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Long-term Impact of Cyclic Use of Sodic and Canal Water for Irrigation on Soil Quality and Wheat Yield in Cotton-Wheat Cropping System

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Increasing scarcity of good quality water in many arid and semi-arid regions necessitates the cyclic use of sodic water (SW) and canal water (CW) for irrigation. Six irrigation treatment combinations of CW (good quality) and SW (residual sodium carbonate, 10 me L^{-1}) were applied in a cyclic mode in a long-term field experiment in cotton-wheat system for investigating their impact on soil quality parameters and wheat yield. Irrigation with SW alone resulted in high soil pH (>9), sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP) and bulk density (BD), and decreased soil organic carbon (SOC) content and availability of macro (N, P, K and S) and micronutrients (Fe, Mn, Zn and Cu). Infiltration rate, saturated hydraulic conductivity, mean weight diameter of soil aggregates, microbial biomass carbon and dehydrogenase activity were lower compared with that under CW irrigation. Continuous irrigation with SW reduced grain yield of wheat by 24 per cent over CW. However, alternate irrigation with CW and SW significantly improved soil quality, resulting in 7-26 per cent higher wheat yields compared with irrigation with SW alone. Ameliorative effect of using 2CW in cyclic use with 1 SW (2CW: SW, SW: 2CW) on soil quality parameters was more significant than 1CW with 1SW (CW: SW, SW: CW) or 2SW irrigations (CW: 2SW, 2SW: CW). The effect of different treatments on crop productivity was adequately explained by changes in either soil ESP or SAR (82%), soil pH and OC (~73%) demonstrating their importance in determining soil quality and wheat yields in a sodic environment. The study also suggested that in situations where canal water is initially not available, occasional pre-sowing irrigation with sodic water can be given to avoid delay in sowing provided canal water irrigations are applied later.

Key words: Sodic water irrigation, pH, ESP, soil quality, cotton-wheat system

In arid and semi-arid regions, many farmers use poor quality ground water to meet the crop water requirements due to inadequate availability of good quality water and insufficient rainfall. In Indian Punjab, out of 42% poor quality waters, 69% are sodic, 25% are saline and 6% are saline-sodic in nature (PRSC 2010). At the tail end of canal commands in many arid and semi-arid regions, canal water is not always available at the time of sowing and thus the farmers are left with no alternative except to use sodic ground water for irrigation to avoid delay in sowing. Long-term use of sodic water (SW) for irrigation degrades soil due to build-up of exchangeable sodium and high soil pH. Soil physical quality parameters such as surface crusting, soil aeration and permeability are adversely affected due to dispersive action of sodium impacting seedling emergence and plant growth (Oster and Jaywardene 1998).

Different irrigation management strategies have been proposed to minimize the harmful effects of using saline/sodic water for irrigation on soil properties and crop productivity. These strategies include conjunctive use of poor quality water with good quality canal water (CW). However, cyclic use is favored over mixing of good quality CW with saline water due to operational advantages and lowering salinity levels than that of mixing two sources of water (Singh 2014). Bajwa and Josan (1989) observed that when SW used in cyclic mode with CW in rice-wheat rotation, yields of both the crops were at par with CW irrigation. However, very few studies are available in the literature on the effects of sodic water applied as

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the first pre-sowing in a cycle on soil quality in cotton based cropping systems.

In a mid-term study (6-year), Choudhary and Ghuman (2008) observed that cyclic use of CW and SW on cotton-wheat system is a sustainable use. Choudhary (2017) also concluded that based on sustainable yield index, two cyclic mode treatments (SW: CW, 2SW: CW) did not remain sustainable on a long-term basis (12 years). However, in both these studies, only a few chemical and physical parameters like pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), bulk density (BD) and infiltration rate were investigated apart from crop yields. The present study was, therefore, undertaken to comprehensively investigate the long-term (after 16 years) impact of cyclic use modes of irrigations with CW and SW on the soil quality parameters (physical, chemical and biological), and crop yields of wheat (*Triticum aestivum*) in the cotton (*Gossypium hirsutum)* - wheat system.

Materials and Methods

Description of the experimental site

A field experiment on cotton-wheat cropping system was initiated in 1996 on a sandy loam (Typic Ustochrept) soil at the experimental farm of the Punjab Agricultural University, Ludhiana (30°56′ N latitude and 75°52′ E longitude) in the Indo-Gangetic plains of North-West India. The soil initially had pH 8.0; ECe 0.54 dS m^{-1}; soil organic carbon (SOC) 2.8 g kg^{-1} soil; calcium carbonate <10 g kg^{-1}; clay content 185 g kg^{-1}; cation exchange capacity (CEC) 9.3 cmol(p^+)kg^{-1} and ESP 3.4. The region has a semi-arid continental monsoon climate with hot, wet summers and cool dry winters. Annual mean precipitation is 760 mm, about 20% of which occurs during wheat growing season (November-April).

