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Manganese availability and transformation in soil profiles under different wheat based cropping systems in north-western India

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ABSTRACT

Long-term (>10 years) changes in depth-wise distribution of DTPA-Mn and Mn fractions of variable solubility in soils under three different cropping systems, viz. rice-wheat (RWCS), maize-wheat (MWCS) and cotton-wheat (CWCS) in Ludhiana, Ropar and Mansa districts of Punjab, north-western India were studied during 2005–18. The surface (0–15 cm) layer of soils under RWCS had significantly lower (by ~31.8%) DTPA-Mn concentration, compared to MWCS. The surface soils under CWCS had ~18.4% higher DTPA-Mn than the soils under RWCS. The DTPA-Mn increased significantly with increased depth of soils under RWCS, in contrast to a significant decrease in MWCS and CWCS. A sequential extraction of Mn in different fractions of variable solubility revealed that the surface layer of soils under RWCS had significantly lower concentration, while the lower layers had higher concentration. The Res-Mn fraction comprised the largest proportion (67–70%) of total-Mn in soils under different cropping systems. The (WSEX+SpAD)-Mn fraction was the smallest Mn fraction of high solubility, comprising ~2–3% of total-Mn in soils under different cropping systems. The relative distribution of different fractions was OM-Mn≤WSEX-Mn≤SpAD-Mn<AFeOX-Mn<CFeOX -Mn < Ox-Mn< residual-Mn.

Keywords: Cropping systems, DTPA-Mn, Sequential extraction of Mn, Soil properties

Rice-wheat (RWCS), maize-wheat (MWCS) and cotton-wheat (CWCS) are predominant cropping systems in north-western India. Due to increase in food grain production, huge depletion of macro and micronutrients has emerged (Shukla *et al.* 2015, Sharma *et al.* 2021). Manganese (Mn) deficiency has emerged due to widespread adoption of intensive agriculture, imbalanced use of macronutrients and decreased use of organic manure and reduced recycling of crop residues (Rattan *et al.* 1999), and has a significant setback on yield potential (Sadana *et al.* 2010) and grain quality (Gomma *et al.* 2015, Shukla *et al.* 2015).

Manganese exists as water soluble (WS-), organic matter bound (OM-), exchangeable (EX-), oxide bound (MnOX-), amorphous Fe+Al bound (AFeOX-), crystalline (CFeOx-) and as the residual fraction (Res-) (Singh *et al.* 2014, Sharma *et al.* 2021). Among different factors, SOC, *p*H, EC, $CaCO_3$, soil-plant and soil-microbial interactions; plant genotypes and cropping systems are considered important to influence Mn transformations in soils (Chhibba *et al.* 2007, Shukla *et al.* 2015). A widespread Mn deficiency due to extension of rice cultivation in coarse textured soils is observed in Punjab due to leaching of soluble Mn in the lower layers of soil profile (Sadana *et al.* 2010). Nonetheless, the crops not only take nutrients from surface, but also from sub-surface layers (Sankar and Dadhwal 2009). The information on depth-wise distribution of DTPA-Mn and Mn fractions of variable solubility in soils under three different wheat based cropping systems (viz. RWCS, MWCS and CWCS) established under contrasting moisture is scarce. The present investigation aimed at studying the distribution of DTPA-Mn and Mn fractions of variable solubility, and to establish relationship between Mn fractions and soils' physico-chemical properties to understand the mechanism governing Mn availability in these soils.

MATERIALS AND METHODS

Study area: Soil samples were collected in May 2018 from Ludhiana, Ropar and Mansa districts of Punjab located in north-western region of India from three major cropping systems, viz. RWCS (Ludhiana district), MWCS (Ropar district) and CWCS (Mansa district). The study sites were selected in such a way that each site had a long history of more than 10 years under each cropping system, so as to discern the long-term impact of soil management and crop production practices followed in each cropping

