Effect of integrated use of farmyard manure and chemical fertilizers on soil physical properties and productivity of soybean


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The effect of sole application of inorganic fertilizers (NPK) (N:P:K:: 30:26:25 kg ha⁻¹) and combined application of farmyard manure (FYM) @ 4 Mg ha⁻¹ and inorganic fertilizers (NPK + FYM) vis-à-vis non-application of fertilizers and manures (control) on changes in soil physical properties and plant growth characteristics of soybean (cv. JS 335) was studied in a deep Vertisol at the Indian Institute of Soil Science, Bhopal during the year 2001–2004. The results indicated that conjunctive use of recommended dose of fertilizer and farmyard manure (NPK + FYM) resulted in significant (P < 0.05) decrease of bulk density (9.3%), soil penetration resistance (42.6%) and increase in hydraulic conductivity (95.8%) and mean weight diameter of the water stable aggregates (13.8%) and soil organic carbon content (45.2%) compared to control. Among the aggregates, in macro-aggregate fraction (250–500 μm and 500–1000 μm size fraction) and in large macro-aggregate fraction (>2000 μm) maximum soil organic carbon concentration was recorded under NPK + FYM. The root mass of soybean was mostly (98%) confined to 15 cm soil depth. Combined application of NPK and FYM recorded significantly higher (P < 0.05) root length density and root mass density of soybean in the 0–15 cm soil layer at flowering stage over NPK (28 and 65%) and control (63 and 175%). The root length density of soybean was significantly negatively correlated with the root mass density of soybean in the 0–15 cm soil layer at flowering stage over NPK (28 and 65%) and control (63 and 175%). The root length density of soybean was significantly negatively correlated with the root mass density of soybean in the 0–15 cm soil layer at flowering stage over NPK (28 and 65%) and control (63 and 175%). The root length density of soybean was significantly negatively correlated with the root mass density of soybean in the 0–15 cm soil layer at flowering stage over NPK (28 and 65%) and control (63 and 175%).

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1. Introduction

Soybean (Glycine max (L) Merr.), a leguminous oil seed crop, is predominantly grown in the Vertisols of Central India as a rainfed crop (Damodaran and Hegde, 1999). It occupies the third place among the oil seeds in India covering about 6.0 million ha with grain production of about 6.0 million tonnes (Singh et al., 1999). However, the productivity of soybean is low (<1 t ha⁻¹) in this region due to erratic distribution of monsoonal rains, imbalanced use of major and minor nutrients, continuously growing of soybean in the same piece of land and low organic carbon status of soil. The low organic carbon content of soil was mainly attributed to harsh climate and low use or non-use of organics by the farmers of this region. Results from different studies revealed that continuous application of farmyard manure and green manure improved the soil organic carbon under different soils and cropping systems (Nambiar, 1994; Swarup, 1998; Kundu et al., 2002). Therefore any nutrient management practice that can improve organic matter status of soil helps in sustaining crop productivity at higher level.

Vertisol, which constitutes about 21.4% of the total geographical area of the country, contributes about 12.5% of the total soil organic carbon stock of India (NBSS and LUP, 1988). The main soil related production constraints in Vertisols is attributed to its poor physical properties including formation of wide and deep cracks, high bulk density, low hydraulic conductivity and narrow range of moisture for field operation. The low content of soil organic carbon in Vertisols is one of the major reasons for the deterioration of soil health resulting in low and unsustainable productivity of soybean in this soil. Organic matter affects crop growth and yield directly by supplying nutrients and indirectly by modifying soil physical
properties such as stability of aggregates and porosity that can improve the root environment and stimulate plant growth (Darwish et al., 1995). Incorporation of organic matter either in the form of crop residues or farmyard manures has been shown to improve soil structure and water retention capacity (Bhagat and Verma, 1991); increase infiltration rate (Acharya et al., 1988) and decrease bulk density (Khaleel et al., 1981). Aoyama et al. (1999a) concluded that manure application contributed to accumulation of macro-aggregate protected carbon and nitrogen.

However, neither inorganic fertilizers nor organic manures alone can sustain productivity (Prasad, 1996). So judicious uses of organic manures and inorganic fertilizers are essential to safeguard soil health and augment productivity and input use efficiency. The positive effect of integrated use of farmyard manure and inorganic fertilizers on productivity of soybean has been reported by many workers (Singh et al., 1999; Hati et al., 2000; Mandal et al., 2000; Bandyopadhyay et al., 2003; Hati et al., 2006; Ghosh et al., 2006; Bhattacharyya et al., 2008).

Plant growth criteria reflect the net movement of many resources in and out of the plant and its various organs. Each resource may be invested differently and provide different insights into the plant’s adaptive mechanisms and physiological balance (Abrahamson and Caswell, 1982). Ritchie et al. (1994) suggested that soybean growth and development can be measured by the amount of dry matter accumulated and partitioned in different plant organs. Biomass accumulation and growth patterns of soybean have been analysed by several workers (Egli, 1993; Mandal et al., 2000; El-Darier et al., 2002; Pospisil et al., 2006) with respect to varieties, spacing and nitrogen and water management regimes.

