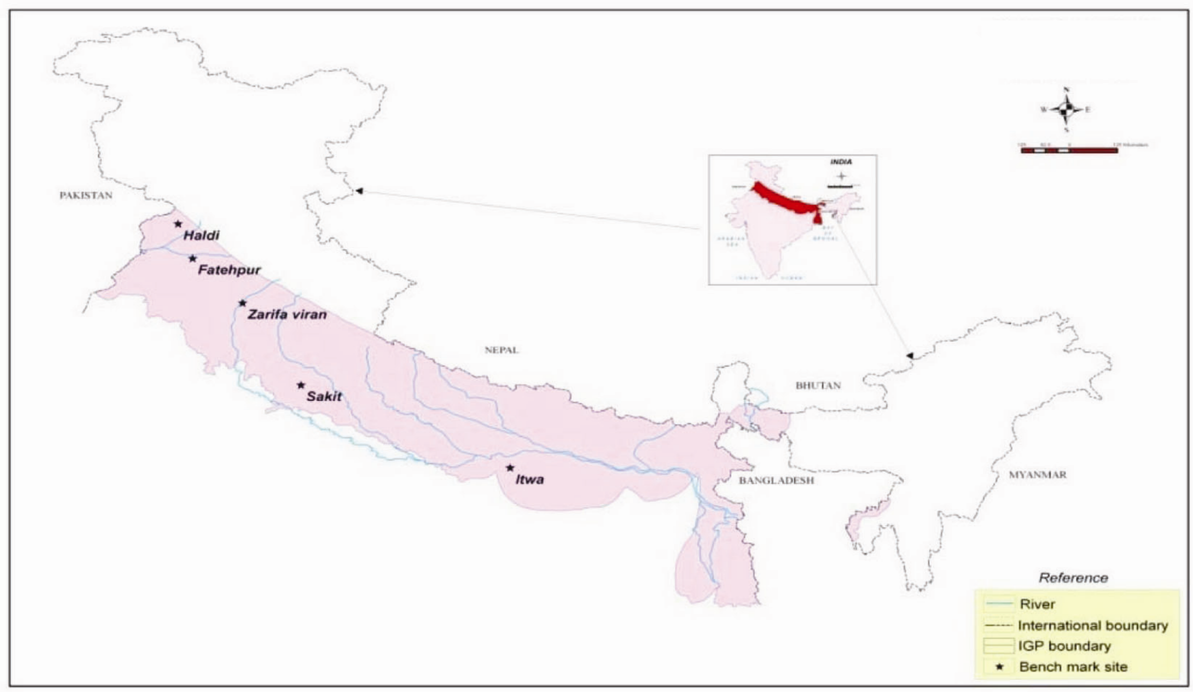
The climate of the area is subtropical, semi-arid to sub-humid and monsoonic with severe summer and winter. June is the hottest and January is the coldest month. Mean maximum and mean minimum summer air temperatures are 41°C and 26°C respectively. Mean maximum and mean minimum winter air temperatures are 19°C and 6°C respectively. The mean annual air temperature is 23.3°C and the difference between mean summer and mean winter temperature is more than 5°C. Hence, the districts in the northwestern part of IGP qualify for classification under hyperthermic temperature regime.

The average annual rainfall ranges from as low as <500 mm in the western part (Abohar, Panjab) to as high as >1600 mm in the eastern part of the IGP (Gorakhpur, Uttar Pradesh). About 70% of the annual rainfall in the area is received between July and September. The moisture regime qualifies as aridic to ustic and udic. The length of growing period (LGP) of the IGP varies from <60 to >300 days.

Selection of benchmark soils

Five benchmark soils, namely Zarifa Viran (Haryana), Sakit and Itwa (Uttar Pradesh) representing salt-affected soils and Fatehpur (Punjab) and Haldi (Uttrakhand) representing normal soils in different agro-ecological setting and cropping patterns were selected for the present study[15,16]. Location of benchmark soils is given in Figure 1. Details of these series are given in earlier publications[15,16]. A brief site information is given below.

The soils in these areas were revisited and soil profiles were studied at two management levels, namely high management (HM) and low management (LM) for each soil, with the exception of Sakit soil series where LM and medium management (MM) levels were considered due to absence of HM practices in the area attributed to low land holding size and poor economic conditions of farmers. In Zarifa Viran, Fatehpur and Haldi soils, HM soils have been selected at research farms of Central Soil Salinity Research Institute (CSSRI), Karnal; Punjab Agricultural University, Ludhiana; GB Pant University of Agriculture and Technology, Pantnagar respectively, where optimum levels of input are being added. LM soils are selected in all cases from the fields of farmers who are not capable of adding optimum levels of input according to the package of practices of the respective Agricultural University or State Department of Agriculture. In Itwa, these are represented by HM and MM sites. Besides, we



Soil series	Agroecological sub-region	Location
Zarifa Viran (Haryana) – LM Zarifa Viran (Haryana) – HM	4.1	Village-Gudha,Tehsil-Gharounda, District Karnal, Haryana CSSRI Farm Tehsil: Karnal, District Karnal, Haryana
Sakit (Uttar Pradesh) – LM Sakit (Uttar Pradesh) – MM	4.1	Village-Ramgarhi, Tehsil-Jalesar, District Etah, Uttar Pradesh Village-Ramgarhi, Tehsil-Jalesar, District Etah, Uttar Pradesh
Itwa (Uttar Pradesh) – LM Itwa (Uttar Pradesh) – HM	9.2	Village-Sakaldiha, Tehsil-Sakaldiha, District Chandoli, Uttar Pradesh Village-Sakaldiha, Tehsil-Sakaldiha, District Chandoli, Uttar Pradesh
Fatehpur (Punjab) – LM Fatehpur (Punjab) – HM	9.1	Village-Kotali, Tehsil-Sidhwan, District Ludhiana, Punjab PAU Farm, Tehsil-Ludhiana, District Ludhiana, Punjab
Haldi (Uttrakhand) – LM Haldi (Uttrakhand) – HM	13.2	TANDA Forest, Tehsil-Rudrapur, District Udham Singh Nagar, Uttarakhand C1, CRC, GBPUAT, Pantnagar

LM, Low management; HM, High management.

Figure 1. Location map of benchmark soils.

also selected sites where management level is low. The past history for land-use/cropping system of these soils was collected from the site through questionnaire and also through secondary data. Zarifa Viran soils belong to hot semi-arid northern plains with soils derived from alluvium and LGP of 120–150 days. Sakit soils belong to hot (hyperthermic), semi-arid to sub-humid, Rohilkhand plain with LGP 120–150 days and Itwa series belong to hot (hyperthermic), semi-arid, Ganga–Yamuna Doab plain with LGP 80–120 days. Haldi soils belong to hot (hyperthermic), sub-humid to humid, piedmont and Terai plain with LGP of 210–300 days. Fatehpur soils belong to semi-arid, northern plain with alluvium-derived soils and LGP of 90–120 days.

The soil analysis was conducted following standard procedures[17,18] to determine pH and electrical conductivity (EC) of the soil in 1 : 2.5 soil : water ratio and exchangeable sodium percentage (ESP); SOC by Walkley and Black method[19]; particle size analysis by Jackson method[20]; calcium carbonate by the method of Richards[21]; cation exchange capacity following the method of Rhoades[22]; calcium carbonates by Williams method[23] and bulk density (BD) by the method of Blake and Hartge[24]. The temporal change of soil properties was observed and compared with respect to the soil properties reported in the literature. The change of land-use/cropping system on soil properties and natural resources was deduced from the above data.

