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Effect of organic inputs on strength and stability of soil aggregates under rice-wheat rotation

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A b s t r a c t. The study aims to elucidate the impact of organic inputs on strength and structural stability of aggregates in a sandy loam soil. Tensile strength, friability and water stability of aggregates, and the carbon contents in bulk soil and in large macro (>2 mm), small macro (0.25-2 mm), micro (0.053-0.25 mm) and silt+clay size (<0.053) aggregates were evaluated in soils from a long-term experiment with rice-wheat rotation at Modipuram, India, with different sources and amounts of organic C inputs as partial substitution of N fertilizer. Addition of organic substrates significantly improved soil organic C contents, but the type and source of inputs had different impacts. Tensile strength of aggregates decreased and friability increased through organic inputs, with a maximum effect under green gram residue (rice)-farmyard manure (wheat) substitution. Higher macroaggregates in the crop residue- and farmyard manure-treated soils resulted in a higher aggregate mean weight diameter, which also had higher soil organic C contents. The bulk soil organic C had a strong relation with the mean weight diameter of aggregates, but the soil organic C content in all aggregate fractions was not necessarily effective for aggregate stability. The soil organic C content in large macroaggregates (2-8 mm) had a significant positive effect on aggregate stability, although a reverse effect was observed for aggregates <0.25 mm. Partial substitution of nitrogen by organic substrates improved aggregate properties and the soil organic C content in bulk soil and aggregate fractions, although the relative effect varied with the source and amount of the organic inputs.

K e y w o r d s: tensile strength, friability, aggregates, soil organic C, rice-wheat rotation mean weight diameter

INTRODUCTION

Sustainability of the rice-wheat system in the indo-gangetic plains (IGP) is crucial for meeting country food demand, and is also at the centre of global food security (Ladha *et al*., 2003a). This sustainability is arguably at stake, partly due to the staggering productivity, and partly due to degradation of soil quality (Ladha *et al*., 2003b). Continuous use of imbalanced fertilizers under intensive rice-wheat cultivation over the years had negative impacts on soil structure, organic carbon and nutrient supplying capacity of the soils (Bhandari *et al*., 2002; Regmi *et al*., 2002). Addition of organic inputs as a partial substitution of N has been one of viable options in restoring the soil quality and subsequently sustaining the system productivity.

As the soil is collectively made of aggregates, the study at the single structural unit or aggregate has been useful to evaluate the soil response to management (Blanco-Canqui *et al*., 2005). Since the rice-wheat system involves two contrasting edaphic environments, the role of soil aggregation is of special importance. The mechanical properties of aggregates are clearly indicative of soil structural condition determining soil functions for plant growth. Tensile strength (*TS*), a fundamental property of aggregates, is a measure of the resistance of the aggregate against breaking forces (Watts and Dexter, 1998), and thus, is highly sensitive to soil management (Blanco-Canqui *et al*., 2005). High *TS* of aggregates helps in proper maintenance of soil tilth and provides a stable traction for farm implements, but limits intra-aggregate root growth (Król *et al*., 2013; Turski, 2002). The friability of the soil, on the other hand, is the tendency of a body of soil to break into smaller pieces under an applied stress or load (Watts and Dexter, 1998). This might be another important physical property of agricultural soils, since the condition of friability is desirable for better tillage

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and sowing of plants (Dexter and Watts, 2001; Watts and Dexter, 1998). However, data on *TS* and friability under various combinations of organic and inorganic inputs and their interrelationships with management-induced changes in SOC are scanty (Blanco-Canqui *et al.*, 2005) and none under the intensive rice-wheat system.

Water stability of aggregates is the indicator of soil resistance against disintegration (Mohanty *et al.*, 2012), while the size of aggregates indicates the influence of management on soil structural stability. Organic binding agents are mostly responsible for development and stability of macro-aggregates (>0.25 mm), implying the role of organic matter in aggregate stability. The SOC content decreases with intensive cultivation, which corresponds to a decrease in aggregate stability by changing its structure (Król *et al.*, 2013).