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system. For this study, six sites under each cropping system were selected to reach a robust conclusion on Mn transformations in response to change in soil management practices. The Ludhiana district in piedmont and alluvial plain agro-eco-sub region had mean maximum summer temperature ranging between 24°C and 26°C and average annual precipitation of 700–1000 mm, covering 52–60% of potential evapo-transpiration (PET). The mean maximum temperature in Ropar lies between 25°C and 36°C, whereas mean minimum temperature lie between 22°C and 28°C. Mean annual precipitation ranges between 850-1200mm covering 75% of PET. The Mansa district in south-western alluvial plain agro-eco-sub region had the mean annual temperature between 24ºC and 27ºC, annual precipitation of 300–450 mm covering 15–24% of PET. Farmyard manure (FYM) @25 Mg/ha was applied before sowing the crop. The fertilizer doses applied were 125 kg N/ha through urea, 62.5 kg P_2O_5/ha through diammonium phosphate (DAP), 30 kg K/ha in RWCS and CWCS and 60 kg K/ha through muriate of potash (MOP) in MWCS. At the time of sowing, half of the recommended N was applied through urea, whole amount of P was applied through DAP. In addition, a full dose of K was applied at the time of sowing of wheat crop. The remaining half N was applied at second irrigation. All the other crop management practices were performed at Farmers' Fields following package and practices for *rabi* crops (2018–19) as recommended by Punjab Agricultural University, Ludhiana, under irrigated conditions.

Sample collection, processing and analysis: From each cropping system, six profile samples were collected from 0–15 cm, 15–30 cm, 30–60 cm and 60–90 cm depth with an auger (inner diameter=5 cm). Soil samples (<2.0 mm) were analyzed for *p*H (1:2 soil: water) with glass electrode and EC with conductivity meter. The particle size distribution was determined using international pipette method. Soil organic C was determined following wet digestion by oxidizing the sample with $K_2Cr_2O_7$. The CEC was determined using sodium acetate solution (*p*H=8.2). The $CaCO_3$ content was determined by rapid titration method. The concentration of DTPA-Mn was extracted with DTPA solution (0.005 M DTPA + 0.01M $CaCl_2$+0.1M TEA buffer adjusted to *p*H=7.3), followed by determination on atomic absorption spectrophotometer (AAS).

Sequential extraction technique: Five gram soil sample was equilibrated with 20 ml 0.005 M $Pb(NO_3)_2$ (*p*H=6.8) for 15 min, followed by centrifugation at 6000 rpm for 10 min to extract the water soluble plus exchangeable-Mn (Singh *et al*. 2014). The residual soil was then equilibrated with 20 ml 0.05 M $Pb(NO_3)_2$ (*p*H=6.0 CH_3COOH) after shaking for 120 min followed by centrifugation for 10 min to extract specifically adsorbed-Mn fraction. To the remaining soil sample, 20.0 ml of NH_2OH. HCl 0.1 mol/L, at *p*H=2.0 was added, and the mixture was shaken for 30 min, centrifuged to extract oxides bound-Mn. To the OX-Mn free soil sample, 20.0 ml of NH_2OH.HCl 0.1 mol/L and HCl 0.25 mol/L, at *p*H 1.3 were added, and the mixture was thereafter, shaken for 30 min at 25ºC in orbital shaker, centrifuged to extract AFeOX-Mn. The residual soil was heated (100°C) with 20.0 ml of 0.25 M NH_2OH.HCl +0.25 M HCl + ascorbic acid 0.01 mol/L (*p*H=1.21) to extract crystalline iron oxide bound-Mn (Singh *et al*. 2014). The residual soil was shaken with 20 ml of 1% $Na_4P_2O_7$ for 1 h at 25ºC followed by centrifugation to extract OM-Mn. The residual-Mn fraction was determined by subtracting all fractions from the total-Mn. For the determination of total-Mn, 0.5 g soil sample was digested with a mixture of 5 ml of HF + 1 ml of $HClO_4$ and 5–6 drops of nitric acid (HNO_3) in platinum crucibles. The solution was filtered and the filtrate was analyzed for Mn with AAS (Varian AASFS Model).