Results and discussion

Impact of soil management levels on soil properties of salt-affected and non-salt-affected soils

(i) *Zarifa Viran series*

Morphological and physical properties: There was no appreciable change in morphological properties, except

Table 1. Physical properties of soils under low and high/medium management

Low management						High/medium management					
		Size class and particle diameter (mm) – Total						Size class and particle diameter (mm) – Total			
Horizon	Depth (cm)	Sand (2–0.05 μm) (% of <2 mm)	Silt (0.05–0.002 μm) (% of <2 mm)	Clay (<0.002 μm) (% of <2 mm)	BD (Mg m^{-3})	Horizon	Depth (cm)	Sand (2–0.05 μm) (% of <2 mm)	Silt (0.05–0.002 μm) (% of <2 mm)	Clay (<0.002 μm) (% of <2 mm)	BD (Mg m^{-3})
Zarifa Viran series (fine-loamy, mixed, hyperthermic Vertic Natrustalfs)											
Ap	0–14	34.9	42.6	22.5	1.59	Ap	0–21	54.7	26.8	18.5	1.48
A2	14–36	32.4	42.1	25.5	1.60	A2	21–38	47.3	30.3	22.5	1.62
Bt1	36–60	29.6	38.0	32.5	1.54	Bt1	38–57	34.7	35.4	30.0	1.77
Bt2	60–88	32.1	28.4	37.5	1.54	Bt2	57–80	37.8	24.8	37.5	1.69
Bt3	88–110	25.7	36.4	38.0	1.71	Bt3	80–98	39.5	24.8	35.8	1.52
Bt4	110–137	30.8	31.5	37.7	1.52	BC	98–119	53.6	27.9	18.5	1.69
BC	137–160	33.1	31.7	35.3	1.64	C1	119–147	55.4	27.1	17.5	1.78
–	–	–	–	–	–	C2	147–170	63.1	19.0	18.0	1.48
Sakit series (fine-loamy, mixed, hyperthermic Typic Natrustalfs)											
Ap	0–12	50.9	27.4	21.8	1.56	Ap	0–17	50.6	30.4	19.0	1.34
A2	12–32	46.2	29.1	24.8	1.39	A2	17–39	32.9	33.9	33.3	1.66
Bt1	32–57	42.0	27.5	30.5	1.30	B1	39–71	28.3	31.5	40.3	1.41
Bt2	57–77	42.7	25.3	32.0	1.18	Bt1	71–101	26.6	31.9	41.5	1.48
Bt3	77–96	33.4	37.1	29.5	1.44	Bt2	101–127	25.2	34.5	40.3	1.51
Bc1	96–120	28.2	40.8	31.0	1.52	Bc	127–152	35.0	30.8	34.3	1.40
Bc2	120–150	23.2	43.5	33.3	1.49	–	–	–	–	–	–
Itwa series (fine, mixed, hyperthermic Vertic Natraqualfs)											
Ap	0–18	45.7	30.8	23.5	1.44	Ap	0–15	50.0	35.5	14.5	1.48
Bt1	18–46	14.4	56.9	28.8	1.68	AB	15–39	42.1	35.4	22.5	1.49
Bt2	46–68	15.6	55.2	29.3	1.55	Bt1	39–67	15.7	48.6	35.8	1.65
Bt3	68–87	13.9	54.9	31.3	1.47	Bt2	67–94	10.0	47.3	42.8	1.53
B4ca	87–114	14.1	52.4	33.5	1.54	Bt3	94–118	10.4	46.1	43.5	1.58
Bc ca	114–130	14.5	51.8	33.8	1.52	Bt4	118–140	9.2	46.1	44.8	1.69
Fatehpur series (coarse-loamy, mixed, hyperthermic Inceptic Haplustalfs)											
Ap	0–25	82.6	7.2	10.3	1.56	Ap	0–15	84.3	8.3	7.5	1.33
Ac1	25–52	82.2	8.3	9.5	1.42	Ac1	15–37	81.2	9.0	9.7	1.71
C2	52–78	80.0	12.3	7.8	1.49	C2	37–62	81.1	9.7	9.2	1.67
C3	78–105	81.2	11.8	7.0	1.48	C3	62–90	84.7	4.8	10.5	1.40
C4	105–132	82.5	10.0	7.5	1.38	C4	90–115	84.2	4.6	11.2	1.47
C5	132–160	80.9	11.9	7.3	1.53	IIC5	115–140	82.0	7.3	10.7	1.27
–	–	–	–	–	–	IIC6	140–165	82.4	7.2	10.5	1.49
Haldi series (coarse-loamy, mixed hyperthermic Typic Hapludalfs)											
A1	0–16	45.4	35.3	19.3	1.42	Ap	0–15	50.5	32.7	16.8	1.39
Bw1	16–36	30.3	46.9	22.8	1.50	Bw1	15–39	34.1	32.9	33.0	1.41
Bw2	36–49	27.1	47.4	25.5	1.44	Bw2	39–64	29.5	37.0	33.5	1.36
Bc	49–71	60.9	25.1	14.0	1.47	Bc	64–88	67.7	15.3	17.0	1.33
C1	71–92	66.7	22.0	11.3	1.29	C1	88–108	83.4	5.7	11.0	1.49
IIC2	92–116	78.2	14.3	7.5	1.47	2c2	108–130	84.8	5.5	9.8	1.55
IIC3	116–129	94.3	2.0	3.6	1.49	3c3	130–160	86.67	5.83	7.50	1.77
IIC4	129–156	95.4	1.7	3.0	1.55	–	–	–	–	–	–

BD, Bulk density.

that the colour of soils was darker (10YR3/3M) under LM compared to lighter colour (10YR4/4M) of HM soils. However, dark layer crust due to water stagnation was observed on the surface along with stagnated water in LM soils in small patches which was not noticed in HM soils. This was due to high amount of sodium in LM soils. Increase in BD in subsurface was observed in both the cases (Table 1). The increase of BD in HM soils was more compared to LM soils. This was due to use of heavy machinery for intensive rice–wheat cropping system and accumulation of clay due to puddling process for rice cultivation. Similar observations were also reported earlier in IGP[25–27]. The relatively higher BD (1.59 Mg m^{-3}) on surface of LM soils compared to that (1.48 Mg m^{-3}) on the surface HM soils is due to less compaction in the latter and also because of addition of plant biomass through continuous and intensive cultivation of crops.

Chemical properties: Under LM, the soils were highly alkaline (pH 8.8–10.2) compared to HM soils (pH 8.2–9.1). Accordingly, exchangeable sodium percentage (ESP) was also high (72–78) in LM soils than HM soils (1.6–7.6; Table 2) due to reclamation in the latter soils by addition of gypsum and adaptation of optimum packages of practice in the research farm at CSSRI, Karnal. The build-up (0.95%) of OC was observed in HM soils compared to low OC (0.30%) in LM soils due to greater plant biomass addition in HM soils[28–30]. More biomass in HM soils is due to crop residues left by harvest combines. Also very little time is left to decompose the straw due to continuous crop cover in these intensively cultivated areas. These changes were more pronounced in surface soils than subsurface soils because active management processes were operated on the surface only. Electrical conductivity (ECe) in LM soils was higher (1.5–2.1 dS m^{-1}) than HM soils (0.45–0 84 dS m^{-1}) due to high amount of soluble salts in LM soils (Table 3). The content of bicarbonates (HCO_3) on the surface of LM soils was high (1.54 mmol l^{-1}) than HM soils (Table 3). Conversely, the content of sulphate (SO_4) was less (3.48 mmol l^{-1}) on the surface of HM soil compared to LM soils (5.50 mmol l^{-1}). It is due to addition of gypsum in HM soils, which brings the level of $CaCO_3$ low in the soil profile. No significant difference was observed in other properties.