Though the effect of manures and fertilizers on crop growth and the soil properties has been studied separately, there is very meagre information on a holistic study on the effect of integrated use of chemical fertilizers and farmyard manure on crop growth and soil properties. It is hypothesized that improvement in the physical properties of soil due to manure application also influences the crop growth characteristics like root growth characteristics, leaf area index, biomass production and partitioning, which ultimately influence the productivity and input use efficiency of soybean.

In this backdrop, the objective of the present investigation was to study the effect of inorganic fertilizers alone or in combination with farmyard manure on changes in soil physical properties, viz., bulk density, hydraulic conductivity, soil penetration resistance, soil aggregation and aggregate associated carbon and soil water dynamics and on the crop growth parameters, viz., root and shoot growth, leaf area index, biomass partitioning, yield and water and nitrogen use efficiency of soybean under soybean–wheat system in a Vertisol of Central India.

2. Materials and methods

2.1. Soil and climate

The field experiment was carried out at the Indian Institute of Soil Science, Bhopal, Madhya Pradesh (23°18’N longitude, 77°24’E latitude and 485 m above mean sea level) during the rainy season of four consecutive years from 2001 to 2004. The region has a hot sub-humid climate with 1200 mm mean annual rainfall and 1400 mm mean annual evapo-transpiration. About 80% of the rainfall is received in the rainy season comprising of 4 months, i.e. June–September. The rainfall patterns for the 4 years during the crop growth season have been depicted in Table 1. The soil of the experimental site is a deep Vertisol (Isohyperthermic typic Haplustert) with clay texture (52% clay), bulk density of 1.34 Mg m⁻³ at 0.27 g g⁻¹ soil water content, neutral to alkaline in reaction (pH = 7.5), 4.4 g kg⁻¹ organic carbon, 0.3 ds m⁻¹ electrical conductivity and 46 c mol (p)⁻¹ kg⁻¹ cation exchange capacity in the Ap horizon. The soil is low in available N (alkaline KMNO₄ oxidizable-N as per Subbiah and Asija, 1956) (145 kg ha⁻¹) and P (0.5 M NaHCO₃ extractable P as per Olsen et al., 1954) (10.7 kg ha⁻¹) but high in available K (1 M ammonium acetate extractable K as per Knudsen et al., 1982) (325 kg ha⁻¹). The soil moisture retention of the surface soil (0–15 cm) was 0.39 cm³ cm⁻³ and 0.25 cm³ cm⁻³ at 0.033 MPa and 1.5 MPa suction, respectively.

2.2. Crop culture

The experiment was laid out in a randomised block design with four replications with the size of each plot being 6 m x 6 m. Soybean (cv. JS 335) was grown in a fixed site under soybean–wheat rotation in rainfed condition during the rainy season (June–September) of 2001 and 2004. The crop was sown at the seed rate of 100 kg ha⁻¹ using a tractor drawn seed-drill with a row spacing of 30 cm in the 2nd week of June to maintain a plant population of 0.4 million ha⁻¹ and harvested in the 4th week of October. The nutrient management practices consisted of T₁: no fertilizer or manure (control), T₂: recommended dose of fertilizer (N:P:K = 30:26:25 kg ha⁻¹) (NPK) and T₃: recommended dose of fertilizer plus farmyard manure (FYM) @ 4 Mg ha⁻¹ (NPK + FYM). The entire dose of NPK and FYM was applied as basal at the beginning of growing season every year as per the treatment. The recommended dose of fertilizers for soybean for the Central India has been decided as per the package of practice suggested by the Jawaharlal Nehru Krishi Vidyashala, Jabalpur, India (Gupta and Rajput, 2001). The farmyard manure was prepared mainly from cow dung and wheat straw, which is normally used as a bedding material in cowshed. The FYM had 9.6% C, 0.48% N, 0.17% P and 0.38% K. The FYM was applied on dry weight basis. Two preparatory tillage operations by duck foot till cultivator were applied for preparation of seed bed and mixing of manures and fertilizers in all the treatments. After soybean harvest wheat was grown with different levels of irrigation. Since the residual effect of wheat was not significant of soybean yield, it has not been presented in this paper.

2.3. Biomass partitioning and leaf area index estimation

During crop growth, plant samples were collected from 1 m row length. These samples were separated into different plant parts, i.e. leaf, stem, root, pod, etc. Then these samples were dried in oven at 65 °C till constant weight and the dry weight was recorded. Plant

Table 1: Weather parameters during soybean growth period in the years 2001–2004.