Statistical analysis: The data were subjected to ANOVA by using SAS software. The cropping systems were considered as treatments (fixed effect) and the sampling sites were considered as replications (random effect). The treatment means were significant at $P<0.05$ by Duncan's Multiple Range Test (DMRT). The correlations significant at $P<0.05$ and $P<0.01$ were marked as * and **, respectively.

RESULTS AND DISCUSSION

Basic soil properties: The surface soils under CWCS had significantly ($P<0.05$) higher *p*H, compared to the soils under other two systems (Table 1). The *p*H did not differ significantly for different soil depths. The surface layer of soils under MWCS had significantly lower electrical conductivity (EC) while the highest for soils under CWCS. The lowest EC values in MWCS might be due to higher rainfall and lower evapo-transpiration whereas, significantly highest EC values in CWCS was due to lower rainfall and higher evapo-transpiration (Garnaik *et al.* 2020). The soils under RWCS had significantly higher EC by ~38.7% than the soils under MWCS, while lower by ~44.2% than the soils under CWCS. The high *p*H and EC in soils under CWCS was ascribed to high concentration of soluble salts and residual sodium carbonate in the underground water used for irrigation (Riaz *et al.* 2018).The EC of soils increased significantly with increasing soil depth, regardless of the cropping system. The soils under CWCS had significantly higher $CaCO_3$ concentration than the soils under other two systems. The soils under CWCS had significantly higher sand content, while had the lowest clay content. The SOC concentration in the surface layer was significantly lower for the soils under CWCS, compared with the soils under other two systems which did not differ significantly. The lower SOC concentration in soils under CWCS could be ascribed to aridic moisture regime and higher temperature that leads to oxidation of organic C. In contrast, the soils under RWCS and MWCS received more rainfall and had lower temperature ranges that helped in preserving SOC content (Garnaik *et al.* 2020). Relatively higher SOC content in soils under RWCS than the CWCS was due to anaerobic decomposition of SOM (Singh and Benbi 2020, Benbi 2021).

Depthwise distribution of DTPA-Mn in soils under different cropping systems: The surface layer of soils under

Table 1 Range and mean of physico-chemical properties of soils under different cropping systems

