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Physical and hydraulic properties of aridisols as affected by nutrient and crop-residue management in a cotton-wheat system

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ABSTRACT. A 5-year cotton–wheat rotation field experiment was conducted on two alkaline-calcareous soils to investigate the impact of integrated nutrient-management and crop-residue incorporation on soil physical and hydrological properties. The nutrient treatments were: T1–farmers' fertilizer use; T2–balanced nutrient management (recommended N, P, Zn. and B from mineral sources); T3–integrated nutrient management, same as T2, except that 75% N was applied from fertilizer and 25% as FYM; and T4 same as T2, except that every alternate year, wheat was substituted by *Berseem* green manure. All treatments were compared with and without crop residue incorporation. Soil organic matter (SOM) content in both the soils was significantly increased with T2, T3 and T4 as compared with T1, and was increased further where the nutrient-management treatments were applied in combination with crop-residue recycling. Higher increase in SOM content was observed in soil having relatively lower initial SOM (0.61%) than soil having initial 0.80% SOM content. Increased SOM content, in return, decreased soil bulk density, improved macro- and meso-porosity, and enhanced percent recovery of stable aggregates correspondingly. Infiltration rates were 20, 49 and 26% higher with T2, T3 and T4, respectively, over T1 and 64% higher with crop-residue incorporation over crop-residue removal. Positive impacts on soil physical properties were also observed in the sub-soil layers.

Keywords: cotton-wheat system, crop-residue recycling, integrated nutrient management, bulk density, water stable aggregate, hydraulic conductivity.

As propriedades físicas e hidráulicas de aridisois influenciadas por manejo de nutrientes e resíduos de colheita em sistema rotativo algodão-trigo

RESUMO. Um experimento rotativo algodão-trigo foi conduzido durante cinco anos em dois solos calcários-alcalinos para verificar o impacto de manejo por nutrientes integrados e por incorporação de resíduos de colheita sobre as propriedades físicas e hidrológicas do solo. Os tratamentos de nutrientes foram: T1 – o adubo usado pelos agricultores; T2 – manejo balanceado de nutrientes (recomendação de N, P, Zn e B de fontes minerais); T3 – manejo integrado de nutrientes, semelhante ao T2, exceto 75% de N foram aplicados a partir de adubos e 25% como FYM; T4, semelhante ao T2, exceto que alternadamente o trigo era substituído por adubo verde *Berseem*. Todos os tratamentos foram comparados com e sem a incorporação do resíduo da colheita. O conteúdo da matéria orgânica do solo (MOS) nos dois tipos de solo foi significantemente aumentado em T2, T3 e T4 quando comparado com o de T1. Esse valor aumentou-se ainda mais onde os tratamentos de manejo de nutrientes foram aplicados junto com a reciclagem do resíduo da colheita. Registrou-se maior aumento de MOS em solo com conteúdo de MOS inicialmente menor (0,61%) quando comparado com o solo com conteúdo de MOS inicial com 0,80%. Por outro lado, o aumento de conteúdo de MOS diminuiu a densidade volumosa do solo, melhorou a macro e meso-porosidade e aumentou a recuperação percentual de agregados estável respectivamente. Os valores de infiltração foram 20, 49 e 26% maiores com os tratamentos T2, T3 e T4, respectivamente, quando comparados com T1, e 64% maiores na incorporação de resíduos da colheita em comparação com a remoção dos resíduos da colheita. Houve impactos positivos nas propriedades físicas do solo nas camadas do sub-solo.

Palavras-chave: sistema algodão-trigo, reciclagem de resíduo da colheita, manejo integrado de nutrientes, densidade de volume, agregado estável hidráulico, condutividade hidráulica.

Introduction

Maintenance and improvement of soil productivity are among the most crucial concerns for sustaining agricultural productivity in arid and semiarid regions of the world. In these climates, desertification, overexploitation and low soil organic matter (SOM) are major constraints to soil productivity as they limit the rehabilitative physical, chemical and biological processes. The SOM is considered a key element for restoring these physical, chemical and biological processes for maintaining and enhancing soil productivity. Enhancement of SOM from the presently low levels can lead to soil productivity improvement on a sustainable basis by improving soil's biophysical properties.

Majority of soils, developed from alluvial deposits in South Asia, are low in organic matter and are weakly structured. These are susceptible to degradation as a result of wetting and drying, compaction caused by on-farm traffic and ill-timed tillage operations. The consequences of the degradation of structure include restricted water and air permeability and drainage, lowered total porosity, increased mechanical impedance to root proliferation and poor crop establishment (BLANCO-CANQUI; LAL, 2009).

Soil organic matter accumulation through management practices improves soil structure and resilience of infiltration and water-holding capacity, and reduces soil-temperature extremes and soil-water loss, all of which are necessary for sustainable agricultural systems (BLANCO-CANQUI; LAL, 2009). The amount of SOM accumulation is dependent on the annual addition of organic materials and the rate of decomposition, the latter being the highest in hot climatic regions (DE RIDDER; VAN KEULEN, 1990; ROWELL, 1994). In the cotton-belt of Pakistan, SOM is restored/maintained traditionally by recycling farm-animal waste organic materials. As adequate quantity of farmyard manure (FYM) is not available to farmers, crop-residue recycling constitutes an important management practice to restore SOM. In the cotton–wheat system, a major cropping system (3.07 million ha) in Pakistan, more than 10 million tons of cotton stalks are produced annually; which are totally removed, physically, from the fields and burn as fuel. Similarly, 15 million tons of wheat-straw, produced annually, is either removed from the field for dry silage/fodder usage or is burned in the fields. The physical removal of crop residues from cotton-wheat fields results in export of nutrients and organic matter from the soil system and, in turn, deteriorates the physical quality. Crop-residue burning causes not only a decline in soil quality but also air pollution (HOOKER et al., 1982; SINGH et al., 2005a).