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall (mm)</th>
<th>Maximum temperature (°C)</th>
<th>Minimum temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>231.1</td>
<td>101.2</td>
<td>223.9</td>
</tr>
<tr>
<td>July</td>
<td>309.8</td>
<td>50.5</td>
<td>372.0</td>
</tr>
<tr>
<td>August</td>
<td>166.2</td>
<td>420.0</td>
<td>224.2</td>
</tr>
<tr>
<td>September</td>
<td>7.4</td>
<td>135.7</td>
<td>237.3</td>
</tr>
<tr>
<td>October</td>
<td>52.2</td>
<td>1.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>
growth stages of soybean were determined using the stage description as outlined by Fehr et al. (1971). The leaf lets of the trifoliate leaves from each plant were removed at different growth stages, wiped free from dust and the leaf area was measured by leaf area meter (CID Inc.). After measuring the leaf area, these leaf samples were dried in oven at 65 °C till constant weight and the dry weight was recorded. Then using specific leaf area method, the leaf area index was calculated as given in Eqs. (1) and (2):

\[
\text{Specific leaf area} = \frac{\text{leaf area (m}^2\text{)}}{\text{leaf dry weight (g)}}
\]

(1)

\[
\text{Leaf area index (LAI)} = \frac{\text{specific leaf area (m}^2\text{)/g}}{\times \text{bulk leaf weight/area (g/m}^2\text{)}}
\]

(2)

Leaf area duration (LAD) was computed using Eq. (3):

\[
\text{Leaf area duration (LAD)} = \sum \frac{[\text{LAI}_{n-1} + \text{LAI}_n]}{2} (t_n - t_{n-1})
\]

(3)

where \(\text{LAI}_n = \text{LAI at sampling time } t_n\) and \(\text{LAI}_{n-1} = \text{LAI at sampling time } t_{n-1}\).

2.4. Root studies

Root samples were collected at flowering stage of soybean in the crop rows using root sampling cores (6 cm height, 8.6 cm diameter) at 7.5 cm depth increments up to a depth of 30 cm. The shoot of the plant was cut close to the soil and the root sampling core was inserted in such a manner that the shoot was at the centre of the core. These cores were immersed in water with 30 ml of 10% sodium hexametaphosphate solution for a period of 24 h to disperse the soil. Then the roots were separated from the soil using a root washer. After staining the roots with methyl violet solution, the root length was determined with the help of Delta T Scanner and image analysis system (Delta T Devices Ltd., Burwell, Cambridge, England). Then these root samples were dried in oven at 65 °C until constant weight and the dry weight was recorded. The root length and mass were divided by core volume to estimate root length density (RLD) and root mass density (RMD), respectively.

2.5. N uptake and N use efficiency

The net plot (5 m x 5 m) was harvested manually by cutting the plants close to ground after leaving the border rows. Then threshing of soybean was carried out in an electrically operated threshing machine. After the harvest of the crop, plant samples were collected and analysed for total N by kjeldhal method (AOAC, 1970). Then using the biomass data, the N uptake by the crop was determined. The agronomic nitrogen use efficiency (ANUE) was estimated using Eq. (4):

\[
\text{ANUE} = \frac{(\text{grain yield in treatment, kg/ha}) - (\text{grain yield in control, kg/ha})}{\text{N applied, kg/ha}}
\]

(4)

2.6. Soil water dynamics and water use efficiency

Soil moisture content of the profile (0–90 cm) was determined gravimetrically at 15 days interval during the crop growth period to study the distribution and redistribution of soil water in the profile.
aggregate retained in each sieve using the following formula (Eq. (7)):

$$\text{MWD (mm)} = \sum_{i}^{n} x_i \times w_i$$ (7)

where \(x_i\) is mean diameter of the sieve (mm) and \(w_i\) is the proportion of the weight of soil retained in each sieve.

Soil organic carbon in each size class was determined by Walkely and Black rapid titration method (Nelson and Sommers, 1975). Sand free total carbon concentration was calculated using the following formula (Eq. (8)):

$$\text{Sand free C}_{\text{fraction}} = \frac{C_{\text{fraction}}}{1 - \text{sand}_{\text{fraction}}}$$ (8)

where \(C_{\text{fraction}}\) is the carbon concentration (g kg\(^{-1}\)) in different aggregate size and \(\text{sand}_{\text{fraction}}\) is the fraction of sand in that aggregate size.

### 2.8. Statistical analysis

The data for the crop and soil properties were analysed by analysis of variance as outlined by Gomez and Gomez (1984). The significance of the treatment effect was determined using F-test, and to determine the significance of the difference between the means of the two treatments, least significant differences (LSD) at 5% probability level and Duncan's multiple range test were used. Correlations and regressions were determined using the data analysis tool pack of MS Excel (2003).

