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SOIL ORGANIC CARBON FRACTIONS, MINERAL N AND HYDRO-PHYSICAL PROPERTIES UNDER DIFFERENT NUTRIENT MANAGEMENT PRACTICES IN PIGEONPEA-WHEAT SEQUENCE

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BY

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This is to certify that the thesis entitled **“Soil organic carbon fractions, mineral N and hydro-physical properties under different nutrient management practices in pigeonpea-wheat sequence”** submitted to the Faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfilment of the requirements for the degree of Master of Science in Soil Science and Agricultural Chemistry, embodies the results of *bonafide* research work carried out by Mr. Nintu Mandal, under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma.

It is further certified that any assistance and help availed during the course of investigation as well as source of information have been duly acknowledged by him.

Place: New Delhi
Date: 03 -07-2010

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Advisory Committee

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1. INTRODUCTION

Continued deterioration of soil health during past three decades is one of the most serious second generation problems of Green Revolution in India, causing not only stagnation in food grain production but also threatening the nutritional and economic security. The problem is more acute in high productivity areas of Indo-Gangetic Plain region (IGPR) *i.e.*, Trans-Gangetic Plains (TGP, representing Punjab and Haryana) and Upper Gangetic Plains (UGP, representing Delhi and Western U.P.), where intensive cereal-cereal cropping systems are predominantly followed with indiscriminate use of nutrients and irrigation water, and also with excessive tillage using heavy machinery (Yadav *et al*. 1998). Depletion of soil organic carbon (SOC) both in terms of quality and quantity is the major soil health problem emerged due to continuous adoption of this kind of farming, followed by other constraints like emergence of multi-nutrient deficiencies and deterioration of soil physical properties-especially sub-surface compaction and poor aggregation (Hobbs and Morris 1996). The sustenance of high yields in these otherwise productive areas is becoming increasingly difficult owing to soil-related constraints.

In recent years, there has been a revival of interest in soil organic carbon (SOC) dynamics, particularly changes in SOC pools consequent to management practices, because of increasing global concerns on climate change and sustainability of agricultural production systems (Lal 2004). A desirable crop management practice would not only support sustained high production but also exhibit simultaneous potential of annual accretion in SOC stocks and thereby improving nutrient availability and soil health (Yadav *et al*. 2000; Sleutel *et al*. 2006). Identification and adoption of such practices assume great significance in subtropical and tropical regions, where SOC levels are inherently low (Mandal *et al*. 2007). With the large-scale adoption of intensive cropping, the long-term balance between additions of organic carbon from different sources and losses through different pathways is disrupted, since on one hand more and more of the C is subjected to oxidative losses due to continued cultivation; while on the other hand, it leads to addition of C to the soil through crop residues resulting either a net build-up or depletion of SOC stock (Kong *et al*. 2005). Although the intensity of land use and management has definite impact on SOC stocks, yet small changes are difficult to detect because of high background levels and natural soil variability (Elliot 1986). This could also be one of the reasons for using different pools or fractions as sensitive indicators of changes in SOC levels (Jenkinson and Rayner 1977).

Deterioration of soil physical properties in the intensively cultivated areas of the IGPR is associated with the cropping systems followed, excessive use of heavy farm-machinery and other crop management practices. For instance, the negative effect of wet-tillage (puddling) for transplanted rice on sub-soil compaction, and also on the growth and yield of subsequent wheat crop in rice-wheat cropping system- the most widely practiced system in the IGPR is well documented (Aggarwal *et al.* 1995; Timsina and Connor 2001; Kukal and Aggarwal 2003). Unfortunately, the farmers in these areas try to compensate the yield loss due to a decline in soil health by excessive use of N fertilizers, which not only enhances the pace of nutrient mining from soil, but also deteriorates the quality of produce besides posing a potential threat of groundwater pollution through nitrate leaching beyond root zone.

Conjoint use of fertilizers and organics, and diversification of nutrient-exhaustive cereal-cereal cropping systems are recognized as promising management strategies to restore soil health and sustain the productivity levels. The same could, however, not be adopted extensively for competitive uses of conventional organic sources (cattle dung, crop residues *etc.*), and also for unavailability of suitable varieties of non-cereal crops, especially monsoon legumes that could diversify the existing cropping system. In fact, for diversification of the most widely practiced rice-wheat system in UGP, pigeonpea has been considered as one of the potential crops to substitute monsoon rice crop (Dahiya *et al.* 2002; Singh and Dwivedi 2006). Development of extra-short duration (ESD) varieties of pigeonpea in recent years made it possible to replace intermittently or permanently a monsoon cereal crop and thus giving rise to the pigeonpea-wheat cropping system. Introduction of pigeonpea may have advantages well beyond N addition through biological nitrogen fixation (BNF) including nutrient cycling from deeper soil layers, recycling of relatively narrow C:N ratio residue and leaf litter, increase in soil organic matter, breaking weed and pest cycles, minimizing soil compaction and lowering the harmful allelopathic effects (Wani *et al*. 1995). The ESD varieties of pigeonpea have, however, retained perenniality trait of retaining substantial amount of green foliage at maturity, which could be recycled into the soil to supply valuable nutrients to the subsequent crop and enrich soil fertility.

Effect of integrated plant nutrient supply (IPNS) on different soil parameters has been studied at IARI and elsewhere mostly in cereal-cereal cropping systems, and with IPNS options that involved one or more of the conventional organic manures. Since pigeonpea-wheat is a relatively new cropping system that came into prominence only after development of ESD varieties of pigeonpea, information pertaining to changes in soil parameters other than available NPK content of surface soil due to nutrient management is scarce, if not lacking altogether. In fact, sporadic studies undertaken so far with this cropping system were generally confined to evaluating yield responses and at the most economic returns vis-à-vis other systems. It would, therefore, be interesting to understand the impact of nutrient management on soil parameters such as soil organic carbon (SOC) fractions, mineral N content and some hydro-physical properties, and their inter-relationships in pigeonpea-wheat system. A field experiment on pigeonpea-wheat system continuing since past five years at the IARI Farm, that comprises integration of three organic inputs of varying chemical composition *viz*., FYM, sulphitation pressmud and pigeonpea leaf-litter was considered an ideal site for such studies.

With this background, the research work was undertaken with the following objectives:

(i) To evaluate the effect of fertilizers alone or in combination with farmyard manure, sulphitation pressmud and pigeonpea leaf-litter on soil organic carbon (SOC) fractions, mineral nitrogen (N) content and hydro-physical properties

(ii) To study the inter-relationships among of SOC fractions, mineral N and hydro-physical properties, and their effect on the productivity of pigeonpea-wheat sequence

2. BACKGROUND

Pigeonpea-wheat is a relatively new cropping sequence that came into prominence due to development of extra-short duration varieties of pigeonpea. Hence, the literature on changes in SOC fractions, mineral-N and hydro-physical properties under varying nutrient management options in this crops sequence *per se* scare. A good deal of information is however, generated in other crops sequence in the IGPR or elsewhere. The relevant literature is cited hereunder as background information to the present investigation.

2.1. Soil organic carbon (SOC) fractions

Soil organic carbon (SOC) is an important component playing key multifunctional roles in soil quality and determining many soil physical and biological properties (Smith *et al*. 1999). As decline in soil organic matter is considered to create an array of negative effects on crop productivity, maintaining and improving its level is pre-requisite to ensuring soil quality, future productivity, and sustainability (Katyal *et al*. 2001). It is a source of energy and nutrients for soil biota which affects the nutrient supplying capacity of soil *via* mineralization. It also affects aggregate stability, trafficability, water retention and hydraulic properties (Haynes 2005). In addition to being a direct source of plant nutrients, SOM also indirectly influences nutrient availability in soil. Besides, it is also extremely important in maintaining overall quality of environment as soil contains a significant part of global carbon stock (Lal *et al.* 1998).

The SOC is considered to be comprised of a small labile or active pool with relatively high turnover rate and a large recalcitrant or passive pool with slower turnover rates (Krull *et al*. 2003). The oxidation of liable C pool drives the flux of CO_2 from soil to the atmosphere, and this pool greatly influences nutrient cycling for maintaining soil quality and its productivity (Chan *et al*. 2001; Majumder *et al*. 2008). Hence, adoption of procedures that can preferentially extract the more labile pools might be a useful approach for the characterization of SOC resulting from different soil management practices including cropping systems and application of organic and inorganic sources of nutrients (Hassink 1994; McLauchlan and Hobbie 2004). On the other hand, highly recalcitrant or passive pool is only very slowly altered by microbial activities (Weil *et al*. 2003) and thus hardly serves as a good indicator for the purpose.

Blair *et al*. (1995) considered SOC oxidized by 333 m*M* $KMnO_4$ ($KMnO_4$-C) as the most useful index of labile C that encompasses all readily oxidisable organic components including humic substances and polysaccharides. This fraction comprises 5-30% of the total organic carbon (TOC), and is considered more sensitive to changes in cultivation or management practices compared to total SOC content (Lefroy *et al*. 1993; Conteh *et al*. 1999; Blair 2000; Graham *et al*. 2002). In fact, $KMnO_4$ extracted higher amount of LBC from manure and fertilizer-treated plots than the control, as this reagent extracts relatively younger organic compounds including labile humic materials and polysaccharides (Conteh *et al*. 1999; Haynes 2005). Soil microbial biomass carbon (MBC) is another important labile fraction that mainly consists of bacteria and fungi and makes up 1-5% of TOC (Haynes 2005). Methods like chloroform fumigation-incubation and chloroform fumigation-extraction have been used widely to determining MBC content (Jenkinson and Powlson 1976; Jenkinson and Ladd 1981). However, this percentage, the 'microbial quotient', has been reported to change in a consistent way and to provide a useful indicator of soil processes (Anderson and Domsch 1989). The proportion of MBC to TOC decreased as soils were restored after mining (Insam and Domsch 1988), and showed a consistent trend depending on climate, as assessed by precipitation evaporation (P/E) quotient (Insam *et al.* 1989). The changes in the MBC/TOC ratio reflect organic matter inputs to these soils, the efficiency of conversion to microbial C, losses of C from the soil, and the stabilization of organic C by the soil mineral fractions. Hence, the MBC/TOC ratio has been found useful as an index of changes in soil organic matter resulting from a change in land management (Ross *et al*. 1982, 1983; Hart *et al*. 1989). The use of the ratio approach appears to normalize some of the variability and allow a better interpretation of trends (Carter 1986).

Most of the conventional methods used in SOC determination aim to maximize oxidation of C (Walkley and Black 1934; Nelson and Sommers 1982). This approach may not be useful for assessing the effect of management practices on the quality of a system for sustainable crop production, since in many TOC failed to serve as a sensitive indicator for such an assessment (Chan *et al.* 2001). The adoption of procedures that can preferentially separate the more labile pools might be a useful approach for characterizing SOC and assessing its quality under different management practices. Several techniques based on chemical, physical, and biological principles are used for partitioning labile pools of SOC (McLauchlan and Hobbie 2004). Some of the commonly used techniques are: oxidation under a gradient of oxidizing condition (Walkley 1947; Blair *et al.* 1995; Chan *et al.* 2001), floatation with a dense liquid (Gregorich and Janzen 1996), sieving into different size class separates and their associated C (Six *et al.* 1998), mineralization under controlled temperature and moisture condition (Pastor *et al.* 1993), and direct measurement of the pool size of living soil organisms and microbial biomass (Paul *et al.* 1999). Some of the important labile pools of SOC currently used as indicators of soil quality are microbial biomass C, mineralizable C, oxidisable organic C fractions, and light-fraction C.

The living fraction of organic matter, the microbial biomass, rather than total amounts of organic C, has been suggested as a useful and more sensitive measure of a change in organic matter status (Powlson and Jenkinson 1981; Powlson *et al.* 1987). Having a comparatively rapid rate of turnover of 1-2 years (Jenkinson and Ladd 1981), it is possible to detect changes in this microbial fraction long before they are detectable in the total organic matter. Changes in the MBC can thus provide an early indication of longer-term trends in the TOC of soils (Powlson and Jenkinson 1981; Carter 1986; Powlson *et al.* 1987). Because of synthesis and mineralization occurring at the same time, the concentration of humic substances is generally at equilibrium and remains constant at the prevailing ecoclimatic condition. However, when the precursors of humic matter disappear, the changes occurring in its composition and chemistry can modify its resistance to decomposition (Stevenson 1982).

Information on particulate organic carbon (POC), the physically protected transitional fraction (Gregorich and Janzen 1996), is relatively scarce and more confined to no-till systems. POC, in addition to the more active pools of soil organic carbon, has recently been shown to be a sensitive indicator of soil management effects on soil organic carbon (Parton *et al.* 1987). This fraction was considered to represent the ‛slow pool’ of soil organic carbon with an intermediate turnover time between the ‘active’ and ‘passive pools’ (Parton *et al.*, 1987) with a lignocellulose index 43 to 50%. This fraction of SOC represents an important intermediate decomposition stage of plant debris that was rapidly lost following soil disturbance with cultivation (Cambardella and Elliott 1992). It is considered as physically protected and moderately stable organic carbon in the size range of 53 to 2000 μm, and this fraction is sensitive to soil disturbances (Camberdella and Elliot 1992).

2.2. Effect of nutrient management on SOC fractions

Multi-location long-term experiments (mostly involving intensive cereal-based cropping sequences) in the sub-tropical and tropical regions have revealed that application of fertilizer NPK at locally recommended rates either increased or at least maintained the SOC stock over the initial values, compared with unbalanced (N or NP) and inadequate (50% of the recommended NPK) fertilization at most of the locations (Swarup and Wanjari 2000; Yadav *et al*. 2000). Conjoint use of organics *viz*. FYM, green manure or crop residues along with fertilizer NPK or application of an enhanced level of NPK not only brought further increase in SOC (Nambiar 1994; Yadav *et al*. 2000a) but also improved soil physical health measured in terms of increased aggregation and a decrease in soil compaction (Timsina and Connor 2001).

Long-term use of FYM (15 t ha^{-1} yr^{-1}) along with recommended NPK fertilizers under maize-wheat sequence on a Typic Haplustept revealed substantial increase in SOC fractions like MBC, $KMnO_4$-C and POC, and an integrated use of fertilizers and manure appeared a better nutrient management option for accumulation of SOC compared with fertilizer alone (Manjaiah and Singh 2001; Rudrappa *et al*. 2006). In a long-term pearl millet-wheat sequence, Goyal *et al*. (1999) concluded that application of organic amendments along with inorganic fertilizers led to increased MBC, as these amendments supplied readily decomposable organic matter in addition to increasing root biomass and root exudates due to increased crop growth. Other studies also substantiated the superiority of integrated use of organics and fertilizers in augmenting SOC stocks under rice-based cropping systems in tropical/sub-tropical environments (Bhattacharyya and Pal 2003; Mandal *et al.* 2007). Mtambanengwe and Mapfumo (2008) reported that the effect of fertilization and manuring on LBC varied with the sources of organic matter addition and indicated that LBC status of soil was significantly affected by nutrient management treatments within short period even under tropical environment.

A comparison of particulate organic matter and mineral associated carbon among three tillage treatments (20 years under cultivation) and an undisturbed grassland at Sydney revealed that particulate organic carbon in the native sod represented 39% of the total TOC and bare fallow, stubble-mulch, and no-till management reduced the carbon content in this fraction to 18, 19, and 25%, respectively (Camberdella and Elliot 1992). Bowman *et al.* (1999) indicated that particulate organic carbon, which usually reflects the amount of residue litter and shallow roots, increased with increasing cropping intensity. The cropping intensity of 1.0 had highest particulate organic carbon content while that of 0.5 the lowest. They also reported that particulate organic carbon in cropping intensity of 1.0 was nearly double to that of particulate organic carbon in cropping intensity of 0.5 treatment, and attributed this to greater plant biomass production in intensive cropping systems that produced more litter and roots for particulate organic carbon accumulation. They revealed that POC contributed about half of the TOC in the treatments without fallow and about 40% in the treatments with fallows.