Experimental details

The experiment was carried out in micro-plots (2.5 m × 2.5 m) separated from each other by an un-vegetated buffer of 0.5 m width. Each plot was lined with polythene sheets all around down to 1 m depth to check lateral salt and water movement. Eight treatments included irrigation with (i) canal water (CW), ii) sodic water (SW) and iii) six combinations of cyclic irrigation with CW and SW (2CW:SW, CW:SW, CW:2SW, SW:2CW, SW:CW and 2SW:CW). The experiment was laid-out in a completely randomized block design with three replications.

Table 1. Composition of irrigation waters used in the study

Characteristic	Canal water (CW)	Sodic water (SW)
Electrical conductivity (dS m^{-1})	0.29	1.40
Ca^{2+} (me L^{-1})	1.50	0.60
Mg^{2+} (me L^{-1})	0.90	0.80
Na^{+} (me L^{-1})	0.40	12.5
CO_3^{2-}+HCO_3^- (me L^{-1})	1.80	11.5
Cl^- (me L^{-1})	0.90	1.60
Residual sodium carbonate (RSC)*	-	10.1
Sodium adsorption ratio (SAR)*	0.37	14.9

*RSC = (CO_3^{2-}+HCO_3^-) - (Ca^{2+}+Mg^{2+}),
SAR = Na^+/ [Ca^{2+}+Mg^{2+})/2]$^{1/2}$ (all ions in me L^{-1})

The SW having residual sodium carbonate (RSC) of 10 me L^{-1} was synthesized by dissolving 0.84 g $NaHCO_3$ L^{-1} in CW (Table 1). Each irrigation consisted of 60 mm water applied using a 5 cm diameter hose-pipe when irrigation water to pan evaporation (cumulative pan evaporation minus rainfall) ratio since previous irrigation reached a value of 0.9 in wheat and 0.3 in cotton. Depending upon the amount and distribution of rainfall, number of irrigations applied to wheat varied between 3 and 5 and for cotton between 1 and 3 in different years. Both cotton and wheat were irrigated with CW, SW or both applied in different cyclic modes. The respective treatments were maintained in same plots for both crops in all the years. Wheat (PBW 621) was planted in first week of November and harvested in second week of April every year. A basal dose of 150 kg N, 60 kg P_2O_5 and 30 kg K_2O ha^{-1} was applied through urea, diammonium phosphate, and muriate of potash, respectively. Nitrogen was applied in two equal doses (at sowing and after 21 days) whereas, P and K were applied at planting. A seed rate of 100 kg ha^{-1} was used for wheat, seeded with row to row spacing of 20 cm. Cotton (cv. MRC 7017 BGII) was grown during *kharif* season (late May–October) and fertilized with 150 kg N, 30 kg P_2O_5 and 25 kg $ZnSO_4$ ha^{-1}. Other recommended package of practices for crops proposed by Punjab Agricultural University was followed to control weeds and insect-pest. Wheat crop was manually harvested close to ground with a sickle and grain yield was reported on air dry weight basis.

Soil sampling and analysis

Soil samples were collected from 0-15 cm depth with the help of tube-auger (25 mm diameter) from 4 places within each plot after the harvest of wheat. The soil samples were mixed, sieved (2-mm) for chemical analysis and fresh soil samples stored at 4

°C for soil biological parameters. Chemical soil parameters (pH, SOC, CEC, Olsen-P, 1*M* NH_4OAc-extractable K, boron, DTPA-extractable Fe, Mn, Zn and Cu). Soil physical parameters like BD, infiltration rate (IR) and mean weight diameter (MWD) were determined by following standard procedures (Black 1965; Jackson 1967). Biological parameters namely microbial biomass carbon (MBC) and dehydrogenase activity (DHA) were determined by following methods as suggested by Vance *et al.* (1987) and Tabatabai (1982).

Statistical analysis

The data were statistically analyzed using ANOVA following a randomized block design using IRRISTAT for windows (IRRI 2016). The Duncan's multiple range test was used to determine differences among treatments at 5% level of significance. Relationship between soil parameters and wheat yield was studied by carrying out correlation analysis.

Results and Discussion

Soil chemical parameters

(i) pH, EC, ESP and SAR

Irrigation with SW significantly increased soil pH to 9.36 in the surface layer compared with 7.41 under CW irrigation (Table 2). Irrigation in cyclic mode starting with one or two SW followed by one CW irrigation (SW: CW, 2SW:CW), decreased pH over the SW irrigation alone treatment but it was not significant. However, soil pH values in the 2CW:SW, CW:SW and SW:2CW treatments were at par to those observed under CW. In other cyclic treatments (CW:2SW, SW:CW and 2SW:CW), pH increased mainly due to higher proportion of SW used for irrigation (Choudhary and Ghuman 2008; Choudhary 2017). The EC under SW significantly increased to 0.396 dS m^{-1} over 0.187 dS m^{-1} under CW irrigation (Table 2). Cyclic treatments using SW as pre-sowing irrigation had higher EC values in soil compared with treatments using CW. Such low soil EC values (<0.5 dS m^{-1}) are not likely to adversely affect the soil quality and yield of wheat crop in the present study.

