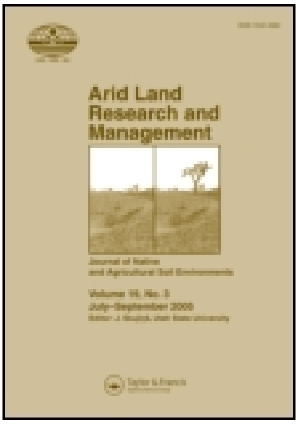

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Differences in Soil Properties Between Irrigation and Cropping Sequences in the Thar Desert of India

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Watering is known to convert deserts into oases. However, information on how irrigation brings changes in physical and chemical properties of soils in a desert biome is not yet known, though pertinent to land use planning. This study reports influence of irrigation and cropping sequence on physico-chemical properties of soils in the Thar Desert, Rajasthan, India. Treatments included three irrigation conditions (not irrigated, low-irrigated, and high-irrigated) and eleven cropping sequences, cotton-gram (C-G), mung bean-mustard (M-Mu), moth bean-wheat (Mo-W), moth bean-mustard (Mo-Mu), cotton-fallow (C-F), cotton-wheat (C-W), cotton-mustard (C-Mu), mung bean-wheat (M-W), moth bean-fallow (Mo-F), mung bean-fallow (M-F), and pearl millet-fallow (P-F). The irrigation reduced soil temperature (9.7 to 12.2%) and bulk density (5.3 to 6.6%), but increased silt (5.1 to 7.2%) and clay (3.8 to 5.4%) content, water holding capacity (50 to 58.3%), moisture content at field capacity (100 to 133.3%), concentration (2.3 to 3.1 times), and stock (2.2 to 3.0 times) of soil organic carbon (SOC), microbial biomass carbon (4 to 8 times), available phosphorus (1.82 to 2.1 times), and potassium (25.9 to 67.1%). These changes were higher in the high-irrigated than the low-irrigated conditions. Cropping sequences C-W, C-Mu, and C-G sequestered more SOC and retained higher microbial biomass carbon, whereas M-Mu, Mo-W, Mo-Mu and M-W maintained the highest level of phosphorus and potassium. These observations suggest that irrigation and cropping sequence are promising management options for enhancing carbon sequestration in soils, which may reduce desertification in the Thar Desert and other similar deserts in the hot tropics.

Keywords cropping sequences, irrigation, soil organic carbon, soil temperature

The Thar Desert spreads over 19.6 million hectare in the state of Rajasthan India. It is characterized with dunes and inter-dune plains, sandy to sandy loam soils,

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experiencing high temperature, very low and sporadic rainfall, very low soil fertility, severe wind erosion, and either no or a little irrigation facilities. The desert is subjected to frequent droughts, once in two and a half years, which intensify the process of desertification (Samra et al., 2006). Subsistence agriculture with pearl millet and pulse based cropping sequences predominates in the region. During the late sixties a canal network was brought in the northern part of the desert, which provides irrigation to about 56% of cultivable fields in some parts of Sri Ganganagar and Hanumangarh districts. Farmers in the districts have started realizing benefits of the canal irrigation since 1982. Extensive plantations and agronomic conservation measures like shelterbelt and wind break are done on the field boundaries for stabilizing the sand dunes, protecting soils from excessive sun heating, reducing wind speed, and enhancing biological processes of biogeochemical cycling (Singh et al., 2007). Cotton and wheat based cropping sequences have been introduced in the canal irrigated area. The cropping sequences probably add organic matter to soils, which affects the organic carbon content and fertility of the soils. However, detailed investigation on how irrigation influences soil organic carbon build up in the Thar Desert is lacking.

Intensive agriculture, in general, is known to cause changes in physical, chemical, and biological properties of soils (Lal, 1995; Pandey et al., 2010). But, limited studies are available in deserts, which report how conversion of traditional agriculture into intensive commercialized agriculture affects physico-chemical characteristics of soils. Intensive agriculture such as application of nitrogen, water, appropriate residue management and manuring is reported to enhance carbon sequestration and soil fertility in the desert of South Central Senegal (Woomer et al., 2004; Wood et al., 2004; Tieszen et al., 2004). Irrigation has been reported to increase organic carbon, total nitrogen, carbohydrate, and particulate organic carbon in the desert of Iran (Fallahzade & Hajabbasi, 2010); nitrogen, phosphorus, and potassium in the arid region of Jordan (Al-Zubi, 2007). Irrigation is found to have enhanced water stable aggregate content in the desert of Iran (Fallahzade & Hajabbasi, 2010). Studies on how irrigation brings changes in physico-chemical soil characteristics in the Thar Desert of India have been awaited for a long time.

The objectives of the present study were to: (i) understand the influence of irrigation and cropping sequences on physico-chemical properties of soils; and (ii) identify the drivers, which regulated the changes in the Thar Desert of India.

Materials and Methods

Study Site

The study site is located between $28^0 0 4'$ to $30^0 06'$ N lat. and $72^0 30'$ to $75^0 30'$ E long. at Sri Gangnangar district of Rajasthan covering 1093 km^2 area of the Thar Desert of India. The altitude of the study area ranges from 150 to 163 m above mean sea level. The soils are Typic Haplocambids, Typic Haplocalcids and Typic Haplogypsids, loamy sand to sandy loam in texture, deep to very deep and excessively drained (Khan et al., 2003). Climate is arid characterized with three seasons: rainy (July to mid-September), winter (November to March) and summer (April to June). October is a transitional month between winter and summer seasons. The average annual rainfall is 255.4 mm of which 82% occurs from June to September. Mean total rainy days are 16. Mean annual temperature is 26.9°C. Mean summer and mean winter temperatures are 33.4°C and 15.9°C. May and June are the hottest months, with temperature rising up to 49°C, and January is the coldest month with temperature dipping down to 4°C.