Fertilizer application shows great impact on SOC storage and cycling (Kaur *et al.* 2008; Triberti *et al.* 2008). Firstly, fertilization affects organic matter input to soil directly through organic amendments and/or indirectly by altering crop growth and residue return (Min *et al.* 2003). Secondly, fertilizer application greatly influences soil aggregation (Tisdall and Oades 1982), which provides physical protection for SOC, thus controlling its decomposition and transformation (Jastrow *et al.* 2007). For example, Whalen and Chang (2002) reported that SOC pools and aggregate formation were significantly enhanced after long-term manure application. Furthermore, manure amendment contributes to the increase of soil aggregate stability (Whalen *et al.* 2003), whereas the effects of inorganic fertilizer application on soil aggregation and SOC sequestration were variable (Halvorson *et al.* 2002; Zaller and Ko¨pke 2004). Therefore, fertilization management may influence the feedback between SOC and soil aggregation and thus the protection of SOC.

The effects of cultivation on the nutrient and microbial characteristics of soil are observed in the C and N-enriched small macro-aggregate fractions (2–0.25 mm) (Cambardella and Elliot 1993; Gupta and Germuda 1988; Elliot 1986; Dormaar 1983; Tisdall and Oades 1980a, b). Dormaar (1983) also reported that SOC, polysaccharides, polyuronides and phenols were associated with water stable aggregates of >0.25 mm size. However, Elliot (1986) noted that whereas the C/N, C/P and N/P ratios of water-stable micro-aggregates were smaller than those of macro-aggregates, the former contained less organic matter associated with silt plus clay than the latter. Findings by Christensen (1985) and Christensen and Sorensen (1985) showed that C and N were associated with finer soil particles and these particles varied among different aggregate fractions. Six *et al.* (2000) reported a lower content of POC in soils disturbed by tillage operations for cultivation. On the contrary, manuring enhanced C content in soils associated with macro-aggregates due to the abundance of root exudates (lignocellulose residues) in organic amended soils (Arshad *et al.* 1990).

In a long-term study, use of NPK + FYM or NPK + rice straw (RS) gave higher values of very labile C due to high content of polysaccharides (cellulose and hemicelluloses) in FYM and RS that could lead to the production of higher amounts of labile fraction of SOC than that produced with green manure (Seneviratne, 2000). Chan *et al.* (2001), while comparing the effectiveness of different pasture species in maintaining labile pools of SOC, observed that very-labile C and labile C contributed a major portion (~65%) of TOC in semi-arid areas of Australia. The other two fractions, namely less labile carbon and non-labile carbon accounted for a smaller proportion (~35%) of the TOC that was within the range of 30 to 40% assigned to the passive pool of SOC used in the Century Model (Parton and Rasmussen 1994).

2.3. Effect of nutrient management on mineral N content

In the sandy loam soils (Typic Haplustept) of New Delhi, nutrient management practices had a significant effect on N content, and plots receiving integrated sources of nutrients showed higher soil mineral N content than control, whereas organic source of nutrients could not maintain the level of mineral N in soil even as that recorded in control (Verma 2010). Application of FYM along with fertilizers reduced the transport of NO_3-N down the profile, which in turn minimized the leaching losses (Verma 2006).

Extensive studies on the benefits of inclusion of legumes in crop sequences as carried out at Modipuram (representing UGP) revealed that legumes raised as grain or forage crop increased SOC, decreased soil bulk density especially in the sub-surface layers, and also minimized downward movement of NO_3-N beyond the effective root zone (Dwivedi *et al*. 2003; Singh *et al*. 2005). In these studies, a greater amount of NO_3-N was retained in the upper profile when pigeonpea preceded wheat, and a reverse was true when a cereal (rice) was the preceding crop. Introduction of a legume crop in cereal-cereal may have advantages well beyond the N addition through BNF including nutrient recycling from deeper soil layers, minimizing soil compaction, increase in soil organic matter, breaking of weed and pest life cycles and minimizing harmful allelopathic effects (Wani *et al.* 1995). As the process of release of N from the organic sources involves a biological decomposition of these materials, the same is controlled by chemical composition of the materials (Fox *et al.* 1990; Rowell *et al*. 2001; Kumar and Goh 2003) and soil environment (Vigil and Kissel 1995; Cookson *et al.* 2002). Legume leaf litter, modules and aboveground biomass are thus likely to release N faster than FYM or cereal crop residues incorporated to the soil.

Soil mineral N (NH_4-N and NO_3-N) is closely correlated with soil fertility (Roy and Singh 2003) and variations in mineral N content can also reflect changes in the soil quality. In agricultural ecosystems, inorganic N is frequently looked upon as the most limiting factor influencing plant growth and crop yields (Ruser *et al.* 1998). Continuous application of FYM over seven years in an intensive cropping system on an Alfisol significantly increased the NH_4-N and NO_3^--N contents, whereas addition of green leaf manures did not leave any profound effect (Udayasoorian *et al.* 1989). On the other hand, a decrease in NO_3-N content of the soil with the application of FYM was observed by Puranik *et al.* (1978) and Prasad and Rokima (1991), although, the highest N content was observed with the integrated use of NPK and FYM.

2.4. Effect of nutrient management on soil hydro-physical properties

Hydro-physical properties such as mean weight diameter, bulk density, porosity and saturated hydraulic conductivity indirectly influence nutrient uptake and yield by affecting ease of tillage, seed-bed quality and root growth (Schjonning *et al*. 1994). Studies have shown that the organic matter has great regulatory roles over several physical soil features like pH, bulk density, hydraulic conductivity, aggregate stability, and erosion susceptibility. Loss of organic matter may encourage breakdown of soil aggregates, thus increasing their vulnerability to erosion (Jastrow 1996). Parallel to the increases in soil organic matter, soil porosity increased, while bulk density and soil erodibility decreased (Cerda 1996). Saturated water flow is an important factor in understanding the dynamic process of water and solute movement in soil. Although in most cases of upland field, saturated water flow is often used to designate an appropriate internal drain-ability for better crop growth (Acharya *et al.* 1988). Saturated hydraulic conductivity is a representative key parameter of the saturated water flow in soil.

Bulk density is a dynamic soil property varying with texture, structural condition and organic matter status of the soil and altered by cultivation, compression by animals, agricultural machinery and weather *etc*. The changes in bulk density are related to cropping, rate of organic matter decomposition, rate and frequency of manuring and fertilizer use practices (Gattani *et al*. 1976).

Anderson *et al.* (1990) found that the annual additions of 13.5 t ha^{-1} of manure for 100 years decreased bulk density by an average of 0.12 Mg m^{-3} compared to unfertilized silt loam soils at Sanborn field, University of Missouri, Columbia. Soil bulk density in the 0-20 cm layer was reduced in FYM and NPK treatments relative to unfertilized control in a sandy loam soil after ninety years of the start of the Askov long-term fertilizer experiment (Schjonning *et al.* 1994). According to Grewal *et al.* (1999) continuous application of potassic (60 kg K_2O ha^{-1}) and phosphatic (60 kg P_2O_5 ha^{-1}) fertilizers lowered the bulk density (1.40 Mg m^{-3}) as compared to control (1.50 Mg m^{-3}). Similarly, Obi and Ebo (1995) reported that the addition of poultry manure (10 t ha^{-1}) significantly decreased soil bulk density of severely degraded sandy soil in southern Nigeria.

In eroded alluvial soils continuous use of N fertilizers alone or in combination with P significantly increased the bulk density of soil, whereas the use of FYM helped in lowering the bulk density (Bhatia and Shukla 1982). Nambiar (1994) reported that incorporation of FYM at 10-15 t ha^{-1} along with NPK for 7-13 years in long-term experiments brought about a slight reduction in bulk density in almost all the soils, which could be taken as an index of improvement in soil properties.

Bulk density normally does not change significantly due to NPK treatments; however, there could be a marginal reduction in bulk density due to NPK levels due to increase in biomass production with consequent increase in organic matter content of the soil (Bharadwaj and Omanwar 1992). Effect of 10 years of rice-rice cultivation showed the lowest bulk density (1.26 Mg m^{-3}) under 50% of recommended NPK + rice straw, whereas the highest bulk density (1.49 Mg m^{-3}) was observed in control (Bellaki *et al*. 1998).

Sheeba and Kumaraswamy (2001) observed a decrease in bulk density with an increase in organic matter content in Vertic Haplustepts of Coimbatore. On these soils, continuous application of balanced fertilizer NPK along with FYM (10 t ha^{-1}) significantly decreased the bulk density (1.30 Mg m^{-3}) compared with unfertilized plots (1.44 Mg m^{-3}) (Selvi *et al.* 2005). In a loess soil of Shaanaxi (China), bulk density at 0-5 and 10-15 cm depths was reduced significantly consequent to conjoint use of manure+NPK compared with fertilizer NPK alone or unfertilized control over a period of 13 years (Zhang *et al*. 2006). Likewise, in the Vertisols of central India, the lowest bulk density was recorded in the plots receiving recommended NPK and FYM (10 Mg ha^{-1}), whereas it was highest in the control plots (Hati *et al*. 2006). Continuous addition of organic manures not only influenced bulk density, but also brought a favorable change in total porosity of soils (Mahimairaja *et al.,* 1986). Incorporation of organic materials (cow dung slurry or paddy straw or glyricidia) either to meet 25% or 50% of N dose along with fertilizers had significantly increased the porosity of Vertisols (Bellaki *et al.* 1998).

Higher bulk density and low porosity observed under unbalanced fertilizer treatments might have affected aeration and entry of water into the soil, which in turn reduced carbon mineralization and uptake of water and nutrients by roots (Arvidson 1994).

Continuous applications of organics in combination with fertilisers improved hydraulic conductivity in black soils, as compared to fertilizers alone (Nambair and Ghosh 1984). Chaula and Chaula (1991) found that in a sodic soil saturated hydraulic conductivity of surface soil increased from 0.40 mm d^{-1} in control to 2.09 mm d^{-1} when only N fertilisers was applied, and further significant increase (3.05 mm d^{-1}) was noticed with the use of P or PK fertilizers along with N. An increase in hydraulic conductivity due to conjoint use of FYM and NPK fertilisers was observed by Bellaki et al (1998) and explained as improvement in soil structural stability and increase in organic matter content, biological activity and phosphate level of surface soil.

Anderson *et al*. (1990) found that the saturated hydraulic conductivity increased about nine times with annual additions of 13.5 t ha^{-1} of manure to silt loam soil for 100 years. Highest hydraulic conductivity (2.32 cm hr^{-1}) was recorded in organic manure applied treatments whereas the lowest (1.65 cm hr^{-1}) was recorded in control in the Vertisols (Chalwade *et al*. 2006).

Other reports also suggested that long-term balanced application of fertilizers along with organic manures maintain soil fertility by improving water holding capacity, porosity and water stable aggregates and decreasing bulk density and surface crusting, which leads to high crop yields (Edwards and Lofty 1982; Schjonning *et al.* 1994; Glendining *et al.* 1996; Manjaiah and Singh 2001). Although some studies indicate that soil fertility declines with continuous application of fertilizers alone (*i.e.* without organic inputs) due to soil acidification and degradation of soil structure (Graham *et al.* 2002; Malhi *et al.* 2003; Edmeades 2003). The same observations could not be supported by the long-term studies being carried out in different agro-ecological conditions in India (Swarup and Wanjari 2000).

Long term use of NPK or NPK+FYM showed significant increase in aggregate stability than under unfertilized control in Vertic Haplustept (Selvi *et al.* 2005). Sharma *et al.* (1998) reported that an increase in the percentage of water stable aggregates of size >0.25 mm due to continuous application of FYM with fertilisers and lime on acid soils of Himachal Pradesh. Increase in mean weight diameter in the FYM plots could be attributed to improved soil aggregation (Prasad and Singh 1980.; Bhatia and Shukla 1982). The surface soils of plots receiving both FYM and recommended dose of NPK had larger MWD (0.50 mm) and a higher percentage of water stable aggregates (55%) than both inorganically (NPK) fertilized and unfertilized control plots (0.41 mm and 45.4% respectively) in Vertisols of central India (Hati *el al*. 2006).

Emerson (1977) observed that organic matter stabilizes the aggregates by forming bonding between quartz particles and clay domains. Similarly, Oades (1994) reported that the organic matter increased the stability of macro-aggregates through the bindings of the mineral particles by polysaccharides.

2.5 Inter-relationships between parameters

Soil organic matter improves the physical conditions of soils by enhancing aggregation, aeration and water retention, thereby creating a suitable environment for root growth (Obi and Ebo 1995; Senesi and Loffredo 1999). The relationship between organic matter and soil aggregation or structure formation was described by Tisdall and Oades (1982) in a conceptual model, affected by three types of aggregation agents. In soils, where the organic matter is the main binding agent, aggregates of different sizes can be formed. Primary particles and clay micro-structure are bound together with bacterial and fungal debris into extremely stable micro-aggregates which may be bound together with fungal and plant debris giving a larger micro-aggregates. The humic matter, considered as a persistent cementing agent, is involved in stabilizing micro-aggregates. These micro-aggregates are bound into macro-aggregates, due to the effect of transient binding agents (polysaccharides derived from plants and microorganisms) and temporary binding agents (fungal hyphae, fine roots, bacterial cells) (Tisdall and Oades 1982; Oades 1993). Particulate organic matter (POM) improves the soil aggregation since it can form an organic core surrounded by clay, silt particles, and aggregates (Jastrow and Miller 1997).

The macro-aggregates are less stable than microaggregates to wetting or mechanical actions such as plowing, and their destruction by tillage may result in exposure of the inner core of organic substances (Golchin *et al.* 1997; Six *et al.* 2000), facilitating rapid oxidation and attack by microorganisms of these important binding agents (Elliott 1986; Angers and Chenu 1997). Increase in soil microbial population enhances aggregation and water stability of soil aggregates. Differences in soil microclimatic condition affect microbial biomass and activity in soils and subsequently affect cycling of carbon and nitrogen (Eaton 2001). Therefore, soil microbial biomass-C is a sensitive indicator of soil quality. It is necessary to identify factors that influence microbial activity and nutrient dynamics, for such information would improve understanding of the relations of soil characteristics, soil moisture and nutrient cycles/dynamics (Eaton 2001). Boparai *et al.* (1992) obtained significant increases in N and C concentrations in addition to changes in soil physical properties, after two-year legume crop fallowing and a year of cropping.

The proportion of labile carbon ($KMnO_4$ oxidisable C) content to the total organic carbon may also provide an early indication of land use effects on long-term TOC. The MBC or POC showed increase in their content consequent to an increase in TOC. Microbial biomass C and POC were linearly related to SOC. A linear relationship also occurred between MBC and POC (Huggins *et al*. 1997; Gregorich *et al*. 1994). Ratio of particulate organic carbon to total organic carbon increased with an increase in SOC level (Huggins *et al*. 1997).

Correlation between TOC and MBC was stronger ($r = 0.90$) than between POC and MBC ($r = 0.82$), whereas correlation between MBC and LBC was in between above. LBC correlated better with POC than TOC (Rudrappa *et al.* 2004). LBC fraction of TOC were more sensitive to change with nutrient management practices as compared to TOC and WBC which may be due to the fact that $K_2Cr_2O_7$ in presence of concentrated H_2SO_4 is more powerful oxidising agent than $KMnO_4$ under neutral condition (Verma 2010). While fractionating C into different pools in soils from five long-term experiments with different management practices and cropping systems, Majumder *et al.* (2007) observed strong relationships of very-labile and labile pools with MBC, mineralizable carbon and crop productivity of the systems, although such relationships for less labile C and non-labile C were weak. Accordingly, very-labile C and labile C might constitute the active pool whereas less-labile C and non-labile C might represent the passive pool of SOC (Chan *et al.* 2001; Majumder *et al*. 2007).