### 3. Results and discussion

#### 3.1. Soil organic carbon

It was observed that integrated use of NPK and FYM significantly improved the soil organic carbon content by 29.8 and 45.2% compared to NPK and control treatment, respectively (Table 2). However, there was no significant difference between the soil organic carbon content of control and NPK treatment. Addition of organic matter through FYM and higher crop growth and biomass addition due to leaf shedding and root biomass addition under NPK + FYM might have contributed to higher soil organic carbon content (Acharya et al., 1988; Benbi et al., 1998; Hati et al., 2006). Based on 25 years of continuous cropping in long term fertilizer experiments, Swarup (1998) also concluded that integrated use of NPK and FYM in soybean–wheat system, significantly improved soil organic carbon content in a Haplustalf and Chromustert. Similarly Aoyama et al. (1999a) reported that after 18 years, manure increased the organic matter level of whole soil and favoured formation of slaking-resistant macro-aggregates (250–1000 µm). This effect was primarily a result of the organic matter added by manure whereas NPK fertilizer did not affect soil organic matter or macro-aggregates.

#### 3.2. Soil physical properties

##### 3.2.1. Water stable aggregates and mean weight diameter

It was observed that there was improvement in the percentage of water stable aggregates (>250 µm) due to integrated use of recommended dose of NPK and farmyard manure (FYM). However, the effect was not statistically significant (Table 2). This finding is in agreement with Acharya et al. (1988) and Benbi et al. (1998). However, there was no significant difference in the percentage of water stable aggregates due to control and NPK treatment. This is because soil organic matter has long been recognized as playing an important role in the formation of water stable aggregates as binding agent of soil particles (Tisdall and Oades, 1982). The mean weight diameter of the water stable aggregates also increased significantly due to integrated use of NPK and FYM (Table 2). The mean weight diameter and the water stable aggregate percentage were significantly positively correlated with the soil organic carbon content of soil \((r = 0.897^{* *})\). This finding is in agreement with Bhagat and Verma (1991), Six et al. (2002) and Biswas et al. (2009). The relationship between the soil organic carbon (SOC) and the percentage of water stable aggregation (WSA) showed that about 80.6% variation in the water stable aggregation can be explained by soil organic carbon as evident from Eq. (9):

$$\text{SOC} = 2.7969 \text{WSA} + 56.422, \quad R^2 = 0.806^{* *}$$ (9)

This finding is in agreement with the hypothesis that soil organic carbon is the major contributor to soil aggregate stabilization (Tisdall and Oades, 1980).

##### 3.2.2. Bulk density

The bulk density under integrated use of NPK and FYM was 5.6% lower than NPK and 9.3% lower than control treatment after 4th year crop cycle (Table 2). Schjønning et al. (1994) also reported reduction in the bulk density of soil due to application of cattle manure in a long term integrated nutrient management experiment. The decrease in the bulk density might be due to higher soil organic carbon content of soil (Tiraks et al., 1974), better aggregation and increased root growth and biopores in the fertilizer and manure treated plots. The bulk density (BD) of 0–15 cm soil layer was significantly negatively correlated with the soil organic carbon (SOC) of this layer \((r = -0.98^{* *})\) as evident from Eq. (10):

$$\text{SOC} = -0.0701 \text{BD} + 1.7838, \quad R^2 = 0.966^{* *}$$ (10)

##### 3.2.3. Saturated hydraulic conductivity

The saturated hydraulic conductivity under integrated use of NPK and FYM was 21.4% higher than sole use of NPK and 95.8% higher than the control treatment (Table 2). The increase in the hydraulic conductivity under integrated use of NPK and FYM was mainly attributed to decrease in the bulk density and increase in the effective pore volume (Flowers and Lal, 1998) because of better aggregation in this treatment. Similar findings have been reported by Bellakki et al. (1998) and Hati et al. (2006). The hydraulic

### Table 2

Percentage of water stable aggregates, mean weight diameter of water stable aggregates, bulk density, hydraulic conductivity and soil organic carbon of surface soil (0–15 cm) under different nutrient management practices.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Water stable aggregates (%)</th>
<th>Mean weight diameter (mm)</th>
<th>Bulk density (Mg m(^{-3}))</th>
<th>Hydraulic conductivity (m s(^{-1}))</th>
<th>Soil organic carbon (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>69.28</td>
<td>0.68</td>
<td>1.50</td>
<td>1.65 \times 10^{-4}</td>
<td>4.2</td>
</tr>
<tr>
<td>NPK</td>
<td>68.06</td>
<td>0.74</td>
<td>1.44</td>
<td>2.66 \times 10^{-4}</td>
<td>4.7</td>
</tr>
<tr>
<td>NPK + FYM</td>
<td>73.88</td>
<td>0.77</td>
<td>1.36</td>
<td>3.23 \times 10^{-4}</td>
<td>6.1</td>
</tr>
<tr>
<td>LSD</td>
<td>NS</td>
<td>0.05*</td>
<td>0.07*</td>
<td>1.14 \times 10^{-4}</td>
<td>0.7</td>
</tr>
</tbody>
</table>

NS = not significantly different; NPK = recommended dose of N, P and K fertilizers; FYM = farmyard manure; LSD = least significant difference. * Significant at \(P < 0.05\).
organic matter increased the stability of macro-aggregates through the binding of the soil mineral particles by polysaccharides. However, the percentage of micro-aggregates (<250 µm) was maximum in NPK treatment (18.6%) followed by control (17.0%) and the minimum value was recorded in NPK + FYM treatment (16.8%). So, there is a negative correlation between the proportion of micro-aggregates and macro-aggregates. This finding supports the hypothesis that the factors that tend to increase the proportion of macro-aggregates by binding micro-aggregates reduce the proportion of micro-aggregates (Tisdall and Oades, 1980; Biswas et al., 2009).