A long-term (>18 years) experiment on integrated nutrient management practices on a sandy loam soil under intensive rice (*cv*. PR 106) – wheat (*cv*. PBW 343) rotation was selected for the study with the following objectives:

– to investigate the impact of the source and amount of organic inputs under rice-wheat rotation on SOC; and
– to evaluate the strength and stability of aggregates as an indicator of soil structural improvement *vis-a-vis* accumulation of C in soil. This experiment has three most frequently used strategies of increasing SOC, *ie* through FYM, incorporation of green manure, and addition of crop residues.

MATERIALS AND METHODS

The climate of the study area (29°40 N latitude, 77°46 E longitude; 237 m a.s.l.) is semi-arid and subtropical, characterized by hot summers and cold winters. The hottest months are May-June (maximum temperatures 45-46°C), whereas December-January are the coldest months (minimum temperatures may go < 5°C). The average annual rainfall is 862.7 mm (75-80% is received through southwest monsoons during July to September). The soil is sandy loam with 55, 18, and 27% sand, silt, and clay, respectively, Typic Ustochrept; non-saline (EC 0.42 dS m^{-1}) but mild alkaline in reaction (pH 7.98). The soil (0-15 cm depth) initially had 4.1 g kg^{-1} of SOC and 16.4, 96, and 14.5 kg ha^{-1} of available P, K, and S, respectively. The experiment has been continuing since 1993 with 11 treatments involving chemical fertilizers alone or in combination with different organic sources *viz.* farmyard manure (FYM), sulphitation pressmud (SPM), green gram residue (GR), and cereal (rice and wheat) residues (CR), and an unfertilized-control in a randomized block design with 4 replications. In the present investigation, 8 treatments were selected *viz.*:

I – recommended NPK (120, 26, and 33 kg ha^{-1} N as urea, P as diammonium phosphate (single super phosphate in treatment with S), and K as murate of potash, respectively) in both rice and wheat with 5 kg ha^{-1} Zn through $ZnSO_4$ to rice;

II – recommended NPK + S (45 kg ha^{-1}) in both rice and wheat with Zn to rice as in I;

III – 75% of recommended N (75% through fertilizers +25% through FYM), P and K in rice and 100% recommended N, P, and K through fertilizers in wheat;

IV – the same as in III except SPM is used as substitution to FYM in rice;

V – 75% N and a full dose of P and K through fertilizers + green gram residues in rice incorporated after pod picking, while 100% NPK are applied in wheat;

VI – the same as V in rice, while in wheat, 25% fertilizer N is substituted by FYM;

VII – 75% fertilizer N and a full dose of P and K + 25% N substituted by crop residues (wheat residue in rice and rice residue in wheat); and

VIII – control (no fertilizer). The N, P_2O_5, and K_2O in FYM, rice straw, wheat straw, SPM, and green gram residue were 0.5, 0.25, 0.3; 0.5, 0.23, 1.14; 0.5, 0.25, 1.21; 0.45, 0.33, 0.5; and 0.72, 0.18, 0.53%, respectively. The size of each plot is 8 x 8 m.

One-third of N and entire P, K, S, and Zn were applied at the time of transplanting/sowing and remaining N was top-dressed in 2 equal splits at maximum tillering and panicle/ear emergence. The FYM and SPM were incorporated in the soil one week while CR was incorporated 15-20 days before transplanting/sowing of the crops. In the treatments involving GR, summer green gram was sown immediately after wheat harvest, and after pod picking, the above ground biomass was incorporated by dry tillage before puddling. Both crops were grown under assured irrigated conditions with recommended agronomic practices.

Soil samples were collected from 0-7.5, 7.5-15, and 15-30 cm layers in 2011 in triplicate after the harvest of wheat crop. Individual aggregates (5-8 mm, 12 aggregates per replication) were placed between two round plates of an apparatus and the force (*P*) needed to crush the aggregate was recorded. The strength of the aggregates (*TS*) was computed using the following equation (Dexter and Watts, 2001), where d_{agg} is the mean aggregate diameter (mm):

$$TS = 0.576\left(\frac{P}{d_{agg}^2}\right). \quad (1)$$

The friability (*F*) of the soil (Watts and Dexter, 1998) was estimated from the coefficient of variation of the measured tensile strength values for each treatment:

$$F = \frac{\sigma_Y}{\bar{Y}}, \quad (2)$$

where: σ_Y is the standard deviation and $\bar{Y}$ the mean of the measured values of *TS* of aggregates for each treatment.