Application of initial soil test based optimum NPK dose along with 15 t FYM ha^{-1} improved soil physical properties as indexed by mean weight diameter, bulk density, saturated hydraulic conductivity which in turn increased availability of nutrients (Thangasamy 2007).

Nonetheless, detailed studies on the impact of nutrient management practices on SOC fractions, soil physical parameters and their inter-relationships under legume or pulse-based cropping systems have rarely been undertaken, mainly because these systems gained prominence in recent years only in the irrigated tracts of sub-tropical regions.

3. MATERIALS AND METHODS

The investigation entitled *"Soil organic carbon fractions, mineral N and hydro-physical properties under different nutrient management practices in pigeonpea-wheat sequence"* was undertaken in a field experiment that continued for five years (2004-05 to 2008-09) at IARI Research Farm, New Delhi. Post harvest soil samples were collected from this field experiment after completion of five cropping cycles. Subsequently, yield data as provided by Division of Soil Science and Agricultural Chemistry were used to draw the inferences as per the objectives of this investigation.

3.1. The experimental site

The field experiment on extra-short duration pigeonpea (*Cajanus cajan* L. Millsp.)-wheat (*Triticum aestivum* L.) sequence, was conducted for five consecutive years *i.e.* 2004-05 to 2008-09 on a Typic Haplustept of the Research Farm of IARI, New Delhi. The experimental site (28°N, 77°E, and 250 m above mean sea level) located in the Upper Gangetic Plain (UGP) zone represented an irrigated, mechanized and input-intensive cropping area. The climate of New Delhi is sub-tropical semi-arid, with dry hot summers and brief severe winters. The average monthly minimum and maximum temperature in January (the coolest month) fluctuated between 5.9 °C and 19.9 °C, respectively. The corresponding temperature in May (the hottest month) ranged between 24.4 and 38.6 °C, respectively. The average annual rainfall is 651 mm, and nearly three-fourth of this is received through north-west monsoon during July to September.

The soil of the experimental site was sandy loam (Typic Haplustept) of Gangetic alluvial origin, very deep (>2 m), flat and well drained. Detailed soil characteristics at the initiation of the experiment are given in Table 3.1, which revealed that the soil was mildly alkaline, non-saline, low in organic C (Walkley and Black C), available N and available S and medium in available P and available K.

3.2. Treatments and crop management

The field experiment on pigeonpea-wheat cropping system commenced in 2004-05 at IARI Research Farm as a part of Institute's in-house project SSAC:04:02(2) was continued for five years *i.e.* up to 2008-09 on an undisturbed layout. In all, 15 treatments comprising different nutrient supply options were evaluated in a randomized block design with three replications. However, nine treatments involving fertilizers, organic manures *i.e.*, farmyard manure (FYM) and sulphitation pressmud (SPM), induced defoliation (ID) in pigeonpea, and unfertilized-control (Table 3.2) were selected for the present investigation. Nutrient contents in FYM and SPM (Table 3.3) showed variation in % N, %P, %K and %S contents.

The plot-size was 5 m × 3.5 m. Pigeonpea (cv. ICPL 88039) was sown every year during first week of June at 70 cm × 20 cm spacing and harvested manually during first week of November. The subsequent wheat (cv. HD 2285) was sown in row 20 cm apart, which was harvested during third week of April. Soil test-based N-P-K fertilizer rates were 25-26-33 kg ha^{-1} for pigeonpea and 150-26-50 kg ha^{-1} for wheat, which were applied through urea, diammonium phosphate and muriate of potash, respectively. Each year one-fourth of total quantity of FYM or SPM *i.e.* 2.5 t ha^{-1} was applied to pigeonpea and subsequent wheat received remaining three-fourth amount *i.e.* 7.5 t ha^{-1}. Induced defoliation (ID) treatment in pigeonpea was imposed by foliar spraying of 10% (w/v) urea solution (in water) at physiological maturity of the crop. The ID treatment brought-in almost complete defoliation within a week time, thus converting entire green foliage into leaf litter (Table 3.4). Nutrient recycled through ID were also analyzed (Table 3.5). Crop varieties and management including rate of nutrient application remained same during all the five years.

3.3. Collection, preparation and preservation of soil samples

Soil samples from two depths (*i.e.* 0-15 and 15-30 cm) were collected following standard procedure from all plots of the three replications after completion of five pigeonpea-wheat crop cycles. Each sample was divided into two parts: the first part was stored in a refrigerator for determination of microbial biomass carbon (MBC) and mineral-N contents, and the second part was processed for other analyses. For determination of bulk density, soil cores were drawn from the above two depths using a core sampler. Saturated hydraulic conductivity of soil was determined using the same soil cores.

3.4. Soil Analysis

3.4.1. Soil reaction (pH) and Electrical conductivity (EC)

Soil pH and EC were determined in 1:2 soil-water suspension using combined electrode for pH and Conductivity Bridge for EC as per procedure given by Jackson (1973).

3.4.2. Soil organic carbon fractions

Total organic carbon

Total organic carbon (TOC) in soil was determined by wet-digestion method using potassium dichromate and acid digestion mixture (Snyder and Trofymow 1984). The 75 cm^3 culture tubes having indentation below the neck were used for digestion of soil. The shell-vials containing standard NaOH solution kept over the indentation inside the tube were used as alkali trap. The CO_2 evolved during digestion was estimated by back titrating unconsumed alkali with standard HCl.

Soil sample was passed through 0.2 mm sieve and 0.5 g of it was taken for determination of TOC. To remove carbonates, soil was pre-treated with 3 ml of 2*N* HCl, and kept for 15 minutes prior to addition of potassium dichromate and acid mixture. After that 1 g of potassium dichromate was added to soil taken in a culture tube and 25 ml of digestion mixture (conc. H_2SO_4 and H_3PO_4 in 3:2 ratio) was added to the tube. In glass vial, 4 ml of 1.38*N* NaOH was taken to trap the evolved CO_2 during digestion. The culture tubes were transferred to digestion block and digestion was continued at 120 °C for 2 hrs. Left over NaOH was titrated against 0.38*N* HCl. From consumed amount of NaOH, CO_2-C was calculated using 1 ml of 1*N* NaOH ≡ 6 mg of CO_2-C.

Particulate organic Carbon

The particulate organic carbon (POC) was determined following the procedure outlined by Camberdella and Elliot (1992). A 10 g portion of 2 mm sieved air-dried soil sample was shaken with 0.5% sodium hexametaphosphate solution on a shaker for 15 hours. Then the soil suspension was passed through 0.053 mm sieve using a mild jet of water from the top of the sieve. The solid portion retained on the sieve was transferred to small pre-weighed plastic boats by washing with jet of water. It contained both particulate organic matter and sand particles. The plastic boats were kept inside the forced air oven at 50 °C temperature for 72 hours for drying, and finally the weight of boats was recorded. The solid materials in the boats were ground in a pestle and mortar to make it a fine powder. The materials were passed through 0.2 mm sieve, and total organic carbon content in particulate organic matter was determined by wet-digestion method of Snyder and Trofymow (1984).

Microbial biomass carbon

Microbial biomass carbon (MBC) was determined by fumigation-extraction method as outlined by Jenkinson and Ladd (1981). For this purpose, 5 g of moist soil sample was fumigated with chloroform ($CHCl_3$) in a vacuum desiccator and extracted with 0.5*M* K_2SO_4 solution (soil: solution:: 1:5). A duplicate soil sample without fumigation (non-fumigated) was also extracted with 0.5*M* K_2SO_4 solution in a similar fashion. The extracts of non-fumigated and fumigated soil samples were subjected to wet-oxidation separately with potassium persulphate and dilute H_2SO_4 by heating the contents on a digestion block for 2 hours. Evolved CO_2 was trapped in 4 mL of 0.1*M* NaOH solution. The amount of CO_2 absorbed was determined by back titration with 0.01*N* HCl. Contents of MBC were computed by subtracting the amount of CO_2 evolved in case of fumigated soil from that of non-fumigated one. A sub-sample of the moist soil was drawn for determination of moisture content so as to express the data on dry weight basis. The amount of MBC in soil was calculated as fallows:

Microbial biomass carbon = $(OC_F - OC_{UF}) / K_{EC}$

Where, OC_F and OC_{UF} are organic carbon extracted from fumigated and unfumigated soil, respectively (expressed on oven dry basis), and K_{EC} is the efficiency of extraction. A K_{EC} value of 0.45 considered as a general value for microbial extraction efficiency was used for the calculation.

Labile carbon

The amount of oxidizable organic carbon in soil by 333 m*M* $KMnO_4$ is considered as the labile carbon (LBC) which was determined following the procedure of Blair *et al*. (1995). For this, 2.0 g of soil was taken in centrifuge tube and oxidized with

25 mL of 333 m*M* $KMnO_4$ by shaking on a mechanical shaker for 1 hour. The contents were centrifuged for 5 minutes at 4000 rpm, and 1.0 mL of supernatant was diluted to 250 mL with double distilled water (DDW). The concentration of $KMnO_4$ was measured at 565 nm wavelength on a spectrophotometer. The change in concentration of $KMnO_4$ is used to estimate the amount of carbon oxidized assuming that 1.0 m*M* of MnO_4^- was consumed ($Mn^{7+} \rightarrow Mn^{4+}$) in the oxidation of 0.75 m*M* (9.0 mg) of carbon.

Oxidizable organic carbon and its fractions

The content of oxidizable organic carbon (OOC) and its different fractions in the soil were estimated following the Walkley and Black (1934) method as modified by Chan *et al*. (2001) using 5, 10 and 20 mL of concentrated (18.0 mol L^{-1}) H_2SO_4 and $K_2Cr_2O_7$ solution. This resulted in three acid-aqueous solution ratios of 0.5:1, 1:1 and 2:1 that corresponded to 6.0, 9.0 and 12.0 mol L^{-1} H_2SO_4, respectively, and produced different amounts of heat of reaction to bring about oxidation of SOC of varying oxidizability. The amounts of OOC thus determined allowed separation of TOC into the following four fractions of decreasing oxidizability as defined by Chan *et al*. (2001):

Fraction I (very labile, C_{VL}) : Organic C oxidizable under 6.0 mol L^{-1} H_2SO_4

Fraction II (labile, C_L) : Difference in OOC oxidizable under 9.0 mol L^{-1} and that under 6.0 mol L^{-1} of H_2SO_4

Fraction III (less labile, C_{LL}) : Difference in OOC oxidizable under 12.0 mol L^{-1} and that under 9.0 mol L^{-1} of H_2SO_4 (12.0 mol L^{-1} H_2SO_4 is equivalent to the standard Walkley and Black method)

Fraction IV (non labile, C_{NL}): Residual organic C after oxidation with 12.0 mol L^{-1} H_2SO_4 when compared with TOC.

Walkley and Black Carbon

Carbon in the soil samples passed through 0.2 mm sieve as determined by the procedure of Walkley and Black (1934) was referred as Walkley and Black carbon (WBC).

3.4.3. Aggregate-associated carbon

Total organic carbon content in different aggregate size fractions (8.0-4.0 mm, 4.0-2.0 mm, 2.0-1.0 mm,1.0-0.5 mm, 0.5-0.2 mm and 0.2-0.1 mm) obtained by the process of wet sieving technique was also determined. The soil samples, after oven drying at 60 °C at 48 hrs and passing through a 0.2 mm sieve, were used for determination. From this, 0.5 g soil sample was taken and TOC content was determined following standard procedure (Snyder and Trofymow 1984).

Macro-aggregate and micro-aggregate associated total organic carbon

To obtain macro-aggregates, 8.0-4.0, 4.0-2.0, 2.0-1.0, 1.0-0.5 and 0.5-0.2 mm size fractions were taken together in a mortar, mixed well with pestle and passed through a 0.2 mm sieve. The 0.2-0.1 mm size was taken as micro-aggregate fraction. The macro-aggregate associated carbon (MaTOC) and micro-aggregate associated carbon (MiTOC) were determined following standard method of Snyder and Trofymow (1984).

3.4.4. Hydro- physical properties

Bulk density

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

Mechanical composition of soil

The per cent sand, silt and clay contents were determined by hydrometer method (Bouyoucos 1962).

Saturated hydraulic conductivity

Saturated hydraulic conductivity was determined in the laboratory using undisturbed soil core. A constant head was maintained at 1 cm and saturated hydraulic conductivity was calculated using Darcy's equation:

$K_{sat} = Q/At \times L/H$

where, K_{sat} is saturated hydraulic conductivity (cm hr^{-1}), A the cross sectional area (cm^2), Q the amount of water passing (cm^3), t the time (hr), Q/At the water flux, and L/H the hydraulic head.

Aggregate stability

Large clods were broken by hand into smaller segments along natural cleavage prior to air-dried soil was sieved to obtain aggregates that passed through 8 mm and retained on 4 mm sieve. The other aggregates were separated using wet-sieving technique (Yoder 1936). After wet-sieving, aggregates from each sieve were transferred to a set of pre-weighed beakers, oven-dried at 60 °C until water evaporated and weighed. The mean weight diameter (MWD) and geometric mean diameter (GMD) were calculated as an index of aggregation (Van Bavel 1949; Kamper and Roseneau, 1986) using following formula:

$MWD=\sum xi\ wi$

where wi is the proportion of each aggregrate class in relation to whole, and
xi the mean diameter of the class (mm).

$GMD = \exp [\sum (wi \log xi)/(\sum wi)$

where, wi is the weight of aggregrates (g) in a size class with an average diameter xi.

Water-stable aggregates (WSA) were computed by adding the aggregates of different size fractions, and expressing them as percentage.

3.4.5. Mineral nitrogen

Ammonium-N (NH_4-N) was estimated following the procedure given by Rowell (1994). A 5 g soil sample was extracted with 25 mL of 2*M* KCl solution. The contents were steam-distilled by adding MgO using a micro-Kjeldahl distillation unit (Gerhardt Vapodest, VAP 30). The liberated NH_3 was absorbed in 20 mL of 2% boric acid containing mixed indicator. The distillation was continued until 100 mL of distillate was collected within a time of 3 minutes, and then titrated with 0.02*N* H_2SO_4. Nitrate-N (NO_3-N) was estimated by distilling the same sample after adding 0.25 g Devarda's alloy (50% Cu, 45% Al and 5% Zn). The NO_3-N liberated during second distillation was absorbed in another conical flask containing 20 mL of 2% boric acid solution and mixed indicator. The contents were then titrated against 0.02*N* H_2SO_4.

3.5. Computations and statistical analysis

Lability index of SOC

A lability index for SOC was computed by first expressing the amounts of each of three labile pools namely (C_{VL}, C_L and C_{LL}) as a fraction of TOC, and then multiplying the fractions with their respective weightages of 3, 2 and 1 given on the basis of ease of their oxidation, and finally adding and averaging them up for different depths and treatments (Bharti 2006; Majumder *et al*. 2007). Accordingly,

Lability index (Li) = (C_{VL}/TOC)*3+ (C_L/TOC)*2+ (C_{LL}TOC)*1

The values thus obtained are compared for assessing the relative performance of different treatments in maintaining labile soil organic carbon at different depths.