Beneficial effects of SOM include increase cation-exchange capacity, facilitate water infiltration and conductance, enhance soil-water retention, and stabilize soil aggregates and reduce soil erosion. Contrarily, low SOM content adversely affects physical and hydrological properties of the soil. Despite high levels of fertilizer use, poor soil structure and low SOM threaten agricultural production in arid and semi-arid regions. Therefore, regeneration of soil structure and improvement in organic matter is an out-and-out requirement for sustainable soil health and crop productivity.

The study was conducted to investigate the effects of integrated nutrient and crop residue management on SOM content and soil physical and hydraulic properties in irrigated cotton–wheat cropping system practiced on Aridisols.

Material and methods

Site description

The 5-year field experiment was conducted on Aridisol - two predominant soil series, i.e., Shahpur – clay 29 and silt 56% (fine-loamy, mixed, hyperthermic Fluventic Camborthid) at Chah A. Rahim (29º 56´ N; 71º 23´ E) and Awagat – clay 12 and silt 46% (coarse silty, mixed, hyperthermic, Fluventic Camborthid) at Chak 5-Faiz (29º 58´ N; 71º 31´ E) in the Punjab province of Pakistan, where the cotton-wheat system is prevalent.

The Shahpur soil is deep, moderately well-drained, calcareous, weak coarse sub-angular blocky, whereas the Awagat soil is deep, well-drained, calcareous, massive and weak coarse sub-angular blocky. The soils of the experimental area were formed from alluvial deposits derived from the Himalayas, and the sediments range from recent to sub-recent and late Pleistocene (AKRAM et al., 1969).

The area has an arid subtropical continental climate with large seasonal fluctuations in temperature as well as rainfall. The summers are very hot, with a mean monthly maximum air temperature of 43°C and minimum of 6°C (Figure 1). The annual rainfall ranged from 80 to 300 mm year^{-1}. About two-thirds of the total rains were received during the monsoon season, from mid-July to mid-September, as heavy downpours. Prior to the initiation of the experiments, continuous cotton-wheat rotation had been practiced at both the field sites using traditional tillage (cultivation with multi-tine tractor driven cultivator and planking with a long flat piece of lumber) and cultural practices.

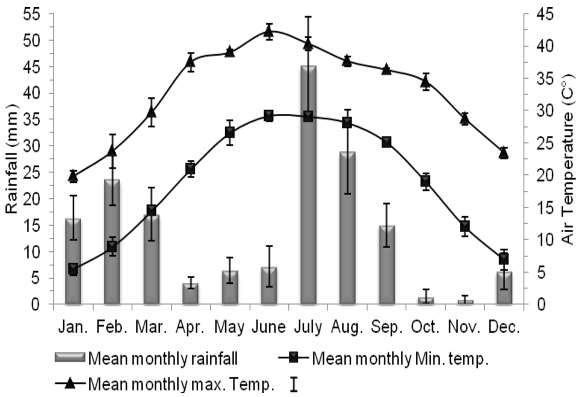

Figure 1. Mean monthly rainfall and air temperature during 2000–2005 at the experimental sites.

Experimental design and treatments

The permanent layout of cotton (*Gossypium hirsutum* L.)–wheat (*Triticum aestivum* L.) system field experiment was started in 2000, with four nutrient-management treatments: T1 – Farmers' fertilizer use (FFU), i.e., 110 kg N ha^{-1} in cotton and 80 kg N + 60 kg P_2O_5 ha^{-1} in wheat; T2 – Balanced nutrient management (BNM), i.e., 170 kg N + 60 kg P_2O_5 + 5 kg Zn + 1 kg B ha^{-1} in cotton and 140 kg N + 100 kg P_2O_5 + 5 kg Zn + 1 kg B ha^{-1} in wheat; T3 – Integrated nutrient management (INM), same as BNM, except that 75% N was applied as fertilizer and 25% N as FYM; T4 – same as BNM, except that wheat was substituted by *Berseem* green manure during years 2 and 4 of the experiment (BNM+GM). All the treatments were replicated four times and imposed with and without incorporation of cotton stalks and wheat-straw into the soil. In crop-residue-recycled plots, cotton stalks (after picking seed cotton) were incorporated into the soil with the help of a rotavator 14-21 days prior to wheat sowing, and wheat straw was incorporated into the soil 14-21 days prior to cotton sowing. In residue-removed plots, all the cotton stalks and wheat straw (harvested at ground level) were removed from the field.

Measurements

During May 2005, after harvesting the fifth wheat crop, soil samples from two depths, 0–15 and 15-30 cm, were taken randomly from all replicated plots. Four intact soil samples, 7.0 cm diameter and 5.0 cm long from each plot,, were taken using a double-cylinder steel core sampler, to measure bulk density and water retention characteristics. Relatively larger four intact samples, i.e., 10 cm diameter and 10 cm long, from each plot, were also collected for measuring saturated hydraulic conductivity. Also, disturbed composite soil samples from both depths were collected to measure aggregation status and organic carbon.