Prior to the year 1960, aeolian activity and sand movement were the prominent soils forming processes. Soil surface in the entire area was blanketed with sand (77 to $>$ 85%). Soil were dominantly low in organic carbon (0.05 to 0.16%), available phosphorus (5 to 15 kg ha^{-1} P_2 O_5) and potassium ($<$200 kg ha^{-1} K_2O) and used for millet cultivation only during good rainfall years (Dhir, 2007). After 1960, canal network was introduced in the desert. Thereafter, farmers leveled sand dunes with levelers and started cultivation on the sandy plains.

The canal network receives water and sediments from Chenab and Vyas rivers, which originate from the Himalaya and run a great distance ($\approx$1000 km) on the plains of Punjab state before entering into the desert. The alluvial plains are rich in silt and clays derived from sedimentary deposits of Himalaya and also contained illite as dominant clay mineral with vermiculite and chloritized smectites (Sehgal, 1996). Intensive cultivation, continuous use of manuring, and fertilization in alluvial plains are part of agriculture. Thus, sediment together with intensive cultivation enriched the fertility of the plains. During the run, the canal water picks sediments (clay and silt) from the plains and brought it into the deserts. It is reported that the sediments contained 8–15 times higher nitrogen (880 to 3234 kg ha^{-1}), 3 to 4 times more available phosphorus (19.7 to 54.6 kg ha^{-1}), 2 to 9 and 10 to 15 times higher available potassium (270 to 1248.7 kg ha^{-1}) and organic carbon (0.32 to 0.65%), respectively, than the desert soils (0–30 cm) of the study area. The pH of the sediments was lower by 0.4 to 0.6 units than the pH of the desert soils (Khan et al., 2003).

Depending upon irrigation intensity, the entire area was divided into three parts: high irrigated (150 ± 1 meters), low irrigated (154 ± 2 meters), and not irrigated (163 ± 3 meters) (Khan et al., 2003). Acreages under low-irrigated were one-and-a-half times greater than under not and high-irrigated conditions. The area under irrigation was used for raising double crops, once in summer and other in winter season; whereas the area under not irrigated conditions was cultivated only in summer. Eleven cropping sequences, moth bean-fallow (Mo-F), mung bean-fallow (M-F), and pearl millet-fallow (P-F) in not irrigated; mung bean-mustard (M-Mu), moth bean-wheat (Mo-W), moth bean-mustard (Mo-Mu), cotton-gram (C-G), and cotton-fallow (C-F) in low-irrigated; and cotton-wheat (C-W), cotton-mustard (C-Mu), and mung bean-wheat (M-W) in high-irrigated condition, were identified using multi-seasonal Indian Remote Sensing Satellite data of 23.5 meter resolution and land-use map of the district (Table 1).

In different cropping sequences under high irrigated conditions, amount of canal water used for irrigation was maximum, ranging from 5400 (M- W) to 12600 (C-W) $m^3ha^{-1}yr^{-1}$. In low irrigated condition, the quantity of irrigation varied from 2000 (C-F) to 4500 (C-G) $m^3ha^{-1}yr^{-1}$ (Khan et al., 2003). Canal irrigation was not used under not irrigated conditions. Tractors were used for tillage operations in high and low irrigated conditions, whereas conventional (bullock drawn plough) method was used under not irrigated conditions. Surface irrigation was the common method for irrigation; sprinklers were used occasionally. Nitrogen, phosphorus and potassium were applied maximum under high irrigated conditions in the proportion of 200:120:20, 140:100:20 and 120:60 kg $ha^{-1}yr^{-1}$ in C-W, C-Mu, and M-W, respectively. The quantities of these nutrients under low irrigated conditions were 80:60:20, 60:40:0, 120:60:0, 60:40:0, and 80:60:20 kg $ha^{-1}yr^{-1}$ in C-G, M-Mu,

Table 1. Influence of different irrigation conditions vis-à-vis elevation and cropping sequences on physical properties of soils at Sri Ganganagar district of Rajasthan, India