Carbon Management Index

Carbon management index (CMI) was computed as per procedure proposed by Blair *et al*. (1995) using the following formula:
CMI = Carbon pool index (CPI) × Lability index (LI) × 100
where, i) CPI = [Sample total C (mg g^{-1})/ Reference total C (mg g^{-1})], ii) Lability of C (L) = (Carbon fraction oxidized by $KMnO_4$/ Carbon remaining unoxidized by $KMnO_4$), and iii) LI = (Lability of C in sample soil/ Lability of C in reference soil).

Microbial quotient

Microbial quotient was computed as the ratio of MBC to TOC.

Statistical analysis

The data generated were processed for analysis of variance as applicable to randomized block design to test differences among the treatment means as described by Gomez and Gomez (1984). Correlation coefficients were computed using SPSS programme (SPSS version 16). (SPSS, 1990)

4. RESEARCH PAPER-I

Soil organic carbon fractions and mineral nitrogen as influenced by different nutrient management practices in pigeonpea-wheat sequence

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Abstract

Soils of the Indo-Gangetic Plain Region (IGPR) are inherently low in organic matter and N contents, hence studying the pace and kind of changes in these parameters owing to nutrient management practices is of great significance with a view point of sustaining agricultural productivity. We, therefore, studied the effect of fertilizer NPK applied alone or in combination with organic inputs of varying nature and composition *i.e.* farmyard manure (FYM), sulphitation pressmud (SPM), and induced defoliation (ID) imposed by foliar spray of urea solution (10% w/v) in pigeonpea at physiological maturity, on soil organic carbon (SOC) fractions and mineral N under pigeonpea-wheat sequence on a Typic Haplustept at IARI Research Farm, New Delhi. Total organic carbon (TOC) and its different fractions, and mineral N (NH_4-N and NO_3-N) in 0-15 cm soil layer increased significantly with conjoint use of fertilizers and organics compared with fertilizers alone, but the extent of increase differed in accordance with the nature of organic inputs. Compared with fertilizer NPK, IPNS involving FYM or sulphitation pressmud (SPM) brought greater increase in Walkley and Black C (WBC), particulate organic C (POC) and TOC, whereas the magnitude of increase in microbial biomass C (MBC) and labile C (LBC) over NPK was greater in case of ID treatments. Contribution of WBC, MBC and LBC towards TOC across the treatment was in the range of 17 to 22%, 1.0 to 1.8% and 6.7 to 11.8%, respectively. Fractionation of oxidizable organic C into different lability pools helped detecting even smaller changes in SOC due to nutrient management. Different SOC fractions were significantly correlated with each other, and also with mineral N and crop yields.

Key words: Soil organic carbon fractions, mineral N, IPNS, induced defoliation (ID), yield, pigeonpea-wheat sequence

4.1. Introduction

The post-Green Revolution scenario in India is characterized by stagnation in food grain production, severe soil degradation, receding ground water table and an overall decline in factor productivity. The decennial compound growth rates of production and productivity of major crops have not only stagnated since early 1990s but also started reflecting negative trends (GOI 2009). A deterioration in the quality and quantity of soil organic carbon (SOC) and its adverse effect on nutrient supply to the crop is considered one of the major causes for such undesirable trends; incidence of widespread nutrient deficiencies, increase in sub-soil compaction and poor crop management particularly indiscriminate use of fertilizers and irrigation water are the other causes (Yadav *et al*. 1988; Ladha *et al.* 2003). The farmers in intensively cultivated areas of the IGPR have in fact started using greater than the recommended rate of N fertilizers to achieve the yield levels obtained earlier with less fertilizer use (Singh *et al.* 2005). Such an indiscriminate use of N fertilizers in these areas not only increases the pace of soil degradation through enhanced nutrient mining but also poses a potential threat of groundwater pollution due to excessive leaching of nitrate beyond the root zone.

Since soil organic matter (SOM) serves as soil conditioner, nutrient source, substrate for microbial activity, preserver of environment and major determinant to sustain agricultural productivity (Schnitzer 1991; Katyal 2001), there is need to develop, refine, and document the management practices that help in addition and enhancement of SOM levels. This is particularly important in tropical and sub-tropical regions where soils are low in SOC contents and inherently low in fertility status (Mandal *et al.* 2005). Increasing or even maintaining SOC levels in tropical and sub-tropical regions is, however, difficult, because the contents decline with decreasing rainfall and also with increase in temperature (Jenny and Raychaudhuri 1960). Lal and

Kang (1982) estimated that maintenance of native SOM levels would necessitate at least four times higher organic inputs in tropical than in temperate environment.

Studies in India and elsewhere revealed that an increase in SOC levels is directly related to manure/residue input to cropping systems and fertilizer application, tillage and crop rotation (Gregorich *et al.* 1996; Swarup and Wanjari 2000). As different fractions of SOC have a turnover time ranging from few years to centuries, a change in management practices within agricultural systems usually bring too small changes in total organic carbon (TOC) content in soil to be measured on short-term basis because of relatively large variability and quantity of background organic matter. Of the two major pools of SOC *i.e.* labile and non-labile (recalcitrant), the labile pool consists of materials in transition between fresh plant residues and stabilized organic matter and has a short turnover time of < 10 years (Janzen *et al.* 1997). The recalcitrant pool, on the other hand, is composed of resistant materials including humic substances and other complex products of biological degradation of plant and animal residues (Baldock and Nelson 2000). Measurement of different fractions of SOC would, therefore, help in identifying the fractions that may prove sensitive indices of a change in SOC level consequent to adoption of different manure and fertilizer management options.

The role of balanced use of fertilizers, integrated plant nutrient supply and inclusion of legumes in improving soil fertility status including SOC and mineral N levels and minimizing nitrate leaching is well documented (Hegde and Dwivedi 1992; Singh and Dwivedi 2006). The options for inclusion of legumes especially in monsoon are however, very limited in the Trans and Upper Gangetic Plain Zone of the IGPR where rice-wheat is the dominant cropping system. Nonetheless, with the development of extra-short duration (ESD) varieties of pigeonpea in recent years, it has become possible to introduce this crop to substitute rice especially in the upland and water scarcity situations. The added advantage of inclusion of pigeonpea is that the ESD varieties retain huge amount of green foliage at the time of maturity, which may serve a valuable organic input if defoliated and recycled to the soil. As pigeonpea-wheat is a relatively new crop sequence, not much information is available on the effect of this *per se* or that of nutrient management options on soil health.

With the above background, the present investigation was undertaken with pigeonpea-wheat sequence on a Typic Haplustept of IARI, New Delhi, to study (i) the effect of conjoint use of fertilizers and organics of varying composition and origin on changes in SOC fractions and mineral N contents, and (ii) the relationship of SOC fractions and mineral N with crop productivity.

4.2. Materials and Methods

The present investigation was based on the analysis of soil samples collected during the fifth (final) year of a field experiment at IARI Research Farm, New Delhi. The details of the field experiments, other materials used, and different analytical methods employed for the present investigation are furnished below:

4.2.1 Site characterization

The experimental site located at 28°N longitude, 77°E latitude and 250 m above mean sea level, in the Upper Gangetic Plain (UGP) zone represents a semi-arid sub-tropical climate. In this irrigated and input-intensive cropping area, pearlmillet-wheat, rice-wheat and maize-wheat are the annual crop sequences. The 10-year average annual rainfall in Delhi is 651.4 mm, most of which is received during July to September.

The Gangetic alluvial sandy loam (Typic Haplustept) soil of the experimental site was mildly alkaline (pH 8.35) and non-saline (EC 0.26 dS m^{-1}), and contained 0.36% organic carbon (Walkley and Black C), 194 kg ha^{-1} available N, 13.7 kg ha^{-1} Olsen-P, 232 kg ha^{-1} NH_4OAc-K and 7.2 mg kg^{-1} available S.

4.2.2 Experimental details

The field experiment on pigeonpea (*Cajanus cajan* L. Millsp.)-wheat (*Triticum aestivum* L.) sequence commenced in 2004-05 at IARI Research Farm was continued for five years *i.e.* up to 2008-09 on an undisturbed layout. The experiment comprised 15 treatments involving different nutrient supply options and an unfertilized control, in a randomized block design with three replications. However, following nine treatments involving fertilizers, organic manures *i.e.*, farmyard manure (FYM) and sulphitation pressmud (SPM), induced defoliation (ID) in pigeonpea, and an unfertilized-control were selected for the present investigation.

Treatment	Details
Control	Unfertilized-control
NPK	Soil test-based recommended NPK
NPK+FYM	NPK+10 t FYM ha^{-1}
FYM	10 t FYM ha^{-1}alone
NPK+SPM	NPK +10 t SPM ha^{-1}
SPM	10 t SPM ha^{-1} alone
NPK+ID	NPK + Induced defoliation in pigeonpea (ID)
NPK+FYM+ID	NPK+10 t FYM ha^{-1} + ID
NPK+SPM+ID	NPK +10 t SPM ha^{-1} + ID

The plot-size was 5 m × 3.5 m. Pigeonpea (cv. ICPL 88039) was sown every year during first week of June at 70 cm × 20 cm spacing, and harvested manually during first week of November. The subsequent wheat (cv. HD 2285) was sown during third week of November, in rows 20 cm apart, and harvested during third week of April. Soil test-based N-P-K fertilizer rates were 25-26-33 kg ha^{-1} for pigeonpea and 150-26-50 kg ha^{-1} for wheat, which were applied through urea, diammonium phosphate and muriate of potash, respectively. Entire amount of NPK for pigeonpea, and one-third of N and entire PK for wheat were applied basally at the time of sowing, whereas the remaining N (for wheat) was top-dressed in two equal splits at 25 and 70 days after sowing (DAS). Pigeonpea seed was also inoculated with *Rhozobium* culture obtained from Microbiology Division, IARI, New Delhi. Each year one-fourth of total quantity of FYM or SPM *i.e.* 2.5 t ha^{-1} was applied to pigeonpea and subsequent wheat received the remaining three-fourth amount *i.e.* 7.5 t ha^{-1}. Induced defoliation (ID) treatment in pigeonpea was imposed by foliar spraying of 10% (w/v) urea solution (in water) at physiological maturity of the crop. The ID treatment brought in almost complete defoliation within a week, thus converting entire green foliage into leaf litter. Crop varieties and management including the rate of nutrient application remained same during all five years.

4.2.3 Soil sampling and analysis

Soil samples from two depths (*i.e.* 0-15 and 15-30 cm) were collected following standard procedure from individual plots of all the three replications after completion of five pigeonpea-wheat crop cycles. Each sample was divided into two parts: the first part was stored in a refrigerator for determination of microbial biomass carbon (MBC) and mineral N contents, and the second part was processed for other analyses.

The soil samples were analysed for pH and EC in 1:2 soil-water suspension (Jackson 1973), mechanical composition of soil (Bouyoucos 1962) and mineral N content (Rowell 1994). Total organic C (TOC) was determined by wet digestion method (Snyder and Trofymow 1984), microbial biomass carbon (MBC) by fumigation-extraction method (Jenkinson and Ladd 1981), labile carbon (LBC) by $KMnO_4$-oxidation method (Blair *et al*. 1995), and particulate organic carbon (POC) using procedure outlined by Camberdella and Elliot (1992). Oxidisable organic carbon (OOC) and its fractions were determined by modified Walkley and Black method as proposed by Chan *et al.* (2001). This modified method involved the use of H_2SO_4 of different strengths (*i*.e. 6.0, 9.0 and 12.0 mol L^{-1}) providing different amounts of heat of reaction to bring about oxidation of the SOC of varying oxidizability. The amounts of OOC thus determined allowed separation of TOC into the following four fractions of decreasing oxidizability as defined by Chan *et al*. (2001):

Fraction I (very labile, C_{VL}) : Organic C oxidizable under 6.0 mol L^{-1} H_2SO_4

Fraction II (labile, C_L) : Difference in OOC oxidizable under 9.0 mol L^{-1} and that under 6.0 mol L^{-1} of H_2SO_4

Fraction III (less labile, C_{LL}) : Difference in OOC oxidizable under 12.0 mol L^{-1} and that under 9.0 mol L^{-1} of H_2SO_4 (12.0 mol L^{-1} H_2SO_4 is equivalent to the standard Walkley and Black method)

Fraction IV (non labile, C_{NL}): Residual organic C after oxidation with 12.0 mol L^{-1} H_2SO_4 when compared with TOC.

For determination of aggregate-associated TOC, different aggregate size fractions were separated by wet sieving as per standard method (Yoder 1936). After wet-sieving, different aggregates (4.0-2.0 mm, 2.0 -1.0 mm, 1.0-0.5 mm, 0.5-0.2 mm and 0.2-0.1 mm) were transferred from sieves to the pre-weighed beakers, dried in an oven at 60 °C and weighed. Aggregate of larger size (8.0-4.0 mm) were separated from soil by breaking large clods into smaller segments along natural cleavage and sieving to separate the aggregate that passed through 8 mm sieve and retained on a 4 mm sieve. The TOC in different size aggregates was determined by following the method of Snyder and Trofymow (1984). In order to measure the TOC associated with macro- and micro-aggregates. The aggregate bigger than 0.2 mm (macro-aggregates) were mixed thoroughly in a mortar and sieved through a 0.2 mm sieve and the TOC was determined. The TOC obtained for aggregate size <0.2 mm was termed as micro-aggregate associated TOC for treatment comparisons *vis-à-vis* macro-aggregate associated TOC.

Computations and statistical analysis

A lability index for SOC was computed by first expressing the amounts of each of the three labile pools namely (C_{VL}, C_L, C_{LL}) as a fraction of the amount of TOC and then multiplying the fractions with their respective weightages of 3, 2 and 1 given on the basis of ease of their oxidation, and finally adding and averaging them up for different depths and treatments (Bharti 2006; Majumder *et al*. 2007). Accordingly,

Lability index (Li) = $(C_{VL}/TOC)*3+ (C_L/TOC)*2+ (C_{LL}/TOC)*1$

The values thus obtained are compared for assessing the relative performance of different treatments in maintaining labile organic carbon at different depths.

Carbon management index (CMI) was computed as per procedure proposed by Blair *et al*. (1995) using the following formula:

CMI = Carbon pool index (CPI) × Lability index (LI) × 100

where, i) CPI = [Sample total C (mg g^{-1})/Reference total C (mg g^{-1})],

ii) Lability of C (L) = (Carbon fraction oxidized by $KMnO_4$/ Carbon remaining unoxidized by $KMnO_4$) and iii) LI = (Lability of C in sample soil/ Lability of C in reference soil).

Microbial quotient was computed as the ratio of MBC to TOC.

The data generated were processed for analysis of variance as applicable to randomized block design to test differences among the treatment means as described by

Gomez and Gomez (1984). Correlation coefficients were computed using SPSS programme (SPSS version 16).

4.3. Results

4.3.1. Soil pH and electrical conductivity

Soil pH and electrical conductivity in 0-15 and 15-30 cm soil depths under different fertilizer and manure treatments are presented in Table 4.1. The data revealed that nutrient management practices did not affect these parameters significantly in surface or sub-surface soil.

4.3.2. Soil organic carbon fractions

Total organic carbon

Total organic carbon (TOC) content of surface soil (0-15 cm) under fertilizer NPK treatment did not differ significantly from the unfertilized-control despite five years of continuous pigeonpea-wheat cropping (Table 4.2). Similarly, use of organic manures (*i.e.*, farmyard manure (FYM) or sulphitation pressmud (SPM) alone, or NPK+induced defoliation (ID) did not bring significant changes in TOC compared with that under NPK. Conjoint application of NPK and organics with or without ID, however, increased the TOC significantly over NPK, and the extent of increase was invariably greater with FYM (22-28%) compared with SPM (16-17%). In sub-surface (15-30 cm) soil, TOC content ranged between 0.82 and 1.13%, but the treatments did not differ significantly (Table 4.3).

