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Soil Organic Carbon, Hydraulic Properties and Yield of Maize and Wheat under Long–term Fertilization in an Inceptisol

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The present investigation was carried out to evaluate the changes in oxidizable soil organic carbon (SOC), hydraulic properties and yield of both maize (*Zea mays*) and wheat (*Triticum aestivum*) under long–term fertilization during 34th cropping cycle. Six fertilizer treatments were selected for the present study. The soil samples were analyzed for oxidizable SOC, bulk density (BD), mean weight diameter (MWD), soil water retention at 33 and 1500 kPa, saturated hydraulic conductivity (*Ksat*) at surface (0-15 cm) and sub–surface (15–30 cm) soil layers. The plant samples were analyzed for nutrient uptake at harvest. The results showed that N and NP fertilizer treatments maintained initial oxidizable SOC and soil physical condition in surface layer, and showed significantly higher values compared with control. However, significant reductions in yield and nutrient uptake by maize and wheat were observed in these treatments compared to nitrogen, phosphorus and potassium (NPK) applied plot, nitrogen, phosphorus, potassium and sulphur (NPKS) applied plot and NPK+ farmyard manure (FYM) treatment. The NPK + FYM application significantly increased oxidizable SOC, MWD and decreased BD compared to control plots and the initial values. Balanced application of plant nutrients through mineral fertilizers and FYM increased oxidizable SOC by 84 per cent and improved soil hydraulic properties, uptake and yield of both maize and wheat compared to control. Integrated use of NPK along with FYM was the best option for sustaining soil physical condition, enhancing nutrient uptake and ultimately crop productivity.

Key words: Mean weight diameter, pore space, available water, soil physical condition, soil health

India currently produces about 230 million tonnes (Mt) of cereals to meet the needs of 1.15 billion populations (Swaminathan and Bhavani 2013). During the green revolution, India attained self sufficiency in food production with introduction of high yielding varieties, mineral fertilizers and intensive copping. Maize–wheat crop rotation is one of the profitable systems followed in upland irrigated Indo–Gangetic Plains. The farmers in this region use fertilizers indiscriminately to get good yield. Indiscriminate use of mineral fertilizers over the years reduced soil organic carbon (SOC) and deteriorated soil physical conditions (Sharma *et al*. 2003). Adoption of intensive cereal–based cropping system, use of mineral fertilizers, intensive tillage operations and removal of crop residues reduced soil organic matter (SOM) in northern India (Kushwaha *et al*. 2001). The low SOC level is one of the major reasons for deterioration of soil health and productivity (Bandyopadhyay *et al*. 2010).

Addition of organic manures is most important to maintain SOC, soil physical conditions and secondary and micronutrients. The previous studies conducted at different locations showed that incorporation of organic matter either through crop residues or organic manure improved SOC, soil structure and water retention capacity (Zhang *et al*. 2014), increased infiltration rate (Hillel 2004) and decreased bulk density (BD) (Liu *et al*. 2003). Addition of organic manures affects crop growth and

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yield directly by supplying plant nutrients and indirectly by modifying soil physical properties such as aggregate stability, porosity, water retention that can improve root growth and stimulates plant growth (Darwish *et al*. 1995). The SOM and structure determines soil water availability (Bhattacharyya *et al*. 2007). Soil water availability controls nutrient solubility and movement within the soil and determines the availability of water and nutrients to the crops (Frissell 1978). However, neither mineral fertilizers nor organic manure alone sustain crop productivity.

Hence, a judicious and combined use of organic and inorganic sources of plant nutrients is a prerequisite to maintain soil health and to augment the nutrient use efficiency. Several studies have been conducted separately to evaluate the effect of integrated use of organic manures and inorganic fertilizers on SOC, soil physical conditions, nutrient uptake and crop yield. The results showed that the integrated use of organic and inorganic fertilizers increased SOC, improved cumulative infiltration, infiltration rate and aggregate mean weight diameter (MWD) and increased crop yield (Hati *et al*. 2006; Brar *et al*. 2015). However, the information on effect of long–term fertilization on soil hydraulic properties and their relationships with nutrient uptake and crop yield under maize–wheat system are limited. Hence, the present investigation was undertaken with the objectives (i) to assess the effect of long–term fertilization on changes in SOC and hydraulic properties, and (ii) to investigate the relationships between soil hydraulic properties and nutrient uptake and yield of both maize and wheat.