Irrigation conditions	Cropping sequence	Mean elevations meters	Soil physical properties*							
			BD gcm^{-3}	WHC m^{3}m^{-3}	FC m^{3}m^{-3}	Sand	Silt+clay	Structure	MST	MWT
						(%)			^{0}C	
Not irrigated	Mo-F	162 ± 2^{a}	1.53 ± 0.2^{a} (4.4)	0.25 ± 0.05^{a} (23.2)	0.12 ± 0.05^{a} (25.6)	77.9 ± 2.1^{a}	22.1 ± 0.5^{a}	sg	34.0 ± 2.1^{a} (1.7)	23.9 ± 1.6^{a} (2.8)
	M-F	164 ± 3^{a}	1.50 ± 0.2^{a} (3.7)	0.27 ± 0.03^{a} (16.3)	0.11 ± 0.03^{a} (17.1)	73.9 ± 2.3^{a}	26.1 ± 0.5^{b}	sg	32.9 ± 2.2^{ab} (2.0)	24.8 ± 1.7^{ab} (2.3)
	P-F	163 ± 2^{a}	1.60 ± 0.3^{a} (4.9)	0.26 ± 0.02^{a} (16.3)	0.11 ± 0.02^{a} (17.3)	85.6 ± 2.5^{b}	14.4 ± 0.4^{c}	sg	34.3 ± 2.3^{b} (5.3)	25.7 ± 1.8^{b} (11.2)
Mean		$\mathbf{163 \pm 3^{A}}$	$\mathbf{1.54 \pm 0.1^{A}}$	$\mathbf{0.26 \pm 0.01^{A}}$	$\mathbf{0.11 \pm 0.01^{A}}$	$\mathbf{79.0 \pm 4.3^{A}}$	$\mathbf{21.0 \pm 1.2^{A}}$	sg	$\mathbf{33.7 \pm 2.4^{A}}$	$\mathbf{24.8 \pm 3.2^{A}}$
Low Irrigated	C-G	153 ± 2^{r}	1.38 ± 0.1^{r} (4.3)	0.45 ± 0.15^{r} (13.2)	0.36 ± 0.01^{r} (16.7)	57.2 ± 3.1^{r}	42.8 ± 0.6^{r}	m, 2, sbk	28.3 ± 1.6^{r} (3.8)	21.7 ± 1.4^{r} (4.9)
	M-Mu	154 ± 3^{r}	1.46 ± 0.2^{s} (4.7)	0.39 ± 0.16^{s} (20.2)	0.26 ± 0.04^{s} (24.5)	71.8 ± 4.2^{s}	28.2 ± 0.7^{s}	f, 2, sbk	31.5 ± 0.8^{s} (3.5)	22.4 ± 1.7^{s} (5.0)
	Mo-W	155 ± 2^{r}	1.51 ± 0.3^{t} (4.4)	0.34 ± 0.14^{t} (16.7)	0.26 ± 0.06^{s} (25.2)	79.1 ± 4.5^{t}	20.9 ± 0.7^{t}	f, 2, sbk	28.0 ± 0.9^{r} (4.0)	21.5 ± 1.8^{r} (5.2)
	Mo-Mu	155 ± 3^{r}	1.51 ± 0.3^{t} (4.4)	0.33 ± 0.16^{t} (20.1)	0.23 ± 0.03^{s} (6.1)	78.6 ± 4.6^{t}	21.4 ± 0.7^{t}	f, 2, sbk	29.2 ± 0.6^{r} (3.8)	22.3 ± 2.1^{s} (5.0)
	C-F	154 ± 2^{r}	1.35 ± 0.2^{r} (5.4)	0.41 ± 0.13^{r} (14.6)	0.31 ± 0.02^{r} (29.3)	62.9 ± 4.2^{u}	36.1 ± 0.7^{u}	massive	32.7 ± 0.7^{s} (3.4)	24.2 ± 2.2^{t} (4.6)
Mean		$\mathbf{154 \pm 2^{B}}$	$\mathbf{1.45 \pm 0.2^{B}}$	$\mathbf{0.38 \pm 0.02^{B}}$	$\mathbf{0.28 \pm 0.02^{B}}$	$\mathbf{70.2 \pm 4.2^{B}}$	$\mathbf{29.8 \pm 1.3^{B}}$		$\mathbf{30.2 \pm 2.5^{B}}$	$\mathbf{22.7 \pm 3.1^{B}}$
High Irrigated	C-W	149 ± 3^{x}	1.37 ± 0.3^{x} (3.7)	0.38 ± 0.11^{x} (14.5)	0.29 ± 0.01^{x} (11.3)	62.7 ± 4.1^{x}	37.3 ± 0.3^{x}	m, 2, sbk	29.6 ± 1.1^{x} (2.2)	21.0 ± 1.3^{x} (5.2)
	C-Mu	151 ± 3^{x}	1.44 ± 0.2^{y} (3.3)	0.36 ± 0.14^{x} (15.5)	0.25 ± 0.03^{x} (13.9)	67.4 ± 4.5^{y}	32.6 ± 0.3^{y}	m, 1, sbk	32.2 ± 1.2^{y} (2.4)	23.8 ± 1.7^{y} (2.9)
	M-W	150 ± 2^{x}	1.43 ± 0.1^{y} (3.3)	0.38 ± 0.13^{x} (15.3)	0.24 ± 0.04^{x} (13.8)	68.2 ± 4.6^{y}	31.8 ± 0.3^{y}	f, 2, sbk	30.5 ± 1.3^{y} (2.3)	22.3 ± 1.8^{y} (3.9)
Mean		$\mathbf{150 \pm 1^{C}}$	$\mathbf{1.42 \pm 0.2^{B}}$	$\mathbf{0.38 \pm 0.03^{B}}$	$\mathbf{0.26 \pm 0.02^{B}}$	$\mathbf{66.1 \pm 5.2^{C}}$	$\mathbf{33.8 \pm .66^{C}}$		$\mathbf{30.7 \pm 2.7^{B}}$	$\mathbf{22.3 \pm 3.3^{B}}$

Note: Data are mean ± SE; Means followed by the same lower case letter (in each irrigation system) and by the same upper case letter (between three irrigation conditions) in a column are not significantly different at $p < 0.5$. Coefficients of variations are given in parentheses.

*Soil physical properties: BD, bulk density; WHC, water holding capacity; FC, field capacity; MST, mean soil summer temperature; MWT, mean winter temperature; Structure: sg, single grained; f, fine; m, medium sized; 1, weak strength; 2, moderate strength. Explanation of cropping sequence is similar to that of Table 2.