(ii) *Sakit series*

Morphological and physical properties: There was no appreciable change in morphological properties, except that the calcareousness was higher on the surface in LM than MM soils. Under MM, calcium carbonate was leached down to lower layers because of better irrigation facilities. However, dark layer of salt crust was observed on the surface along with stagnated water in LM soils, which was almost absent in HM soils. This was due to high amount of sodium in LM soils (Table 2). Increase in BD on the subsurface was observed in LM soils, but its increase was more (1.66 Mg m^{-3}) in MM (Table 1) due to use of tractor for cultivation and accumulation of clay due to puddling process for rice cultivation, as observed in Zarifa Viran soils.

Chemical properties: LM level surface soils were highly alkaline (pH 9.8) compared to HM soils (pH 9.2; Figure 2). Accordingly, ESP was also high (70.9) in LM soils than in MM soils (48.3; Table 2) which was 95 in the year 1979 (ref. 15). The decrease in ESP in soils under MM is caused by addition of gypsum and growing rice as the first crop. No build-up of OC was noticed in MM soils, as observed in Zarifa Viran soils. The ECe on the surface of LM soils was higher (3.1 dS m^{-1}) as compared to HM soils (1.1 dS m^{-1}). The concentration of Na was lower (9.5 $mmol_c$ l^{-1}) in MM soils compared to LM soils (12.13 $mmol_c$ l^{-1}). Also, the concentration of bicarbonates was lower in MM soils (5.28 $mmol_c$ l^{-1}) than LM soils (5.5 $mmol_c$ l^{-1}; Table 3). These findings show that the decrease in HCO_3 content on the surface of MM soils is due to addition of gypsum and more leaching of these salts to lower horizons in MM soils. But the results are not so pronounced as observed in Zarifa Viran soils, due to the fact that management level of two soils was more distinct in Zarifa Viran (LM versus HM) than Sakit soils (MM versus LM).

(iii) *Itwa series*

Morphological and physical properties: There was no appreciable change in morphological properties, because these soils are under rice–wheat cropping system. There was increase in bulk density in subsurface soils (Table 1) of LM (1.68 Mg m^{-3}) as well in HM soils (1.6 Mg m^{-3}). Since both of these soils are under rice–wheat system for >300 years, the increase in bulk density of subsurface is almost same. Under HM the calcium carbonates leached down to lower layers, but in LM soils the calcium carbonates contents are high and ranged from 7.5 to 36.0. Interestingly, the contents (6.6–10.56 cmol (p+) kg^{-1}) of exchangeable calcium (Ca) and magnesium (Mg) (2.64–3.96 cmol (p+) kg^{-1}) in HM soils were higher compared to those in LM soils (1.32–3.52 and 0.88–1.76 cmol (p+) kg^{-1} respectively). This is due to high clay content of HM soils, which have adsorbed more Ca and Mg than LM soils having less clay content (Table 1). However, dark layer along with cracks observed on the surface in LM soils was almost absent in HM soils. This is due to high amount of sodium in LM soils (Table 2).

Chemical properties: LM level surface soils were highly alkaline (pH 9.1), which further increased to 10.2 in the subsurface soils. Compared to these, pH of 8.2 was observed in HM soils which increased to 9.0 in subsurface

Table 2. Chemical properties of soils under low and high/medium management

Depth (cm)	pH (1 : 2) H_2O	EC (1 : 2) (dS m^{-1})	OC (%)	$CaCO_3$ (%)	Exchangeable bases Ca^{2+}	Mg^{2+}	Na^+	K^+	CEC	ESP	BS
					◄ [cmol (p+) kg^{-1}]			►			
Zarifa Viran series											
Low management											
0–14	8.8	0.57	0.30	2.4	1.32	0.88	9.85	0.43	13.50	73	92
14–36	9.9	0.77	0.27	0.9	1.76	0.88	10.39	0.41	14.00	74	96
36–60	9.9	1.00	0.19	0.0	2.64	1.32	12.68	0.39	17.48	72	97
60–88	10.0	1.20	0.19	0.6	3.52	1.32	15.03	0.38	20.45	73	99
88–110	10.0	1.30	0.15	1.3	2.64	1.32	16.06	0.38	20.50	78	99
110–137	10.2	1.60	0.11	4.1	3.08	1.76	16.00	0.37	21.30	75	100
137–160	10.2	1.60	0.11	5.9	2.64	1.32	14.09	0.30	18.40	77	99
High management											
0–21	8.2	0.30	0.95	1.9	6.60	4.40	0.2	0.3	12.5	2	92
21–38	8.3	0.33	0.80	1.3	6.16	4.40	0.2	0.3	11.2	2	99
38–57	8.3	0.31	0.76	0.3	6.16	4.40	0.3	0.3	11.2	3	99
57–80	8.2	0.43	0.69	0.4	5.72	3.52	0.4	0.2	10.3	4	95
80–98	8.5	0.26	0.46	5.5	5.28	3.52	0.3	0.2	9.8	3	95
98–119	8.5	0.32	0.42	8.6	5.28	3.52	0.4	0.2	9.7	4	97
119–147	9.1	0.32	0.30	12.4	4.84	2.64	0.5	0.1	8.3	6	98
147–170	7.8	0.45	0.30	8.0	4.40	2.20	0.6	0.1	8.0	8	92
Sakit series											
Low management											
0–12	9.8	1.10	0.31	13.3	1.76	0.88	8.66	0.31	12.22	71	95
12–32	10.3	1.30	0.23	10.0	2.20	0.88	10.39	0.34	14.09	74	98
32–57	10.4	2.60	0.08	12.2	2.20	1.32	12.01	0.40	16.09	75	99
57–77	10.5	3.10	0.08	23.3	2.20	1.32	12.08	0.28	16.00	76	99
77–96	10.4	2.60	0.04	35.9	2.64	0.88	11.66	0.17	15.36	76	99
96–120	10.2	1.70	0.04	35.9	2.64	1.32	11.41	0.17	15.96	72	97
120–150	9.8	0.75	0.04	35.9	2.20	1.32	10.23	0.14	14.58	70	95
Medium management											
0–17	9.2	0.50	0.27	7.3	2.64	2.20	5.80	0.39	12.00	48	91
17–39	10.5	3.50	0.27	9.8	2.20	1.32	16.10	0.48	21.00	77	95
39–71	10.7	4.70	0.23	8.7	1.32	1.32	20.00	0.48	24.00	83	96
71–101	10.7	3.70	0.15	8.2	1.32	0.88	17.40	0.42	20.89	83	95
101–127	10.5	2.80	0.08	9.6	0.88	1.32	16.50	0.32	19.10	86	99
127–152	10.4	2.00	0.04	11.2	0.88	0.88	12.50	0.28	14.70	85	98
Itwa series											
Low management											
0–18	9.1	0.78	0.27	12.5	1.32	0.88	4.95	0.17	7.60	65	96
18–46	10.2	1.00	0.24	7.5	2.20	1.32	10.7	0.16	14.65	73	98
46–68	10.1	1.00	0.04	24.0	2.64	1.32	13.13	0.23	17.42	75	99
68–87	9.8	0.62	0.08	35.5	2.20	1.32	13.66	0.28	17.50	78	100
87–114	9.4	0.40	0.04	36.0	3.52	0.88	9.98	0.18	15.00	66	97
114–130	9.1	0.32	0.04	28.3	3.08	1.76	7.53	0.16	13.02	58	96
High management											
0–15	8.2	0.36	0.60	2.6	6.60	2.64	0.65	0.50	13.24	5	78
15–39	8.8	0.57	0.22	3.5	8.36	3.52	0.59	0.50	16.00	4	81
39–67	8.9	0.69	0.22	3.3	8.80	3.52	0.96	0.30	15.88	6	85
67–94	9.0	0.59	0.17	2.8	10.12	3.96	1.11	0.30	15.75	7	98
94–118	8.8	0.53	0.15	4.3	10.12	3.96	1.04	0.30	18.12	6	85
118–140	8.7	0.47	0.15	2.7	10.56	3.96	0.79	0.20	19.68	4	79
Fatehpur series											
Low management											
0–25	7.1	0.08	0.35	8.3	1.32	0.88	0.01	0.04	2.50	0.4	90
25–52	7.6	0.07	0.08	8.5	2.20	1.32	0.01	0.04	3.80	0.3	94
52–78	7.7	0.07	0.19	11.0	2.64	1.32	0.02	0.03	4.20	0.5	95
78–105	7.8	0.06	0.15	10.5	3.52	1.32	0.03	0.03	5.10	0.6	96
105–132	8.0	0.06	0.23	10.0	3.52	1.32	0.02	0.03	5.00	0.4	98
132–160	8.2	0.11	0.19	8.0	3.08	1.76	0.02	0.02	4.95	0.4	99