Materials and Methods

Experimental location

For the present investigation, an ongoing All India Coordinated Research Project on Long–term Fertilizer Experiment (AICRP-LTFE) was used. The experimental field is located in ICAR-Indian Agricultural Research Institute (IARI), New Delhi at latitude 28° N and longitude 77° E and at 750 m above mean sea level. Climate of New Delhi is semi-arid and sub–tropical, characterized by hot summers and cold winters. Mean annual precipitation is about 650 mm, most of which received through south west monsoon during July to September. Total rainfall received during study period was 581 mm. The mean monthly maximum and minimum temperature ranged from 21.2 to 40.3 ^{o}C and 4.1 to 27.4 ^{o}C, with an average of 31.3 and 17.6 ^{o}C, respectively. The soils of the experimental field is of alluvial origin, sandy clay loam in texture, alkaline in reaction, non–calcareous and bears low cation exchange capacity (Table 1).

Field experiment

Long–term fertilizer experiment at ICAR–IARI was set up in 1971 with ten treatments under intensive cropping sequence. The experiment was laid out in a randomized block design with four replications, keeping a plot size of 21 m × 8 m. Out of ten, six fertilizer treatments were selected for the present investigation during *kharif* 2005 and *rabi* 2005-06. The treatment details were 100% N (N), 100% NP (NP), 100% NPK (NPK), 100% NPK + FYM (NPK + FYM), 100% NPKS (NPKS) and control. Maize cv. Ganga Safed–2 was sown during the second week of July 2005 (*kharif*) followed by wheat cv. HD–2329 during the third week of November, 2005. Farmyard manure (FYM) with 0.58, 0.27 and 0.65% N, P and K, respectively, was incorporated to NPK + FYM treatment. Required quantities of P_2O_5 (60 kg ha^{-1}), K_2O (40 kg ha^{-1}), S (45 kg ha^{-1}) and 50% of N (60 kg ha^{-1}) were applied before sowing for both maize and wheat crops and remaining 50% of N (60 kg ha^{-1}) was top dressed on 40 days after sowing for maize and 60 days after sowing for wheat. Recommended

Table 1. Properties of surface soils (0–15 cm) of the experimental field (2005)

Treatments	Oxidizable SOC (g kg^{-1})	Available macronutrients (kg ha^{-1})				Available micronutrients (mg kg^{-1})			
		N	P	K	S	Fe	Mn	Cu	Zn
N	0.51	218	19.6	204	51.3	5.8	16.8	1.65	1.31
NP	0.48	230	29.4	216	59.3	6.3	18.1	1.72	1.37
NPK	0.50	239	30.4	257	73.7	6.5	18.6	1.89	1.34
NPK + FYM	0.67	251	39.9	284	76.4	6.3	19.5	1.97	1.56
NPKS	0.52	235	31.6	265	99.9	5.1	18.7	1.79	1.41
Control	0.34	206	17.0	211	52.6	4.9	15.6	1.57	1.19
Initial value (1971)	0.44	210	16.0	155	50.4	106	20.0	1.35	1.11

SOC: Soil organic carbon

herbicides atrazine and isoproturon at 1 kg active ingredient ha^{-1} were applied for maize and wheat, respectively. The crop was harvested after maturity, threshed after thorough sun–drying to separate grains and recorded grain yield.

Soil and plant sampling

Composite samples were collected from surface (0–15 cm) and sub–surface (15–30 cm) soil layer after harvest of each crop to analyse available nutrients and to determine water retention at 33 and 1500 kPa. Collected soils were air-dried and sieved using a 2-mm sieve and used for further analysis. Intact core samples were collected from surface (0–15 cm) and sub–surface (15–30 cm) soil layers to determine BD and saturated hydraulic conductivity (*Ksat*). Soil aggregates were collected from both surface and sub–surface soils to determine aggregate stability and MWD. Soils from fallow fields were also collected for analysis. Fifteen plants samples per treatment were collected randomly for determining nutrient uptake for both maize and wheat crops harvest. Grain and stover/straw of maize and wheat samples were washed and dried in oven at 65±2 °C until reached constant weight and ground using stainless steel Wiley mill for analysis.

Plant analysis

Total N in plant samples was determined by Kjeldhal method (Page *et al*. 1982). Processed plant samples were pre–digested using nitric acid and finally with di–acid mixture (9:4 HNO_3:$HClO_4$). The final volume was made up to 100 mL with double distilled water. In the di–acid digestion extractant, P was determined using the vanadomolybdate yellow colour method, K using a flame photometer (Jackson 1973), S by turbidimetric method (Chesnin and Yien 1951) and total micronutrients using a atomic absorption spectrophotometer. The nutrient concentration was multiplied by dry matter yield to drive nutrient uptake. Macronutrient uptake was expressed in kg ha^{-1} and micronutrient uptake in g ha^{-1}.

