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

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Abstract. 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 macropores (>2 mm), small macro (0.25-2 mm), micro (0.053-0.25 mm) and silt+clay size (<0.053 mm) 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 on 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.

Key words: 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 (Kröl 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
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, i.e. 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 muriate of potash, respectively) in both rice and wheat with 5 kg ha⁻¹ Zn through ZnSO₄ to rice;
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:

\[
MWD = \sum x_i w_i ,
\]

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 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

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**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.
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 Schjønning, 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%).

**Table 1.** Cumulative (1993-2011) biomass and components of organic inputs added to soil under different treatments

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

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.
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