Mo-W, Mo-Mu and C-F, respectively. However, no or minimum fertilizer was added under not irrigated conditions (Nehra, 2007). Generally, farmers apply FYM in the fields close to their residences; such fields were not considered for the study. About 300 g m^{-2} below ground biomass and 150 g m^{-2} stubbles under high irrigated; 200 g m^{-2} below ground biomass and 100 g m^{-2} stubbles under low irrigated conditions; and 50 g m^{-2} below ground biomass and 30 g m^{-2} stubbles in not irrigated conditions are left in the field every year.

Soil Sampling and Laboratory Analysis

Depending on the area under different conditions of irrigation, total two hundred eighty samples (0–30 cm) approximately at 2 kilometer interval were collected across the cropping sequences in the year 2007 (three cropping sequences each replicated 20 times in high irrigated; five cropping sequences each replicated 32 times in low irrigated; three cropping sequences each replicated 20 times in not irrigated conditions). Samples (at field conditions) were divided into two parts. One part was air dried and passed through a 2-mm sieve. Air dried samples were analyzed for organic carbon (SOC) concentration by Walkley and Black's (1934) rapid titration method. Another part of the samples was used for soil microbial biomass C (MB-C) which was estimated by the chloroform fumigation (24-hr) extraction method (Vance et al., 1987). It was determined in the K_2SO_4 soil extracts of fumigated and unfumigated samples, by dichromate oxidation in a reflux system and titrated with ferrous ammonium sulfate. MB-C was then estimated from the equation:

$$\mathrm{MB-C} = 2.64\mathrm{Ec}$$

where Ec is the difference value as estimated from fumigated and unfumigated soils and 2.64 is the proportionality factor of MB-C released by the fumigation extraction (Vance et al., 1987), available phosphorus by 0.5 N $NaHCO_3$ extraction using spectrophotometer, and potassium by 1 N NH_4OAc extraction using a Flame photometer. Soil pH was measured with glass electrode and EC with electrical conductivity bridge using 1:2 soil:water ratio. Physical properties were determined only on eleven benchmark sites (>1 hectare area). Each of them represented one cropping sequence. Bulk density was determined by inserting a metallic tube of known volume in the soils at each site and thereafter estimating the dry weight of a unit volume of the soils (Brady, 1984). Soil particle size was analyzed by hydrometer. Water holding capacity (WHC) of the soils was measured in saturated soil samples by leaving them to drain till field capacity (for about 48 hours). Then the samples were dried at at 105°C overnight to measure water content. Moisture retention at field capacity (FC) was measured by pressure plate apparatus (Klute, 1986). Soil temperature (0–30 cm) was measured at each site at three locations by thermometer three times at 11 AM, 12 AM, and 2 PM (Pandey et al., 2010) to cover variations over a day in both summer and winter seasons. The SOC concentration was multiplied with thickness and bulk density for SOC stock calculation (Singh et al., 2011)

Statistical Analysis

Data were subjected to one-way ANOVA to obtain significance of differences due to cropping sequences separately under each irrigation conditions (Table 2a). Treatments

Table 2a. F value of soil organic carbon (SOC, %), microbial biomass carbon (MB-C, $\mu g\,g^{-1}$), SOC stock ($kg\,m^{-2}$), mean summer soil temperature (MST,°C), mean winter soil temperature (MWT,°C), phosphorus (P, $kg\,ha^{-1}$), potassium (K, $kg\,ha^{-1}$), sand (%), silt (%), clay (%), bulk density (BD, $g\,cm^{-3}$), water holding capacity (WHC, %) and field capacity (FC, %) in different irrigation conditions and cropping sequences at Sri Ganganagar district of Rajasthan, India

Source of variation	df	SOC	MB-C	SOC stock	MST
Cropping sequence	2	143.42***	190.83***	126.661***	24.970***
Error	57				
Cropping sequence	4	93.523***	38.36***	434.815***	177.430***
Error	95				
Cropping sequence	2	149.31***	227.07***	82.67***	72.70***
Error	57				
Irrigation conditions	2	529.066***	1478***	658.869***	200.330***
Error	57				

	MWT	pH	P	K	Sand
		Not-irrigated condition			
Cropping sequence	38.365***	0.02^{NS}	1402.824***	574815.0***	2746.947***
Error					
		Low-irrigated condition			
Cropping sequence	47.323***	0.702^{NS}	184.321***	215711.7***	3893.939***
Error					
		High-irrigated condition			
Cropping sequence	5.019**	2.017^{NS}	771.345***	347397.5***	369.05***
Error					
Irrigation sequence	96.957***	1.134^{NS}	1455.681***	48202.89***	2206.198***
Error					

	Silt	Clay	BD	WHC	FC
Cropping sequence	557.315***	284.651***	10.527***	1.310^{NS}	0.305^{NS}
Error					
Cropping sequence	3215.848***	651.4***	19.591***	11.461***	11.278***
Error					
Cropping sequence	339.218***	2.836^{NS}	9.715***	0.648^{NS}	13.376***
Error					
Irrigation conditions	721.739***	327.604***	44.274***	34.541***	96.532***
Error					

$^{**}P < 0.01$. $^{***}P < 0.0001$.