Soil physical and hydraulic properties were measured following the procedures described by Sparks et al. (1996) and Dane and Topp (2002). Organic carbon was determined via the rapid titration method (NELSON; SOMMERS, 1996). Aggregate stability was determined by wet-sieving method and water-stable aggregates were expressed as the sand-corrected weight, as described by Nimmo and Perkings (2002). The undisturbed soil cores were dried in an oven at 105°C for 24h and then weighed to calculate bulk density (GROSSMAN; REINSCH, 2002). Total porosity was calculated as 1-(bulk density/particle density), assuming that particle density = 2.65 mg m^{-3} (MARSHALL et al., 1996). Soil texture was determined using the hydrometer method (GEE; OR, 2002) and saturated hydraulic conductivity (K_s) with a constant-head method (REYNOLDS et al., 2002). Water-retention characteristics were measured using saturated (for 24 hours) undisturbed soil cores, successively at -1, -5, and -10 kPa using a fine-sand tension table with a hanging water column and at -30, -100, -500 and -1500 kPa with a pressure plate apparatus.

Pore-size distribution was calculated from water-retention data estimating equivalent mean pore diameter for a particular soil matric pressure using equation described by Danielson and Sutherland (1986). Unsaturated hydraulic conductivity, in relation to the water content, was calculated from the Campbell (1974) empirical relationship. Infiltration was measured, *in situ*, by double ring infiltrometers of 41– 52 cm inner diameter of rings according to Bertrand (1965).

Statistical Analysis

Analysis of variance of the measured parameters was performed using MSTAT-C and treatment means were compared using Duncan's multiple range test (DMRT) at 5% probability level.

Results and discussion

Soil organic matter

After 5 years of following the cotton-wheat rotation in the Aridisol SOM content in the surface soil (0–15 cm) was significantly increased by BNM, INM and BNM+GM treatments in comparison with the FFU treatment in both Awagat and Shahpur soils (Table 1). Significant increase in

SOM was also observed with crop-residue incorporation compared with crop-residue removal treatment in both depths ($p \leq 0.05$). Zeleke et al. (2004); Singh et al. (2007) also observed increases in organic carbon contents of soils following incorporation of crop residues compared with soils where residues were removed. The percent increases in SOM contents over FFU in Awagat soil were 4.7, 9.4, and 6.3 for the BNM, INM, and BNM+GM treatments, respectively; whereas the corresponding increases at Shahpur soil were 3.6, 7.1 and 3.6. The highest SOM content was recorded with INM, where 25% N was supplied through FYM. The magnitude of increase in SOM with INM over FFU was greater in Awagat soil (9.4%) compared with Shahpur soil (7.1%). Because the initial SOM in Shahpur soil was higher than that of Awagat soil. The observed 9% SOM increase after five continuous incorporations of wheat and cotton residues was rather low considering the 17% SOM increase after continuous incorporation of wheat and cotton residues for three years (GURSOY et al., 2011) and 63% in a three year field experiment under maize-based system (ZELEKE et al., 2004). Low SOM increase in this study could be because of high summer temperatures prevailing in the study area as well as because of the nature of the crop constituents. Thornley and Cannell (2001) reported that high temperature led to accelerated oxidation rates of the added crop residues.

The organic-matter buildup (up to ≈ 0.86%) is straightforward in aridisol (soils exist in study area) having low initial organic matter and afterwards increase is very slow (RAFIQUE et al., 2012). Higher increase in SOM (9%) in Awagat soil with relatively low initial SOM (0.61%) than in Shahpur soil having higher initial SOM content (0.80%) was in good agreement with the observation made by Zeleke et al. (2004). They reported lesser increase in SOM for Humbo site having relatively higher initial SOM than Alaba site having relatively lower initial SOM after continuous incorporation of maize residues for three years in a field experiment. In the 15-30 cm soil layer, SOM contents with FFU, BNM, and BNM+GM treatments were statistically similar and were significantly lower than in the INM treatment where 25% mineral N was substituted by organic N supplied (as FYM) in both the soils. A significant increase in SOM content was observed following incorporation of crop residue than when crop residue was removed. Increases in SOM content in the 15-30 cm layers suggested that a fraction of the added organic manure and crop residues was placed down to the 15-30 cm soil layers during incorporation operations or over the 5-year period of field experimentation.

Bulk density

Crop-residue incorporation across a period of five years significantly lowered bulk density of the surface 0-15 cm soil (Table 2). Bulk density was significantly less for balanced nutrient management treatment than for the farmers' fertilizer use treatment in both the soils. A bulk-density reduction trend was observed with the expected increase in biomass incorporated into the soils, i.e., 1.37, 1.34, 1.31 and 1.31 mg m^{-3} at Awagat and 1.34, 1.30, 1.27 and 1.29 mg m^{-3} bulk density at Shahpur corresponding to FFU, BNM, INM and BNM+GM treatments, respectively. Increasing biomass input to the soil through residue incorporation and enhanced crop growth have been reported to improve soil quality relative to organic carbon and biotic activity (LAL, 1989; KARLEN et al., 1994), and this might be the reason for the significantly lower bulk density following BNM, INM and BNM+GM treatments. This assumption was further substantiated by the strong correlations ($r = 0.87$ and 0.90) observed between bulk density and organic carbon content in Awagat soil and Shahpur soil ($p \leq 0.05$).