Air-dried aggregates (<8 mm) were separated through wet-sieving (Cambardella and Elliott, 1992). During wet-sieving, a 50 g sample was quickly submerged in water for 5 min and the sieves were moved up and down 3 cm with 30 cycles per minute for 2 min. Large (>2 mm) and small (0.25-2 mm) macroaggregates, microaggregates (0.053-0.25 mm), and 'silt+clay' sized aggregate fractions (<0.053 mm) were separated through a series of 2, 0.25, and 0.053 mm sieves. The mean weight diameter (*MWD*) of the aggregates was computed as:

$$MWD = \sum x_i w_i , \quad (3)$$

where: w_i is the proportion of each aggregate class i in relation to the weight of the soil sample taken for analysis, and x_i is the mean diameter of the class (mm).

Soil organic C (SOC) was measured using an automatic elemental analyser systeme (Vario EL, GmbH, Hanau, Germany). The cumulative biomass C inputs into the soils were calculated by multiplying the total biomass amount of stubble, straw, roots, and rhizodeposition (rhizodeposition biomass was computed as 15.0 for rice and 12.6% for wheat of the total aboveground biomass harvested at maturity, Bronson *et al.*, 1998) by their respective C concentration. The additional organic C addition through SPM, FYM, green manure, and crop residue was also included. All the data were analysed using statistical analysis system software (SAS, 2006) at a 5% level of significance.

RESULTS AND DISCUSSION

There was a strong linear relationship between the additions of organic matter over the years and the subsequent SOC built up in the plough layer (0-15 cm) (Fig. 1). The aboveground biomass varied between 7.8 and 24.6 Mg ha^{-1} year^{-1} (Table 1) while root biomass ranged between 0.5-2.7 Mg ha^{-1} year^{-1}. The cumulative rhizodeposition values were estimated between 1.1 (control) and 3.4 (NPK+Zn+S) Mg ha^{-1} year^{-1}. The estimated C in the left-over biomass (excluding the control) had a little variation (2.1-3.0 Mg ha^{-1} year^{-1}) and therefore, addition of organic sources for partial substitution of N contributed mostly to build-up of SOC. Thus, treatments

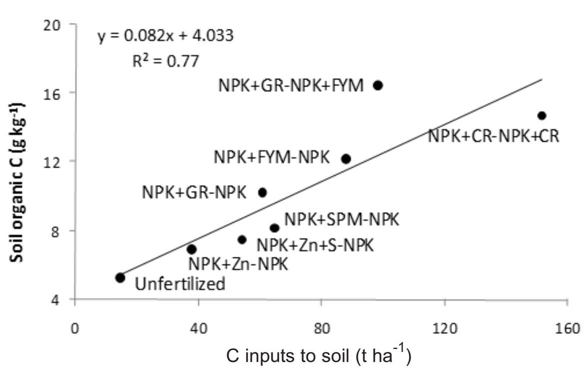

Fig. 1. Effect of the source and amount of organic inputs on the soil organic carbon content in the 0-15 cm layer of a sandy loam soil under the rice-wheat rotation.

with only inorganic sources of N increased the SOC by 32-44% over the unfertilized treatment, while there was a nearly 200% increase through addition of green manure in rice + FYM in wheat, or crop residues in both. The impact of the SOC build-up varied broadly with the source of organic substrates; a 60% increase in SOC was achieved through SPM, but nearly 130% was obtained through FYM. Additional C addition over the years in the form of crop residues and FYM was reported to increase the SOC content (Hati *et al.*, 2008). Similar results on higher SOC due to application of chemical fertilizers combined with manure (Rudrappa *et al.*, 2006), paddy straw (Verma and Bhagat, 1992), and green manure (Yadav *et al.*, 2000) were also reported from long-term experiments in India and elsewhere (Liu *et al.*, 2003; Schjonning *et al.*, 1994).