(*Contd*)

Table 2. (*Contd*)

Depth (cm)	pH (1 : 2) H_2O	EC (1 : 2) (dS m^{-1})	OC (%)	$CaCO_3$ (%)	Exchangeable bases Ca^{2+} [cmol (p+) kg^{-1}]	Mg^{2+}	Na^+	K^+	CEC	ESP	BS
High management											
0–15	7.2	0.14	0.58	0.8	3.08	1.32	0.03	0.02	5.25	0.6	85
15–37	7.6	0.09	0.27	1.0	3.08	2.64	0.03	0.01	6.50	0.5	89
37–62	7.7	0.08	0.15	2.0	3.52	1.76	0.01	0.01	5.65	0.2	94
62–90	7.7	0.08	0.19	1.2	3.52	1.76	0.02	0.01	5.75	0.4	92
90–115	7.7	0.10	0.19	1.5	3.08	1.32	0.02	0.01	4.69	0.4	95
115–140	7.6	0.10	0.19	9.4	2.64	1.32	0.02	0.01	4.50	0.4	89
140–165	7.7	0.10	0.04	9.67	1.76	1.32	0.02	0.01	3.40	0.6	91
Haldi series											
Low management											
0–16	7.2	0.15	1.26	0.2	5.72	2.64	0.10	0.75	10.50	1	88
16–36	7.4	0.13	1.14	0.9	5.72	2.64	0.20	0.70	10.55	2	88
36–49	7.9	0.16	1.07	2.8	6.60	3.08	0.30	0.70	11.75	3	91
49–71	7.1	0.13	0.95	4.2	3.52	1.76	0.30	0.70	7.00	4	88
71–92	7.3	0.08	0.88	1.0	2.64	1.32	0.20	0.65	5.20	4	93
92–116	7.6	0.11	0.91	3.1	2.20	1.32	0.20	0.35	4.52	4	90
116–129	8.0	0.07	0.69	3.0	0.88	0.88	0.10	0.22	2.27	4	92
129–156	8.0	0.09	0.38	4.3	0.88	0.88	0.10	0.10	2.11	5	93
High management											
0–15	6.9	0.14	1.18	2.7	4.40	2.64	0.30	0.30	9.50	3	80
15–39	7.3	0.24	1.14	1.6	8.36	3.52	0.40	0.20	14.95	3	83
39–64	7.5	0.20	1.07	7.9	8.36	3.52	0.30	0.20	14.15	2	87
64–88	7.4	0.13	0.95	2.0	4.40	2.64	0.10	0.20	8.65	1	85
88–108	7.5	0.10	0.84	1.2	3.52	1.76	0.20	0.20	6.55	3	87
108–130	7.5	0.10	0.76	3.0	2.64	1.32	0.10	0.10	4.75	2	88
130–160	8.3	0.12	0.69	25.1	2.20	1.32	0.10	0.10	4.09	2	91

EC, Electrical conductivity; OC, Organic carbon; CEC, Cation exchange capacity; ESP, Exchangeable sodium percentage; BS, Base saturation.

soils (Figure 3). ESP was also high (57.8–78.1) in LM soils compared HM soils (3.7–7.1; Table 2). This is because of the reclamation in HM areas by gypsum and adaptation of optimum packages of practice under better management. Build-up of OC was noticed in HM soils which show 0.60% OC compared to 0.27% in LM soils. The initial content (year 1979) of OC in these soils was 0.43% (ref. 15), which shows that HM improved the SOC, whereas in LM soils SOC decreased compared to its original content. Cover crops contribute to the accumulation of organic matter in the surface soil horizon[31–35]. The saturation extract analysis (Table 3) shows that the concentration of bicarbonates was lower in HM soils (3.96 $mmol_c\ l^{-1}$) than in LM soils (4.6 $mmol_c\ l^{-1}$).

Non-salt-affected soils

Two benchmark soils designated as normal soils (non-sodic and non-saline) representing different agro-ecological sub-regions, viz. Fatehpur in Punjab and Haldi in Uttrakhand, were selected for studying changes in morphological, physical and chemical properties under LM and HM levels. The results are discussed in the following:

(i) *Fatehpur series: non-sodic soils*

Morphological and physical properties: Level of management might have influenced soil colour as evidenced by darker shade (10YR 4/3) in HM than a lighter shade (10YR 5/3) in the LM soils. Dark colour of HM soils is due to introduction of rice crops along with wheat and other short-duration crops like sunflower, potato, toria, etc. An increase in bulk density on the subsurface was observed in HM soils (1.71 Mg m^{-3}) and no such change was observed in LM soils (Table 1).

Chemical properties: LM level soils were slightly alkaline (pH 7.1–8.2) compared to HM soils (7.2–7.7; Figure 4). There is no significant change in soil pH in LM and HM soils, as these are basically neutral to slightly alkaline. A build-up of OC (0.58%) was noticed in HM soils compared to low OC (0.35%) in LM soils. This is due to addition of plant biomass through continuous and intensive cultivation of rice and wheat crops along with short-duration crops like potato, sunflower and toria. These changes were more pronounced in surface soils than in subsurface soils, because of the effect of active

Table 3. Electrical conductivity (ECe) and soluble cations and anions in the saturation extract properties of soils