Table 2. Effect of different irrigation treatments on pH, EC, exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR)

Irrigation treatment†	pH	EC (dS m^{-1})	ESP	SAR (1:1 soil:water)
CW	$7.41^{a‡}$	0.19^{a}	2.55^{a}	3.69^{a}
SW	9.36^{g}	0.40^{e}	38.6^{h}	27.2^{g}
2CW:SW	7.82^{b}	0.21^{ab}	4.90^{b}	7.26^{b}
CW:SW	8.10^{bcd}	0.23^{bc}	6.62^{d}	8.73^{c}
CW:2SW	8.40^{de}	0.27^{c}	12.2^{f}	12.0^{d}
SW:2CW	8.06^{bc}	0.23^{bc}	5.79^{c}	8.46^{c}
SW:CW	8.53^{e}	0.20^{ab}	10.6^{e}	15.0^{e}
2SW:CW	8.84^{f}	0.34^{d}	15.9^{g}	20.6^{f}
LSD (P=0.05)	0.30	0.04	0.83	0.57
SE_{mean}	0.14	0.02	0.39	0.27

†CW – Canal water; SW – Sodic water; 2CW:SW – Irrigation with 2 CW followed by 1 SW; CW:SW – Irrigation with 1CW followed by 1 SW; CW:2SW – Irrigation with 1 CW followed by 2 SW; SW:2CW – Irrigation with 1SW followed by 2CW, SW:CW – Irrigation with 1 SW followed by 1 CW and 2SW:CW – Irrigation with 2 SW followed by 1 CW

‡Values sharing the same letter(s) in a column do not differ significantly at $p<0.05$ according to Duncan's Multiple Range Test

Continuous irrigation with SW significantly increased the ESP and SAR of the soil compared with CW (Table 2). Cyclic use of SW and CW also increased ESP and SAR but to levels lower than that observed under SW irrigation alone. Low build-up of soil ESP in the irrigation cycle starting with CW/2CW irrigations was mainly due to low amounts of SW used and thereby low permeability problems, which facilitated downward movement of salts beyond the root zone (Choudhary *et al.* 2006). In irrigation cycles starting with SW (SW or 2SW) and involving one CW (2SW: CW, SW:CW), ESP and SAR were significantly lower than in SW treatment, but it remained significantly higher as compared to those starting with CW (CW:2SW, CW:SW) treatments. This increase in Na saturation of soils under SW irrigation was attributed to the precipitation of calcite in the presence of high concentrations of carbonates and bicarbonates. Consequently, the sodium concentration in the soil solution as well as the fraction on the soil exchange complex increased (Choudhary *et al.* 2011).

(ii) Organic carbon and macronutrients

A significant decline in soil OC was observed due to irrigation with SW as compared to CW (Table 3). The reduction in SOC values was greater in the treatments involving 2SW irrigations (2SW:CW, CW:2SW) in a cycle. The high soil sodicity created hostile environment to the microbial community causing decline in MBC (Setia *et al.* 2011).

Available P, K and sulphur (S) were deficient and significantly lower under SW than CW irrigation. Relative to the values of 22.6, 115.4 and 9.0 mg kg^{-1} soil of P, K and S under CW irrigation, the corresponding values of these macronutrients under SW irrigation decreased by 57, 17 and 52 per cent,

Table 3. Effect of irrigation treatments on SOC, available phosphorus, potassium and sulphur in soil

Irrigation treatment†	SOC (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})
CW	3.8^{f‡}	22.6^{f}	115.4^{d}	18.6^{g}
SW	2.3^{a}	9.78^{a}	95.3^{a}	9.0^{a}
2CW:SW	3.6^{e}	20.3^{e}	106.3^{c}	16.8^{f}
CW:SW	3.2^{d}	17.3^{d}	105.0^{c}	13.8^{d}
CW:2SW	2.8^{c}	15.3^{c}	100.6^{b}	12.7^{c}
SW:2CW	3.2^{d}	18.0^{d}	104.7^{c}	15.8^{e}
SW:CW	2.9^{c}	16.0^{c}	100.6^{b}	12.6^{c}
2SW:CW	2.4^{b}	14.3^{b}	99.4^{b}	11.2^{b}
LSD (P=0.05)	0.10	0.88	1.76	0.89
SE_{mean}	0.05	0.41	0.08	0.41

†For treatment details, see table 2.
‡Values sharing the same letter(s) in a column do not differ significantly at $p<0.05$ according to Duncan's Multiple Range Test

respectively. Cyclic use of CW and SW for irrigation significantly increased the content of the three macronutrients (Table 3). Treatments starting with CW (2CW: SW, CW: SW) or having 2CW (SW:2CW) in a cycle had significantly higher P, K and S contents compared with other cyclic treatments. High soil pH, ESP and concentration of soluble CO_3^{2-} and HCO_3^- adversely affected the availability of soil nutrients (Chhabra and Abrol 1983) causing their deficiency. Recently Choudhary and Mavi (2019) opined that high pH, excessive exchangeable Na and adverse soil physical properties due to long-term use of sodic waters also influence the transformations and availability of native and applied fertilizer nutrients.