The mineral associated fraction and micro-aggregate fraction were not significantly influenced by different nutrient management practices whereas, the small and large macro-aggregate fractions were significantly influenced by nutrient management practices (Fig. 2). In the 250–500 µm size fraction, the maximum aggregate mass was observed under control treatment, whereas, in the 500–1000 µm and 1000–2000 µm size fraction, NPK + FYM registered the maximum aggregate mass. However, in large macro-aggregate size fraction (>2000 µm), maximum aggregate mass was recorded under NPK treatment (Fig. 2).

3.3. Distribution of soil organic carbon in different aggregates

Among the aggregates, the concentration of soil organic carbon decreased with the decrease in the size of the aggregates (Fig. 3). This finding is in agreement with that of Mikha and Rice (2004) and Biswas et al. (2009). Puget et al. (1995) also suggested that greater

\[ \text{SOC} = 0.0007HC - 0.0012, \quad R^2 = 0.829^{**} \]  

(11)

3.2.4. Soil penetration resistance

The penetration resistance of the soil profile measured at the flowering stage of soybean during the 4th year of cropping (2004) increased with depth in all the treatments because of higher intrinsic bulk density of soil at deeper soil layer (Unger and Jones, 1998). Up to 28 cm soil depth, the penetration resistance in the NPK + FYM treatment was significantly lower than that of the control whereas at 7 and 10.5 cm soil depth they were significantly lower than that under NPK treatment (Fig. 1). This lower penetration resistance in NPK + FYM treatment may be attributed to lower bulk density recorded in this treatment. This finding is in agreement with that of Zhang (1994) and Hati et al. (2006).

3.2.5. Aggregate size distribution

It was observed that irrespective of the treatments, the maximum concentration of water stable aggregates was observed in the 250–1000 µm size fraction (Fig. 2). This finding is in agreement with Six et al. (2000) and Mikha and Rice (2004). The relative distribution of particle size fraction shows that, in general, less than 1% of soil mass was present in the mineral associated fraction (<53 µm), 12–14% in micro-aggregate fraction (53–250 µm), 42–53% in small macro-aggregate fraction, (250–2000 µm) and 5–7% in large macro-aggregate fraction (>2000 µm). Sand particles constituted 18–29% of the bulk soil mass and about 6–11% of soil mass could not be accounted in different size fractions. In control (22%) and NPK (16%) treatments, soil macro aggregate mass was found in 250–500 µm size fraction whereas in NPK + FYM treatment the maximum aggregate mass was found in 500–1000 µm size fraction (18%). The percentage of water stable macro-aggregates (>250 µm) was maximum in NPK + FYM treatment (73.6%) followed by control (69.3%) and NPK (68.1%) treatment. This finding supports the hypothesis that annual addition of manure favoured the formation of macro-aggregates (Sun et al., 1995). Oades (1984) reported that organic matter increased the stability of macro-aggregates through the binding of the soil mineral particles by polysaccharides. However, the percentage of micro-aggregates (<250 µm) was maximum in NPK treatment (18.6%) followed by control (17.0%) and the minimum value was recorded in NPK + FYM treatment (16.8%). So, there is a negative correlation between the proportion of micro-aggregates and macro-aggregates. This finding supports the hypothesis that the factors that tend to increase the proportion of macro-aggregates by binding micro-aggregates reduce the proportion of micro-aggregates (Tisdall and Oades, 1980; Biswas et al., 2009).

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carbon content in macro-aggregates could be due to higher decomposable soil organic carbon associated with these aggregates. In general, <1% soil organic carbon was present in the mineral associated fraction, 7–12% was present in micro-aggregates, 41–53% was present in macro-aggregates, 5–9% was present in large aggregates and about 29–47% of the soil organic carbon could not be accounted in different nutrient management practices. In control (23%) and NPK (17%) treatment, the maximum soil organic carbon accumulation was found in 250–500 μm size fraction whereas in NPK + FYM treatment, maximum soil organic carbon was accumulated in 500–1000 μm size fraction (15%). Aoyama et al. (1999b) observed a threefold increase in protected C and fourfold increases in protected N following manure application in aggregates of 250–1000 μm sizes.