		Soluble cations ($mmol_c\ l^{-1}$)					Soluble anions ($mmol_c\ l^{-1}$)				
Depth (cm)	ECe ($dS\ m^{-1}$)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Sum of anions	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	Sum of anions
Zarifa Viran series											
Low management											
0–14	1.50	2.40	1.60	3.35	0.44	7.79	0.00	1.54	1.08	3.48	6.10
14–36	1.50	3.40	1.40	3.48	0.32	8.60	0.00	2.42	2.88	3.34	8.64
36–60	1.00	4.60	1.20	2.89	0.31	9.00	0.00	2.64	2.54	3.25	8.43
60–88	2.00	3.40	1.00	2.67	0.17	7.24	0.00	1.98	3.24	1.56	6.78
88–110	1.20	0.93	0.08	2.67	0.56	4.24	0.00	1.98	1.98	0.92	4.88
110–137	2.10	0.93	0.07	1.37	0.57	2.94	0.00	1.32	0.72	0.68	2.72
137–160	1.90	0.80	0.40	1.37	0.56	3.13	0.00	1.10	0.36	0.72	2.18
High management											
0–21	0.57	2.40	1.40	3.35	0.78	7.93	0.00	1.32	1.08	5.50	7.90
21–38	0.57	3.60	1.40	1.37	0.82	7.19	0.00	2.42	2.52	1.85	6.79
38–57	0.66	4.40	1.40	1.37	0.02	7.19	0.00	2.20	2.88	1.85	6.93
57–80	0.84	6.20	2.80	3.07	0.72	12.79	0.00	1.76	5.76	5.50	13.02
80–98	0.45	4.20	1.20	4.13	0.80	10.33	0.88	6.47	1.98	1.23	10.56
98–119	0.54	6.20	3.40	3.35	0.78	13.73	0.00	3.08	1.98	1.04	6.10
119–147	0.66	0.60	0.20	3.48	0.12	4.39	0.00	2.64	1.08	0.97	4.69
147–170	0.76	0.60	0.20	2.98	0.23	4.01	0.00	3.08	0.72	0.97	4.77
Sakit series											
Low management											
0–12	3.10	0.80	0.60	12.13	0.03	13.56	0.00	5.50	3.24	5.24	13.98
12–32	2.40	0.80	0.40	7.61	0.03	8.84	0.00	5.94	1.44	2.15	9.53
32–57	4.30	0.80	0.10	21.28	0.04	22.22	2.64	11.88	1.98	5.59	22.09
57–77	5.30	1.00	0.20	36.29	0.06	37.55	8.80	14.96	2.52	11.69	37.97
77–96	5.20	0.40	0.80	36.46	0.16	37.82	4.84	20.20	3.24	7.97	36.25
96–120	2.40	0.60	0.20	6.72	0.18	7.70	0.00	4.18	1.98	2.15	8.31
120–150	1.90	1.20	1.00	10.37	0.12	12.69	0.00	3.08	2.88	6.15	12.11
Medium management											
0–17	1.10	1.00	0.60	9.50	0.06	11.16	0.00	5.28	1.98	3.10	10.36
17–39	9.20	0.80	0.40	54.24	0.04	55.48	8.80	23.65	12.60	10.11	55.16
39–71	10.00	0.40	0.20	69.39	0.03	70.02	20.90	27.50	12.60	9.19	70.19
71–101	7.00	0.60	0.20	57.24	0.04	58.08	17.60	19.80	12.60	9.13	59.13
101–127	4.90	0.40	0.20	34.46	0.09	35.15	7.04	19.80	1.98	5.50	34.32
127–152	2.90	1.00	0.60	17.89	0.11	19.60	0.88	6.30	1.44	11.45	20.07
Itwa series											
Low management											
0–18	1.30	0.60	0.80	6.33	0.82	8.55	0.00	4.62	0.72	4.04	9.38
18–46	1.20	1.40	0.20	4.24	0.72	6.56	0.00	3.30	1.80	1.46	6.56
46–68	1.10	0.80	0.20	5.30	0.10	6.41	0.00	2.42	1.08	3.34	6.84
68–87	1.20	0.80	0.80	5.41	0.13	7.14	0.00	4.18	1.80	2.25	8.23
87–114	0.81	0.80	0.80	6.33	0.18	8.11	0.00	5.50	1.98	1.62	9.10
114–130	0.63	1.00	0.20	6.33	0.19	7.72	0.00	5.06	1.80	0.53	7.39
High management											
0–15	0.80	1.60	1.60	5.46	0.82	9.48	0.00	3.96	2.88	3.07	9.91
15–39	0.97	1.00	0.80	4.70	0.72	7.22	0.00	3.08	1.80	2.25	7.13
39–67	1.70	0.80	1.00	2.41	0.78	4.99	0.00	3.08	1.44	0.53	5.05
67–94	0.51	1.00	0.40	2.67	0.57	4.64	0.00	2.42	1.80	0.53	4.75
94–118	0.40	0.60	1.00	4.41	0.56	6.57	0.00	3.30	1.80	1.42	6.52
118–140	0.60	0.40	1.20	5.39	0.82	7.81	0.00	5.28	1.98	0.53	7.79
Fatehpur series											
Low management											
0–25	0.16	1.20	0.80	0.04	0.05	2.09	0.00	0.88	0.72	0.63	2.23
25–52	0.15	1.20	1.00	0.07	0.09	2.36	0.00	0.88	0.72	0.90	2.50
52–78	0.12	1.20	1.00	0.15	0.08	2.43	0.00	1.54	1.08	0.03	2.65
78–105	0.15	1.00	0.80	0.39	0.08	2.27	0.00	1.54	0.36	0.66	2.56
105–132	0.17	0.80	0.60	0.50	0.07	1.97	0.00	1.54	0.36	0.03	1.93
132–160	0.21	1.40	1.00	0.72	0.07	3.19	0.00	0.88	1.44	0.76	3.08

(*Contd*)

Table 3. (*Contd*)

Depth (cm)	ECe (dS m^{-1})	Soluble cations ($mmol_c\ l^{-1}$)				Sum of anions	Soluble anions ($mmol_c\ l^{-1}$)				Sum of anions
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}		CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	
High management											
0–15	0.29	1.60	1.20	0.37	0.04	3.21	0.00	2.20	0.36	1.03	3.59
15–37	0.25	2.20	1.40	0.98	0.07	4.65	0.00	2.42	1.80	0.14	4.36
37–62	0.29	1.60	1.20	0.35	0.09	3.24	0.00	1.98	0.72	0.88	3.58
62–90	0.23	1.40	1.00	0.20	0.08	2.68	0.00	0.88	0.72	0.69	2.29
90–115	0.24	1.20	1.00	0.30	0.08	2.59	0.00	1.32	1.08	0.70	3.10
115–140	0.25	1.40	1.20	0.48	0.07	3.15	0.00	1.54	1.08	0.68	3.30
140–165	0.23	1.40	1.20	0.30	0.07	2.97	0.00	1.10	1.08	0.92	3.10
Haldi series											
Low management											
0–16	0.39	2.60	0.80	0.63	0.03	4.06	0.00	2.20	1.98	0.53	4.71
16–36	0.29	1.80	1.20	0.56	0.12	3.68	0.00	1.54	1.80	1.11	4.45
36–49	0.35	1.60	1.40	0.43	0.16	3.60	0.00	1.32	1.98	0.91	4.21
49–71	0.29	1.40	1.40	0.40	0.10	3.31	0.00	1.98	0.72	0.84	3.54
71–92	0.17	1.20	0.80	0.17	0.17	2.34	0.00	1.32	0.72	0.53	2.57
92–116	0.22	1.20	1.80	0.08	0.11	3.20	0.00	1.98	1.44	0.24	3.66
116–129	0.16	1.60	0.80	0.16	0.19	2.75	0.00	1.32	0.72	0.60	2.64
129–156	0.15	1.40	0.40	0.10	0.16	2.07	0.00	1.98	0.36	0.24	2.58
High management											
0–15	0.74	4.60	1.40	0.74	0.15	6.89	0.00	2.42	1.98	2.04	6.44
15–39	0.43	2.20	1.40	0.89	0.13	4.62	0.00	2.64	1.44	0.60	4.68
39–64	0.35	1.80	1.20	1.37	0.23	4.60	0.00	2.64	1.44	1.18	5.26
64–88	0.46	1.80	1.80	1.33	0.20	5.13	0.00	2.64	1.80	0.99	5.43
88–108	0.37	2.00	1.80	1.35	0.17	5.32	0.00	2.86	1.80	1.08	5.74
108–130	0.38	2.00	1.20	0.78	0.19	4.17	0.00	1.32	1.80	0.99	4.11
130–160	0.19	2.60	0.80	0.78	0.18	4.36	0.00	1.98	1.80	1.18	4.96

management processes at the surface. The ECe in LM soils was higher (0.15–0.21 dS m^{-1}) compared to HM soils (0.23–0.29 dS m^{-1}). No significant difference was observed in other properties (Table 3).