NS, Not significant.

included: cropping sequences, that is, three cropping sequences in high-irrigated, five cropping sequences in low-irrigated, and three cropping sequences in not irrigated condition. The number of replicates was twenty samples at each site. Though the samplings for the studied parameters were done in 32 replicates of each cropping sequence in low-irrigated conditions, for the ANOVA only twenty random replicates were used, because replicates were not different significantly, and results were presented on the basis of 20 replicates only. To know the effect of irrigation conditions on the studied parameters, one-way ANOVA was performed using irrigation conditions (three: not irrigated, low-irrigated, and high-irrigated) as treatment. Data for irrigation conditions were obtained by averaging values of the studied parameters across the cropping sequences of corresponding irrigation condition. As the cropping sequences were not common in all the irrigation conditions (three in not irrigated and high-irrigated, but five in low-irrigated condition), two-way ANOVA was not able to detect the effects of interactions of cropping sequences x irrigation conditions. LSD ($P < 0.05$) was computed by univariate analysis of General Linear Model of SPSS statistical package; LSD was used to compare means of the studied parameters (across the irrigation conditions, $N = 60$). The Pearson's correlation coefficient (across the irrigation conditions, $N = 280$) was used to establish relationship between two parameters.

Results

Soil Physical Properties

In a span of 47 years of irrigation treatments, among the physical properties (Table 1) silt and clay content increased (7.2% and 5.4%, respectively) whereas sand content declined (12.5%). Silt and clay content were highest (17.3% and 16.5%, respectively) in the high irrigated and lowest (10.10% and 11.1%, respectively) in the not irrigated conditions. Cropping sequences also increased the silt and clay content. The order of increase in silt content due to cropping, the sequence was: Mo-F = M-F>P-F in the not irrigated conditions; C-G>C-F>M-Mu>Mo-Mu>Mo-W in the low irrigated, and C-W>C-Mu = M-W in the high irrigated conditions. Bulk density was reduced due to the irrigation being lowest in the high irrigated and highest in the not irrigated conditions. The bulk density was lower in C-W than C-Mu as well as M-W cropping sequences in the high irrigated conditions. In the low irrigated condition, bulk density was lowest in the C-G and C-F and highest in the M-Mu as well as Mo-W cropping sequences; and in not irrigated conditions it was highest in the P-F and lowest in the M-F. Water holding capacity (WHC) and moisture content at the field capacity (FC) increased with the irrigation. WHC and moisture content at FC were highest in the C-W cropping sequence; these parameters corresponded to soil organic carbon and fine soil particles (silt). Soil temperature declined significantly due to the irrigation, both during summer and winter season; however, difference in soil temperature between the high and low irrigation conditions was not significant. The soil temperature was lower in Mo-F and M-F than P-F in the not irrigated condition; it was lower in Mo-W, Mo-Mu and C-G than M-Mu and C-F in the low irrigated; and lower in the C-W and M-W and C-Mu in the high irrigated condition during summer season. An almost similar pattern of variation in soil temperature was observed during the winter season in the cropping sequences. WHC, FC, concentration, and stock of SOC were inversely related with the soil temperature in the cropping sequences (Table 2b).

Table 2b. Correlation (Pearson's) matrix showing relationship among soil organic carbon (SOC, %), microbial biomass carbon (MbC, $\mu g\, g^{-1}$), SOC stock (SOCS) ($kg\, m^{-2}$), mean summer soil temperature (MST,°C), mean winter soil temperature (MWT,°C), phosphorus (P, kg ha^{-1}), potassium (K, kg ha^{-1}), sand (%), silt (%), clay (%), bulk density (BD, g cm^{-3}), water holding capacity (WHC, %), field capacity (FC, %) in different irrigation conditions and cropping sequences at Sri Ganganagar district of Rajasthan, India

Variables	SOC	SOCS	MST	MWT	pH	P	K	Sand	Silt + clay	BD	WHC	FC
SOCS	0.89^{*}	–										
MST	-0.65^{*}	-0.61^{*}	–									
MWT	-0.64^{*}	-0.60^{*}	0.88^{*}	–								
Ph	-0.01^{NS}	0.05^{NS}	0.41^{**}	0.48^{**}	–							
P	0.77^{*}	0.80^{*}	-0.54^{**}	-0.57^{**}	0.05^{NS}	–						
K	0.68^{*}	0.72^{*}	-0.38^{**}	-0.61^{*}	-0.02^{NS}	0.54^{**}	–					
Sand	-0.42^{**}	-0.48^{**}	0.25^{NS}	0.32^{NS}	0.16^{NS}	-0.12^{NS}	-0.38^{NS}	–				
Silt+clay	0.42^{**}	0.52^{**}	-0.13^{NS}	-0.15^{NS}	0.05^{NS}	0.13^{NS}	0.37^{NS}	-0.96^{*}	–			
BD	-0.28^{NS}	-0.32^{NS}	0.17^{NS}	0.25^{NS}	0.11^{NS}	-0.10^{NS}	-0.25^{NS}	0.71^{*}	-0.68^{*}	–		
WHC	0.39^{**}	0.45^{**}	-0.25^{NS}	-0.20^{NS}	0.12^{NS}	0.24^{NS}	0.24^{NS}	-0.59^{**}	0.63^{*}	-0.33^{NS}	–	
FC	0.50^{**}	0.57^{**}	-0.46^{**}	-0.41^{**}	0.00^{NS}	0.36^{NS}	0.30^{NS}	-0.63^{*}	0.63^{*}	-0.46^{**}	0.87^{*}	–
MbC (μg/g)	0.95^{*}	0.88^{*}	-0.59^{*}	-0.62^{*}	-0.01^{NS}	0.72^{*}	0.72^{*}	-0.47^{**}	0.46^{**}	-0.31^{NS}	0.38^{**}	0.47^{**}

$^{*}P < 0.05$. $^{**}P < 0.01$.
^{NS}non-significant.