Table 1. Effect of nutrient managements and crop residue incorporation on soil organic matter content (%) after 5 years.

Nutrient Treatments	Awagat						Shahpur					
	0-15 cm			15-30 cm			0-15 cm			15-30 cm		
	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean
FFU	0.62[¶]	0.66[¶]	0.64[¶¶]	0.42	0.45	0.44	0.81	0.87	0.84	0.53	0.58	0.56
BNM	0.64	0.69	0.67	0.45	0.49	0.47	0.84	0.90	0.87	0.57	0.61	0.59
INM	0.67	0.72	0.70	0.48	0.54	0.51	0.87	0.92	0.90	0.60	0.66	0.63
BNM+GM	0.66	0.70	0.68	0.44	0.50	0.47	0.84	0.90	0.87	0.58	0.64	0.61
Mean	0.65	0.69	0.67	0.45	0.50		0.84	0.90	0.87		0.57	0.62
LSD ($p \leq 0.05$)												
Treatments			0.02			0.02			0.02			0.02
Interaction			0.03			0.03			0.03			0.03

CRR: crop-residue removed; CRI: crop-residue incorporated; LSD:l least significance difference; ¶: average of four replicates; ¶¶: means of eight values.

Table 2. Effect of nutrient managements and crop residue incorporation on soil bulk density (mg m^{-3}) after 5 years.

Nutrient Treatments	Awagat						Shahpur					
	0-15 cm			15-30 cm			0-15 cm			15-30 cm		
	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean
FFU	1.41¶	1.33¶	1.37¶¶	1.62	1.56	1.59	1.37	1.31	1.34	1.60	1.54	1.57
BNM	1.37	1.31	1.34	1.59	1.54	1.57	1.32	1.28	1.30	1.57	1.55	1.56
INM	1.34	1.28	1.31	1.55	1.50	1.53	1.30	1.25	1.27	1.54	1.49	1.51
BNM+GM	1.33	1.29	1.31	1.56	1.53	1.55	1.31	1.27	1.29	1.56	1.52	1.54
Mean	1.36	1.30		1.58	1.53		1.33	1.28		1.57	1.52	
LSD ($p \leq 0.05$)												
Treatments			0.0			0.02			0.02			0.02
Interaction			0.02			0.02			0.02			0.02

CRR: crop-residue removed; CRI: crop-residue incorporated; LSD: least significance difference; ¶: average of four replicates; ¶¶: means of eight values.

Mostly, the Aridisols with low organic matter under extensive cultivation and extreme climate conditions (high temperature and low rainfall), those exist in the cotton belt of Punjab, Pakistan, are even more susceptible to soil compaction. It is evident from the results reported by Rafique et al. (2012) that the bulk density of surface soil (0–15 cm) varied from 1.25 to 1.66 mg m^{-3} and sub-surface (15–30 cm) from 1.50 to 1.82 mg m^{-3} in the cotton-wheat system.

The compaction increases soil strength and adversely affects the water retention and availability to plant as well as nutrients supply and hence ultimately affects the crop productivity. Similar results have been reported by Zeleke et al. (2004); Ghuman and Sur (2001) in Ethiopia and by Singh et al. (2007) in Punjab, India; the latter observed significant decreases in bulk density after 3-5 years of crop-residue incorporation. The lowest bulk density of 1.25 mg m^{-3} of Shahpur soil and 1.28 mg m^{-3} of Awagat soil was observed following INM treatment in combination with crop-residue incorporation (Table 2). Our results reveal that FFU in combination with crop-residue incorporation had an effect on bulk density improvement (1.33 and 1.31 mg m^{-3} in Awagat and Shahpur soils, respectively) comparable to that of INM treatment alone (1.34 and 1.30 mg m^{-3} in Awagat and Shahpur soils, respectively). Thus, the addition of organic matter, either in form of FYM or crop residue after every crop, may be preferred to improve and sustain the soil physical conditions for optimum crop growth. This was consistent with the earlier reports of bulk density reduction as a result of inorganic fertilizer application and crop-residues incorporation (ZELEKE et al., 2004; BELLAKKI; BADANUR, 1997).

Aggregation

Percent water-stable aggregates (PWSA) in both the soil series were significantly ($p \leq 0.05$) higher with BNM, INM, and BNM+GM treatments than with FFU (Figure 2). The treatment effects on PWSA were larger in the surface soil layers (0-15 cm depth) than in the sub-soils (15-30 cm depth). The large effect on surface PWSA was most probably consequent of large increase in surface SOM that enhanced the microbial activities and help in stable aggregation (ROBERSON et al., 1995) The PWSA increased further with crop-residue incorporation. The order of treatment effects on aggregation improvement was in accordance with that of the SOM content (Table 1) resulting from BNM, INM and crop-residue incorporation practices.