(ii) *Haldi series*

Morphological and physical properties: Two pedons were taken for the Haldi soils. One is forest soil representing LM and the other was collected at the experimental farm of GBPUAT, Pantnagar, representing HM. There was no appreciable change in morphological properties, including soil colour. Increase in BD (1.50 Mg m^{-3}) in subsurface soils (1.42 Mg m^{-3}) was observed in LM soils (Table 1). Bulk density on the surface was less due to addition of biomass (foliage, etc.) and less cropping intensity in these soils. Slight increase in BD of subsurface soils (1.41 Mg m^{-3}) than surface soils (1.39 Mg m^{-3}) in HM soils, compared to other soils in rice–wheat system, is due to the richness of OC (1.18%; Table 2) even though these soils were brought under cultivation after clearing the forests.

Chemical properties: Under LM level the surface soils have slightly higher pH (7.2) than HM soils (pH 6.9). No significant difference was observed in ECe and other chemical properties (Table 2). High ECe (0.74 dS m^{-1}) was noticed in surface soils under HM compared to LM soils (0.39 dS m^{-1}). It is due to more use of irrigation water containing high contents of salt and application of chemical fertilizers in HM soils. There were no significant changes observed in other characteristics of saturation extract (Table 3).

Impact of change in land-use/cropping system on soil properties of salt-affected and non-salt-affected soils

The impact of change in land-use/cropping system during 1979 (benchmark soils) and 2010 (revisited under NAIP) on soil properties (mainly soil pH, OC, EC, cation exchange capacity (CEC) and BD in some soils) was analysed and interpreted for five benchmark soils as given below.

(i) *Salt-affected soils*

Zarifa Viran soils: It was found that Zarifa Viran soils located in CSSRI, which were highly salt-affected (pH of surface soils as high as 10.3) during 1979, were reclaimed by adopting recommendations of the Institute and brought under rice–wheat cropping system under high management level. During 2010, these soils were revisited and it was noticed that soil pH decreased to as low as to 8.2 (Figure 2). There was appreciable build-up of OC during this period and its content increased to 0.91% from 0.31% in 1979. However, bulk density of the surface soils increased to 1.69 Mg m^3 during 2010 compared to 1.64 Mg m^3 in 1979.

Sakit soils: These soils of Etawah district, Uttar Pradesh could not be reclaimed fully as in the case of Zarifa Viran soils, due to poor economic conditions of farmers. These soils have been brought recently under rice and wheat cropping system, but under medium management level. There was slight decrease in soil pH (9.6) in surface soils during 2010 compared to 1979 (10.50; Figure 3). The OC content of surface soils remained almost same, i.e. 0.30–0.40% during this period.

Itwa soils: These soils are under rice–wheat cropping system for the last 300 years. No appreciable changes in soil properties were observed. There was slight increase in pH of surface as well as subsurface soils, which tends to be same in lower horizons (Figure 4). The soil OC (0.40%) remained almost same during 1979 and 2010. These soils are not cultivated intensively like Zarifa Viran soils, where 3–4 crops are taken in a year. Therefore, no build-up of OC was noticed. There was an increase in BD of sub-surface soils (from 1.55 to 1.65 Mg m^3) during 2010, which may be ascribed to replacement of bullocks with tractors for cultivation purposes. Also, continuous puddling processes led to movement of fine clay to subsurface soils, which caused formation of crust as evidenced by increase in BD.

(ii) *Non-salt-affected soils*

Fatehpur soils: These soils underwent tremendous changes in land-use since 1979. Previously these soils were lying as wastelands in the form of sand cover adjoining sand dunes[15] in central Punjab, which later on were levelled and brought under irrigation and cultivated for rice and wheat. These led to changes in soil properties. The soil pH reduced to 7.2 during 2010 from 7.8 during 1979; similarly, soil EC also reduced to 0.1 dS m^{-1} from 0.80 dS m^{-1} (Figure 5). There was significant build-up of OC, to the extent of 0.8% during 2010 from 0.11% during 1979. These changes are due to intense cultivation, which has led to depletion of the groundwater table at an alarming rate of more than a metre per annum[5,6].

Haldi soils: These soils at the research farm of GBPUAT, Pantnagar, did not show any change in pH in

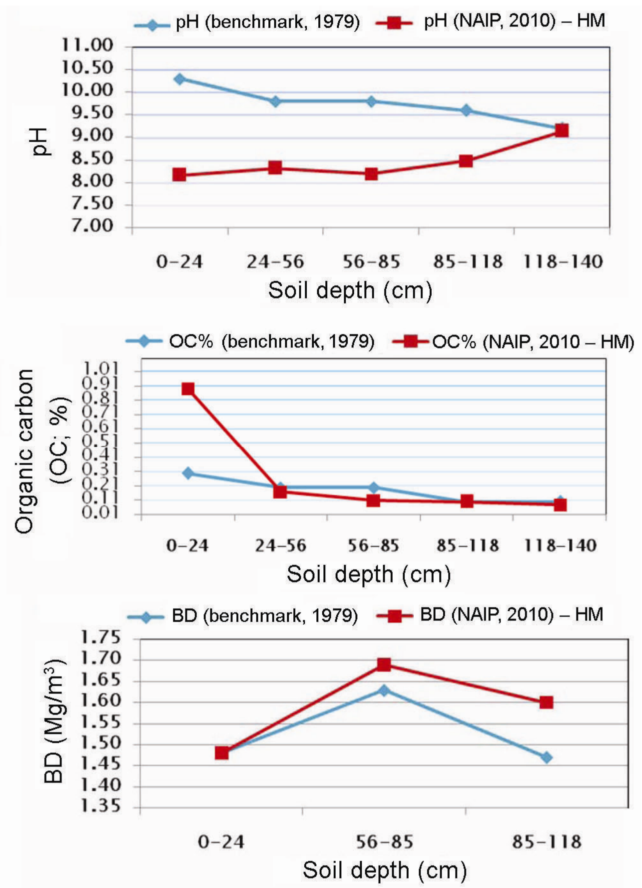


Figure 2. Effect of temporal changes of land-use on bulk density (BD) of soil in high management (HM) practice areas of Zarifa Viran soils.