Table 3. Influence of different irrigation conditions and cropping sequences on pH, soil organic carbon (SOC) concentrations (%), stock ($Mg\,ha^{-1}$), microbial biomass carbon [MB-C, ($\mu g\,g^{-1}$)] phosphorus, and potassium ($Kg\,ha^{-1}$) in Sri Ganganagar district of Rajasthan, India

			pH	SOC		MBC	Phosphorus	Potassium
Irrigation conditions	*Cropping sequence	Crop duration (Days)	(1:2)	(%)	$Mg\,ha^{-1}$	$\mu g\,g^{-1}$	$Kg\,ha^{-1}$	
Not irriga-	Mo-F	60–75	8.6 ± 0.3^{a} (5.4)	0.16 ± 0.4^{a} (19.5)	6.6 ± 0.5^{a} (10.1)	64.0 ± 4.5^{a} (19.5)	15.5 ± 0.3^{a} (4.3)	397.5 ± 2.6^{a} (0.2)
ted	M-F	60–75	8.6 ± 0.3^{a} (5.3)	0.08 ± 0.02^{b} (11.2)	3.4 ± 0.7^{b} (19.3)	32.0 ± 1.8^{b} (11.8)	6.2 ± 0.6^{b} (10.7)	226.8 ± 3.2^{b} (0.3)
	P-F	60–75	8.6 ± 0.3^{a} (5.3)	0.06 ± 0.03^{c} (14.9)	2.8 ± 0.3^{c} (24.0)	18.0 ± 1.9^{c} (11.8)	5.8 ± 0.6^{b} (11.2)	185.6 ± 2.9^{c} (0.4)
Mean			**8.6 ± 0.2^{A}**	**0.10 ± 0.02^{A}**	**4.3 ± 0.5^{A}**	**38.1 ± 2.1^{A}**	**9.2 ± 1.2^{A}**	**270.6 ± 2.1^{A}**
Low irriga-	C-G	300–325	8.3 ± 0.3^{r} (6.1)	0.33 ± 0.05^{r} (24.4)	13.4 ± 0.6^{r} (7.9)	267.0 ± 7.3^{r} (24.4)	17.4 ± 0.5^{r} (6.3)	396.0 ± 4.2^{r} (0.3)
ted	M-Mu	150–200	8.5 ± 0.3^{r} (6.0)	0.17 ± 0.02^{s} (24.5)	8.4 ± 0.7^{s} (11.8)	122.7 ± 4.5^{s} (20.3)	16.2 ± 0.4^{s} (5.2)	393.3 ± 5.2^{r} (0.3)
	Mo-W	150–180	8.4 ± 0.3^{r} (6.1)	0.30 ± 0.08^{r} (7.6)	12.2 ± 0.6^{r} (9.1)	213.5 ± 1.8^{t} (5.3)	24.7 ± 0.4^{tu} (4.5)	296.4 ± 6.2^{s} (0.4)
	Mo-Mu	150–180	8.5 ± 0.3^{r} (6.0)	0.22 ± 0.06^{t} (18.6)	8.1 ± 0.7^{t} (13.8)	142.0 ± 4.6^{u} (17.3)	12.9 ± 0.6^{t} (8.6)	379.9 ± 7.3^{t} (0.3)
	C-F	120–160	8.5 ± 0.2 (6.0)	0.14 ± 0.05^{u} (26.9)	6.1 ± 0.9^{u} (18.3)	69.2 ± 4.5^{v} (27.9)	9.8 ± 0.7^{rt} (11.4)	234.0 ± 5.2^{u} (0.5)
Mean			**8.4 ± 0.3^{A}**	**0.25 ± 0.06^{B}**	**9.9 ± 1.1^{B}**	**171.0 ± 4.2^{B}**	**16.3 ± 1.6^{B}**	**339.8 ± 4.8^{B}**
High irriga-	C-W	300–325	8.5 ± 0.2^{x} (3.9)	0.36 ± 0.5^{x} (8.6)	15.3 ± 0.3^{x} (4.4)	360.9 ± 13.9^{x} (8.2)	16.6 ± 2.5^{x} (3.4)	536.0 ± 2.6^{x} (0.1)
ted	C-Mu	300–325	8.5 ± 0.2^{x} (4.0)	0.24 ± 0.13^{y} (13.2)	10.4 ± 0.9^{y} (14.0)	219.0 ± 4.0^{y} (12.6)	17.4 ± 3.2^{x} (3.7)	382.6 ± 6.2^{y} (0.2)
	M-W	150–180	8.7 ± 0.3^{x} (3.9)	0.38 ± 0.05^{x} (4.4)	16.3 ± 1.2^{x} (10.5)	387.0 ± 1.8^{x} (4.9)	13.0 ± 0.8^{y} (3.9)	434.0 ± 5.2^{z} (2.9)
Mean			**8.6 ± 0.4^{A}**	**0.33 ± 0.08^{C}**	**12.9 ± 1.4^{C}**	**322.5 ± 5.7^{C}**	**16.9 ± 2.1^{C}**	**450.1 ± 5.2^{C}**

Note: Data are mean ± SE; Means followed by the same lower case letter (in each irrigation treatment) and by the same uppercase letter (between three irrigation conditions) in a column are not significantly different at $p < 0.05$. Coefficient of variations are given in parentheses.