Oxidizable soil organic carbon

Soil samples, passed through a 0.2 mm sieve, were analyzed for oxidizable SOC following the wet oxidation method (Walkley and Black 1934). Oxidizable SOC stock was calculated by multiplying SOC, BD and soil depth and expressed in t ha^{-1}.

Soil nutrient analysis

Soil available N was analyzed by alkaline permanganate method (Subbiah and Asija 1956). Available P was extracted by sodium bicarbonate method using ascorbic acid as reducing agent (Watanabe and Olsen 1965), 0.15% $CaCl_2$ extractable S by turbidimetric method and available K by flame photometer method. The available Fe, Mn, Zn and Cu were extracted with DTPA (Lindsay and Norvel 1978) and analyzed using the atomic absorption spectrometer.

Bulk density and pore space

The core sampler was pushed into the desired soil depth in such a way that soil is collected from the centre of the given depth (0–15 and 15–30 cm). Soil samples were oven-dried at 105 °C for 48 h. Soil bulk density (Mg m^{-3}) was calculated by dividing weight of dried soil by the volume of core used (Veihmeyer and Hendrickson 1948). Pore space was derived from BD using the following formula:

Per cent pore space= [1 - BD/particle density] ×100

We have used particle density of 2.65 Mg m^{-3} for calculating pore space.

Aggregate stability

Large clods were broken into smaller segments along natural cleavage by hand prior to air drying. The air–dried soil was sieved to obtain aggregates that passed through a 8-mm and retained on a 5-mm sieve. The aggregates were sieved using the wet sieving technique (Yoder 1936). After wet sieving, aggregates from each sieve were transferred to a set of pre–weighed beakers, oven–dried at 60 °C until water evaporated, weighed, and the mean weight diameter MWD was calculated (van Bavel 1949).

Infiltration rate

Infiltration studies were carried out in the field using a double ring infiltrometer having 15 cm height, and diameter of 30 and 20 cm outer and inner rings, respectively. The rings were inserted to 5 cm soil depth. Depth–wise soil samples, at an interval of 7.5 cm, were collected during infiltration to study the distribution of moisture content in soils (Black 1965).

Saturated hydraulic conductivity

The *Ksat* was determined in the laboratory using undisturbed soil core (Booltink and Bouma 2001). Constant head was maintained at 1 cm and *Ksat* was calculated using Darcy's equation (Klute 1965):

$$K_s = Q/At \times L/H$$

where, K_s = *Ksat* (cm h^{-1}), A= Cross sectional area, Q/t = Water flux, and L/H = Hydraulic gradient

Water retention characteristics

Moisture retentions at 33 kPa (field capacity) and 1500 kPa (permanent wilting point) were determined using a pressure plate apparatus, following Richards (1943). Samples were saturated with water for about 24 h, after which these samples were transferred to the pressure plate for determining moisture retention at 33 and 1500 kPa suction, respectively. After attaining equilibrium, the soil samples were weighed and moisture content retained in the soil was determined gravimetrically, by oven drying the sample at 105 °C.

Statistical analysis

The data generated were processed for analysis of variance using PROC GLM and means were differentiated using Duncan multiple range test at 5% significance using a SAS software package version 9.3. Correlation co–coefficients and stepwise regression analysis were carried out using SAS JMP genomics software version 10.2 to predict the relationship of hydraulic properties with nutrient uptake and crop yield.

Results and Discussion

Oxidizable soil organic carbon

In the 0–15 cm soil layer, application of NPK + FYM showed significantly higher oxidizable SOC (6.69 g kg^{-1}) followed by NPKS (5.39 g kg^{-1}) and NPK (4.99 g kg^{-1}) treatments compared with control (Fig. 1). The NPKS addition increased 49 per cent oxidizable SOC followed by NPK (37%), NP (35%) and N (28%) compared to control and the difference were significant. Similar results as in surface 0–15 cm soils were observed in sub-surface soils. In sub–surface soil, application of NPK + FYM recorded 5.03 g kg^{-1} oxidizable SOC followed by NPKS, NPK, NP and N and these treatments showed significantly higher oxidizable SOC than control. Intensive cropping using NPK fertilizers alone or in combination with FYM increased oxidizable SOC compared to the initial value (4.4 g kg^{-1}). The magnitude of increase varied from 5 per cent in N alone to 48 per cent under NPK + FYM treatment. Addition of NPKS, NPK, NP and N alone maintained initial oxidizable SOC level and recorded significantly higher SOC than control. Fallow plot showed 4.69 g kg^{-1} oxidizable SOC, which was 7 and 19 per cent higher than the initial value and control, respectively. Oxidizable SOC stock increased with continuous application of NPK + FYM by 41.4 per cent in surface soil (0–15 cm), followed by NPKS (18.9%), compared to the initial value (7.94 t ha^{-1}). Continuous cropping without fertilizer application negatively affected oxidizable SOC stock and decreased SOC stock by 18.7 per cent compared to the initial value (Table 2). Application of NPK + FYM increased oxidizable SOC by 84 per cent compared to control in the surface layer. The increase in oxidizable SOC in this treatment could be due to direct addition of FYM and indirectly through addition of crop residues and root biomass to soils (Hati *et al*. 2006; Bandyopadhyay *et al*. 2010; Dong *et al*. 2012). The increased oxidizable SOC in remaining fertilizer treatments could be due to better