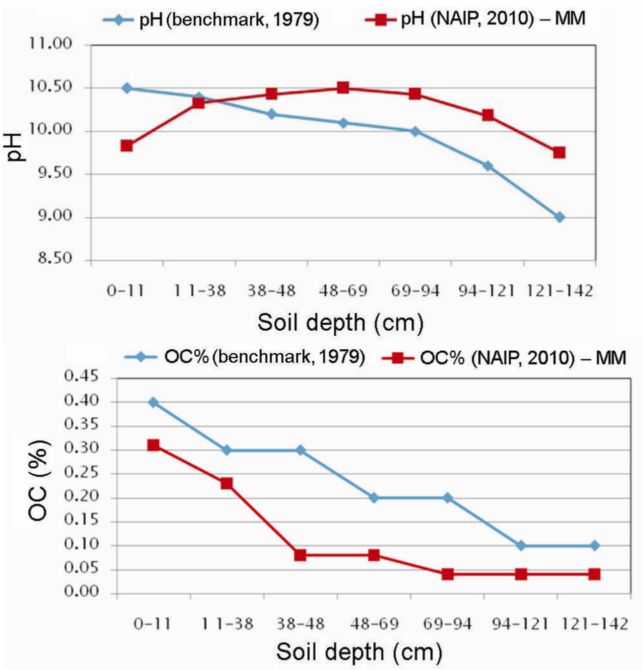


Figure 3. Effect of temporal changes of land-use on soil chemical properties (pH and OC) of HM practice areas in Sakit soils.

surface soils (7.1–7.2), but pH increased abruptly to 8.0 below plough layer, which may be due to leaching of salts through fertilizer application. There was appreciable increase in soil OC on the surface layers from 0.7% in 1979 to 1.3% during 2010 (Figure 6). The BD of these soils slightly decreased from 1.46 Mg m^3 in 1979 to 1.42 Mg m^3 during 2010.

General discussion

The above findings indicate that soil properties are being influenced by the level of management and change of cropping pattern in this important agricultural region of the IGP. With the introduction of modern varieties of wheat and rice in India in the 1960s, farmers in northwest India (Trans IGP region), introduced rice into the prevalent wheat system in light and medium textured soils; farmers on the eastern side of India (IGP region) introduced wheat into their rice system in mostly heavy textured soils, despite the fact that wheat is generally grown in the cool dry season and rice in the warm wet monsoon months. Rice–wheat system is now one of the most important cropping systems for food security in India along with rice–rice systems. Based on the experience and experimental results, following management interventions may help sustain the crop yield and also improve and maintain the soil physical and chemical properties. Compact layer in subsurface soils (as indicated by high BD) of the IGP formed as a result of puddling and continuous use of heavy machinery which affected soil structure, especially stable soil aggregates, and led to the formation of compacted layers[36] and soil cracking[37]. These difficulties need to be corrected by various management interventions. Direct-seeded rice without puddling and/or non-tillage (NT) maintained soil in a better physical condition. This method reduces the cost, energy consumption and time spent on ploughing which often results in late planting and decline in wheat yield potential[38–40]. NT helps maintain macro pore connectivity while generating inconsistent responses in total porosity and soil bulk density compared to conventional tillage practices. Higher BD and penetration resistance have been reported under zero-tillage compared with tillage[41]. This problem of low-stability soil aggregates[42,43] in soils like Fatehpur soils in the semi-arid of IGP could be

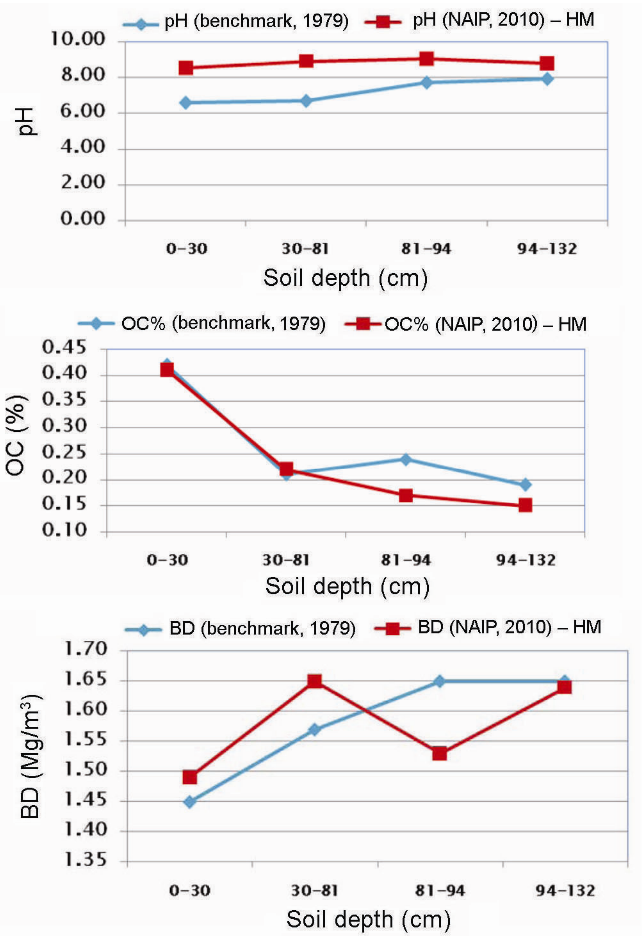


Figure 4. Effect of temporal changes of land-use on soil properties (BD and OC) in HM practice areas of Itwa soils.

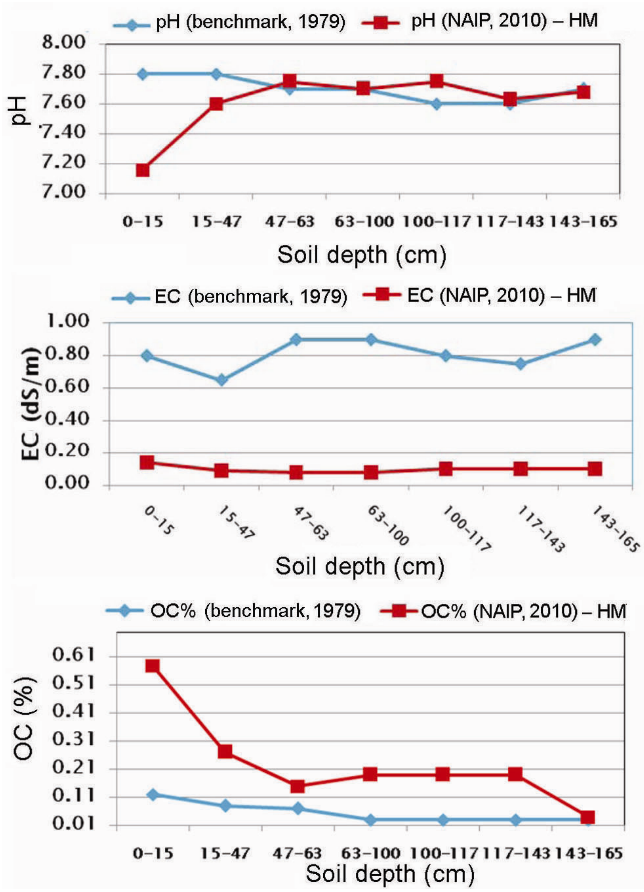


Figure 5. Effect of temporal changes of land-use on soil chemical properties (electrical conductivity (EC) and OC) in HM practice areas of Fatehpur soils.