In the mineral associated fraction (<53 μm), nutrient management did not influence the soil organic carbon concentration (Fig. 3). However, in the micro-aggregate fraction, in 53–125 μm size class, relatively higher soil organic carbon concentration was recorded under control treatment. In small macro-aggregate fraction (250–2000 μm), NPK + FYM and NPK recorded significantly higher soil organic carbon concentration than control. In 250–500 μm and 500–1000 μm size fraction, maximum soil organic carbon concentration was recorded under NPK + FYM whereas, in 1000–2000 μm size fraction maximum soil organic carbon concentration was recorded under NPK. In large macro-aggregate fraction (>2000 μm) also, higher soil organic carbon concentration was recorded under NPK + FYM. This finding is in agreement with Bhatnagar and Miller (1985), Mbagwu and Piccolo (1990) and Aoyama et al. (1999b), who observed that organic carbon addition through manure led to higher concentration of total carbon in dry sieved macro-aggregates than in micro-aggregates.

3.4. Soil water dynamics

The peaks in the soil moisture storage in the profile (0–90 cm) coincide with the rainfall pattern during that particular year (Fig. 4). It is noteworthy that during the period of dry spell in the years 2002 and 2004, the moisture storage of the profile (0–90 cm) has gone below 15 bar suction in certain occasions but the crop could survive. This is a typical characteristic of Vertisol, where substantial amount of water was released even beyond 15 bar suction, the classical static lower limit of suction for plant available water, which is utilized by rainfed crops (Kauraw, 1982).

It was observed that conjunctive use of NPK + FYM resulted in relatively lower soil moisture storage in the profile than NPK and control (Fig. 4). Crops under NPK + FYM extracted more water from the soil profile than that under NPK and control. This was attributed to the higher evapo-transpiration under NPK + FYM because of better crop growth in the presence of FYM in this treatment (Hati et al., 2000). The positive effect of integrated use of NPK and FYM on evapo-transpiration was attributed to the stimulation of above ground biomass because of the availability of higher amount of nutrients in this treatment and improvement.

Fig. 4. Temporal variation in the soil moisture storage in the profile (0–90 cm) during soybean growth in the years 2001–2004; NPK = recommended dose of N, P and K fertilizer; FYM = farmyard manure at 4 Mg ha⁻¹; the error bars indicate least significant difference at P < 0.05.
in root proliferation due to improved physical properties, leading to more interception of incoming solar radiation. This resulted in higher transpiration demand while at the same time more soil water was made available through root proliferation (Corbeels et al., 1998). The differences in the soil moisture storage due to nutrient management were more evident during the period of dry spell (Bandyopadhyay et al., 2003).

3.5. Root growth

It was observed that most of the root mass of soybean was present in the 15 cm soil depth. There was decline in the root length density (RLD) (Fig. 5a) and root mass density (RMD) (Fig. 5b) of soybean with depth. However, the rate of decline in RMD with depth was more than that of RLD, which indicated that the finer roots of soybean were mostly present in the deeper layers. The percentage of total RLD within 0–15 cm soil depth was 86.7, 85.3 and 85.5% in control, NPK and NPK + FYM treatments, respectively. However, the percentage of total RMD within the 0–15 cm soil depth was 98.6, 97.4 and 97.9% in control, NPK and NPK + FYM treatments, respectively. The length to mass ratio of soybean roots increased with depth. Pooled over all the treatments, the average length to mass ratio of soybean roots were 1161 cm g⁻¹, 1396 cm g⁻¹ and 12,226 cm g⁻¹ in 0–7.5 cm, 7.5–15 cm and 15–22.5 cm and 22.5–30 cm soil depths, respectively.

Figure 5. (a) Root length density and (b) root mass density of soybean as influenced by nutrient management practices (pooled over 2002–2004); bars with same letters are not significantly different at P < 0.05 as per Duncan’s Multiple Range Test; NPK = recommended dose of N, P and K fertilizer; FYM = farmyard manure at 4 Mg ha⁻¹.

This finding is in agreement with that of Hati et al. (2006). The RLD and RMD at 0–30 cm soil depth could account for 40.1 and 81.8% variations in grain yield of soybean (Y), respectively as evident from Eqs. (13) and (14), respectively:

\[ Y = 145.39 \text{RLD} + 655.02, \quad R^2 = 0.401 \]  \tag{13}

\[ Y = 242.723 \text{RMD} + 578.29, \quad R^2 = 0.818^* \]  \tag{14}

3.6. Leaf area index

The leaf area index (LAI) of soybean increased till 50–60 days after sowing and then it declined (Fig. 6). The sharp fall in LAI during the later part of crop growth was due to senescence of older leaves. The peak value of leaf area index coincided with flowering stage. This finding is in agreement with Beaver et al. (1985), who observed that the LAI of soybean could reach a maximum of 4.0 at the end of flowering under optimum growth condition. Integrated use of NPK and FYM resulted in higher (P < 0.05) RLD and RMD of soybean up to 30 cm soil depth than NPK and control treatments. This may be attributed to better nutrient supply and creation of better physical environment by way of lowering of bulk density and penetration resistance in the presence of manures. The RLD of soybean was significantly negatively correlated with the soil penetration resistance. The soil penetration resistance (CPR) could account for 97% variation in the root length density of soybean as evident from Eq. (12):

\[ \text{RLD} = -1.872 \text{CPR} + 3.503, \quad R^2 = 0.967^{**} \]  \tag{12}

The average total leaf area duration (LAD) under NPK + FYM (236.2) was higher (P < 0.05) by 13.7 and 48%, respectively than NPK (207.7) and control (159.6) whereas the total average LAD under NPK was 30% higher (P < 0.05) than that under control. The LAD could account for 80.2% variation in the grain yield (Y) of soybean as evident from Eq. (16):

\[ Y = 2.7236 \text{LAD} + 324.35, \quad R^2 = 0.802^* \]  \tag{16}

Figure 6. The leaf area index of soybean as influenced by nutrient management (pooled over 2002–2004). The error bars indicate least significant difference at P < 0.05; NS indicates not significantly different at P < 0.05.
3.7. Biomass production and partitioning