(iii) Micronutrients

The content of DTPA extractable micronutrients (Fe, Mn, Zn and Cu) was observed to be minimum under the SW treatment (Table 4). Irrigation with SW significantly decreased DTPA Zn to 0.53 from 1.00 mg kg^{-1} observed under CW irrigation. Decrease in DTPA Zn might have resulted from fixation as insoluble $ZnCO_3$ formed due to high soil pH and high HCO_3 content present in applied sodic water (Choudhary *et al*. 2011). Chauhan *et al*. (1999) reported that the use efficiency and recovery of applied Zn is further adversely affected due to 85-90 per cent fixation of applied Zn in a sodic environment. It is slightly lower than the threshold level of 0.6 mg kg^{-1} below which Zn deficiency occurs in plants. Availability of Zn significantly increased by 17-51% when SW and CW were cyclically used. Magnitude of increase in Zn concentration was more (36-51%) in treatments (2CW:SW, SW:2CW) having 2CW irrigations than those having higher 2SW irrigations (2SW:CW,CW:2SW) (17-21%). The DTPA extractable concentrations of Fe, Mn and Cu in the soil under SW irrigation were affected to a lesser extent compared to Zn. Nevertheless, different cyclic treatments of SW and CW resulted in significant increase in availability of these micronutrients. Higher soil pH due to SW irrigation should have caused significant decrease in the availability of these micronutrients. Furthermore, long-term irrigation with SW increases precipitation of $CaCO_3$ in soil resulting in reduced availability of micronutrient cations which is controlled by the carbonate equilibria in the soil solution (Choudhary *et al.* 2011).

In contrast to the availability of other micronutrients, acid soluble boron concentration was higher under SW (7.80 mg kg^{-1} soil) than under CW (4.56 mg kg^{-1} soil) irrigation (Table 4). Treatments involving more CW irrigations (2CW:SW, SW:2CW) recorded lower boron concentration as compared to treatments with more SW irrigations (2SW:CW, CW:2SW) in a cycle. It can be ascribed to the fact that pH greater than 7.6 is associated with increased availability of boron in soil.

Table 4. Effect of irrigation treatments on DTPA-extractable micronutrient cations (mg kg^{-1}) in soil

Irrigation treatment†	Zinc	Iron	Manganese	Copper	Acid soluble boron
CW	1.00^{d‡}	9.29^{f}	15.6^{f}	1.75^{g}	4.56^{a}
SW	0.53^{a}	5.19^{a}	7.0^{a}	0.90^{a}	7.80^{e}
2CW:SW	0.80^{c}	8.54^{e}	13.7^{e}	1.41^{f}	5.85^{b}
CW:SW	0.67^{b}	8.21^{d}	12.0^{d}	1.34^{ef}	6.28^{bc}
CW:2SW	0.64^{b}	7.44^{c}	11.1^{cd}	1.10^{c}	6.83^{d}
SW:2CW	0.72^{c}	8.43^{e}	11.3^{cd}	1.32^{e}	5.93^{b}
SW:CW	0.65^{b}	8.19^{d}	10.7^{c}	1.20^{d}	6.63^{cd}
2SW:CW	0.62^{b}	6.83^{b}	9.5^{b}	0.99^{b}	7.01^{d}
LSD (P=0.05)	0.06	0.16	0.99	0.08	0.45
SE_{mean}	0.03	0.08	0.46	0.04	0.21

†For treatment details, see table 2.
‡Values sharing the same letter(s) in a column do not differ significantly at $p<0.05$ according to Duncan's Multiple Range Test

Table 5. Effect of irrigation treatments on soil physical parameters

Irrigation treatment†	Bulk density (g cm^{-3})	Saturated hydraulic conductivity (cm h^{-1})	Infiltration rate (cm h^{-1})	Mean weight diameter (mm)
CW	1.43^{a‡}	2.63^{f}	2.80^{g}	0.96^{f}
SW	1.72^{e}	1.13^{a}	1.23^{a}	0.78^{a}
2CW:SW	1.56^{b}	2.36^{e}	2.56^{f}	0.94^{e}
CW:SW	1.60^{c}	2.04^{cd}	2.16^{de}	0.87^{c}
CW:2SW	1.64^{d}	1.73^{b}	1.76^{c}	0.80^{b}
SW:2CW	1.58^{bc}	2.16^{d}	2.27^{e}	0.92^{d}
SW:CW	1.62^{cd}	1.90^{c}	2.03^{d}	0.86^{c}
2SW:CW	1.71^{e}	1.60^{b}	1.50^{b}	0.79^{ab}
LSD (P=0.05)	0.02	0.14	0.21	0.01
SE_{mean}	0.01	0.07	0.10	0.005