Walkley and Black carbon

Use of fertilizer NPK at soil test-based recommended rate to both the crops resulted in higher contents (0.35%) of Walkley and Black carbon (WBC) compared with control (0.30%) in 0-15 cm layer, and inclusion of FYM or SPM in fertilization schedule, further increased the WBC content by 23-26% over NPK (Table 4.2). The ID treatment imposed over NPK was not as effective as FYM or SPM in increasing WBC, but when imposed over NPK+FYM or NPK+SPM, a significant increase in WBC over NPK or NPK+ID was recorded. The WBC content was highest (0.50%) under

NPK+FYM+ID, followed by NPK+SPM+ID (0.46%) and the lowest under control. Use of organic manures alone (*i.e.* in absence of fertilizer) did not bring significant improvement in WBC over the fertilizer NPK treatments. The WBC content in sub-surface soil (15-30 cm) was relatively smaller (Table 4.3). Although the treatments that received FYM and ID along with NPK showed significantly greater WBC compared with NPK alone.

Microbial biomass carbon

Microbial biomass carbon (MBC) fraction in surface soil ranged between 174 mg kg^{-1} in control and 410 mg kg^{-1} in NPK+FYM+ID treatment (Table 4.2). The corresponding values for sub-surface soil were 96 and 224 mg kg^{-1}, respectively (Table 4.3). Use of FYM, SPM or ID along with NPK brought a significant increase in MBC content of surface soil compared with sole NPK to the extent of 63, 34 and 46%, respectively, although the soil MBC contents under organics alone were statistically similar with NPK. Treatments NPK+FYM and NPK+SPM differed significantly, with relatively higher MBC under FYM treatment, but the difference was not significant when ID was imposed over these IPNS treatments.

Microbial quotient (MQ) was invariably greater under IPNS treatments (Fig. 4.1). The MQ values were highest in treatments receiving ID along with NPK+manure, which in fact indicated the advantage of these nutrient management options in improving the relative proportion of MBC for each unit of TOC.

Labile carbon

In case of labile carbon (LBC), a significant increase over sole NPK treatment was recorded in 0-15 cm soil when NPK was supplemented with organic manures or ID (Table 4.2); the magnitude of increase was, however, highest (47%) with ID followed by 37% with FYM and 24% with SPM. The highest value of LBC was recorded under NPK+FYM+ID, which were closely (not significantly) followed by NPK+SPM+ID; registering 78% and 61% increase over NPK, respectively. In the 15-30 cm soil layer (Table 4.3), LBC content was much lower than 0-15 cm soil and, the ID imposed with

NPK or NPK+manure treatment showed substantial increase in LBC content compared with no-ID treatments.

Particulate organic carbon

The physically protected fraction termed as particulate organic carbon (POC) ranged from 0.38 to 0.96% in 0-15 cm, and 0.13 to 0.37% in 15-30 cm soil under different nutrient supply options (Table 4.2 and 4.3). Chemical fertilization alone did not improve POC significantly over control, but organics or ID used along with NPK brought significant increase in POC over sole NPK treatment or unfertilized-control, especially in 0-15 cm soil layer. The increase in POC under different treatments was in the order: NPK+FYM+ID > NPK+SPM+ID > NPK+FYM > NPK+SPM > NPK+ID > NPK.

4.3.3. Contribution of different fractions to total organic carbon

The proportion of WBC, MBC and LBC to TOC under different treatments in 0-15 cm soil varied from 17 to 22, 1.0 to 1.8 and 6.7 to 11.8%, respectively (Fig 4.2a). The corresponding proportion of these fractions in 15-30 cm soil was 14 to 19, 0.8 to 1.6 and 5.1 to 7.6%, respectively (Fig. 4.2b). The treatment effects were inconsistent in case of WBC, but the proportion of MBC in 0-15 cm layer and that of LBC in both the layers (0-15 and 15-30 cm) was invariably greater under conjoint use of NPK and organic manures compared with sole application of NPK or organic manures. The proportion of LBC fraction to TOC was substantially increased under ID treatment.

4.3.4. Carbon management index

Carbon management index (CMI) computed to evaluate the effect of nutrient supply *vis-à-vis* unfertilized-control on changes in SOC stocks revealed marked variation among the treatments (Fig. 4.3). Highest value of CMI was recorded under NPK+ FYM+ID, followed by NPK+ FYM, NPK+SPM+ID and NPK+SPM. The CMI for NPK+ID was apparently greater than that for NPK, but application of organic manures alone led to lower CMI compared with NPK.

4.3.5. Inter-relationships between SOC fractions

All the SOC fractions were correlated with each other significantly mostly at *P*=0.01 level, in surface as well as sub-surface soil (Tables 4.4 and 4.5). Nonetheless, correlation coefficients (r-values) of different fractions with TOC were comparatively lower than those pertaining to correlations between other SOC fractions, more so in the surface soil.

Highly significant linear relationships of WBC with MBC (Fig. 4.4a) and LBC with WBC (Fig. 4.4b) revealed the possibilities of prediction of MBC and LBC from the WBC contents particularly in surface soil. Similarly, positive relationship between TOC and MBC, LBC and MBC, POC and MBC, and POC and WBC are illustrated in Fig. 4.5a and 4.5b, and Fig. 4.6a and 4.6b, which could help in prediction of different SOC fractions. In most cases, the relationships were stronger in surface than in sub-surface soil.

4.3.6. Aggregate-associated total organic carbon

Total organic carbon (TOC) associated with different aggregate-size fractions in 0-15 cm and 15-30 cm soil depths are given in Tables 4.6 and 4.7. In general, larger the aggregate size, higher was the TOC content, except for 2.0-1.0 mm aggregates, wherein the TOC content was lower than 0.1-0.5 mm aggregates in both the soil depths. Treatment effects were more pronounced in the case of relatively large aggregates, especially in surface soil where application of organics alone or in combination of fertilizer NPK resulted in a significant change in TOC compared with NPK or control, and the contents were highest under NPK+FYM+ID. Changes in aggregate associated TOC owing to nutrient management options tended to become more inconsistent with a decrease in aggregate size, as also with increasing soil depth.

Different aggregate size fractions were grouped into macro-aggregates (8.0-4.0 mm to 0.5-0.2 mm) and micro-aggregates (0.2-1.0 mm), and the TOC associated with these groups of aggregates is illustrated in Fig. 4.7a and 4.7b. Both macro-aggregate associated TOC (MaTOC) and micro-aggregate associated TOC (MiTOC) were greater in IPNS treatments, particularly under NPM+FYM+ID, compared with application

NPK or manure in isolation. Not only the TOC contents (MaTOC and MiTOC) were higher in surface soil but the treatment effects were also consistent.

4.3.7. Oxidizable organic carbon fractions

Oxidizable organic carbon (OOC) determined with modified Walkley and Black method as suggested by Chan *et al.* (2001) was grouped into 4 fractions *viz,* very labile C (C_{VL}), labile C (C_L), less labile C (C_{LL}) and non-labile C (C_{NL}) and the values of these fractions in surface and sub-surface soil are presented in Tables 4.8 and 4.9, respectively. Application of fertilizer NPK increased C_{VL} and C_L fractions significantly over control in the surface soil, and a further significant increase in these fractions was recorded with inclusion of manures and or induced defoliation. Among the organic sources applied along with NPK, the extent of increase in C_{VL} fraction over sole NPK was in the order: ID (88%) > FYM (70%) > SPM (65%). This order for C_L was: FYM (19%) > ID (10%) > SPM (9%). The other two fractions *i.e.* C_{LL} and C_{NL} were apparently greater under NPK+FYM treatments, whereas the effect of SPM or ID was not spectacular. In sub-surface layer, variations between treatments were generally inconsistent.

Lability index (LI)

The LI, computed by adding the proportions of the OOC fractions of variable lability to the TOC after assigning suitable weightages as proposed by Majumder *et al.* (2008) is depicted in Fig. 4.8. Data revealed the highest values of LI under NPK+ID followed by treatments receiving FYM with or without ID, indicating that these treatments maintained relatively higher amount of C in active (*i.e.* labile + very labile) pools compared with NPK, NPK+SPM or unfertilized-control.

4.3.8. Mineral N content

Ammonium-N and NO_3-N contents in surface soil ranged between 14 and 59 mg kg^{-1} and 9 and 44 mg kg^{-1}, respectively under different treatments (Fig. 4.9). These values in sub-surface soil were 10 and 32 mg kg^{-1} and 7 and 25 mg kg^{-1}, respectively. The lowest values of mineral N were recorded in unfertilized-control, which were significantly increased with fertilizer application. In IPNS options, use of FYM, SPM or ID along with NPK increased NH_4-N over NPK treatment by 52, 63 and 70%, respectively. The corresponding increase in NO_3-N was relatively greater. The mineral N contents were highest under NPK+SPM+ID, followed by NPK+FYM+ID in both soil layers.

Different SOC fractions showed significant and positive relationship with NH_4-N and NO_3-N contents in surface soil (Table 4.10). Relatively higher values of coefficients of correlation (r-values) were registered with LBC and WBC fractions, whereas the same were lowest with TOC. Linear relationships of mineral N (NH_4-N + NO_3-N) with WBC and LBC are also depicted in Fig. 4.10a and 4.10b.

4.3.9 Pigeonpea and wheat yields

During the fifth and terminal crop cycle (2008-09), application of soil test-based recommended NPK produced 1.88 t ha^{-1} of pigeonpea grain that was significantly greater than FYM or SPM used alone (0.90-1.16 t ha^{-1}), or unfertilized-control (0.74 t ha^{-1}) (Fig. 4.11). Conjoint use of NPK and organics, however, gave an additional yield of 0.24 to 0.42 t ha^{-1} over sole NPK. Induced defoliation (ID) did not affect pigeonpea yield. In case of wheat, the yield gain due to NPK over control was 2.30 t ha^{-1}, and use of organics along with NPK further increased the yield response by 0.66 to 1.18 t ha^{-1}. Addition of pigeonpea leaf litter to the soil owing to ID increased the wheat yield by 0.45 t ha^{-1}. Highest wheat yield (5.62 t ha^{-1}) was obtained with NPK+SPM+ID, followed by NPK+FYM+ID (5.28 t ha^{-1}), and these treatments did not differ significantly from each other.

Highly significant and positive relationships of wheat yield with SOC fractions *viz*. WBC, MBC, LBC and POC in surface soil were registered (Table 4.10). The relationship between wheat yield and TOC, though significant, was not as robust as that in case of other fractions.

4.4. Discussion

Soils of the IGPR are inherently low in organic matter and N content (Yadav *et al.* 2000b). Nonetheless, these soils may support high productivity with the application of nutrients in adequate amounts through fertilizers and manures. A desirable nutrient management practice would be one that sustains reasonably high yield levels and simultaneously helps in fertility status, especially soil organic carbon (SOC) stocks (Sleutel *et al.* 2006). In the present investigation, different nutrient management practices were evaluated in pigeonpea-wheat sequence on a sandy loam (Typic Haplustept) in terms of their effect on SOC fractions, mineral N content and crop yields. Changes in total organic C (TOC) due to NPK fertilization over unfertilized-control or those due to organics (FYM or SPM) alone over NPK were not significant, even after completion of five cropping cycles (Table 4.2). Changes in TOC are generally large and more apparent when natural ecosystems are converted to arable farming (Katyal 2001; Dhaliwal 2003). Soil management practices within agriculture systems, on the other hand, bring too small changes in TOC content of the soil to be measured over short-term because of large quantity of background organic matter already present in the soil (Elliot 1986). Thus, a marked change in soil TOC owing to usual fertilization practices is not expected during the short period of five years. The increase in TOC content of soil (0-15 cm) as observed under conjoint use of fertilizers and organics in the present case may be attributed to recycling of additional roots, above ground residues and stubble due to higher biomass production in these treatments, in addition to the C added through manures (Manjaiah and Singh 2001; Majumder *et al.* 2008). The values of TOC and all other SOC fractions were greater in surface (0-15 cm) than sub-surface (15-30 cm) soil across the treatments, obviously due to higher residue recycling and other biological activities in this soil layer (Gupta *et al.* 1994; Potter *et al.* 1998; Singh *et al.* 2010). There were no significant changes in TOC as compared to NPK in case of induced defoliation (ID), which is due to lower C/N ratio of leaves leading to rapid mineralization and subsequent loss of C as CO_2. Compared to TOC, Walkley and Black C (WBC) was more sensitive to change in nutrient management, due to the fact that dichromate method adopted for determination of WBC uses the heat of dilution or minimal heating which does not allow complete oxidation of organic matter in soil, although the most reactive forms of organic carbon are converted to CO_2 (Page *et al.* 1982). Significant increase in WBC due to NPK fertilization over control as noticed in this study is substantiated with long-term studies, which showed advantage of balanced fertilizer use in improving WBC content on several sites in the IGPR (Yadav *et al.* 2000a; Swarup and Wanjari 2000). Greater increase in soil WBC content in FYM treatments compared to SPM observed in the present case is understandable because the later is not as rich carbon source as FYM. The proportion of WBC to TOC in our case ranged between 17 and 22% in different treatments, which is very low compared to generally reported values. In earlier studies involving different land uses and agricultural management practices, WBC on average accounted for 25.4% of the TOC (Verma 2006). Chemical recalcitrance of residues (*i.e.* higher lignin and polyphenol contents), physical recalcitrance (*i.e.* aggregate protection) and organo-mineral complexation may provide some explanation to such a low recovery of WBC. Nonetheless, this aspect needs to be further investigated.

Both 333 m*M* $KMnO_4$-oxidizable labile C (LBC) and microbial biomass C (MBC) were significantly greater in surface soil under NPK+organics treatments compared with sole NPK, although the extent of increase in these fractions of SOC differed in accordance with the nature of organic C input (Table 4.2). Whereas increase in MBC was more associated with FYM treatments, the effect of ID was greater on LBC. These fractions are considered more sensitive to change in management practices than TOC or other fractions of SOC (Blair *et al.* 1995; Conteh *et al.* 1999; Graham *et al.* 2002; Haynes 2005), and the present findings on the positive effect of LBC and MBC contents get support from several workers (Ismail *et al.* 1994; Graham *et al.* 2002; Buchnan and King 1992; Rudrappa *et al.* 2006). Since application of organic manures adds substantial amount of organic matter to the soil, $KMnO_4$ extracted higher amounts of LBC from manure/fertilizer treatments than from control (Fig 4.2), as this reagent extracts relatively younger organic compounds including labile humic materials and polysaccharides (Conteh *et al.* 1999; Haynes 2005). Relatively greater increase in LBC due to ID is also explainable, as the pigeonpea leaf litter added in ID was an easily decomposable (narrow C/N ratio) material that led to a faster change in LBC compared with SPM and FYM. Recent studies by Verma *et al.* (2010), in fact, suggested LBC as a more sensitive and consistent index of labile pool of SOC compared with MBC. Similarly, significant increase in particulate organic C (POC) under NPK or NPK +organics treatments over unfertilized-control (Table 4.2) may be attributed to greater amount of fresh plant residues and humified organic matter in these treatments (Gregorich and Janzen 1996). This fraction primarily composed of plant debris with a recognizable cellular structure, fungal hyphae, spores, faunal skeleton *etc*. (Spycher *et al*.1983; Skjemstad *et al.* 1990), has a short turnover time and thus serves as an important source of carbon and nutrients.