*Cropping sequences: Mo-F, moth bean-fallow; M-F, Mungbean-fallow; P-F, Pearl millet- fallow; C-G, Cotton-gram; M-Mu, Mung bean-mustard; Mo-W, Moth bean-wheat; Mo-Mu, Moth bean- mustard; C-F, Cotton-fallow; C-W, Cotton-wheat; C-Mu, Cotton-mustard;M -W, Mung bean-wheat.

Soil pH, Available Phosphorus, and Potassium

The irrigation conditions and cropping sequences did not affect soil pH significantly in a span of 47 years of irrigation treatment (Table 3). Available P content increased owing to the irrigation treatments. It was highest in the high irrigated and lowest in the not irrigated conditions. In the cropping sequences, the available P content corresponded to the silt and clay content and was highest in the Mo-F and lowest in the P-F as well as M-F in the not irrigated conditions; it was highest in the Mo-W and lowest in the C-F in the low irrigated conditions; and it was highest in the Mo-W and lowest in the C-Mu and C-W cropping sequences in the high irrigated conditions. Across the cropping sequences, available K was highest in the irrigated and lowest in the not irrigated conditions. In the not irrigated conditions, K was highest in the Mo-F and lowest in the P-F; in the low-irrigated condition, it was highest in the M-Mu as well as C-G and lowest in the C-F; and in the high irrigated condition, it was highest in the C-W and the lowest in the C-Mu cropping sequences. EC, across the irrigation conditions and cropping sequences, ranged from 0.3 to 0.7 dS m^{-1} in the soils, and 0.3 to 0.5 dS m^{-1} in canal water.

Soil Organic Carbon (SOC) Stock

Concentration and stock of soil organic carbon (SOC) was highest in the high irrigated and lowest in the not irrigated conditions (Table 3). Cropping sequences had influence on the concentration and stock of the SOC. In the not irrigated conditions, SOC stock builds up in the cropping sequences and followed the pattern as: Mo-F > M-F > P-F. In the low irrigated conditions, the pattern was: C-G > Mo-W > Mo-Mu > M-Mu > C-F. However, in the high irrigated conditions the pattern was: C-W > M-W > C-Mu. Microbial biomass carbon (MB-C) contributing 2.9 to 4.1% to the SOC increased with irrigation. Cropping system like cotton-wheat in the high irrigated condition and cotton-gram in the low irrigated condition contained higher MB-C. Concentration and stock of SOC were inversely correlated with soil temperature; however, with the exception of BD, these parameters were positively correlated with WHC, FC, available phosphorus, and potassium (Table 2b).

Discussion

Increased fine soil particles (silt and clay) in a span 47 years of irrigation treatment may have attributed to the sediment brought by the canal. Canal water is reported to carry fine soil particles (Khan et al., 2003). Highest silt and clay in the high irrigated condition could be due to greatest number of irrigations. Irrigation probably enhanced cropping intensity, thereby added greater amount of crop residue into the soils. Fullen et al. (1995) and Dhir (2007) have observed that intensive cropping influenced pedogenic processes and resulted in fine to medium, moderate sub-angular blocky soil structure in the irrigated compared to single grained loamy sand soils in the not irrigated conditions. The irrigation seemed to have caused greater amount of root biomass production which together with more crop residue could have supported more micro-organisms and microbial activities. Thus, increased cropping intensity and irrigation together might have led to the formation of macro and micro-aggregates (Jastrow & Miller, 1997; Tisdale & Oades, 1982). In the field observations, we found absence of loose sands and prevalence of micro-aggregates (fine to medium size of moderate strength, as shown in Table 1 for 0–30 cm soils in the high irrigated conditions. Probably this may be the reason for lower bulk density in the irrigated conditions. These activities seem to have occurred mostly in the cotton-wheat cropping sequence in the high irrigated conditions and M-Mu, Mo-W, and C-G in the low and Mo-F and M-F in the not irrigated conditions. The observation suggested the influence of irrigation as well as cropping sequence in soil aggregate formation.

Soil Moisture and Temperature

The increased silt and clay content and higher organic matter concentrations may be accounted for higher water holding capacity in the irrigated than the not irrigated conditions (Abrol et al., 1968; Gupta & Larson, 1979). Probably irrigation induced high biological activity together with developed soil structure resulted in higher water retention at the field capacity.

In the irrigated condition, the high soil moisture increased vegetal cover under different cropping sequences and subsequently transpiration of water both in summer and winter seasons might have reduced the soil temperature. The reduction in soil temperature was more pronounced in cotton based cropping sequences due to the cooling effect induced by cotton on transpiration of larger volume of water (Thomas et al., 2010). Similar results could not be obtained in other cropping sequences because of the lower leaf area expansion. Denser canopy of cotton-wheat and cotton-gram protected soils from direct sun for longer period than cotton-fallow and cotton-mustard. The result was in accordance with the study of Zhang et al. (2007) who reported negative correlation between soil water content and temperature below the crop canopy. The influence of cotton based cropping sequence for reducing soil temperature was more prominent in soils rich in silt and clay content. This could be attributed to the higher moisture content at the field capacity which ensured availability of moisture for transpiration. Significant negative correlation between the moisture content at the field capacity and soil temperature in the present investigation also confirmed the observation. Significantly increased silt and clay content in irrigated conditions could have been another reason for lowering soil temperature. It is also well-known that temperature rises abruptly in sandy soils, whereas the soils rich in silt and clay content absorb energy slowly and steadily (Brady, 1984).