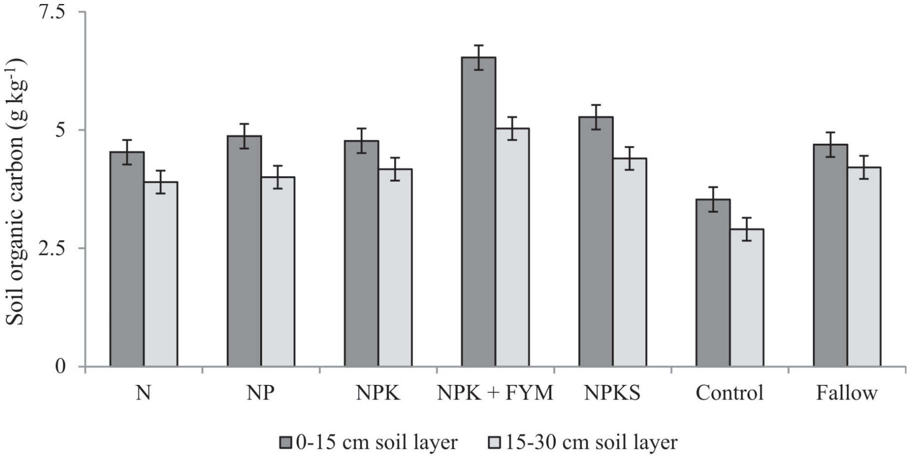

Fig. 1. Oxidizable SOC level in surface and sub–surface soil as affected by fertilization after 34th cropping cycle under maize–wheat system. Error bar indicate standard error of the mean (n=21). Treatment details: N: 100% N, NP: 100% NP, NPK: 100% NPK, NPK + FYM: 100% NPK + 20 t FYM ha^{-1}, NPKS: 100% NPKS, Control: Unfertilized control, Fallow: Uncropped area near experimental field

Table 2. Soil hydraulic properties after 34 years of long–term fertilization

Treatments	Oxidizable SOC stock (t ha^{-1})		Pore space (%)		*Ksat* (cm h^{-1})		FC (%)		PWP (%)		AWC (%)		MWD (mm)		Infiltration rate (cm h^{-1})
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	
N	10.06	10.2	44.4b	35.7b	0.541bc	0.404a	17.3b	14.9a	5.6a	5.7a	11.7b	9.2a	0.357c	0.328a	1.18c
NP	10.81	10.2	44.0bc	35.8b	0.557bc	0.386a	17.1b	15.0a	6.6a	6.0a	10.5bc	9.0a	0.380bc	0.346a	1.20c
NPK	10.59	10.8	44.0bc	36.6ab	0.691ab	0.412a	17.9ab	15.6a	6.7a	6.4a	11.2b	9.2a	0.447b	0.349a	1.48b
NPK + FYM	13.81	12.9	46.9a	37.4a	0.761a	0.472a	20.8a	17.2a	6.6a	5.9a	14.2a	11.2a	0.504a	0.347a	2.22a
NPKS	11.62	11.5	44.6b	36.6ab	0.539bc	0.369a	18.4ab	15.6a	7.1a	6.7a	11.3b	9.9a	0.426bc	0.345a	1.48b
control	7.94	7.3	43.2c	36.1b	0.445c	0.335a	15.4b	13.8a	6.8a	6.2a	8.6c	7.6a	0.365c	0.323a	0.92c
Fallow	9.80	10.8	46.1a	36.6ab	0.465c	0.357a	18.4ab	15.3a	6.5a	6.1a	11.9ab	9.2a	0.484ab	0.349a	1.50b

SOC: Soil organic carbon, *Ksat*: Soil saturated hydraulic conductivity, FC: Water retention at field capacity, PWP: Water retention at permanent wilting point, AWC: Available water content, MWD: Mean weight diameter

*Values with same letter are not significantly different each other

spreading and proliferation of the roots and better crop growth, the plant remains added soils (Manjaiah and Singh 2001). The lowest oxidizable SOC in plots under control could be due to poor crop growth and biomass addition (Sharma *et al*. 2002). Biomass added through weed residue incorporation and root biomass without tillage operation maintained initial oxidizable SOC in fallow fields.