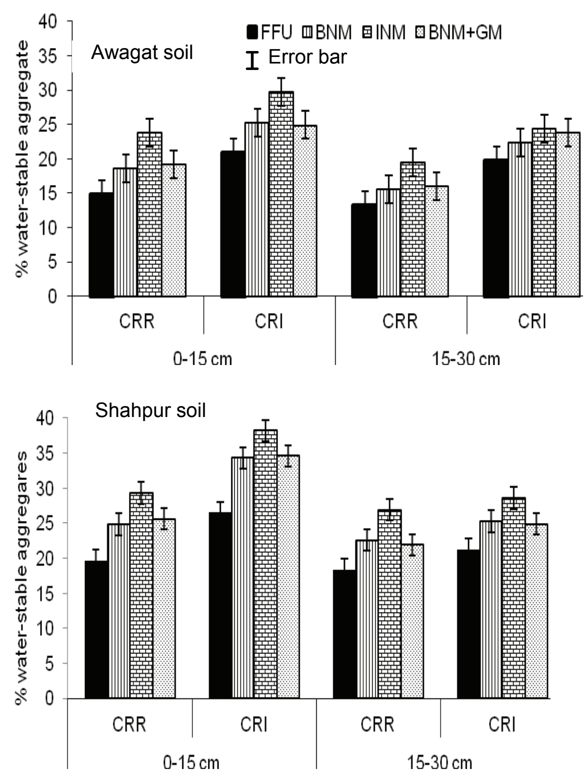

Figure 2. Effect of nutrient managements and crop residue incorporation on water stable aggregates after 5 years. CRR: crop residue removed; CRI: crop residue incorporated.

Different crop residues have different type of impacts on aggregation and aggregate stability. The impact depends upon the decomposition rates, chemical compositions, C:N ratio and quantity of crop residues. For example, residues of cereal and legumes crop are more frequently incorporated than cotton crop to improved SOM and soil structure. But these residues decomposed more rapidly than cotton crop because of lower C:N ratio (legume crop ≈ 23 and cereal crops ≈ 55). Crop residues that decomposed easily (cereal and legume) generate binding substances in the short term and even become even shorter in hot climate prevails in cotton areas of Pakistan. Contrarily, the cotton crop residues have both, short- and long-term impacts on aggregation and aggregate stability. Because its stalks fraction is rich in cellulose and lignin compounds decomposed slowly and provide binding agent over long-term. While, it leave fraction decompose rapidly and provide binding agent for short-term.

Balanced and integrated nutrient applications to crop not only increased the shoot biomass but also increased the root biomass. Crops that produce large amounts of residues result in greater soil aggregation than those with lower biomass production because of differences in decomposition rates. Large quantities of organic materials are supplied to surface and sub-surface soils by the shoot and root system, respectively, during their growth period. Exudates of added organic matter through shoot, roots and FYM resulted in the production of a large amount of active polysaccharide-binding agent in surface and sub-surface soil (DEGENS, 1997; HAYNES et al., 1991). Addition of organic matter to soils also enhances microbial activities and biomass, which would produce extracellular mucilaginous polysaccharide materials having the capacity to stabilize soil aggregates (ROBERSON et al., 1995). Increased aggregate stability in this experiment is consistent with the results of Singh et al. (2005b, 2007) who observed that, in rice-wheat cropping systems, soil aggregate stability was greater with straw incorporation than from where straw was removed. Similar results were also reported by Sarwad et al. (2005) under sorghum-chickpea crop sequence.

Contrary to earlier studies on cereal and legume crop residues incorporation (SINGH et al., 2005a; ZELEKE et al., 2004), significant positive impact on aggregate stability below 10 cm depth was observed. It is most likely that the deeper root system of cotton crop, compared with cereal crops and legumes, may have contributed to sub-surface SOM. Further, the addition of fresh carbon has a larger impact on aggregation of a soil with low organic carbon (e.g. soils under studied) compared with a high carbon content soil. The slow decomposition and long residence time of the cotton roots by-product in the soil may allow the byproduct to make a large and long-term contribution to SOM and hence on aggregation. The contribution of SOM by the cotton crop roots to sub-surface could directly be involved in stability of soil aggregates.

Total porosity and volumes of macro- and micro-pores

Total soil porosity of 0-15 cm depth was significantly higher for BNM, INM and BNM+GM treatments than for FFU treatment in both soil types (Table 3). The total soil porosity was highest with INM treatment in the Shahpur soil, which was statistically higher than with BNM and BNM+GM treatments; BNM and BNM+GM were statistically similar. However, in Awagat soil, INM and BNM+GM treatments were statistically similar but significantly higher than BNM. Further, the increase in total soil porosity after 5-year cotton and wheat crop-residue incorporation was higher in Awagat soil (coarse silty in texture and low in initial SOM) than that of Shahpur (fine loam in texture and high in initial SOM). The results showed that the relatively lighter textured soils with low initial SOM and nearly massive structure were more susceptible to addition of fresh carbon in improving soil structure (aggregation and porosity) than those otherwise.

Table 3. Effect of nutrient managements and crop residue incorporation on total porosity (%) after 5 years.

Nutrient Treatments	Awagat						Shahpur					
	0-15 cm			15-30 cm			0-15 cm			15-30 cm		
	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean
FFU	46.8¶	49.8¶	48.3¶¶	38.9	41.3	40.1	48.4	50.7	49.6	39.8	41.9	40.8
BNM	48.2	50.6	49.4	39.9	41.9	40.9	50.1	51.6	50.8	40.9	41.6	41.3
INM	49.4	51.6	50.5	41.4	43.3	42.4	51.1	53.0	52.0	42.0	43.8	42.9
BNM+GM	49.7	51.2	50.4	41.1	42.3	41.7	50.4	52.2	51.3	41.0	42.6	41.8
Mean	48.5	50.8		40.3	42.2		50.0	51.9		40.9	42.5	
LSD ($p \leq 0.05$)												
Treatments			0.45			0.66			0.66			0.75
Interaction			0.53			0.69			0.65			0.78

CRR: crop-residue removed; CRI: crop-residue incorporated; LSD: least significance difference; ¶: average of four replicates; ¶¶: means of eight values.