Soil property	Soil depths (cm)							
	0–15		15–30		30–60		60–90	
	Range (mean)†	SE‡	Range (mean)	SE	Range (mean)	SE	Range (mean)	SE
Rice-wheat cropping system (RWCS)								
*p*H(1:2)	7.41-7.97 (7.55aB)	0.09	7.41-8.04 (7.65aB)	0.09	7.63-8.19 (7.81aB)	0.08	7.64-8.21 (7.82aB)	0.09
EC (1:2) (dS/m)	0.24-0.55 (0.43dB)	0.05	0.42-0.74 (0.62cB)	0.05	0.68-0.96 (0.85bA)	0.04	0.84-1.18 (1.05aA)	0.05
SOC (%)	0.49-0.75 (0.59aA)	0.04	0.35-0.59 (0.44bA)	0.04	0.22-0.43 (0.31cA)	0.03	0.21-0.45 (0.33cA)	0.03
$CaCO_3$ (%)	0.75-1.95 (1.28dB)	0.16	1.75-2.88 (2.33cB)	0.17	2.88-3.97(3.38bAB)	0.15	4.06-5.01 (4.69aA)	0.14
CEC (meq/100 g soil)	7.88-11.4 (10.1aB)	0.48	7.05-10.5 (9.17abB)	0.47	6.14-9.84 (8.41bB)	0.50	6.08-9.68 (8.34bB)	0.49
Sand (%)	58.4-66.3 (61.1bB)	1.23	60.7-68.4 (63.5abB)	1.19	63.1-71.4 (66.3aAB)	1.19	62.5-70.3 (65.4aB)	1.28
Silt (%)	20.6-26.9 (23.4aA)	0.98	19.5-25.7 (22.3aA)	0.98	18.4-24.0 (21.2aAB)	0.89	17.9-23.9 (20.9aA)	1.05
Clay (%)	13.1-19.3 (15.5aA)	0.86	12.2-18.3 (14.2aA)	0.91	10.3-16.1 (12.6aA)	0.97	11.5-18.8 (13.7aA)	1.08
Maize-wheat cropping system (MWCS)								
*p*H(1:2)	6.85-7.46 (7.15aC)	0.10	6.93-7.57 (7.18aC)	0.11	7.04-7.58 (7.30aC)	0.09	6.99-7.69 (7.33aC)	0.11
EC (1:2) (dS/m)	0.24-0.36 (0.31aC)	0.02	0.24-0.64 (0.42bC)	0.06	0.43-0.66 (0.51bB)	0.04	0.54-0.74 (0.62cB)	0.03
SOC (%)	0.39-0.70 (0.55aA)	0.05	0.25-0.59 (0.42bA)	0.06	0.16-0.45 (0.31cA)	0.05	0.18-0.47 (0.34cA)	0.05
$CaCO_3$ (%)	0.83-1.41 (1.14cB)	0.09	1.51-3.56 (2.28bB)	0.33	2.54-3.71 (3.04aB)	0.19	3.01-3.98 (3.56aB)	0.13
CEC (meq/100g soil)	14.0-20.2 (16.7aA)	1.01	12.9-19.4 (15.8bA)	1.05	12.0-18.1 (14.8cA)	1.04	12.4-18.4 (15.0cA)	0.98
Sand (%)	56.1-71.4 (62.8cB)	2.49	57.6-73.5 (64.4bB)	2.52	58.9-74.6 (65.7aB)	2.60	57.1-74.6 (65.1aB)	2.70
Silt (%)	19.6-26.9 (23.3aA)	1.10	18.9-26.1 (22.6aA)	1.08	18.0-25.2 (21.7aA)	1.06	17.9-25.1 (21.7aA)	1.06
Clay (%)	7.70-19.5 (13.9aB)	1.67	6.32-18.7 (13.0bA)	1.73	5.97-18.4 (12.6bA)	1.79	5.71-20.0 (13.1bA)	2.02
Cotton-wheat cropping system (CWCS)								
*p*H(1:2)	8.15-8.73 (8.51aA)	0.08	8.23-8.81 (8.58aA)	0.08	8.30-8.94 (8.72aA)	0.10	8.30-8.98 (8.71aA)	0.11
EC (1:2)(dS/m)	0.65-0.96 (0.77cA)	0.05	0.75-1.05 (0.86bcA)	0.05	0.84-1.14 (0.95abA)	0.05	0.94-1.25 (1.06aA)	0.05
SOC (%)	0.28-0.46 (0.39aB)	0.03	0.19-0.35 (0.29bB)	0.03	0.08-0.25 (0.18bcB)	0.03	0.12-0.27 (0.20cB)	0.03
$CaCO_3$ (%)	1.85-2.41 (2.10cA)	0.11	2.17-3.85 (2.95bcA)	0.24	3.17-5.02 (3.84abA)	0.26	2.56-6.62 (4.35aAB)	0.53
CEC (meq/100g soil)	7.11-9.21 (8.22aC)	0.35	6.36-8.54 (7.43abB)	0.34	5.43-7.49 (6.51bB)	0.36	5.68-7.78 (6.77bB)	0.37
Sand (%)	59.1-73.6 (66.6bA)	2.10	60.9-76.0 (68.6aA)	2.15	64.7-79.0 (72.2aA)	2.06	63.3-78.4 (71.3aA)	2.16
Silt (%)	20.0-22.9 (21.4aB)	0.47	19.4-22.2 (20.8aB)	0.46	17.6-20.5 (19.0bB)	0.45	17.8-20.6 (19.1bA)	0.45
Clay (%)	6.41-18.7 (12.0aC)	1.84	4.66-17.7 (10.7aB)	1.88	3.32-15.6 (8.80aB)	1.82	3.80-16.9 (9.50aB)	1.94

†Mean values followed by different letters are significantly different by DMRT. Small letters have been used to differentiate soil depths and capital letters to differentiate cropping systems. ‡SE=Standard error of mean.