An alternative approach of determining oxidizable SOC fractions using modified Walkley and Black method, and their categorization into different lability groups as proposed by Chan *et al.* (2001) was also attempted in the present study, which gave interesting results. Whereas organic manures (FYM and SPM) brought greater increase in labile (C_L) and less labile (C_{LL}) fractions, pigeonpea leaf litter addition through ID resulted in a greater increase in the very libile (C_{VL}) fractions (Table 4.8). The higher lability of SOC in ID treatments could help in explaining the significant wheat yield responses to ID over NPK despite relatively small C inputs (compared with C inputs through FYM or SPM). A further grouping of oxidizable organic C fractions into active (C_{VL} + C_L) and passive (C_{LL} + non-labile C *i.e.* C_{NL}) pools as suggested by Mandal *et al.* (2008) revealed that the active pool had highly significant linear relationship with wheat yield and mineral N content of the surface soil (Fig. 4.12).

Although the proportion of SOC in active pool under different treatments in the present study was smaller than that reported by Chan *et al.* (2001) for pasture systems in Australia, the oxidizable organic C fractions, especially C_{VL} and C_L, may prove useful index for detecting small changes in SOC due to management, which might otherwise go unnoticed. Further detailed studies under different soils and cropping systems are needed to evaluate the sensitivity of these fractions *vis-à-vis* others like MBC (Jenkinson and Ladd 1981) and LBC (Blair *et al.* 1995).

Induced defoliation (ID) in pigeonpea was attempted in this investigation as a non-conventional approach of legume residue (leaf litter) recycling. In fact, genetic improvements in recent years though led to shortening of pigeonpea duration making possible to grow it in rotation with wheat (*i.e.* pigeonpea-wheat annual crop sequence), yet extra-short duration varieties of pigeonpea still have fair degree of perennial characteristic of retaining substantial amount of green foliage at maturity (Sheldrake 1974). As much of the N retained in the non-grain portion of the crop remains confined to the green leaf containing about 4% N (Sheldrake and Narayanan 1979), defoliation and subsequent incorporation of these retained leaves at maturity may increase residual benefit to the subsequent wheat crop. The ID resulted in the incorporation of 1.2 to 1.4 t ha^{-1} additional leaf litter over the natural senescence under non-ID treatments. Substantial increase in soil mineral N contents particularly in surface layer under ID (Fig. 4.9) is very much expected, for the additional leaf litter recycled in this treatment not only added about 50 kg N ha^{-1}, but also the N and other nutrients contained therein were possibly released faster (due to narrow C/N ratio) compared with FYM and SPM. Studies on the effect of ID on crop yield and soil properties are not many, yet the limited available literature (Chauhan *et al.* 2001) supports the findings of this investigation. Highest wheat yields and mineral N contents were registered under NPK+SPM+ID, although most of the SOC fractions were highest under NPK+FYM+ID. These contradictions are also explainable, because SPM is a rich nutrient source (containing about 3 times greater N, P and K than FYM) whereas annual carbon inputs were relatively higher in treatments involving FYM.

4.5 Conclusion

The results of the present study inferred that inclusion of organic manures, particularly FYM, in fertilization schedule is beneficial to improve SOC and mineral N levels in pigeonpea-wheat sequence. Addition of pigeonpea leaf-litter through induced defoliation enhanced labile SOC fractions greater than the organic manures, and augmented the wheat yield when imposed in the recommended NPK or NPK+organics plots. Sulphitation pressmud (SPM), on the other hand, proved a good nutrient source to enhance the yield, but its effect on SOC fractions was not as pronounced as FYM. Fractions of oxidizable organic carbon (Chan *et al.* 2001) needs to be compared with LBC (Blair *et al.* 1995) in diverse soil and crop management conditions to evaluate their utility/sensitivity to detect management-induced smaller changes in SOC levels.

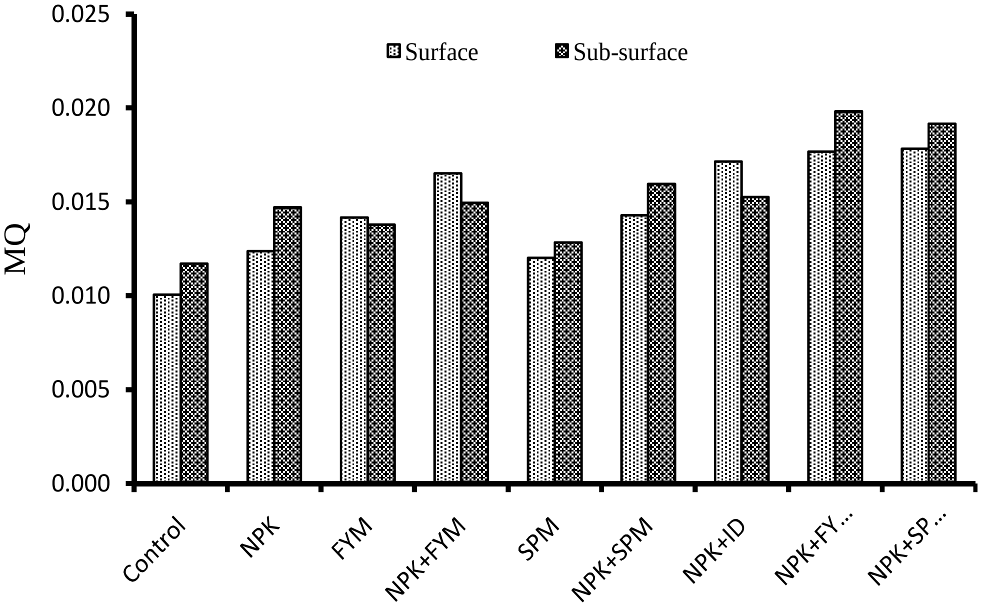
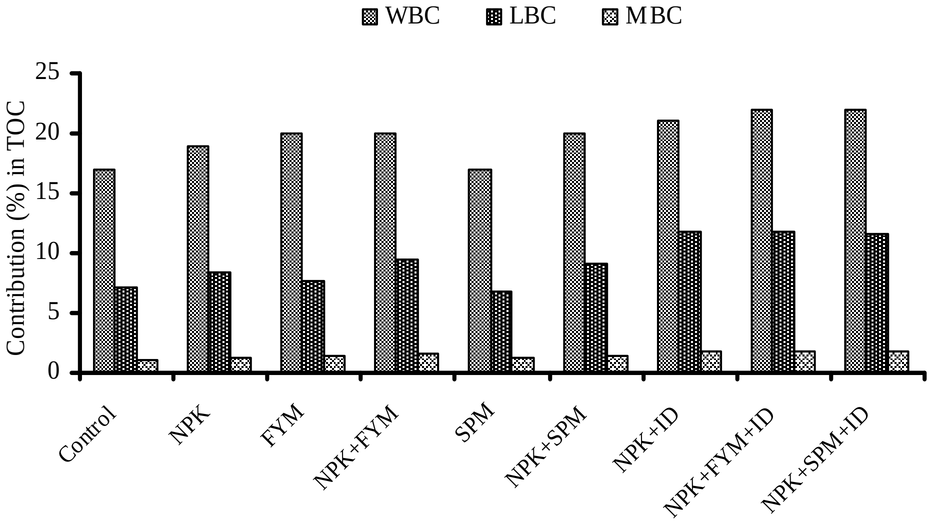


Fig. 4.1. Effect of nutrient management on microbial quotient (MQ) in surface and sub-surface soil

(a) Surface soil



(b) Sub-surface soil

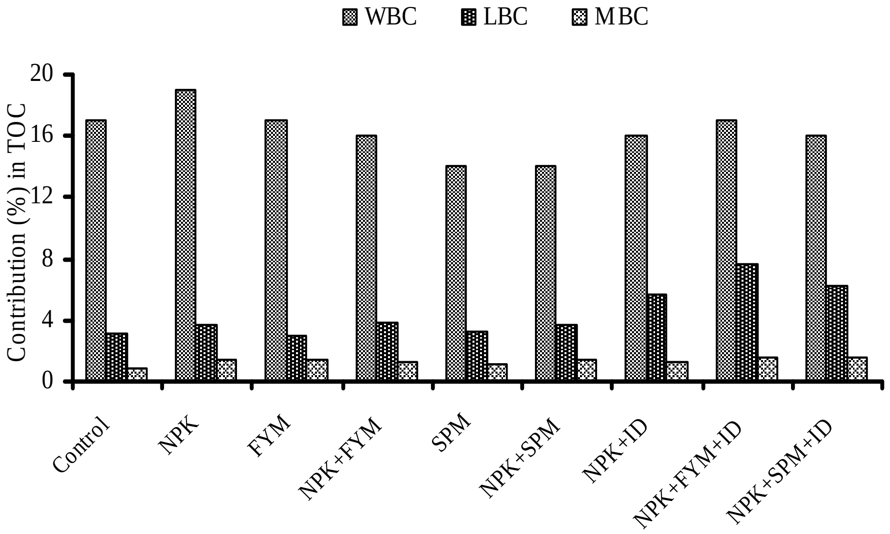


Fig. 4.2. Organic carbon fractions as proportion of TOC in (a) surface, and (b) sub-surface soil layers

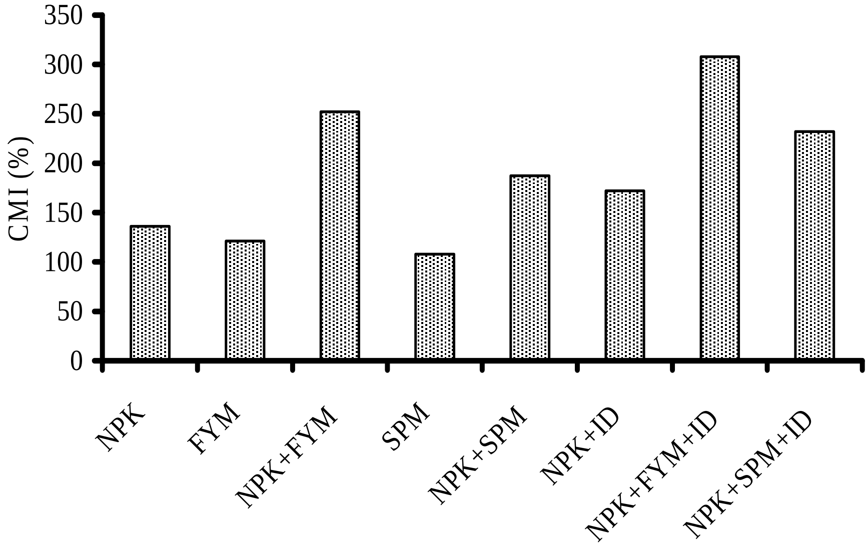
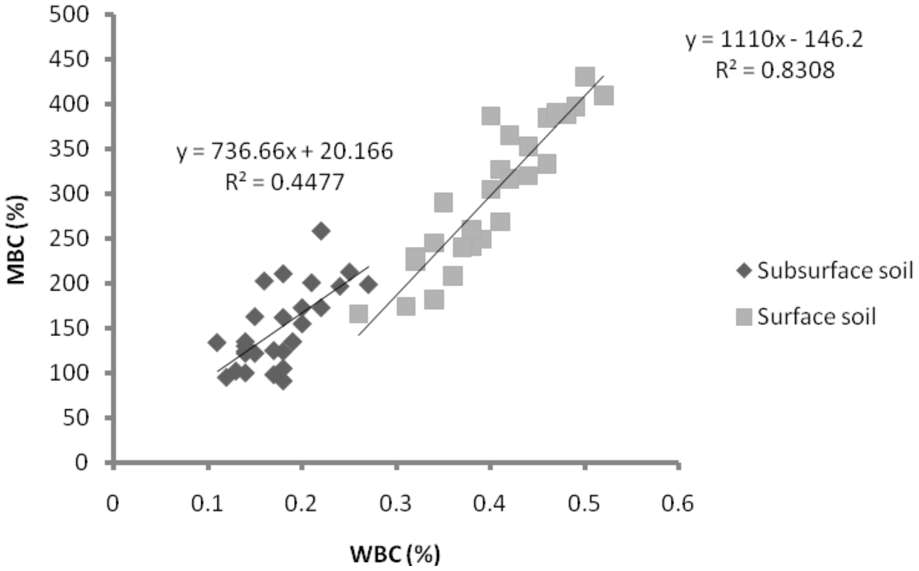


Fig. 4.3. Carbon management index (CMI) in surface soil as influenced by different nutrient supply options

(a) WBC *vs* MBC



(a) LBC *vs* WBC

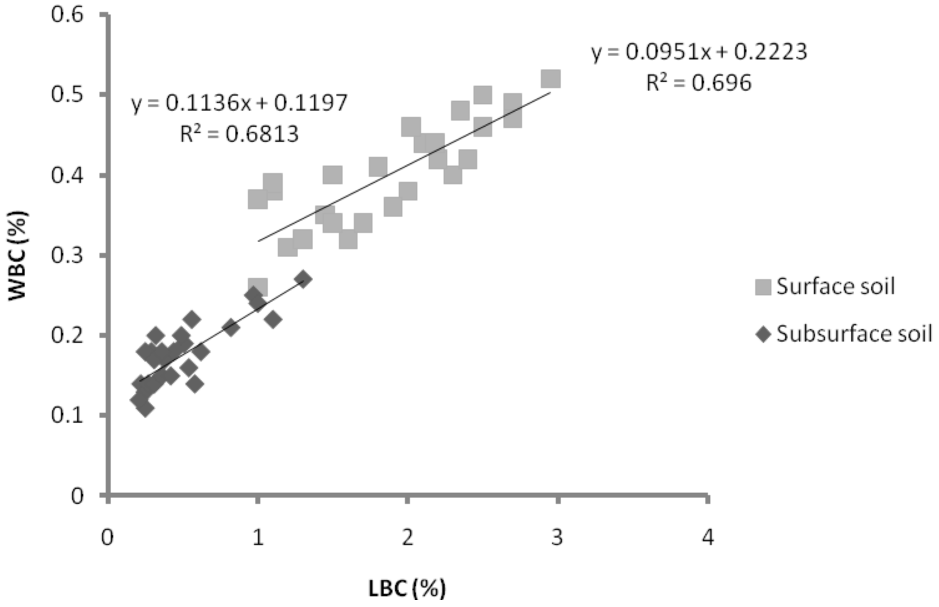
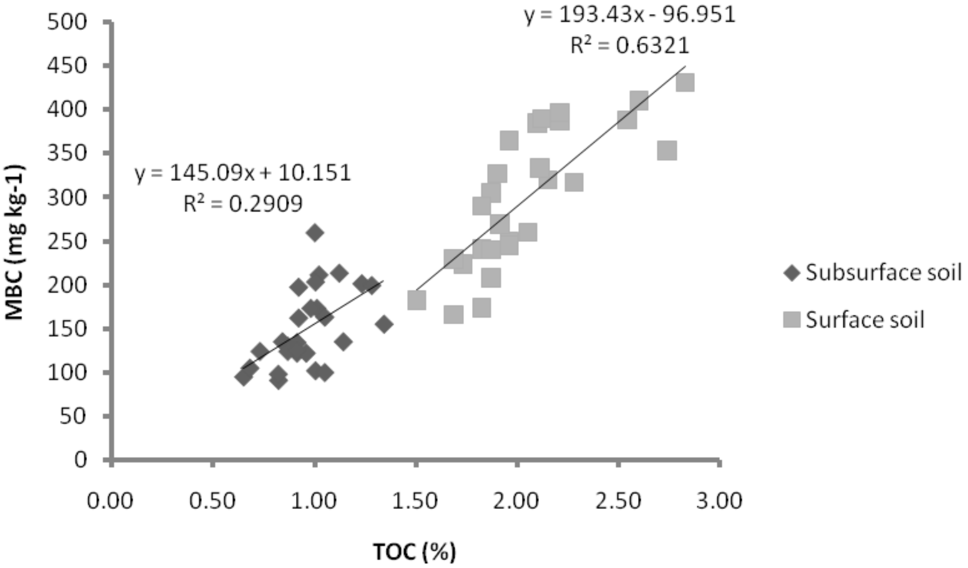


Fig. 4.4. Scatter diagrams showing linear relationship between (a) WBC and MBC, and (b) LBC and WBC in surface and sub-surface soil.