†For treatment details, see table 2.
‡Values sharing the same letter(s) in a column do not differ significantly at *p<0.05* according to Duncan's Multiple Range Test

Soil physical parameters

Highest BD values of 1.72 g cm^{-3} were observed in SW-irrigated plots (Table 5). Likewise, significant decline in infiltration rate (IR) was recorded in plots irrigated with SW (1.2 cm h^{-1}) compared with 2.8 cm h^{-1} measured in CW irrigated plots (Table 5). Maximum increase in BD and IR relative to SW irrigation was observed in treatments with 2CW irrigations applied in a cycle (SW: 2CW, 2CW: SW). When SW/2SW preceded one CW (SW:CW, 2SW:CW), IR values were significantly lower than treatments starting with CW/2CW irrigations (CW:SW,2CW:SW). These results suggest that decrease in the number of SW irrigations in a cyclic treatment decreased BD and increased IR that might impact soil compaction. Singh *et al.* (2014) observed that decreased compaction in sodic soils will lead to better aeration and, leaching of salts. On the other hand, clay dispersion, migration and clogging in the soil pores under SW alone and in cyclic treatments with higher proportion of SW would cause structural problems and increase in BD and decline in IR.

Similar to BD values, saturated hydraulic conductivity (Ks) was the lowest under SW irrigation. Cyclic use of SW and CW significantly increased the Ks values compared with SW irrigation (Table 5). In irrigation cycles involving 2CW (2CW: SW and SW: 2CW), Ks decreased to a greater extent than in cycles having 2SW irrigations (CW: 2SW and 2SW: CW). Also, first irrigation with CW had a positive influence on hydraulic conductivity in 2CW: SW and CW: SW treatments than with SW (SW: 2CW and SW: CW). Long-term irrigation with SW significantly decreased MWD to 0.78 mm from 0.96 mm under CW irrigation (Table 5). In treatments with 2CW (2CW: SW, SW: 2CW), significantly higher MWD was recorded than with treatments having one CW (CW: SW, SW: CW) or 2SW (CW: 2SW, 2SW:CW) in a cycle. The reduction in the rate of water transmission in the SW alone or cyclic treatments with SW/2SW irrigations can be attributed to decrease in pore size distribution as a result of swelling and dispersion of clays due to high soil ESP (Oster and Jaywardane 1998) resulting in reduced aggregation.

Soil biological parameters

Long-term irrigation with SW significantly decreased MBC (234.6 to 129.2 µg g^{-1}) than that observed under CW irrigation (Fig. 1). However, cyclic use of SW and CW irrigation significantly increased MBC over the SW alone treatment. Maximum MBC was recorded in 2CW: SW (202 µg g^{-1} soil) while minimum in 2SW:CW (166 µg g^{-1} soil). Lower MBC in SW alone and 2SW treatments can be ascribed to soil structural degradation, toxicities of Na and other accompanying ions along with the high soil pH and the osmotic stress inhibiting microbial growth and activity (Setia *et al.* 2011; Choudhary *et al.* 2013).

Dehydrogenase activity, measure of total oxidative activity of the microbial biomass (Nannipieri *et al.* 1990) was lowest (18.7 µg TPF g soil^{-1} 24h^{-1}) in SW and maximum in CW (41.7 µg TPF g soil^{-1} 24h^{-1}) irrigated plots (Fig. 1b). Significant increase in DHA values was recorded in treatments with cyclic use of CW and SW than the SW alone. Higher DHA was measured under SW:2CW compared with SW:CW and 2SW:CW treatments. Reitz and Haynes (2003) observed that irrigation induced sodicity depressed enzyme activity. This was because sodicity exhibit unique structural problems that result from soil

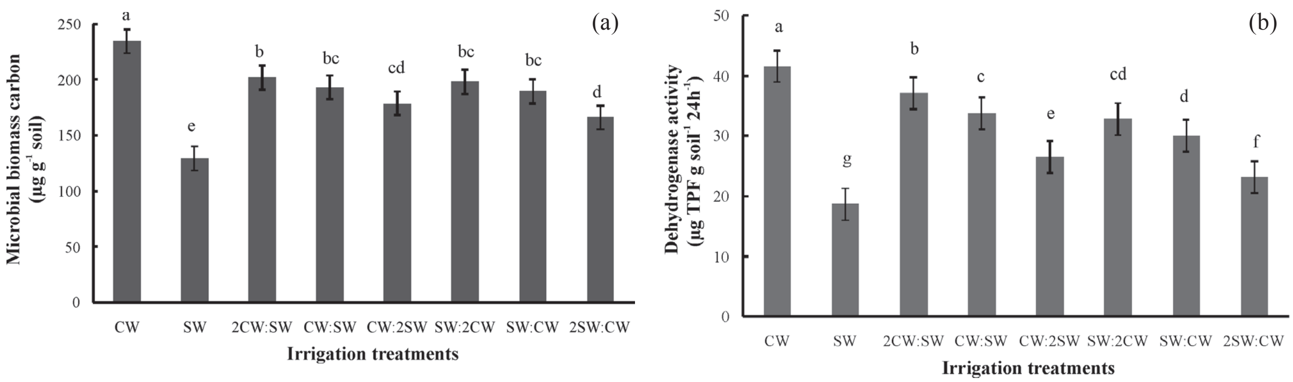

Fig. 1. Influence of cyclic use of sodic water and canal water on (a) microbial biomass carbon and (b) dehydrogenase activity. Vertical lines show standard error of the mean (n=3)