As compared to the initial SOC, there has been a substantial increase in all the treatments, but both the amount and the source of organic substrates significantly ($p<0.05$) affected the SOC. The amount of C added in the treatment with FYM in rice was 91.5 Mg ha^{-1} and the equivalent SOC in soil was 12 g kg^{-1} of soil (Fig. 1). A larger amount of C in soil was achieved through green manuring in rice, although the C input through green manuring was much lower (63.9 Mg ha^{-1}). Similarly, SPM referred to a greater amount of addition of C (68.9 Mg ha^{-1}) compared to NPK+Zn+S and FYM addition in rice, while the resultant SOC (8.2 g kg^{-1}) was close to NPK+Zn+S (7.5 g kg^{-1}) and less than FYM (10.2 g kg^{-1}). Addition of green manure in rice followed by FYM in wheat resulted in greater SOC content (16.4 g kg^{-1}) than either green manuring or FYM addition in rice. Straw incorporation in both rice and wheat crops indicated a large amount of organic matter (154.4 Mg C ha^{-1}) addition to soil, which was higher than any other treatment. However, the corresponding SOC content was lower (14.7 g kg^{-1}).

Tensile strength of aggregates had a logarithmic relation with soil organic C (Fig. 2). Aggregate strength decreases with increase in SOC, initially at a faster rate and then gradually. The tensile strength was the highest in the unfertilized plots. Due to the low amount of SOC, the air-dry aggregates from the unfertilized plots had increased internal friction between the particles upon drying (Schjonning *et al.*, 1994), and a large amount of readily dispersible clay was available for internal crust formation, cementation of particles and aggregates (Elmholt *et al.*, 2008). The impact of the treatments was mostly similar across the depths. The tensile strength of aggregates was the lowest in the plots with the addition of either rice-wheat or green gram crop residue. The decrease in the strength of air-dry aggregates with the increase in organic inputs agrees with other studies (Arthur *et al.*, 2012; Schjonning *et al.*, 2007), but differs from a few (Bartoli *et al.,* 1992). Organic matter helps in particle orientation to form aggregates and also reduces the amount of non-complexed clay for cementation upon drying of the aggregates (Schjonning *et al.*, 2012). Our data suggest

T a b l e 1. Cumulative (1993-2011) biomass and components of organic inputs added to soil under different treatments

Treatments	Stubble biomass		Root biomass		Rhizodeposition		Total biomass		External organic source inputs		Total C inputs
	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	
	(Mg ha^{-1})										
Unfertilized or Control	2.1	0.9	5.4	4.1	12.6	7.2	20.1	12.2	0	0	15.8
NPK+Zn	5.2	3.0	12.2	16.4	25.7	21.5	43.1	40.9	0	0	40.5
NPK+Zn+S	7.6	4.3	21.0	26.2	34.5	26.8	63.1	57.3	0	0	57.8
NPK+FYM	6.5	3.8	18.7	23.4	32.3	24.5	57.5	51.7	90.0	0	91.5
NPK+SPM	7.3	4.4	21.4	26.7	34.5	26.7	63.2	57.8	45.0	0	68.9
NPK+GR	6.1	3.7	18.8	22.3	31.0	23.8	55.9	49.8	36.0	0	63.9
NPK+GR+FYM	6.1	3.8	18.1	23.2	28.8	23.4	53.0	50.4	36.0	90.0	101.8
NPK+CR	5.5	3.3	16.4	20.5	27.3	21.0	49.3	44.8	117.0	99.0	154.4