Bulk density and pore space in soils

In general, mean BD of surface (0–15 cm) soil was lower (1.47 Mg m^{-3}) than the sub–surface (15–30 cm) soil (1.68 Mg m^{-3}) irrespective of the treatments (Fig. 2). The BD was significantly ($P<0.01$) and negatively correlated with oxidizable SOC (r = -0.658**) and available P (r = -0.618**) (Table 5). The effect of fertilizer treatments on BD was significant in both surface and sub–surface soil layers. However, the magnitude of difference between the treatments was more pronounced in surface layer. Application of NPK + FYM significantly reduced BD and increased pore space compared to remaining fertilizer treatments and control (Table 2). This treatment reduced the BD by 9.3 per cent compared to the value recorded in the same experimental field during 1980 (Pawar 1980). The NPKS application reduced BD by 4.7 per cent compared to control and has similar values to N, NP and NPK application. Darwish *et al*. (1995) observed small changes in soil BD with continuous cropping for 15 years in sandy loam, silt loam and clay loam soils of humid sub-tropical climate. The lower BD in surface soil was attributed to the higher SOC (Bandyopadhyay *et al*. 2010; Tripathi *et al*. 2014), higher SOM, better aggregation and increased root growth with balanced fertilization (Chalwade *et al*. 2006; Bandyopadhyay *et al*. 2010). Further, tillage operations carried out were also restricted mostly to surface soil, leaving the sub–surface soil undisturbed and compacted. The marginal reduction in BD at 15–30 cm soil depth could be due to incorporation of crop residues and root biomass with consequent increase in SOC (Celik *et al*. 2010).

Mean weight diameter

All fertilizer treatments improved MWD compared to the initial value recorded in 1980 (0.309 mm) (Pawar 1980). The NPK + FYM treatments significantly ($P<0.01$) increased MWD compared to control and remaining fertilizer treatments. It is observed that NPK + FYM treatment increased MWD by 38.1 and 63 per cent compared to control and

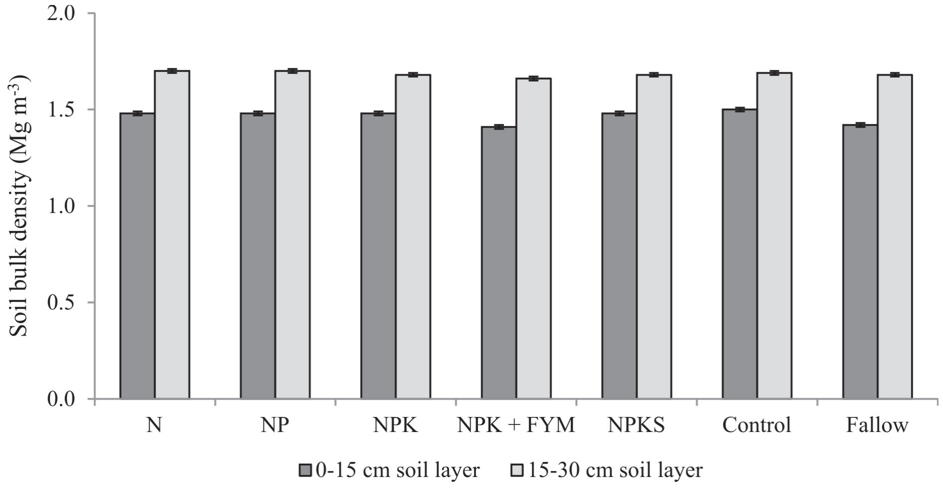

Fig. 2. Bulk density as influenced by long–term fertilization in an Inceptisol. Error bar indicate standard error of the mean (n=21). Treatment details: N: 100% N, NP: 100% NP, NPK: 100% NPK, NPK + FYM: 100% NPK + 20 t FYM ha^{-1}, NPKS: 100% NPKS, Control: Unfertilized control, Fallow: Uncropped area near experimental field

initial value, respectively. Fertilizer treatments did not influence MWD in the sub–surface soil (Table 2). The MWD was significantly ($P<0.01$) and positively correlated with SOC (r = 0.600**) and soil available P (r = 0.619**). Thin increase MWD with NPK + FYM addition could be due to direct addition of SOM through FYM, increased SOC through better crop growth, addition of crop residues through well proliferated roots and the binding of soil particles by phosphate ions (Rasool *et al.* 2008). Organic matter increased the stability of aggregates through binding of the soil mineral particles by polysaccharide (Benbi and Senapati 2010; Chen *et al.* 2010).