Table 6. Effect of irrigation treatments on spike weight, thousand grain weight (TGW) and grain yield of wheat

Irrigation treatment†	Spike weight (g)	TGW (g)	Wheat yield (Mg ha^{-1})	Relative yield§ (%)
CW	3.82^{g‡}	46.24^{f}	7.61^{d}	100
SW	2.77^{a}	36.35^{a}	5.84^{a}	76
2CW:SW	3.54^{f}	44.92^{e}	7.27^{c}	96
CW:SW	3.24^{d}	42.93^{d}	7.11^{c}	93
CW:2SW	3.09^{c}	42.15^{c}	6.86^{bc}	90
SW:2CW	3.41^{c}	43.14^{d}	7.24^{c}	95
SW:CW	3.14^{c}	41.76^{c}	6.68^{b}	87
2SW:CW	2.99^{b}	40.67^{b}	6.30^{a}	82
LSD (P=0.05)	0.08	0.63	0.51	
SE_{mean}	0.04	0.29	0.24	

†For treatment details, see table 2.
‡Values sharing the same letter(s) in a column do not differ significantly at $p<0.05$ according to Duncan's Multiple Range Test
§Yield expressed as a fraction of the yield under CW irrigation

physical processes such as slaking, swelling and dispersion of clay (Tejada and Gonzalez 2005) thereby, adversely affecting soil microbial community and DHA.

Wheat yield

Irrigation with SW significantly decreased the wheat yield by 24 per cent compared with CW irrigation (Table 6). Decline in crop yields in treatments involving SW irrigations could be ascribed to the deteriorating effect of high pH and RSC on chemical, physical and biological soil fertility parameters (Choudhary *et al.* 2004), along with Ca deficit in the soil solution (Choudhary *et al.* 1996). Alternating CW and SW in cyclic mode significantly increased the yields of wheat over SW treatment. Significantly higher yield (95-96% relative yield to CW) over SW treatment (76% relative yield) was achieved under irrigation cycles involving 2CW (2CW:SW, SW: 2CW). However, the irrigation cycle starting with SW (SW:CW, 2SW:CW) significantly increased grain yield over SW irrigation alone though increase was not significant. Results from the study showed that the first irrigation to wheat should be given with good quality CW to ensure better seed germination. Occasionally, sustained wheat yield can be obtained even with pre-sowing irrigation with SW provided it is followed by 2CW irrigations (SW: 2CW because of restricted precipitation of $CaCO_3$ and low build-up of ESP in this treatment (Choudhary and Ghuman 2008; Choudhary *et al.* 2011; Choudhary 2017). This treatment mimics the situation where CW is not available at the time of sowing.

Relationships between soil parameters and wheat yield

Soil physical and biological parameters were significantly influenced by ESP, SAR and pH. Soil sodicity (ESP and SAR) accounted for 64 to 92% variation in physical parameters (IR, BD and MWD) while soil pH accounted for 74 to 85% variation. Soil organic carbon, available P, K, S and micronutrients were also strongly influenced by pH (R^2=0.76-0.88) and soil sodicity (R^2 = 0.66-0.85).

Microbial biomass carbon and DHA were significantly influenced by soil pH, ESP and SAR (Fig. 2). Higher coefficient of determination (R^2 = 0.84-0.88) was observed for DHA than MBC (R^2 = 0.78-0.80) highlighting that DHA is one of the most important indicators of overall soil microbial activity (Singh *et al.* 2018), because these occur intracellular in all living microbial cells. The SAR influenced DHA and MBC to the same extent as did soil ESP.

Several soil properties influenced wheat yield. Highest coefficient of determination (R^2 = 0.82) was observed with ESP and SAR (Fig. 3). Soil pH and SOC also explained >70% variations in wheat yield. Wheat yield was also strongly influenced by DHA (R^2 = 0.75) (Fig. 3f) than MBC (R^2 = 0.67). Furthermore, soil physical properties such as BD and MWD significantly influenced wheat yield (R^2 = 0.66-0.68). Deterioration in soil physical quality occurs because the forces that bind clay particles together are disrupted when too many sodium ions come