Soil Organic Carbon

The higher amount of SOC in the irrigated than in the not irrigated condition might be related to the higher carbon inputs and improved physical and chemical properties of the soils through the irrigation practices (i.e., by soil moisture and the reduction in soil temperature) might be a side effect. The higher amount of SOC in the irrigated than in the not irrigated conditions in our study supported the findings of Lal et al. (1999) who found that irrigation and fertilizer applications increased SOC in arid and semi-arid conditions. The increased SOC stock in the irrigated conditions in our study may also be explained on account of reduced summer fallowing (Miglierina et al., 2000), which is known for SOC depletions in arid and semi-arid tropics (Doran & Zeiss, 2000) including the Thar desert of India (Singh et al., 2007). The irrigation keeps soils under crop cover for about 8–10 months (Table 3) during a year. Increased crop cover seems to have added organic matter to soils in the form of crop residue and protected them from baking under the direct sun. Poor vegetal cover (forced fallowing due to lack of irrigation water) on the other hand seems to have increased oxidation of SOC, resulting in the lowest SOC concentration and stock in the not irrigated conditions. This explanation is also appropriate for the lower SOC concentration and stock in cotton-fallow than in the other cropping sequences in the low irrigated conditions.

Several researchers have observed lower SOC due to intensive agriculture (Lal, 1995; VandenBygaart et al., 2003) owing to: (a) tillage induced high rate of carbon mineralization; (b) decrease in physical protection of SOC due to the tillage and its exposure to the sun; and (c) relatively greater mining of nutrients by crops and their export from the system. In the present investigation higher soil organic carbon concentrations under intensive agriculture like cotton-gram, cotton-wheat, and cotton-mustard in irrigated conditions was in sharp contrast with aforementioned findings. The intensive agriculture, which reduced summer fallowing, probably added more organic matter (dead roots and crop residues) and thus seemed to have more positive effect on soil organic carbon build up than SOC loss due to increased tillage in lieu of intensive cropping (Rasmussen et al., 1988). In a long-term experiment of twelve years, Campbell et al. (1998) observed non-significant impact of tillage on total organic carbon, nitrogen, and microbial biomass.

Available Phosphorus and Potassium

The increase in phosphorus and potassium content in the irrigated conditions may be attributed to the canal irrigation since there is a high amount of phosphorus and potassium in the sediment brought by canal water. Every year addition of fertilizer and manures in different cropping sequences may be the other source of phosphorus and potassium in the irrigated conditions. It is well-known that soil organic carbon together with silt and clay particles are important determinants for increasing biological activity, preventing soil erosion and stabilizing soil structure vis-a-vis cation exchange capacity, (Batjes, 1999; Lal et al., 1999; Al-Zubi, 2007; Pandey et al., 2010). The increased level of SOC, silt, and clay in the present investigation might have acted together to prevent losses of phosphorus and potassium added through fertilizers and sediments by developing different chemical complexes (Batjes, 1999).

Isolated patches of higher concentration of phosphorus and potassium in irrigated conditions may be also attributed to the differential level of fertilizers application under the prevailing cropping sequences. Improved phosphatase (Praveen Kumar et al., 2007) and other related biochemical activities (Beiderbeck et al., 1997) under the legume based cropping sequences may be the other reason for isolated patches of raised level of phosphorus and potassium. Singh et al. (2008) also reported increased level of available phosphorus and potassium under legume based cropping sequence in drought prone area of Ranchi, India. However, depletion in phosphorus and nitrogen was reported due to continuous cultivation of millets on sandy soils in Burkina Faso (Krogh, 1997). This may be the reason for the lowest phosphorus and potassium levels in our study under pearl millet-fallow cropping sequence in not irrigated conditions.

Conclusion

Our study concludes that canal irrigation increases silt and clay content, enhances moisture content at the field capacity, extends the period of crop cover, and reduces the period of summer fallowing thereby resulting in an overall improvement of the physicochemical characteristics of the soils in the Thar desert of India. Cotton based cropping sequence was more efficient in augmenting all such effects. Probably increased organic matter inputs (root litters and crop residues), improved cropping situation, reduced summer and winter soil temperature, provided suitable environment for decomposition of organic matter, reduced soil respiration, and thereby enhanced concentration and stock of soil organic carbon (SOC) and microbial biomass carbon. A better cropping situation improved structure, reduced bulk density, and ultimately resulted in increased available phosphorus and potassium in the soils. Soil moisture content at field capacity is probably one of most important factors governing SOC in the desert. Legume based cropping sequences are efficient in enhancing phosphorus and potassium in irrigated and not irrigated conditions as well. These observations suggest that irrigation and cropping sequence together may be one of the management options for greater sequestration of organic carbon, improving physico-chemical conditions of the soils, reducing desertification in the Thar Desert of India and other similar deserts in the world.

The extent of the found differences between irrigation treatments was somewhat exacerbated by the original elevation differences. Elevation reflected the geomorphic position and the original accumulation pattern of fine materials/soil organic matter. Larger accumulation of fine materials/soil organic matter in deeper positions might have contributed to the significant differences found in this study between the irrigation treatments.

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