(a) TOC *vs* MBC



(b) LBC *vs* MBC

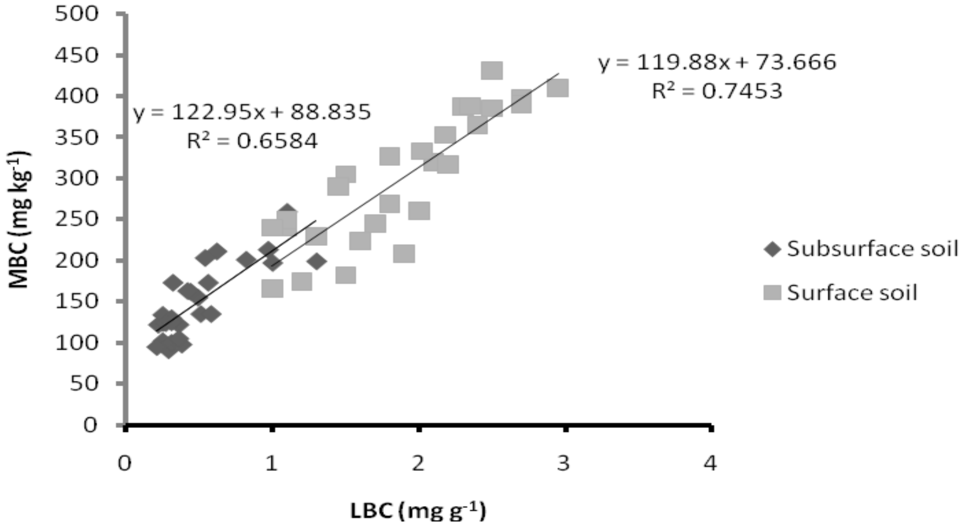
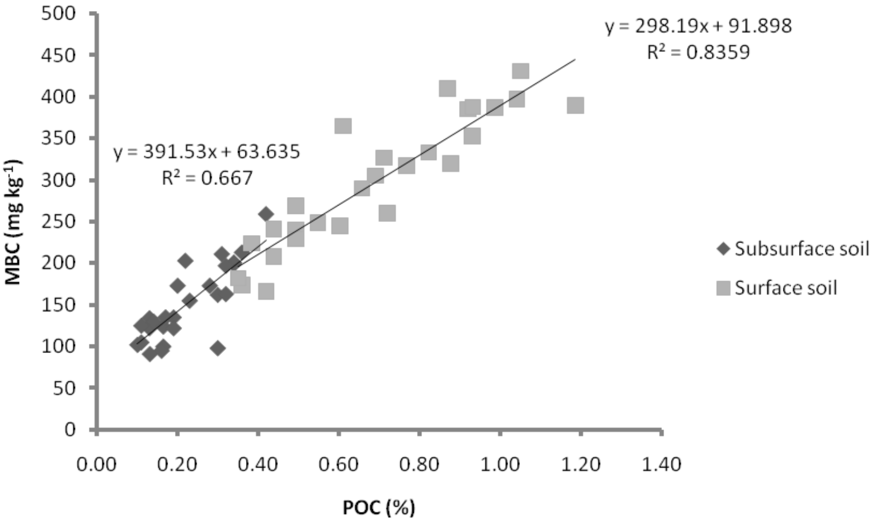


Fig. 4.5. Scatter diagrams showing relationship between (a) TOC and MBC, and (b) LBC and MBC in surface and sub-surface soil.

(a) POC *vs* MBC



(b) POC *vs* WBC

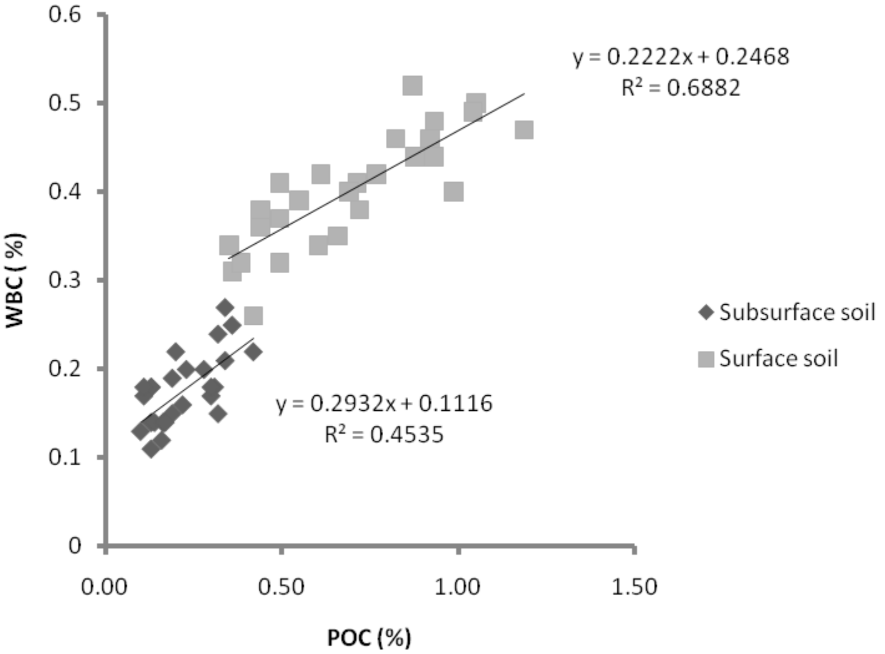
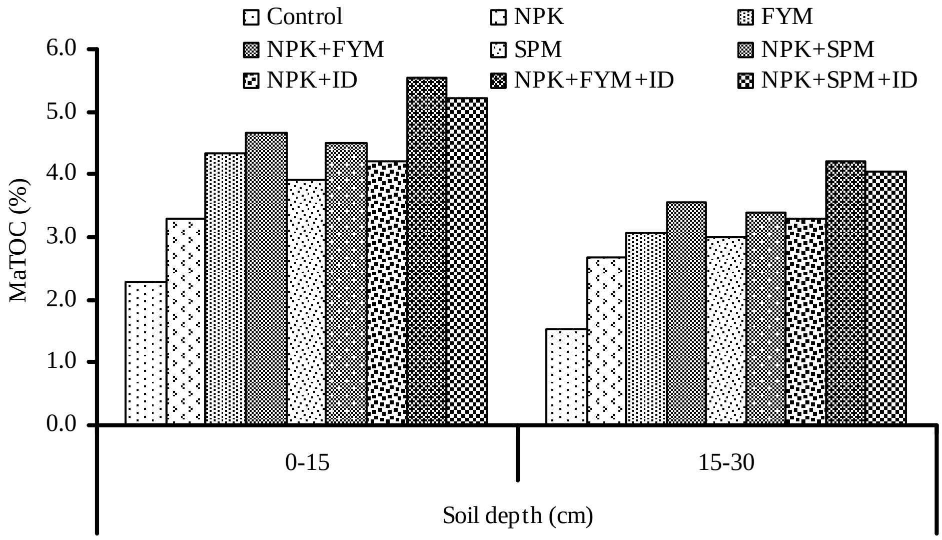


Fig.4.6. Scatter diagrams showing relationship of POC with (a) MBC and (b) WBC in surface and sub-surface soil.

(a) Macro-aggregate associated TOC (MaTOC)



(b) Micro-aggregate associated TOC (MiTOC)

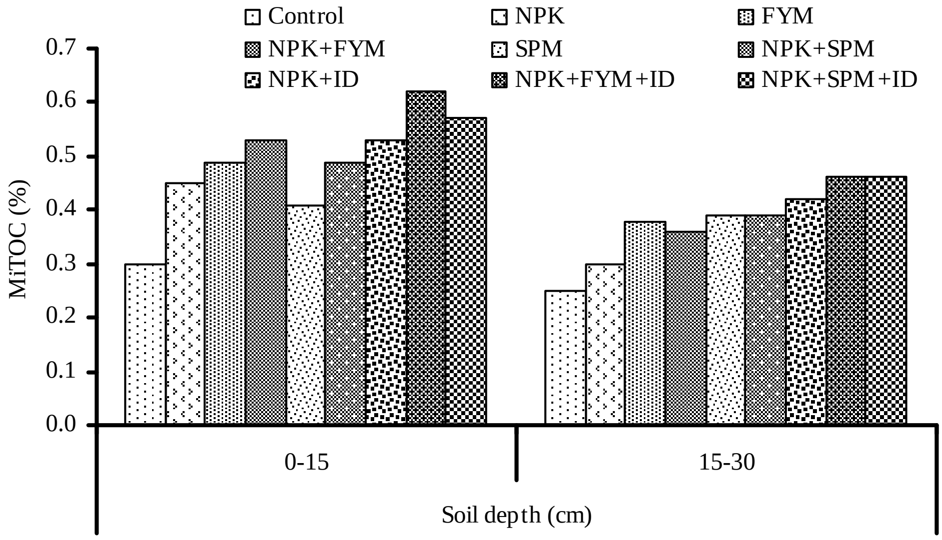


Fig. 4.7. Aggregate-associated total organic carbon under different nutrient management practices

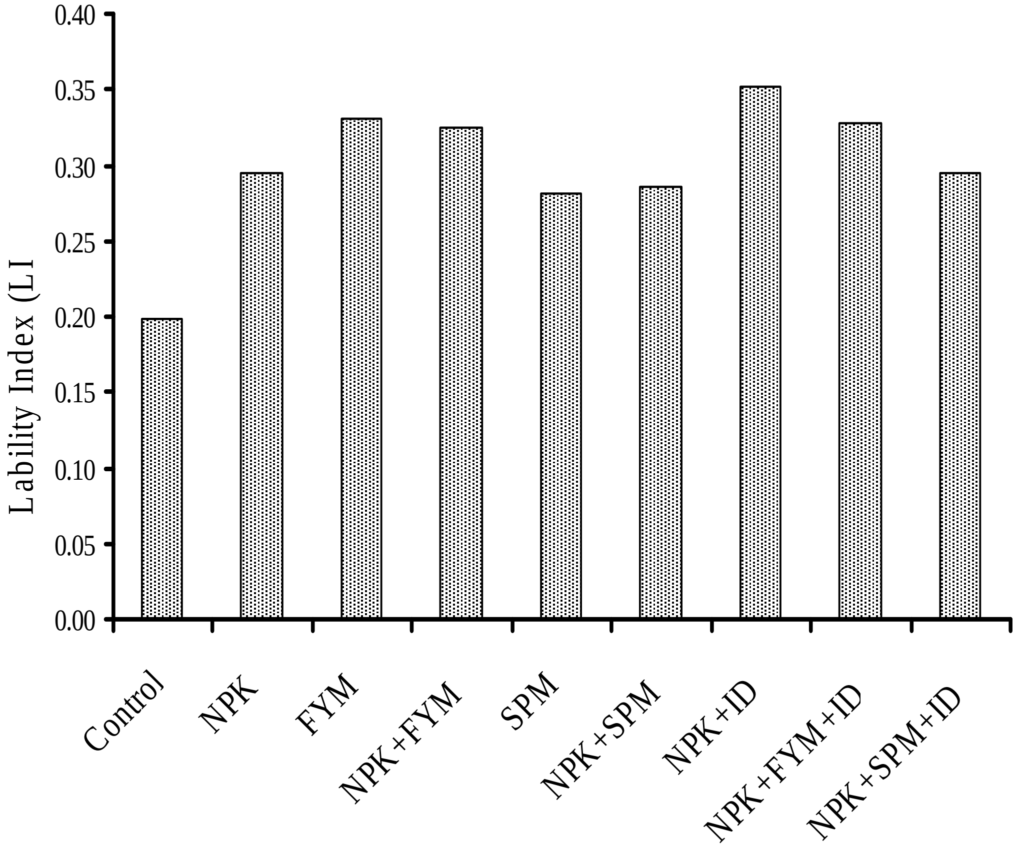
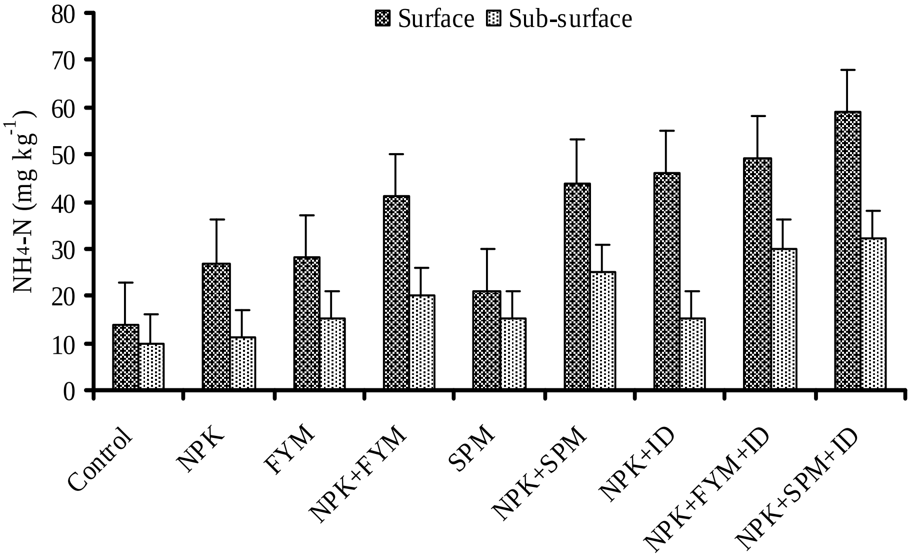


Fig. 4.8. Carbon lability index (LI) in surface soil under different nutrient management options

(a) NH_4-N content



(b) NO_3-N content

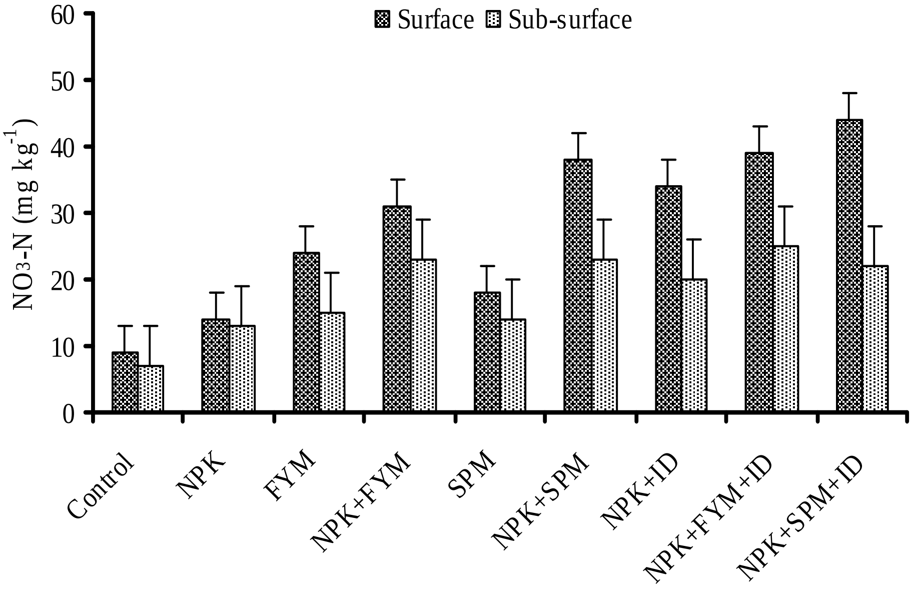
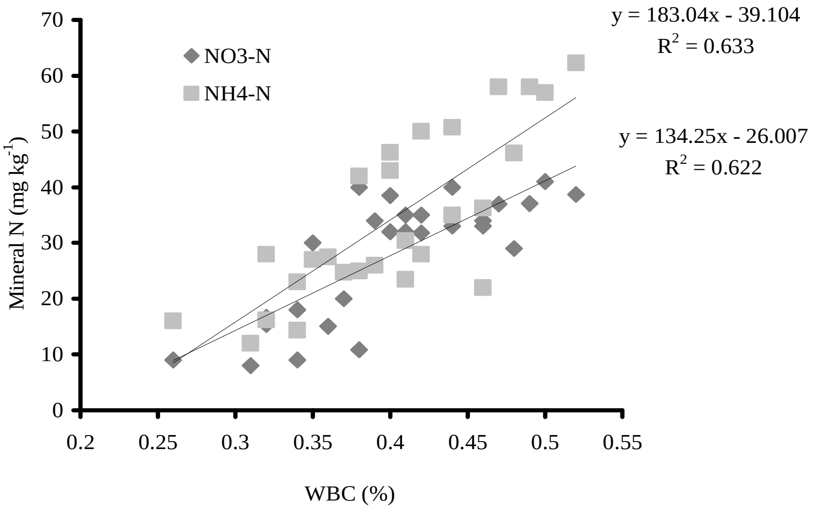


Fig. 4.9. Effect of nutrient management options on mineral N content (mg kg^{-1}) in surface and sub-surface soil layers. Error bars indicate LSD (*P*=0.05).