Similarly, the increase in volume of the macropores (equivalent diameter > 60 μm) and mesophores (equivalent diameter 60 – 30 μm), described by Luxmoore (1981), determined from the water retention curves of the soils, by crop-residue incorporation was higher in Awagat soil than the Shahpur soil (Figure 3). However, this impact was more intense where the INM treatment was applied in combination with crop-residue incorporation. The results of this study revealed that the volumes of macro- and mesopores (as result of aggregation) depend on crop residue incorporation rather than clay content of the soils, seems to contradict the results of Wagner et al. (2007).

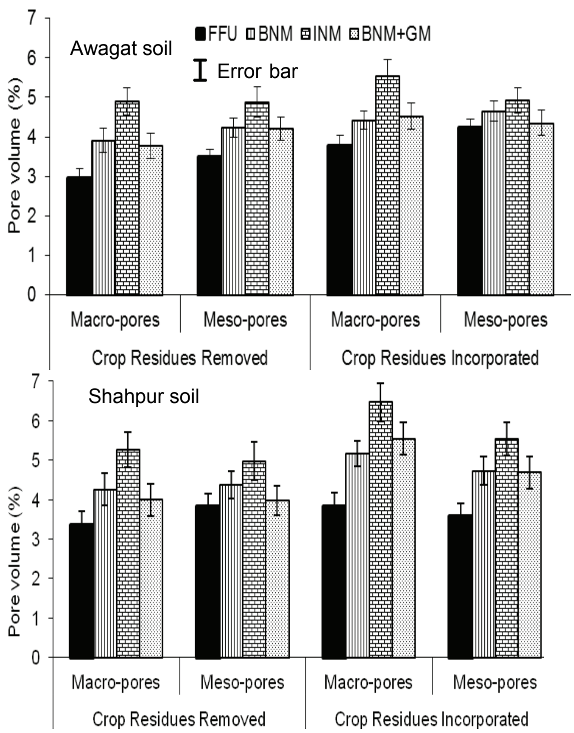

Figure 3. Effect of nutrient managements and crop residue incorporation on volume of macro-pores (equivalent diameter > 60 μm) and meso-pores (equivalent diameter 30-60 μm).

They suggested that macro-aggregation largely depends on soil clay content rather than straw incorporation. According to Tisdall and Oades (1982), inorganic and relatively persistent organic binding agents are important to the development of microaggregates, whereas physical entanglement of the hyphae of microorganisms and roots which are labile or subject to rapid decomposition the major mechanisms in binding microaggregates into macroaggregates. Increases in macro- and mesopores volume which is a useful indicator of soil structure improvement caused by the incorporation of crop residues in both soils, i.e., Awagat and Shahpur, were comparable. Significantly lower bulk density and higher organic matter content because of crop-residue incorporation were in agreement with the higher macro- and mesoporosity. This effect of improved soil structure was more intense where the integrated nutrient management treatment was applied in combination with crop-residue incorporation (BHATTACHARYYA et al., 2007). Further, micropore (equivalent diameter >30 μm) volume was relatively uniform among the different treatments under crop residues incorporated and removed conditions in Awagat soil. While in Shahpur soil, INM treatment showed relatively lower microporosity than those of other nutrient treatments (Figure 4).

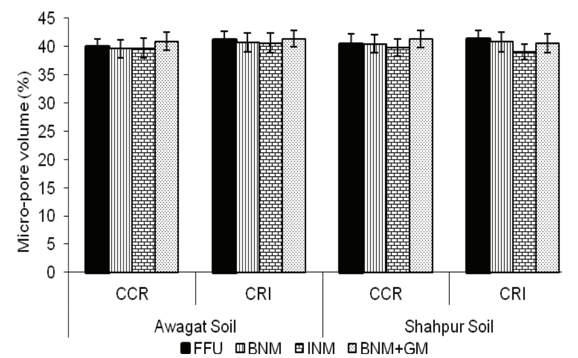

Figure 4. Effect of nutrient managements and crop residue incorporation on volume of micro-pores (equivalent diameter > 30 μm).

Infiltration

Cumulative infiltration as a function of different nutrient management treatments, with and without crop-residue incorporation, is illustrated in Figure 5. Empirical model; $I = at^b$, where a and b are empirical constants, was used to derive relationships between measured cumulative infiltration (I) and time (t) and values of constants as well as final infiltration rates (Table 4). The high r values showed strong relationship between measured and predicted infiltration values.

Beneficial effect of crop-residue incorporation on infiltration was consistent with the greater macro- and meso-porosities (Figure 3) and lesser bulk density (Table 2) in both the soils. However, overall impact of crop-residue incorporation was more pronounced (41% increase over crop residue removal) in the Awagat soil than in the Shahpur soil (38% increases over crop-residue removal).

The BNM, INM and BNM+GM treatments increased infiltration rates by 25, 50, 32%, respectively, over FFU treatment in Awagat soil. Relatively less increase, i.e., 16, 46, 23% in infiltration rates with BNM, INM and BNM+GM treatment over FFU was observed in Shahpur soil. Integrated nutrient management treatment increased infiltration the most: 56% in Awagat soil and 46% in Shahpur soil over FFU treatment when applied without crop-residue incorporation; with crop-residue incorporation, the increase was 50% in Awagat soil and 44% in Shahpur soil. The greater cumulative impact of addition of organic material (FYM, crop residues, green manure) in Awagat soil than in Shahpur soil was probably related to the differences in native organic matter contents and structure development of the both soils (LIU et al., 2005). The values of empirical constant *b* (slope of the cumulative infiltration line) were smaller where nutrient management treatments were applied without crop-residue incorporation than with crop-residue incorporation. Consequently, infiltration rates were lesser without crop-residue incorporation than with crop-residue incorporation.