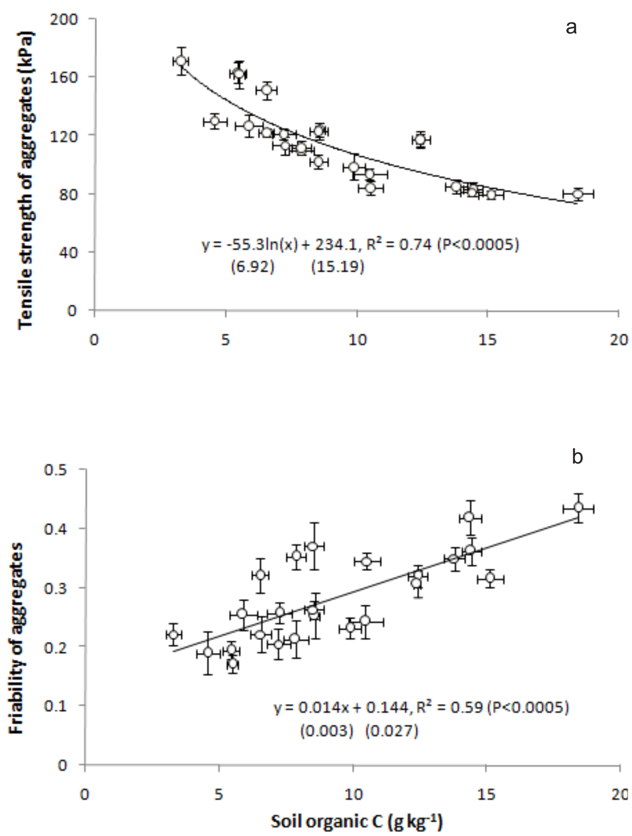

Fig. 2. Relations between: a – tensile strength and b – friability of aggregates and soil organic carbon (SEE at 5% associated with the coefficients are given in parentheses). SEE stands for standard error of estimates. It is a measure of prediction accuracy and is calculated as the difference between actual and predicted values.

that tensile strength is further reduced with the addition of organic resources in both the rice and wheat crops. Whether it is a combination of FYM (in wheat) and green manuring (in rice) or left-over biomass of the crops, soils with higher organic matter had effectively lower strength of aggregates and, thus, were likely to offer lesser resistance to mechanical disturbance. This makes seedbed preparation easier with lesser energy inputs (Munkholm and Schjonning, 2004). Nevertheless, the logarithmic relation implies that incremental addition of organic inputs may not equally affect the tensile strength; the kind of organic matter addition does have a greater role to play. We could obtain variation in aggregate tensile strengths with different SOC levels, but could not identify aggregate-associated C fractions responsible for the effect. A larger dataset with wider SOC variations would help in elucidating which fraction of C might be responsible. Friability of soil aggregates increases with addition of organic inputs and has a strong linear relation with C content in soil (Fig. 2). Greater friability is always associated with a higher C content, allowing the soil to withstand stress by breaking into smaller fragments, a desirable characteristic (soil crumbling) for fine seedbed preparation.

Stability of aggregates is expressed by the mean weight diameter of the size range, which is proportional to the amount of larger water stable aggregates. Increased amounts of large (>2 mm) macroaggregate fractions in NPK + GR (rice) + FYM (wheat) and NPK + CR (rice and wheat) are associated with the very large *MWD* in these treatments. Similar trends are observed in other organic treatments, with a large amount of small macroaggregate fractions, along with large macroaggregates. A higher amount of silt- and clay-sized fractions was observed in the control (43.84%).

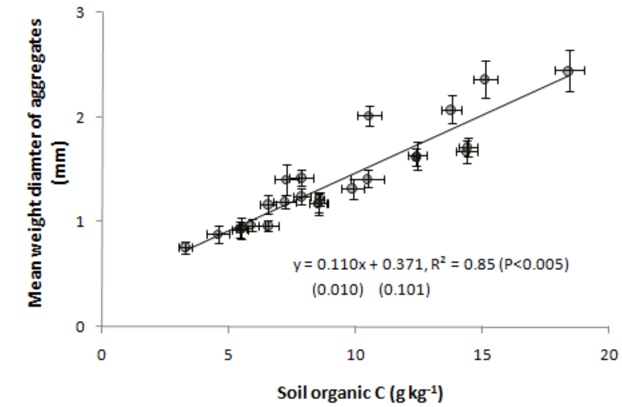

Fig. 3. Mean weight diameter of aggregates as related to the soil organic carbon content (data in parentheses indicate SEE at 5%).

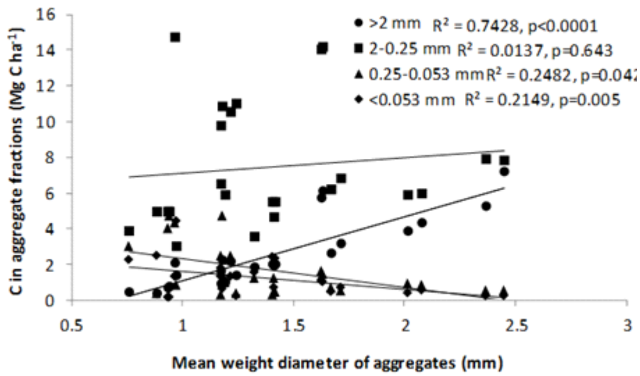

Fig. 4. Relationship between the mean weight diameter and C content in major fractions of aggregates < 8 mm.