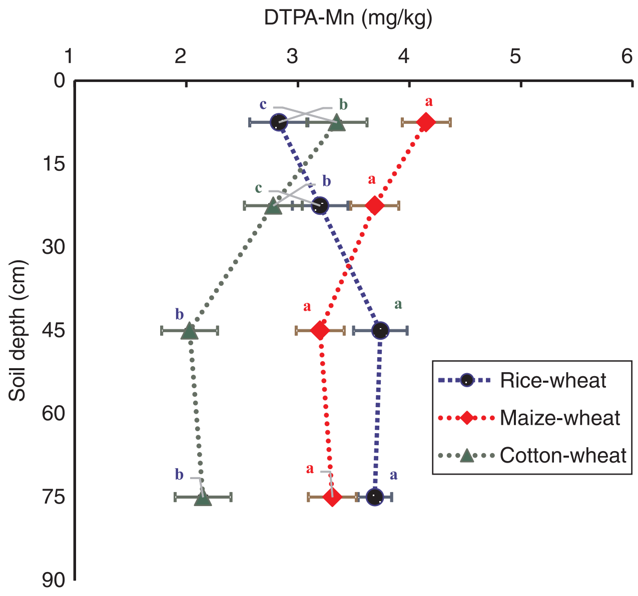

Fig 1 Depthwise (0–15, 15–30, 30–60 and 60–90 cm) distribution of DTPA-Mn (mg/kg) in soils under different cropping systems (Data pooled for different locations).

MWCS had significantly higher DTPA-Mn concentration while the soils under RWCS had the lowest concentration (Fig 1). The lowest concentration of DTPA-Mn in soils under RWCS was ascribed to leaching of soluble Mn from upper to lower layers in soil profiles with the submergence of soil (Singh *et al*. 2011).The surface soils under CWCS had ~18.4% higher DTPA-Mn concentration than the soils under RWCS, while it was ~19.3% lower than the soils under MWCS. Soils under RWCS had significantly lower DTPA-Mn concentration in the surface (0–15 cm) than the lower soils depths (Fig 1). Lu *et al.* (2004) also reported leaching of soluble Mn in soils under RWCS that are coarse in texture. The continuous flooding of the soil increased the availability of Mn due to submergence and a decrease in redox potential that lead to leaching of Mn (Nadeem and Farooq 2019). In contrast, the surface soils under MWCS and CWCS had the significantly higher DTPA-Mn concentration, compared with the lower layers of soil profile and were significant up to a depth of 60 cm. These results revealed that DTPA-Mn decreased with increased soil depth (Table 2). Earlier reports (Chhibba *et al.* 2007) also suggested that DTPA-Mn concentration was higher in the AP horizons and decreased considerably with depth.

Mn fractions of variable solubility in soils under different cropping systems: In the soils under RWCS, the concentration of WSEX-, SpAD-, OX-, AFeOx- and CFeOx-Mn fractions was significantly higher in the lower soil depths (30–60 cm and 60–90 cm), compared with 0–15 cm and 15–30 cm soil depths (Table 2). The OM-Mn fraction did not differ significantly among different depths of soil profile under RWCS. The higher concentration of Mn fractions in lower layers of soils under RWCS may be due to effect of submergence which caused decrease in redox potential and leaching down of different fractions of variable solubility (Singh *et al.* 2013). The soils under MWCS and CWCS had significantly higher concentration of different Mn fractions of variable solubility in the surface soil layer, and exhibited a decreasing concentration with increased soil depth. These results suggest that the surface soil layer under MWCS had ~55% higher WSEX-Mn compared with the soils under RWCS. The concentration specifically adsorbed-Mn fraction was ~2.7 times higher in the surface soil layer under MWCS, compared with the RWCS. The surface soil layer under MWCS had ~14.1 and 12.0% higher total-Mn concentration than the soils under RWCS and the CWCS, respectively. However, the concentration of Res-Mn fraction did not differ significantly in the surface layer of soils under three contrasting wheat based cropping systems. Similar findings were also reported by Chhibba *et al.* (2007). Unlike, the soils under RWCS, the different Mn fractions of variable solubility had significantly higher concentration in the surface soil layer, compared with the lowers layers of soils under MWCS (Singh *et al.* 2013).