Hydraulic conductivity

The percent increase in the saturated hydraulic conductivity was of the order of 17, 78, and 24% in the Awagat soil and 15, 69, and 25% in the Shahpur soil with the BNM, INM, and BNM+GM treatments, respectively, over FFU (Table 5). This increase could possibly be because of an increase in macro- and meso-porosity fraction (volume of larger water-conducting pores) of the 0-15 cm depth of the soil (Figure 2). The unsaturated hydraulic conductivity as a function of soil-water content is shown in Figure 6. Calculated results showed no difference between hydraulic conductivities of any of the nutrient-management treatments.

Table 4. Infiltration rate parameters as affected by crop residue incorporation after 5 years.

Nutrient Treatments	Awagat								Shahpur							
	CRR				CRI				CRR				CRI			
	a¶	b†	r!!	FIR‡	A	b	r	FIR	a	b	r	FIR	a	b	r	FIR
FFU	0.42	0.48	0.98	0.61	0.47	0.53	0.99	1.04	0.46	0.50	0.99	0.75	0.53	0.54	0.99	1.22
BNM	0.43	0.51	0.99	0.75	0.47	0.57	0.99	1.32	0.50	0.51	0.98	0.87	0.52	0.57	0.99	1.41
INM	0.44	0.52	0.99	0.95	0.48	0.59	0.99	1.52	0.52	0.55	0.99	1.12	0.50	0.59	0.99	1.76
BNM+GM	0.43	0.51	0.99	0.81	0.47	0.56	0.99	1.36	0.48	0.53	0.99	0.92	0.52	0.57	0.99	1.51

¶: imperial constant (intercept of the fitted equation); b†: imperial constant (slope of the fitted equation); ‡: final infiltration rate after 6 hours (cm h^{-1}); !!: correlation coefficient CRR: crop-residue removed; CRI: crop-residue incorporated.

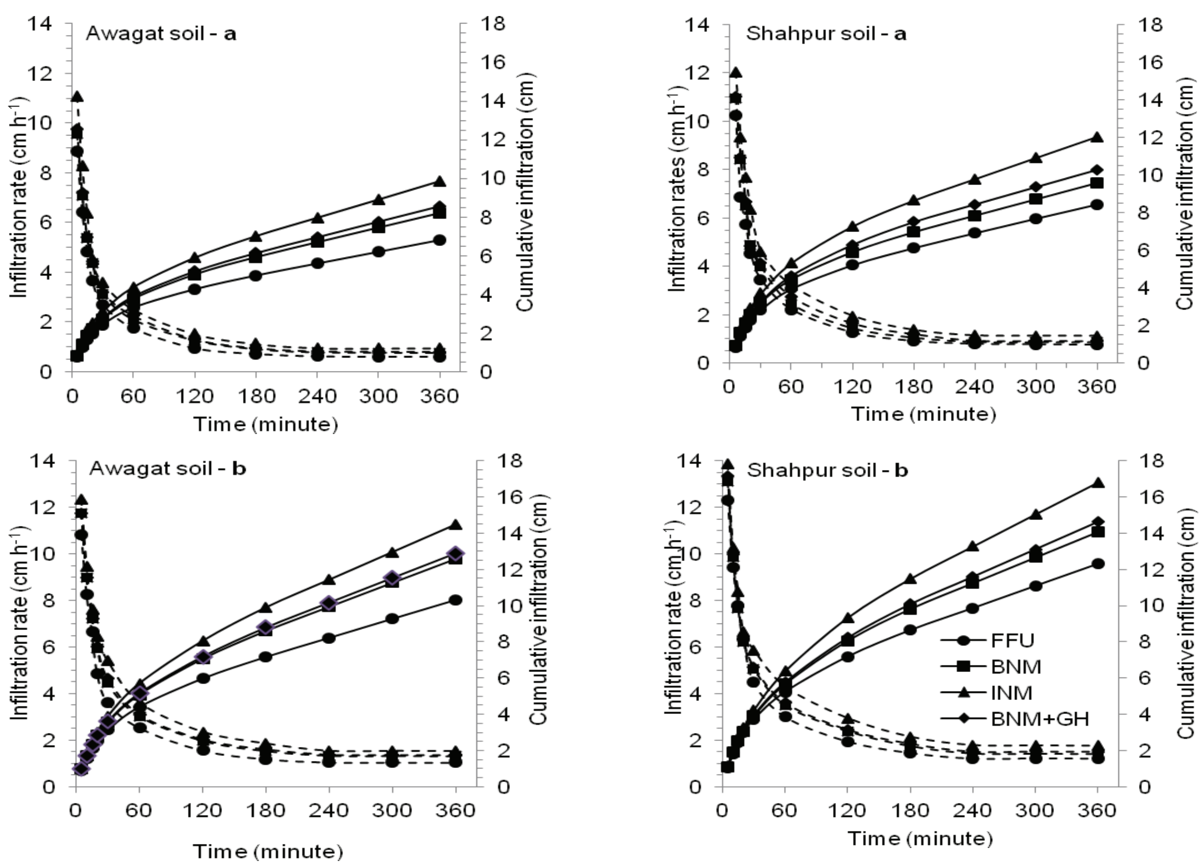

Figure 5. Infiltration and cumulative infiltration as affected by nutrient management treatments after 5 years: (a) crop residue removed and (b) crop residue incorporated.