The higher percentage of water-stable aggregates (WSA > 0.25 mm) under organic amendments was a result of the higher organic matter accumulation in the soils. Soil organic matter (SOM) is a well-known soil-binding agent that improves soil structure (Igwe *et al.*, 2001). All these resulted in increasing the *MWD* in soil receiving organic amendments than the mineral-fertilizers alone, which is therefore strongly correlated with organic C built up in soil (Fig. 3). The strong linearity between the *MWD* and SOC indicates that long-term application of organic amendments can impart a significantly higher stability to the aggregates and thus, highly improves the soil structure (Abrishamkesh *et al.*, 2011). Positive effects of manure and straw application on the *MWD* have been reported in a number of other studies (Singh *et al.*, 2007). However, the variation of the *MWD* among the treatments could be attributed to their biochemical composition of organic substrates. A lower C/N ratio and polyphenol content of green manure are susceptible to rapid decomposition and yield lower values of the *MWD* as compared to FYM and paddy straw with a greater C/N ratio and lignopolyphenol contents, as reported by Majumder *et al.* (2008). The strong linearity between SOC in bulk soil and the *MWD* of aggregates is not necessarily the same for the C content in aggregate fractions (Fig. 4).

The C content in large (<2 mm) macroaggregates is likely to be the most effective in imparting higher stability to aggregates ($p<0.0001$), compared to the C content in other size fractions. Even the C content in smaller (0.25-2 mm) macroaggregates is not significantly related to the *MWD*. It is also observed that the C content in microaggregates and in silt + clay sized aggregates has relatively weak but significant ($p = 0.005$ and 0.042) negative relations with the *MWD*, and hence, aggregate stability.

CONCLUSIONS

1. Long-term application of a fertilizer in conjunction with organic manures induced a significant increase in the organic carbon status of the soil. This was clearly reflected by aggregate properties and stability.

2. However, the relative effect varies with the source (kind) and amount of organic matter. Green manuring in rice followed by farmyard manure addition (25% N substitution) in wheat emerges as the best option in intensive rice-wheat rotation.

3. Addition of crop residue may also be a viable option, since it is always available and disposal elsewhere or burning *in situ* will be avoided.

REFERENCES

Abrishamkesh S., Gorji M., and Asadi H., 2011. Long-term effects of land use on soil aggregate stability. Int. Agrophys., 25, 103-108.

Arthur E., Schjonning P., Moldrup P., and de Jonge L.W., 2012. Soil resistance and resilience to mechanical stresses for three differently managed sandy loam soils. Geoderma, 173-174, 50-60.

Bartoli F., Burtin G., and Guerif J., 1992. Influence of organic matter on aggregation in Oxisols rich in gibbsite or in goethite. II. Clay dispersion, aggregate strength and water stability. Geoderma, 54, 259-274.

Bhandari A.L., Ladha J.K., Pathak H., Padre A.T., Dawe D., and Gupta R.K., 2002. Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Sci. Soc. Am. J., 66, 162-170.

Blanco-Canqui H., Lal R., Owens L.B., Post W.M., and Izaurralde R.C., 2005. Mechanical properties and soil organic carbon of soil aggregates in the northern Appalachians. Soil Sci. Soc. Am. J., 69, 1472-1481.

Bronson K.F., Cassman K.G., Wassmann R., Olk D.C., Noordwijk M., and van Garrity D.P., 1998. Soil carbon dynamics in different cropping systems in principal eco-regions of Asia. In: Management of Carbon Sequestration in Soil. (Eds R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart). CRC Press, Boca Raton, FL, USA.

Cambardella C.A. and Elliott E.T., 1992. Particulate organic matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J., 56, 777-783.

Dexter A.R. and Watts C.W., 2001. Tensile strength and friability. In: Soil and Environmental Analysis. Physical Methods (Eds K.A. Smith, C.E. Mullins). Dekker Press, New York, USA.

Elmholt P., Schjonning P., Munkholm L.J., and Debosz K., 2008. Soil management effects on aggregate stability Geoderma, 144, 455-467.