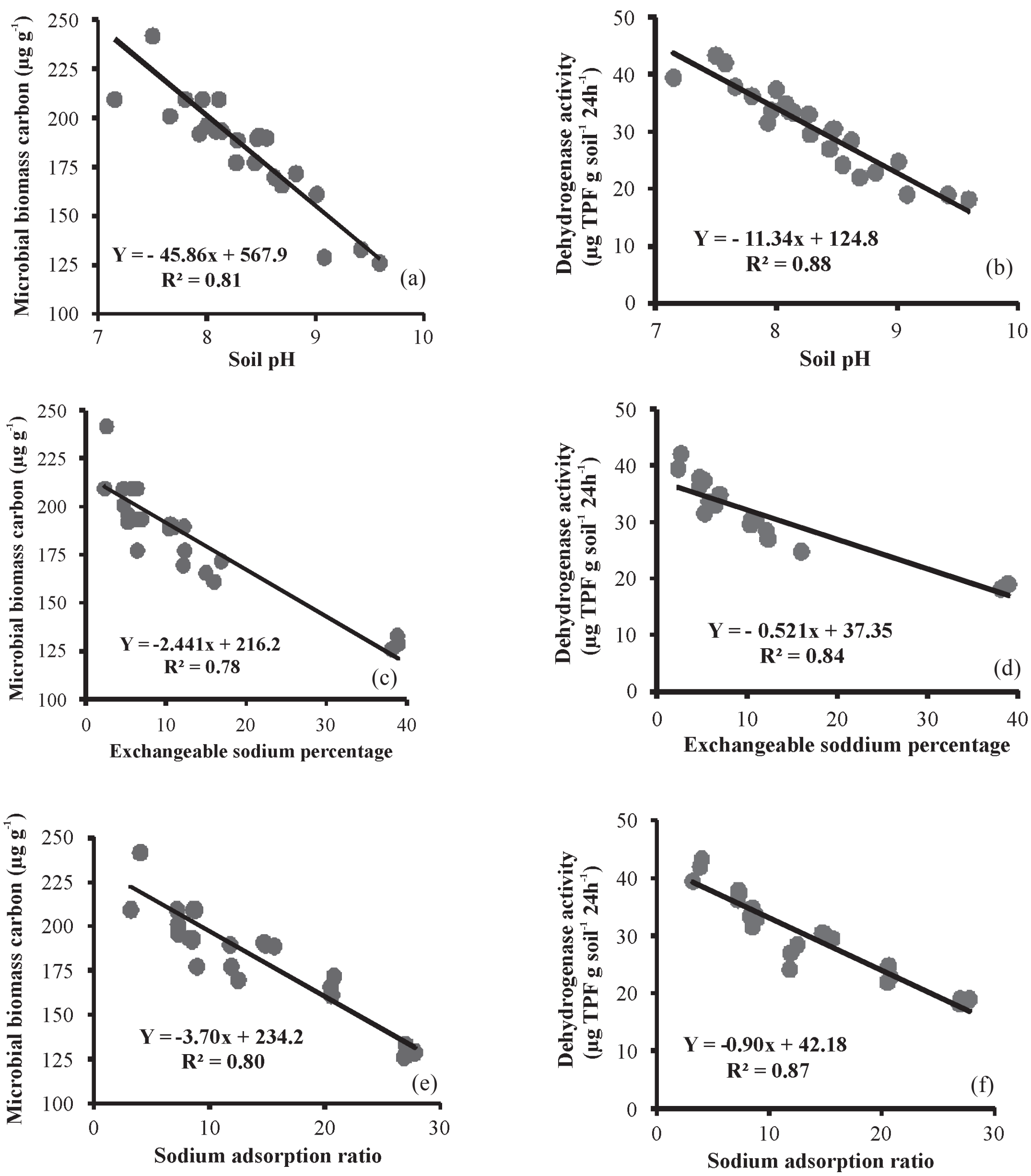

Fig. 2. Relationship of microbial biomass carbon and dehydrogenase activity with some soil properties. (a), (c) and (e) show relationships of microbial biomass carbon with soil pH, exchangeable sodium percentage and sodium adsorption ratio, respectively; (b), (d) and (f) show relationships of dehydrogenase activity and those soil properties