Table 5. Effect of nutrient managements and crop residue incorporation on saturated hydraulic conductivity (mm day^{-1}) after 5 years.

Nutrient Treatments	Awagat						Shahpur					
	0-15 cm			15-30 cm			0-15 cm			15-30 cm		
	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean	CRR	CRI	Mean
FFU	134	205	170	59	86	72	177	264	221	70	128	99
BNM	149	222	186	67	92	80	193	278	236	82	134	108
INM	174	258	247	75	109	92	220	359	290	103	150	127
BNM+GM	154	231	193	66	97	82	202	289	246	93	140	117
Mean	153	229		67	96		198	298		97	138	
LSD ($p \leq 0.05$)												
Treatments			9.5			6.3			14.0			6.9
Interaction			14.3			7.0			25.6			9.9

CRR: crop-residue removed; CRI: crop-residue incorporated.

However, there was a 7-fold decrease in conductivity, from 140 to 20 mm day^{-1} as volumetric water content decreased from 48 to 42%. This drastic decrease in unsaturated conductivity was presumably because of the emptying of inter-aggregate porosity (macro- and meso-pores) that cannot hold and conduct water at potentials ≥ -10 kPa (BOUMA, 1991; MAHMOOD-UL-HASSAN; GREGORY, 2002). The considerable difference between the unsaturated hydraulic conductivity of crop residues incorporated and removed plots near saturation were very much consistent with the increase in macro- and meso-porosity due to crop residues incorporation (Figure 3). Once the water content of a soil system is exceeded the intra-aggregate (microporosity or matrix porosity), water starts flowing through the inter-aggregate pore network. When the inter-aggregate pore network is started to conduct water, a very small increase in water content can then result in very large increase in unsaturated hydraulic conductivity. Then there was a relatively small change, from 20 to 2 mm d^{-1} over the range of 42 to 35% of water content. At water contents < 35%, the values of hydraulic conductivity were fairly constant. The finding of the experiment revealed that increase in macro- and meso-pores volumes (inter-aggregated pores) enhanced the profile water storage capacity; firstly by increasing infiltration, and secondly by increasing water retention due to increased SOM. The unsaturated hydraulic conductivity was higher where crop residues were incorporated than where crop residues were removed at given water content near saturation (means saturation values for crop residues incorporated plots was 51 and 49% for crop residues removed plots). However, at lower water content, the similar conductivity of crop residue-incorporated and removed plots was in line with the almost similar micro-porosity, i.e., 44.3 and 45.5%, respectively.

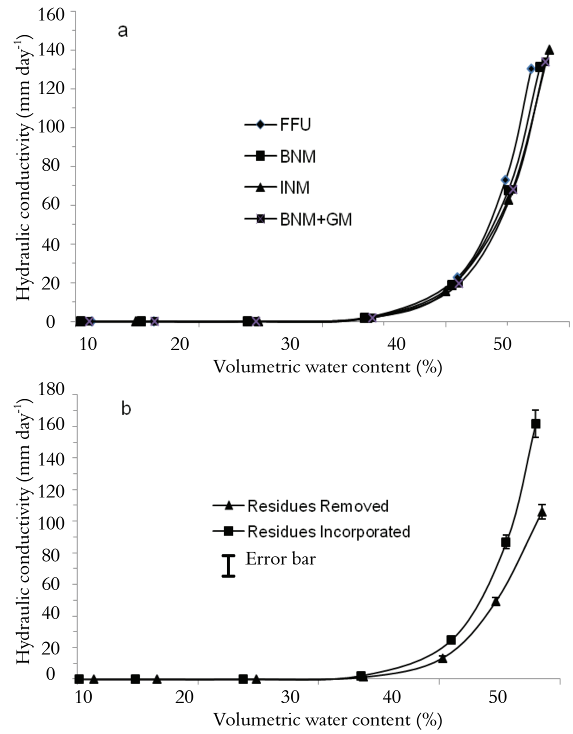

Figure 6. Unsaturated hydraulic conductivity as a function of water content as affected by (a) nutrient managementtreatments and (b) crop residue incorporation (means of two sites).

Conclusion

Results of this five-year field experiment on two predominant soils under cotton-wheat cropping system demonstrated that incorporation of cotton and wheat residue enhanced soil organic matter content and helped generate soil structure and improve soil physical and hydraulic properties in an arid subtropical continental climate. Based on these beneficial impacts, it is suggested that indiscriminate crop residue removal need to be discouraged. Further, its removal can be detrimental to future soil productivity and environmental quality. Alternatively, integrated nutrient management and crop-residue incorporation could help in averting organic matter decline, nutrient depletion, soil structure deterioration, and loss of biodiversity. As a consequence, it could help in improving and sustaining soil productivity. The beneficiaries would include: firstly farmers (by way of increased/sustained soil health and crop productivity); secondly the nation (by reducing environmental pollution caused by burning of crop residues); and thirdly the future generations (as a consequence of sustaining the precious non-renewable soil resource).

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