The total biomass production at physiological maturity (pooled over 2002–2004) under NPK + FYM was 5.2 and 45.6% higher than that under NPK and control treatment, respectively (Fig. 7). The biomass partitioning showed that up to R6 stage (75 days after sowing), leaf was the major sink of photosynthates (Fig. 7c) with the proportion varying from 38.1% in NPK to 43.7% in control and after this stage, pod became the major sink of photosynthate (Fig. 7d). This finding is in agreement with Pospisil et al. (2006). At this stage, root biomass varied from 10.1% in control to 12.8% in NPK + FYM (Fig. 7a) and the stem biomass varied from 21.2% in control to 30% in NPK + FYM (Fig. 7b). At harvest the partitioning of biomass towards pod was more in control (50.4%) than NPK (47.1%) and NPK + FYM (47.4%) treatments. So the harvest index in control was more than NPK and NPK + FYM treatments.

The root biomass increased gradually till 75 days after sowing (R6) and after that it slightly decreased and maintained a plateau towards the maturity of the crop (Fig. 7a). The root biomass in NPK + FYM was higher than NPK and control treatments. The progressive development of the root biomass (RBM) with time followed a quadratic relationship for all the treatments as given in Eq. (17):

\[
RBM = -0.082 t^2 + 16.386 t - 265.521, \quad R^2 = 0.89^{**}
\]  

(17)
The above ground shoot biomass (SBM) accumulation also followed a quadratic relationship with time for all the treatments as given in Eq. (18):

\[
SBM = -0.451t^2 + 110.673t - 1835.5, \quad R^2 = 0.92^{**} \tag{18}
\]

### 3.8. Yield of soybean

Fertilizers and manure application significantly improved the grain and above ground residue (straw) yield of soybean over control (Table 3). The relationship of grain yield with the total above ground biomass production at different growth stages showed that at R8 growth stage, total biomass could account for 89% variation in the seed yield of soybean, which was higher than other growth stages (Table 4). The relationship between the grain yield of soybean with the LAI at different growth stages showed that at R8 growth stage, total biomass could account for 63% variation in the seed yield of soybean, which was higher than other growth stages (Table 4).

Annual application of FYM @ 4 t ha\(^{-1}\) along with recommended dose of fertilizers (NPK) significantly improved the grain yield of soybean by 14.2% over NPK and by 50.3% over control treatment. Recommended dose of NPK also improved the grain yield of soybean by 31.6% over control. The straw yield of soybean followed the similar trend as the grain yield (Table 3). The higher grain yield of soybean in NPK + FYM is attributed to better root growth and efficient utilization of water and nutrients in this treatment than NPK and control. This finding is in agreement with that of Bandyopadhyay et al. (2003), Hati et al. (2006) and Bhattacharyya et al. (2008). The grain and straw yield of soybean during the year 2004 was less than the other 3 years due to severe pest infestation during this year.

### 3.9. Nitrogen uptake and nitrogen use efficiency

Integrated use of NPK and FYM significantly improved the N uptake by soybean grain, straw and grain + straw by 55.5, 63.2, and 58.6%, respectively over control (Table 3). Similarly use of recommended dose of NPK increased the N uptake by soybean seed, straw and seed + straw by 34.4, 38.0 and 35.9%, respectively over control. Use of additional 4 t of FYM increased the N uptake by grain, straw and grain + straw by 15.7, 18.3 and 16.8%, respectively over recommended dose of NPK. The higher N uptake in NPK and NPK + FYM treatments over control was due to both higher biomass production and also higher N concentration in the plant parts. Better root proliferation and better availability of N and better soil physical environment under NPK + FYM treatment might have resulted in higher N uptake in this treatment. The nitrogen harvest index, i.e. the proportion of N in reproductive parts, ranged from 58 to 60%. However, there was no significant difference among the nutrient management treatments with respect to the nitrogen harvest index. The agronomic N use efficiency of soybean under NPK + FYM treatment (10.5 kg soybean/kg N applied) was higher than that under NPK alone (6.6 kg soybean/kg N applied) (Table 3). Bhattacharyya et al. (2008) also reported significantly higher agronomic N use efficiency in soybean under integrated nutrient management in a soybean–wheat system.