Relative distribution of Mn fractions of variable solubility: The relative preponderance of occurrence of different Mn fractions of variable solubility in soils followed an order: OM-Mn≤WSEX-Mn≤SpAD-Mn<AFeOX-Mn <CFeOX-Mn<Ox-Mn<residual-Mn. The Res-Mn fraction comprised the largest proportion (67–70%) of total-Mn in soils under different cropping systems. The (WSEX + SpAD)-Mn fraction was the smallest Mn fraction of high solubility, comprising ~2–3% of total-Mn. These results were in conformity with the earlier research (Singh *et al.* 2014). Such variation was ascribed to the nature of parent material, climatic conditions and susceptibility of Mn to change from oxidized to reduced states and vice versa (Behera and Shukla 2014).

Relationship between soil physical-chemical properties and Mn fractions: The correlation matrix revealed a highly (P<0.01) significant linear relationship between soil *p*H and EC with Mn fraction of different solubility. All fractions of Mn varied from significantly to highly significantly and correlated to SOC (r=0.282-0.966**, P<0.01).These results suggested that the concentration of Mn in different fractions decreased with increased $CaCO_3$.

The concentration of Mn fractions decreased with increased sand content, while increased with increased fine fraction (silt and clay). A highly significant correlation between different Mn fractions of variable solubility revealed that these fractions exist in a dynamic equilibrium with each other. The DTPA-extractable Mn was positively and significantly correlated with SOC and clay content in soils and negatively correlated with EC. These results showed that the soils under MWCS and CWCS exhibited a decrease in DTPA-Mn concentration with increasing soil depth, in contrast to increase in soils under RWCS. The Res-Mn fraction comprised the highest proportion (67–70%), while OM-Mn fraction was the smallest (0–1%) proportion of total-Mn in soils under different cropping systems.

Table 2 Different Mn fractions (mg/kg) of variable solubility in soils under different cropping systems