Infiltration rate and Ksat

Basic Infiltration rate of fertilizer treatments varied from 0.95 to 2.22 cm h^{-1} (Table 2). Fertilizer treatments had significant effect on infiltration rate, wherein NPK + FYM treatments showed significantly ($P<0.01$) higher rate than NPKS, NPK, NP, N and control. The NPK + FYM applied treatments increased infiltration rate by 130 per cent compared to control. Application of NPKS registered infiltration rate similar to NPK treatments. Application of NPK and NPKS increased infiltration by 40 per cent compared to control. Plots receiving N showed infiltration rate similar to NP and significantly higher rate than control. Fertilizer treatments had significantly ($P<0.01$) influenced *Ksat* of the surface soils. Continuous application of NPK + FYM increased *Ksat* by 21 per cent compared to control. Application of N, NP, NPK and NPKS maintained the *Ksat* value recorded during 1980 (0.67 cm h^{-1}) (Pawar 1980). In the sub–surface layer, *Ksat* ranged from 0.335 in control to 0.472 cm h^{-1} in NPK + FYM treatment. No significant difference was observed between the fertilizer treatments in sub–surface layer for *Ksat*. This could be due to lower SOC, higher clay content, increased compaction and reduced pore volume in sub–surface soil. The NPK treatments showed *Ksat* values similar to NP, N and NPKS. Application of N, NP, NPK and NPKS maintained the *Ksat* value recorded during 1980 (0.67 cm h^{-1}) (Pawar 1980). In the sub–surface layer, *Ksat* ranged from 0.335 in control to 0.472 cm h^{-1} in NPK + FYM treatment. No significant difference was observed between the fertilizer treatments in sub–surface layer for *Ksat*. The *Ksat* had positively ($P<0.01$) correlated with SOC (r = 0.681**), available P (r = 0.711**) and negatively ($P<0.05$) correlated with clay content (r = -0.335*). Soil permeability is a function of effective pore volume and increased pore volume has direct influence on the *Ksat* of the soil (Flowers and Lal 1998). Improved soil structure through aggregation might have increased porosity, infiltration rate and water permeability of soil (Chalwade *et al.* 2006).

Water retention and available water

Water retention at field capacity (FC) on weight basis varied from 15.4% for control to 21.3% for NPK + FYM (Table 2). The fertilizer treatments had significant ($P<0.01$) effect on water retention at FC in the 0–15 cm soil layer, but not in the 15-30 cm depth. Application of NPK + FYM significantly increased the soil water retention at FC compared to remaining fertilizer treatments and control. Water retention at FC was significantly ($P<0.01$) and positively correlated with SOC (r = 0.563**), clay content (r = 0.615**) and soil available P (r = 0.428*). The amount of water retained at FC primarily depends on capillary effect, pore size distribution and soil structure (Hillel 2004). The NPK and NPKS applied treatments significantly ($P<0.05$) increased water retention at FC compared to N, NP and control. That higher water retention could be due to better aggregation and higher SOC in surface soil. The water retention at FC in 15-30 cm depth ranged from 13.2% for control to 17.2% for NPK + FYM. Water retention at permanent wilting point (PWP) on weight basis in surface and sub–surface soil varied from 5.6 to 7.1% and 5.7 to 6.7%, respectively (Table 2). Fertilization did not improve water retention at FC in sub–surface soil and water retention at PWP both in surface and sub–surface soils. Water retention at 1500 kPa is a function of soil texture rather than structure (Obi and Ebo 1995). Water retention at 1500 kPa had positive correlation ($P<0.01$) with clay content (r = 0.740**). All fertilizer treatments showed significant increase in available water content compared to control. Application of NPK + FYM significantly increased the available water content compared to remaining treatments and control. However, the fertilization did not influence available water content in the 15–30 cm soil layer.

Nutrient uptake

Application of NPK + FYM increased nutrient uptake significantly compared to remaining fertilizer treatments and control (Table 3 and 4). This treatment acquired 131.3 to 227.3 per cent higher N, P, K and S compared to control and 11.2 to 29.2 per cent compared to NPK and NPKS treatments, respectively. Micronutrient uptake in NPK + FYM treatments increased by 95.6–153.4 per cent compared to control and 6.0–28.9 per cent compared to NPK and NPKS treatments, respectively. This higher macro and micronutrient uptakes with NPK + FYM addition compared with remaining treatments were due to supply of macronutrient from mineral fertilizers and FYM, micronutrient from FYM and through increased biomass yield. Additionally, FYM application might have increased the availability of native micronutrients through chelation (Gupta 1995). The NPK and NPKS treatments acquired significantly higher nutrients than N, NP and control. Application of NPK and NPKS increased macronutrient uptake by 89.7-175.8 per cent and 70.1-118.7 per cent micronutrients compared to control. Unbalanced fertilizer application (N or NP alone) had resulted in significantly higher K uptake than control. This is attributed to K mining from relatively unavailable forms from soils. Continuous application of NPK + FYM or NPKS significantly increased sulphur uptake compared to remaining fertilizer treatments and control.