### 3.10. Water use efficiency of soybean

Integrated use of NPK + FYM resulted in higher water use efficiency (19.28 kg/ha cm) than NPK (17.04 kg/ha cm) and control (13.63 kg/ha cm) (Table 3). Sharma (1997), Bandyopadhyay et al. (2004), Hati et al. (2006) and Ghosh et al. (2006) have also reported higher water use efficiency of soybean under integrated use of fertilizers and farmyard manure in Vertisol. The increase in water use efficiency of soybean with conjunctive use of fertilizer and manure might be ascribed to more rapid crop biomass growth during periods when vapour pressure deficit was low, which decreased the evaporation: transpiration (Es/T) ratio and in turn improved the transpiration efficiency of the crop (Zhang and Oweis, 1998).

### 4. Conclusions

Thus from the present investigation it may be concluded that integrated use of farmyard manure at 4 Mg ha\(^{-1}\) and the recommended dose of fertilizers in every crop season resulted in the significant improvement in the physical properties of Vertisol, i.e. decrease in bulk density, penetration resistance and increase in hydraulic conductivity, soil aggregation and aggregate associated carbon, compared to the sole use of fertilizer NPK and non-use of fertilizer and manure. It was also observed that integrated use of farmyard manure and recommended dose of chemical fertilizers led to improvement in crop growth param-

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### Table 3
Grain and straw yield, nitrogen uptake and water and nitrogen use efficiency of soybean under different nutrient management practices (pooled over 4 years, i.e. 2001–2004).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Grain yield (kg ha(^{-1}))</th>
<th>Straw yield (kg ha(^{-1}))</th>
<th>N uptake by grain (kg ha(^{-1}))</th>
<th>N uptake by straw (kg ha(^{-1}))</th>
<th>Water use efficiency (kg/ha cm)</th>
<th>Agronomic N use efficiency (kg N applied)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>626</td>
<td>1720</td>
<td>37.39</td>
<td>25.29</td>
<td>13.63</td>
<td>6</td>
</tr>
<tr>
<td>NPK</td>
<td>824</td>
<td>2252</td>
<td>50.25</td>
<td>34.91</td>
<td>17.04</td>
<td>6.6</td>
</tr>
<tr>
<td>NPK + FYM</td>
<td>941</td>
<td>2596</td>
<td>58.15</td>
<td>41.28</td>
<td>19.28</td>
<td>10.5</td>
</tr>
<tr>
<td>LSD</td>
<td>78.5*</td>
<td>109.7*</td>
<td>5.89**</td>
<td>1.88**</td>
<td>1.18**</td>
<td>3.0</td>
</tr>
</tbody>
</table>

NS = not significantly different; NPK = recommended dose of N, P and K fertilizers; FYM = farmyard manure; LSD = least significant difference.

* Significant at P < 0.05.
** Significant at P < 0.01.

### Table 4
Relationship between grain yield (Y) of soybean and biomass production (TDM) and leaf area index (LAI) at different growth stages.

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Days after sowing</th>
<th>Relationship</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relationship between grain yield and TDM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V8</td>
<td>32</td>
<td>Y = 0.1397TDM + 899.57</td>
<td>0.06</td>
</tr>
<tr>
<td>R2</td>
<td>52</td>
<td>Y = 0.1201TDM + 499.27</td>
<td>0.15</td>
</tr>
<tr>
<td>R4</td>
<td>60</td>
<td>Y = 0.1383TDM + 323.46</td>
<td>0.38</td>
</tr>
<tr>
<td>R6</td>
<td>75</td>
<td>Y = 0.1157TDM + 280.11</td>
<td>0.44</td>
</tr>
<tr>
<td>R7</td>
<td>90</td>
<td>Y = 0.0689TDM + 481.53</td>
<td>0.31</td>
</tr>
<tr>
<td>R8</td>
<td>113</td>
<td>Y = 0.0915TDM + 298.56</td>
<td>0.69</td>
</tr>
</tbody>
</table>

| Relationship between grain yield and LAI | | | |
| V8           | 32                | Y = 0.7924LA + 894.78 | 0.13 |
| R2           | 52                | Y = 28.84LA + 864.28 | 0.07 |
| R4           | 60                | Y = 90.67LA + 426.85 | 0.33 |
| R6           | 75                | Y = 118.25LA + 335.85 | 0.17 |
| R7           | 90                | Y = 66.05LA + 662.22 | 0.06 |
| R8           | 113               | Y = 525.31LA + 458.88 | 0.63 |
etters, viz., root length density, root mass density, leaf area duration, biomass partitioning towards pod and resulted in higher nitrogen uptake and higher grain yield and water and nitrogen use efficiency of soybean than that of sole of recommended dose of fertilizers and non-use of fertilizers and manures. So integrated use of farmyard manure at 4 Mg ha$^{-1}$ and recommended dose of chemical fertilizers in every crop season may be practiced in Vertisols to improve soil physical environment and enhance carbon sequestration and for achieving higher productivity through efficient utilization of water and nutrients in soybean.

**References**