Soil property	Soil depths (cm)							
	0–15		15–30		30–60		60–90	
	Range (mean)†	SE‡	Range (mean)	SE	Range (mean)	SE	Range (mean)	SE
Rice-wheat cropping system (RWCS)								
WSEX-Mn	1.98-4.12 (3.07^{cB})	0.36	2.44-5.25 (3.52^{bB})	0.44	3.23-5.24 (4.20^{aA})	0.33	2.55-5.49 (4.12^{aA})	0.46
SpAD-Mn	1.53-2.78 (2.34^{bB})	0.17	2.12-3.61 (2.72^{bB})	0.25	2.54-3.78 (3.37^{aB})	0.19	2.82-3.97 (3.35^{aB})	0.20
OX-Mn	47.6-58.8 (53.5^{bB})	1.59	49.2-60.2 (55.2^{bB})	1.66	55.5-65.5 (59.8^{aA})	1.47	52.1-64.5 (60.2^{aA})	1.92
AFeOX-Mn	13.5-19.7 (17.1^{cB})	0.94	14.6-22.1 (18.8^{bAB})	1.21	17.5-26.8 (21.1^{aA})	1.34	18.1-22.5 (20.5^{aA})	0.83
CFeOX-Mn	15.2-33.4 (28.0^{bB})	2.65	17.5-35.9 (29.9^{bB})	2.62	18.7-37.5 (32.4^{aA})	2.84	18.1-40.1.9 (31.3^{aB})	2.93
OM-Mn	0.01-0.02 (0.02^{aC})	0.002	0.00-0.02 (0.02^{abC})	0.003	0.00-0.01 (0.01^{bcC})	0.00	0.00-0.01 (0.01^{cC})	0.00
Res-Mn	245.6-278.5 (259.6^{cA})	5.25	250.3-280.8 (265.8^{bA})	5.40	250.5-297.2 (276.3^{aA})	7.45	211.6-339.3 (275.8^{aA})	17.1
Total-Mn	342.2-381.4 (363.6^{cB})	6.35	359.5-396.3 (375.9^{bB})	6.55	368.2-413.3 (397.3^{aA})	6.70	341.5-469.7 (395.5^{abA})	17.5
Maize-wheat cropping system (MWCS)								
WSEX-Mn	3.41-7.00 (4.76^{aA})	0.55	2.85-6.59 (4.34^{bA})	0.55	2.17-5.88 (3.62^{cB})	0.53	2.28-6.06 (3.76^{cB})	0.57
SpAD-Mn	4.40-8.31 (6.22^{aA})	0.59	4.05-7.94 (5.89^{bA})	0.58	3.24-7.12 (5.10^{cA})	0.61	3.38-7.29 (5.21^{cA})	0.58
OX-Mn	44.1-86.9 (62.9^{aA})	7.40	41.1-83.6 (59.0^{bA})	7.49	35.7-78.6 (54.4^{cA})	7.45	36.9-82.9 (55.6^{cB})	7.51
AFeOX-Mn	17.4-33.7 (24.3^{aA})	2.92	16.3-32.6 (23.1^{bA})	2.87	15.4-31.7 (21.9^{cA})	2.89	14.8-32.3 (22.3^{cA})	2.92
CFeOX-Mn	29.4-49.0 (37.9^{aA})	3.26	27.4-47.1 (36.0^{bA})	3.24	25.3-43.9 (33.2^{cA})	3.14	24.1-46.0 (34.1^{cA})	3.29
OM-Mn	2.55-4.85 (3.83^{aA})	0.35	2.28-4.44 (3.50^{bA})	0.34	1.54-3.81 (2.84^{cA})	0.35	1.61-3.89 (2.92^{cA})	0.36
Res-Mn	214.1-337.4 (275.2^{aA})	20.4	201.3-324.5 (261.2^{bA})	20.2	183.1-302.3 (240.1^{cA})	19.9	196.4-348.0 (250.1^{bcA})	22.2
Total-Mn	315.3-527.2 (415.0^{aA})	35.0	295.4-506.8 (393.0^{bA})	34.8	266.5-473.2 (361.2^{cA})	34.3	279.5-526.3 (374.0^{bcA})	36.6
Cotton-wheat cropping system (CWCS)								
WSEX-Mn	3.66-5.57 (4.60^{aA})	0.31	3.22-5.24 (4.24^{bA})	0.32	2.59-4.62(3.52^{cB})	0.32	2.75-4.81(3.68^{cB})	0.32
SpAD-Mn	4.51-6.96 (5.77^{aA})	0.41	3.98-6.42 (5.20^{bA})	0.40	2.86-5.61(4.32^{cAB})	0.43	3.02-5.75(4.17^{cB})	0.46
OX-Mn	41.3-64.4 (54.2^{aB})	4.23	34.7-58.1 (47.3^{bC})	4.24	27.7-49.5(39.5^{cB})	3.93	28.9-51.3(41.0^{cC})	3.94
AFeOX-Mn	11.2-20.0 (15.9^{aB})	1.54	9.04-18.0 (13.8^{bC})	1.53	5.53-13.9 (10.1^{cB})	1.36	6.16-14.5(11.1^{cB})	1.48
CFeOX-Mn	24.1-40.5 (32.2^{aAB})	2.27	22.2-37.8 (30.1^{bB})	2.21	18.0-34.0(27.2^{cB})	2.50	18.6-35.1(27.3^{cC})	2.55
OM-Mn	1.31-2.73 (2.02^{aB})	0.24	1.15-2.49 (1.81^{bB})	0.23	0.75-2.01(1.36^{cB})	0.21	0.82-2.09(1.42^{cB})	0.22
Res-Mn	180.0-323.4 (255.8^{aA})	21.9	168.1-310.0 (259.5^{aA})	20.7	106.0-252.1 (182.3^{bB})	22.4	104.0-258.2 (184.6^{bB})	22.5
Total-Mn	268.0-444.5 (370.4^{aB})	29.5	243.8-419.6 (362.0^{bC})	25.9	166.4-341.7 (268.3^{cB})	29.4	167.9-351.1 (273.8^{cB})	29.6

†Mean values followed by different letters are significantly different by DMRT. Small letters have been used to differentiate soil depths and capital letters to differentiate cropping systems. ‡SE=Standard error of mean.

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