Table 3. Macronutrient uptake (kg ha^{-1}) of maize and wheat crops

Treatments	Grain yield (t ha^{-1})		Nitrogen		Phosphorus		Potassium		Sulphur	
	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
N	1.18d	3.59c	24.6c	78.0d	3.6d	12.0d	15.0d	72.1d	2.2d	8.7d
NP	1.41c	4.12bc	30.0c	91.8c	4.7c	15.0c	18.9c	78.9c	2.6c	10.0c
NPK	1.59bc	4.58ab	36.4b	111.7b	5.9b	17.4b	26.2b	91.4b	3.3b	11.6b
NPK + FYM	1.89a	4.81a	43.7a	131.2a	6.9a	21.6a	30.5a	107.0a	3.7a	12.9a
NPKS	1.71ab	4.67a	35.8b	110.5b	5.9b	18.2b	23.6b	90.7b	3.6ab	13.7a
Control	0.91e	2.35d	16.9d	44.6e	2.4e	6.6e	11.3e	47.8e	1.6e	5.1e

*Values with same letter are not significantly different each other

Table 4. Micronutrient uptake (g ha^{-1}) of maize and wheat crop

Treatments	Iron		Zinc		Manganese		Copper	
	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat
N	702c	1772c	77.4b	281.1c	52.3c	296.6b	16.2c	57.3c
NP	822bc	2192bc	91.4b	291.7c	60.9c	321.2ab	16.7c	68.1b
NPK	952ab	2462b	113.2a	339.1b	79.1b	338.5ab	21.3b	72.7b
NPK + FYM	1095a	2816a	120.9a	404.6a	97.3a	382.6a	25.5a	81.7a
NPKS	905b	2413b	114.9a	332.9b	75.5b	348.8ab	18.9bc	75.2b
Control	532d	1126d	61.8c	176.1d	38.4d	173.5c	10.6d	35.3d

*Values with same letter are not significantly different each other

Table 5. Correlation coefficient of hydraulic properties with oxidizable soil organic carbon

Parameter	Oxidizable SOC (g kg^{-1})	Clay (%)	Available P (kg ha^{-1})
Bulk density	-0.658**	0.218	-0.618**
MWD	0.600**	-0.084	0.619**
Infiltration rate	0.731**	0.025	0.778**
Ksat	0.681**	-0.335*	0.711**
Pore space	0.657**	-0.222	0.615**
Field capacity	0.563**	0.615**	0.428*
Permanent wilting point	0.232*	0.740**	0.159
Available water	0.778**	0.342*	0.642**

*Significant at 0.05 level, **Significant at 0.01 level, n=96

Influence of hydro–physical properties on nutrient availability and uptake and crop yield

Application of NPK + FYM enhanced soil physical condition which increased plant nutrient availability. Stepwise regression analysis carried out between soil available nutrient and hydro-physical properties showed that pore space and infiltration rate explained 92.2, 81.7, 86.6, 59.6 and 84.7% of variation in available N, P, K, S and Zn, respectively (Table 6). Soil BD and infiltration rate in both surface and sub–surface layers had 48.2, 53.1 and 10.4% for available Cu, Mn and Fe, respectively. This indicated that the BD, pore space and infiltration rate significantly influenced the plant nutrient availability. Water entering into the soil moves downwards through pores and contributes directly to soil solution. Parts of nutrients present on the exchange complex may be released into the soil, which in turn, increases the concentration of available nutrients in soil solution. Like us, Dong *et al*. (2012) observed substantial increase in SOC, available N, P and K under organic manure and NPK treatments in red soil regions of southern China.