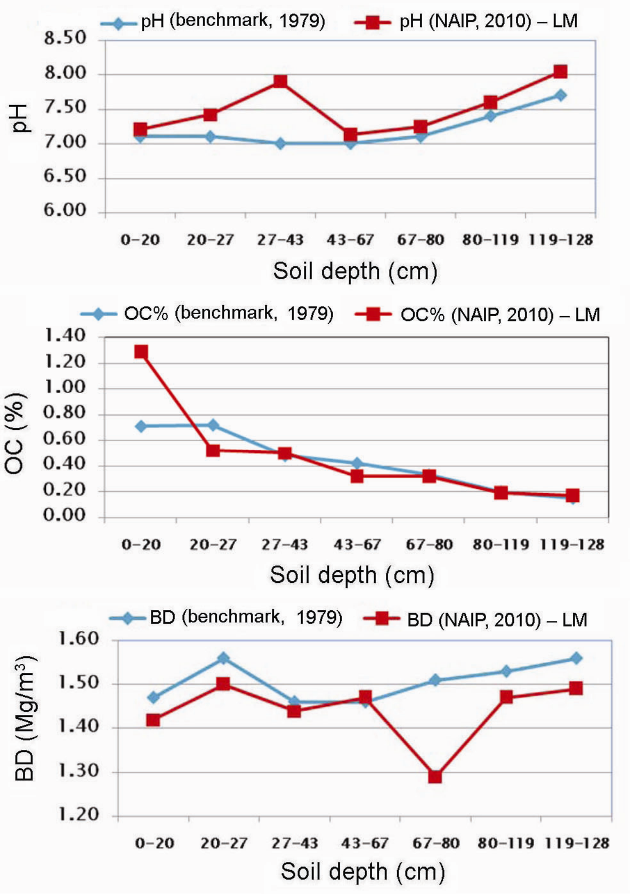


Figure 6. Effect of temporal changes of land-use on soil chemical properties of HM practice areas in Haldi soils.

overcome by zero-tillage plus mulch, which can reduce BD. The quantitative effect of tillage on physical soil environment vis-à-vis physical soil quality is affected by tillage, which can influence productivity[44–46] and help improve SOC[47,48]. There is a need to manage the paddy straw in an economically and environmentally safe way[40]. Sowing and transplanting of paddy using various techniques (bed-furrow or ridge-furrow) saved soil moisture. During the rainy season, these techniques harvest the water and crop does not need to be irrigated for long periods and thus the soil quality improves because no puddling is required to pond the water constantly[49]. These techniques check the formation of hardpan in the soil earthworms develop in the soil and micro-climate remains comparatively dry which lowers the incidence of insect pests and diseases. Emission of greenhouse gases, specially CO_2 and methane decreases drastically with favourable impact on the environment; the systems are equitable for the small and marginal farmers and to save labour wages required for transplantation. No till wheat in the rice–wheat system has shown similar system productivity as of conventional till wheat (in rotation with puddled transplanted rice). It also shows low water use and more farm profitability in the western and eastern IGP[50]. In addition, use of innovative, precise (cupping type, inclined plate) seed metering systems and machinery have improved soil quality in IGP[45].

Amendments such as residues and manure promote soil microbial biomass (SMB), while burning and removal of residues decrease it[32,51–56]. Puddling affects the soil biological properties[57,58]. Therefore, an alternative method like cultivation on raising permanent beds (aerobic conditions) helps improve the SBM. In irrigated lowland (i.e. Itwa and Sakit series), rice cultivation commonly practised by puddling is done for easy transplanting of rice, as a part of weed control and incorporation of organic matter[59]. Puddling condition on certain types of lowland could be achieved by irrigation water without intensive tillage[60]. Results of experiments conducted in rice–wheat cropping zone of Haryana[61] and in Indonesia[62] show feasibility of successful cultivation of zero-tilled transplanted rice with slight yield gain and water saving. Some of the cropping systems may help reduce water loss, soil compaction and improve SMB in non-salt-affected soils like Fatehpur and Haldi series. Introduction of maize–wheat rotation on permanent beds (PB)[63], rice–maize (RM) rotation in the eastern IGP, and innovative new generation planters for sugarcane resulted in higher grain and water productivity of the systems to the extent of 17% increase in RM and PB system and farm income by 21–58% in sugarcane. Farm income compared to conventional planting techniques in sugarcane-based system (through advancing cane planting in furrows) and wheat or other winter crops (on top of the raised beds) increased by 15–20%. Also, the development of innovative bullock-drawn and modular power tiller-operated zero tillage planters has made significant impact on small and marginal farmers. Shallow tillage with herbicide application has reduced the impact of weed, and 50% use of irrigation water which increased yield of crop when compared to that of zero-tillage system[64]. Application of glyphosate herbicide before transplanting may speed up weed and ratoon decay without any residual effects on rice crop[62]. Also allelopathic properties of cereal residues inhibit surface weed seed germination[65–67] and weeds can be suppressed by the biological agents[68] through farming practices which will help increase crop yield. These soils are inherently not rich in soil nutrients. In the upper and middle Gangetic Plains, majority of the soils tested medium for SOC and medium to high for available P and K. The dominance of medium status of available P in soils could be due to mining of soil P by the rice–wheat cropping system practised in these regions for more than 300 years[69]. The intensively cultivated Trans-Gangetic transect area showed that 17–20% of soil samples was low to medium in Zn and 5–8% was low in Fe. In the upper Gangetic Plains, only 25% of the samples was deficient in Zn, especially in the central and southwest plains. In the middle Gangetic Plains, 20–30% of samples was deficient in Zn, and very few samples were deficient in other micronutrients[70]. Therefore, there is a need for application of optimum doses of nutrients as well as organic manure as integrated nutrient management measure to maintain the fertility status for improved crop yields on sustainable basis in this intensively cultivated region.

The soil parameters, viz. BD, OC and soil acidity increased in salt-affected soils (Zarifa Viran, Itwa and Sakit) under high management, mostly cultivated for rice–wheat cropping system. The increase in soil acidity is due to self-reclaiming effect under reducing conditions because of waterlogging in rice crop. The movement of $CaCO_3$ layer, as observed under medium management of Sakit soils, shows the effect of adequate irrigation which results in the movement of calcium carbonate to lower depths under medium management level compared to low management. Cracks in surface soils under high management level of rice–wheat system were observed, which may be due to continuous puddling practices in rice-growing soils. The high BD in subsurface layers may inhibit the soil aeration and impose physical hindrance to root proliferation, which together may result in a decline in crop yield. The movement of clay from surface to subsurface layers has been observed in most of the soils under high management, which may change the soil classification characteristics. However, to prove this point further investigations on this aspect are required.

Although the rice–wheat cropping system enhances the soil health by sequestering more organic matter in soils[3,71], the increase in bulk density, especially in layers below the root zone seems a potential threat. This requires careful management in this important food-growing zone in the country[72].

Conclusions

Following the management interventions advocated by the National Agricultural Research Systems (NARS) for the last several decades to raise the rice–wheat productivity of non-sodic and sodic soils of the northwestern parts of the IGP, an increase in SOC, and decrease in soil sodicity are observed, with an increase in BD. While the enrichment of SOC and reduction in sodicity indicate better soil health, rise in BD in sub-soils remains a potential threat for sustenance of better rice–wheat productivity. This dismal situation warrants fine-tuning of the management interventions of NARS.

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ACKNOWLEDGEMENTS. The present study was carried out by the National Agricultural Innovative Project (Component 4), sponsored research on ‘Georeferenced soil information system for land use planning and monitoring soil and land quality for agriculture’ through Indian Council of Agricultural Research, New Delhi. The financial assistance is gratefully acknowledged.