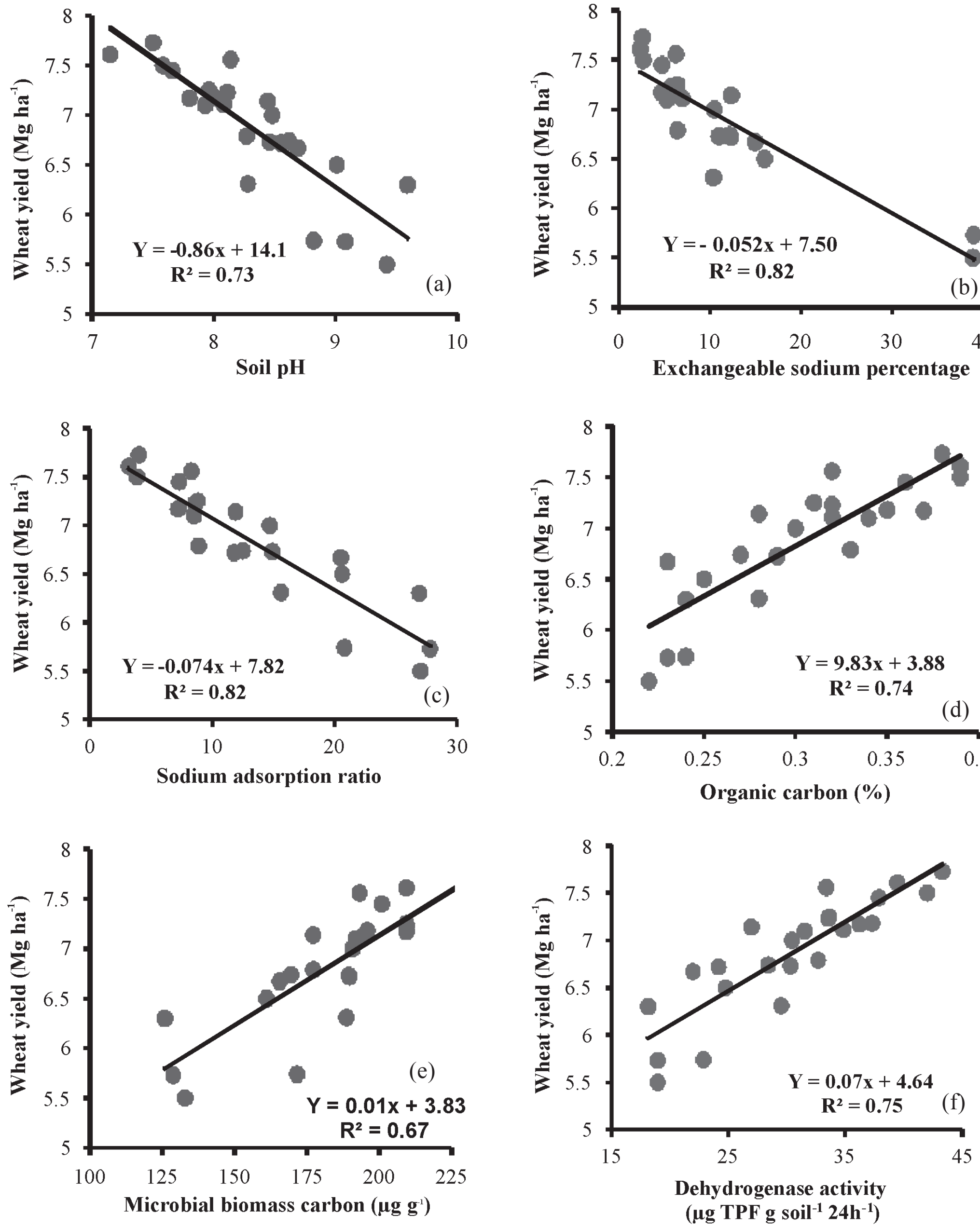

Fig. 3. Relationship of wheat yield with (a) soil pH, (b) exchangeable sodium percentage, (c) sodium adsorption ratio, (d) organic carbon, (e) microbial biomass carbon and (f) dehydrogenase activity

between them. When this separation occurs, the clay particles expand, causing swelling and soil dispersion, ultimately clogging the micro-pores in soil resulting in increased bulk density and reduced permeability. Yaduvanshi and Swarup (2005) reported that continuous use of sodic irrigation water without gypsum adversely affected soil properties such as pH, ESP, SAR and SOC as well as yields of rice and wheat in a long term experiment.

The multiple regression analysis suggested that other soil parameters in the regression did not improve predictability of wheat yield over that observed with ESP or SAR. It suggests ESP and SAR of the soil strongly influenced wheat yield followed by pH. Compared to ESP, SAR of soil solution can be easily and quickly determined and it is highly correlated with soil ESP (Rengasamy and Churchman 1999). Further more, like ESP, SAR can also reflect the adverse effects of sodium on soil structural degradation and thus, can also be used to evaluate sodicity hazards of soil.

Conclusions

Long-term impact of irrigation with SW deteriorated physical, chemical and biological soil quality, decreased the availability of nutrients and significantly reduced wheat yield in cotton-wheat system. On the other hand, cyclic use of CW and SW significantly improved wheat yield and soil parameters, and increased availability of nutrients than irrigation only with SW. Maximum ameliorative effect was observed in cyclic options with 2CW (2CW:SW and SW:2CW) whereas, least improvement was found in treatments with 2SW (CW:2SW and 2SW:CW). Variation in wheat yield due to irrigation treatments was adequately explained (82%) by either ESP or SAR. Soil pH and SOC accounted for 73%, BD and MWD explained 66-68% and MBC and DHA explained 67-75% variation in the wheat yield. Soil ESP/SAR, pH and SOC were the most important parameters for assessing soil quality and crop productivity in a sodic environment created by cyclic use of CW and SW for irrigation. In addition, pre-sowing irrigation to wheat should be preferably given with good quality canal water. However, in situations where canal water is not available, occasional pre-sowing irrigation with sodic water can be given to avoid delay in sowing provided canal water irrigations are applied later.

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