Infiltration rate and available water related 70.5% of variation for maize yield and infiltration rate alone explained 82.0-94.1% of variation in nutrient uptake by maize (Table 7). Infiltration alone related 71.6% of yield and 79.4-91.2% of nutrient uptake by wheat. Out of all hydro-physical properties, infiltration rate significantly related with nutrient uptake in maize and wheat, whereas, maize yield was significantly related with infiltration rate and available water content. The reason for such effect of infiltration rate on yield and nutrient uptake could be that water infiltrated into the soil is the main source to plant growth and nutrients dissolved in soil solution moves to the plant along with water. Other hydraulic properties such as MWD, BD, porosity and soil

Table 6. Multiple regression equation relating plant available nutrient with hydraulic properties

Available nutrient	Regression equation	R^2 value
N	$Y=511.835-191.964X_1$	0.698
	$Y=417.530-169.728 X_1+43.488 X_3$	0.922
P	$Y=--9.052+25.279X_3$	0.574
	$Y=62.177+21.902 X_3-42.271 X_1$	0.817
K	$Y=-653.748-278.162 X_1$	0.651
	$Y=514.64-245.363 X_1+64.091 X_3$	0.866
	$Y=434.747-212.003 X_1+59.299 X_3+ 89.351 X_2$	0.876
S	$Y=-85.281-39.385 X_1$	0.369
	$Y=61.497-33.777 X_1+10.958 X_3$	0.545
	$Y=943.223-365.523 X_1+11.084 X_3- 8.867 X_5$	0.598
Zn	$Y=--0.849+5.095E-2X_2$	0.793
	$Y=-1.014+4815E-2X_5+0.204 X_3$	0.847
Cu	$Y=3.537-1.201X_1$	0.482
Mn	$Y=-35.553-12.461 X_1$	0.473
	$Y=-31.724-11.558 X_1+1.764X_3$	0.531
Fe	$Y=-4.306+0.883X_3$	0.104

X_1–Soil bulk density, X_2– Mean weight diameter, X_3–Infiltration rate, X_4– Soil saturated hydraulic conductivity, X_5–pore space and X_6–Available water content, where n=18, $P<0.05$

Table 7. Multiple regression equation relating nutrient uptake and yield with hydraulic properties

Plant parameters	Regression equation	R^2 value
Maize		
Grain yield	$Y=3.453+7.782X_1$	0.651
	$Y=2.055+6.708 X_1+0.287X_2$	0.705
N uptake	$Y=-8.850+29.385X_1$	0.907
P uptake	$Y=-1.992+5.053 X_1$	0.874
K uptake	$Y=-9.202+22.091 X_1$	0.903
S uptake	$Y=-0.488+2.424 X_1$	0.820
Zn uptake	$Y=1.490+69.746 X_1$	0.824
Fe uptake	$Y=8.206+606.113 X_1$	0.895
Cu uptake	$Y=-3.216+15.703 X_1$	0.933
	$Y=-4.211+14.984 X_1+0.192 X_2$	0.941
Mn uptake	$Y=-22.726+65.982 X_1$	0.941
Wheat		
Grain yield	$Y=4.853+26.443 X_1$	0.716
N uptake	$Y=-30.226+91.502X_1$	0.903
P uptake	$Y=-6.342+15.747X_1$	0.900
K uptake	$Y=-2.046+61.105X_1$	0.912
S uptake	$Y=-1.606+8.745X_1$	0.759
Zn uptake	$Y=-8.427+229.144 X_1$	0.906
Fe uptake	$Y=-285.941+1770.790 X_1$	0.876
Cu uptake	$Y=-0.124+47.790 X_1$	0.821
Mn uptake	$Y=30.691+204.820 X_1$	0.794

X_1–Soil bulk density, X_2– Mean weight diameter, X_3–Infiltration rate, X_4– Soil saturated hydraulic conductivity, X_5–pore space and X_6–Available water content, where n=18, $P<0.05$

permeability characters indirectly influenced the nutrient uptake and yield by affecting the ease of tillage, seed bed quality and root growth (Yang *et al*. 2004; Rasool *et al*. 2008). High BD, low porosity and infiltration rate observed under unbalanced fertilization might have affected entry of water into soil, which in turn reduced water and nutrient uptake by roots (Arvidsson 1999; Rasool *et al*. 2008).

Conclusions

The results of present investigation showed that imbalanced fertilization maintained lower initial oxidizable SOC level and soil physical condition, and showed significantly higher values compared with unfertilized control. However, significant reduction in nutrient uptake and maize and wheat yields were observed with imbalanced fertilization compared to NPK + FYM application. Integrated use of mineral fertilizers along with FYM significantly increased oxidizable SOC and improved soil hydraulic properties compared to unfertilized control and the initial values. This improved hydraulic properties had positive relationships with plant available nutrients, nutrient uptake and yields of both maize and wheat crops. The NPK + FYM addition improved soil hydraulic properties and increased plant nutrient available concentration, nutrient uptake and yields of both maize and wheat under long–term fertilization. Thus, NPK + FYM was the best option for increasing SOC, soil hydro–physical conditions and for enhancing nutrient uptake and crop yield.

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