Hati K.M., Swarup A., Mishra B., Manna M.C., Wanjari R.H., Mandal K.G., and Misra A.K., 2008. Impact of long-term application of fertilizer, manure and lime under intensive cropping on physical properties and organic carbon content of an Alfisol. Geoderma, 148, 173-179.

Igwe C.A., 2001. Effects of land use on some structural properties of an Ultisol in south-eastern Nigeria. Int. Agrophysics, 15, 237-241.

Król A., Lipiec J., Turski M., and Kuś J., 2013. Effects of organic and conventional management on physical properties of soil aggregates. Int. Agrophys., 27, 15-21.

Ladha J.K., Dawe D., Pathak H., Padre A.T., Yadav R.L., and Singh B., 2003a. How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crop. Res., 81, 159-180.

Ladha J.K., Hill J.E., Duxbury J.M., Gupta R.K., and Buresh R.J., 2003b. Improving the productivity and sustainability of rice-wheat systems: Issues Impacts. ASA, Special Publication, 65, Madison, WI, USA.

Liu X.B., Han X.Z., Herbert S.J., and Xing B., 2003. Dynamics of soil organic carbon under different agricultural management systems in the black soil of China. Commun. Soil Sci. Plan., 34, 973-984.

Majumder B., Mandal B., Bandyopadhyay P.K., Gangopadhyay A., Mani P.K., Kundu A.L., and Mazumdar D., 2008. Organic amendments influence soil organic carbon pools and rice-wheat productivity. Soil Sci. Soc. Am. J., 72, 775-785.

Mohanty M., Sinha N.K., Hati K.M., Painuli D.K., and Chaudhary R.S., 2012. Stability of soil aggregates under different vegetation covers in a vertisol of central India. J. Agric. Physics., 12, 133-142.

Munkholm L.J. and Schjonning P., 2004. Structural vulnerability of a sandy loam exposed to intensive tillage and traffic in wet conditions. Soil Till. Res., 79, 79-85.

Regmi A.P., Ladha J.K., Pathak H., Pasuquin E., Bueno C., Dawe D., Hobbs P.R., Joshy D., Maskey S.L., and Pandey S.P., 2002. Yieldand soil fertility trends in a 20-year rice-rice-wheat experiment inNepal. Soil Sci. Soc. Am. J., 66, 857-867.

Rudrappa L., Purakayastha T.J., Singh D., and Bhadrarary S., 2006. Long-term manuring and fertilization effects on soil organic carbon pools in a Typic Haplustept of semiarid sub-tropical India. Soil Till. Res., 88, 180-192.

Schjonning P., Christensen B.T., and Carstensen B., 1994. Physical and chemical properties of a sandy loam soil receiving animal manure, mineral fertilizer or no fertilizer for 90 years. Eur. J. Soil Sci., 45, 257-268.

Schjonning P., de Jonge L.W., Munkholm L.J., Moldrup P., Christensen B.T., and Olesen J.E., 2012. Clay dispersibility and soil friability-testing the soil clay-to-carbon saturation concept. Vazose Zone J., 11, doi:10.2136/vzj2011.0067.

Schjonning P., Munkholm L.J., Elmholt S., and Olsen J.E., 2007. Organic matter and soil tilth in arable farming: Management makes a difference within within 5-6 years. Agr. Ecosyst. Environ., 122, 157-172.

Singh G., Jalota S.K., and Singh Y., 2007. Manuring and residue management effects on physical properties of a soil under the rice-wheat system in Punjab, India. Soil Till. Res., 94, 229-238.

Turski M., 2002. Influence of the physical properties of soil aggregates for the growth of wheat plant in initial development phase (in Polish). Acta Agrophysica, 78, 263-269.

Verma T.S. and Bhagat R.M., 1992. Impact of rice straw management practices on yield, nitrogen uptake and soil properties in a wheat-rice rotation in northern India. Fert. Res., 33, 97-106.

Watts C.W. and Dexter A.R., 1998. Soil friability: Theory, measurement and the effects of management practices and organic carbon content. Eur. J. Soil Sci., 49, 73-84.

Yadav R.L., Dwivedi B.S., Prasad K., Tomar O.K., Shurpali N.J., and Panday P.S., 2000. Yield trends, and changes in soil organic-C and available NPK in a long-term rice-wheat system under integrated use of manures and fertilizers. Field Crop. Res., 68, 219-246.