(a) MBC *vs* Mineral-N



(b) LBC *vs* Mineral-N

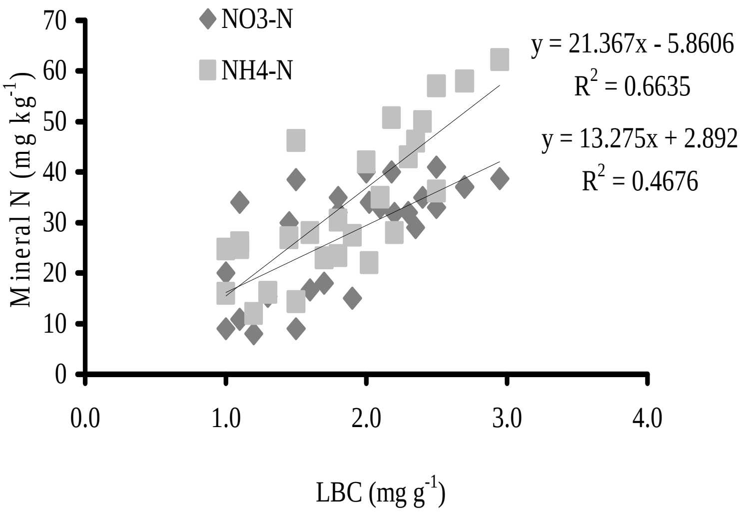


Fig. 4.10. Scatter diagrams showing linear relationship between SOC fractions and mineral N in 0-15 cm soil depth

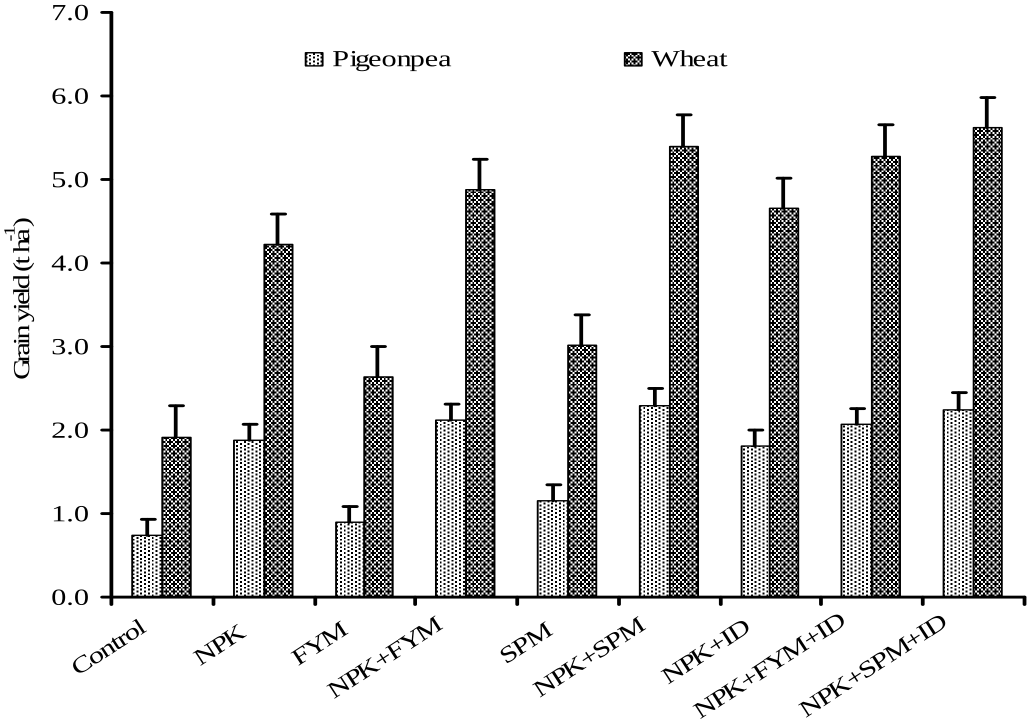
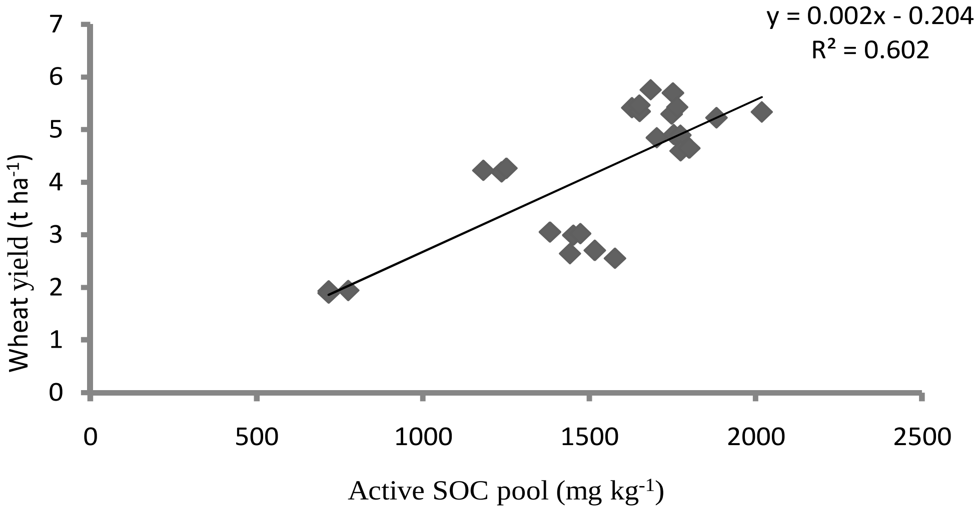


Fig. 4.11. Grain yield of pigeonpea and wheat under different nutrient management options during fifth crop cycle (2008-09). Error bars indicate LSD (*P*=0.05).

(a) Wheat yield



(b) Mineral N content

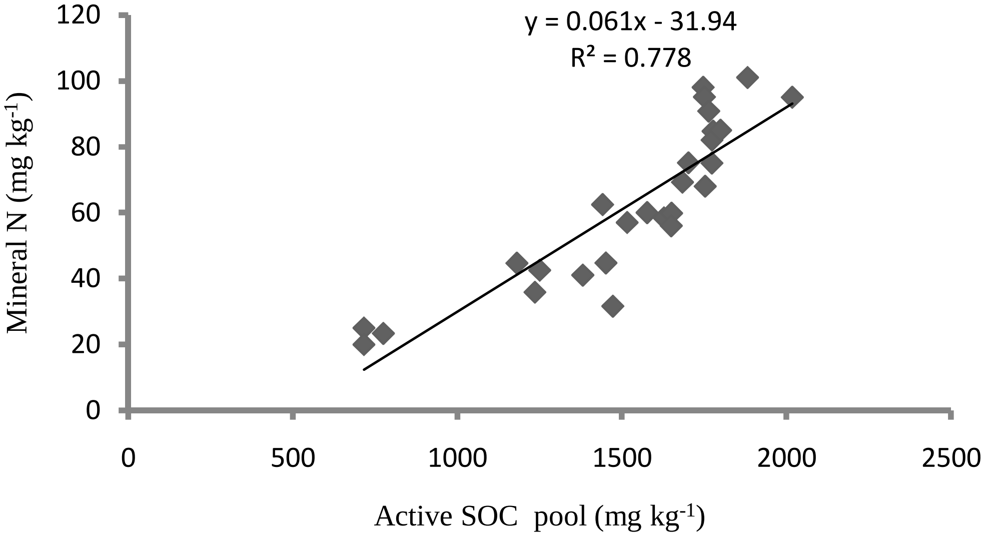


Fig. 4.12. Scatter diagrams showing relationship of active SOC pool (very labile + labile C) with (a) wheat yield, and (b) mineral N content of surface soil

Table 4.1. Changes in pH and EC in surface (0-15 cm) and sub-surface (15-30 cm) soil layers

Treatment	pH 1:2		EC (dS m^{-1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Control	8.36	8.46	0.29	0.22
NPK	8.35	8.46	0.28	0.21
FYM	8.33	8.44	0.27	0.18
NPK+FYM	8.30	8.38	0.26	0.17
SPM	8.40	8.42	0.31	0.25
NPK+SPM	8.20	8.33	0.28	0.24
NPK+ID	8.31	8.38	0.26	0.19
NPK+FYM+ID	8.29	8.36	0.27	0.21
NPK+SPM+ID	8.19	8.33	0.29	0.24
SEm (±)	0.3	0.05	0.01	0.01
LSD (*P*=0.05)	NS	NS	NS	NS

Table 4.2. Soil organic carbon fractions in surface (0-15 cm) soil as influenced by nutrient management practices in pigeonpea-wheat sequence

Treatment	Soil organic carbon fractions				
	WBC (%)	MBC (mg kg^{-1})	LBC (mg g^{-1})	POC (%)	TOC (%)
Control	0.30	174	1.23	0.38	1.73
NPK	0.35	224	1.53	0.42	1.81
FYM	0.38	269	1.45	0.57	1.90
NPK+FYM	0.44	365	2.10	0.93	2.21
SPM	0.34	238	1.33	0.53	1.98
NPK+SPM	0.43	300	1.90	0.77	2.10
NPK+ID	0.40	326	2.25	0.67	1.90
NPK+FYM+ID	0.50	410	2.72	1.04	2.32
NPK+SPM+ID	0.46	378	2.46	0.96	2.12
SEm (±)	0.02	20	0.16	0.04	0.06
LSD (*P*=0.05)	0.05	60	0.47	0.14	0.19

Table 4.3. Soil organic carbon fractions in sub-surface (15-30 cm) soil as influenced by nutrient management practices in pigeonpea-wheat sequence

Treatment	Soil organic carbon fractions				
	WBC (%)	MBC (mg kg^{-1})	LBC (mg g^{-1})	POC (%)	TOC (%)
Control	0.14	96	0.25	0.13	0.82
NPK	0.16	125	0.31	0.15	0.85
FYM	0.15	124	0.27	0.13	0.90
NPK+FYM	0.20	163	0.50	0.24	1.09
SPM	0.14	113	0.31	0.13	0.88
NPK+SPM	0.16	158	0.37	0.19	0.99
NPK+ID	0.17	145	0.54	0.30	0.95
NPK+FYM+ID	0.25	224	1.12	0.37	1.13
NPK+SPM+ID	0.21	203	0.81	0.32	1.06
SEm (±)	0.01	13	0.05	0.02	0.09
LSD (*P*=0.05)	0.02	40	0.15	0.06	NS

Table 4.4. Inter-relationships of soil organic carbon fractions in surface (0-15 cm) soil

Treatment	Correlation coefficients (r-values)				
	TOC	WBC	MBC	LBC	POC
TOC	1.00				
WBC	0.91**	1.00			
MBC	0.89**	0.97**	1.00		
LBC	0.78*	0.93**	0.95**	1.00	
POC	0.95**	0.97**	0.97**	0.91**	1.00

*Significant at *P*= 0.05 ** Significant at *P*=0.01

Table 4.5. Inter-relationships of soil organic carbon fractions in sub-surface (15-30) soil

Treatment	Correlation coefficients (r-values)				
	TOC	POC	MBC	LBC	WBC
TOC	1.00				
POC	0.85**	1.00			
MBC	0.93**	0.91**	1.00		
LBC	0.86**	0.86**	0.96**	1.00	
WBC	0.91**	0.91**	0.95**	0.94**	1.00

** Significant at *P*=0.01

Table 4.6. Effect of nutrient management on aggregate-associated total organic carbon in surface (0-15 cm) soil

Treatment	Aggregate size (mm)					
	8.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	0.5-0.2	0.2-0.1
	Aggregate-associated TOC (%)					
Control	3.23	0.74	0.68	0.50	0.34	0.30
NPK	4.22	0.55	0.47	0.62	0.79	0.45
FYM	5.89	0.82	0.45	0.55	0.45	0.49
NPK+FYM	6.56	1.02	0.59	0.74	0.63	0.53
SPM	4.88	0.67	0.46	0.68	0.40	0.41
NPK+SPM	5.16	1.02	0.50	0.73	0.67	0.49
NPK+ID	5.30	0.88	0.65	0.85	0.63	0.53
NPK+FYM+ID	6.66	1.14	0.73	1.05	1.11	0.62
NPK+SPM+ID	5.65	1.02	0.75	0.92	0.78	0.57
SEm (±)	0.18	0.03	0.02	0.02	0.02	0.02
LSD (*P*=0.05)	0.58	0.09	0.07	0.09	0.05	0.07

Table 4.7. Effect of nutrient management on aggregate-associated total organic carbon in sub-surface (15 -30 cm) soil

Treatment	Aggregate size (mm)					
	8.0-4.0	4.0-2.0	2.0-1.0	1.0-0.5	0.5-0.2	0.2-0.1
	Aggregate-associated TOC (%)					
Control	2.27	0.40	0.34	0.34	0.22	0.25
NPK	3.22	0.53	0.50	0.65	0.32	0.30
FYM	3.97	0.59	0.42	0.49	0.43	0.38
NPK+FYM	4.30	0.68	0.45	0.45	0.48	0.36
SPM	3.52	0.46	0.40	0.57	0.40	0.39
NPK+SPM	3.68	0.55	0.40	0.68	0.49	0.39
NPK+ID	3.57	0.64	0.56	0.53	0.34	0.42
NPK+FYM+ID	4.48	0.75	0.50	0.73	0.38	0.46
NPK+SPM+ID	4.24	0.66	0.54	0.68	0.42	0.46
SEm (±)	0.12	0.02	0.02	0.02	0.01	0.01
LSD (*P*=0.05)	0.52	0.08	0.06	0.09	NS	0.06

Table 4.8. Fractions of oxidizable organic carbon in surface (0-15 cm) soil as influenced by nutrient management practices

Treatment	Organic carbon fractions (mg kg^{-1})			
	Very labile carbon (C_{VL})	Labile carbon (C_L)	Less labile carbon (C_{LL})	Non-labile carbon (C_{NL})
Control	380	355	1580	14900
NPK	561	661	2320	14322
FYM	974	537	2289	15100
NPK+FYM	955	788	2741	21133
SPM	888	547	1795	14567
NPK+SPM	925	718	1775	19678
NPK+ID	1055	729	2077	15600
NPK+FYM+ID	1017	865	2817	24233
NPK+SPM+ID	975	758	1823	23367
SEm (±)	41	20	132	473
LSD (*P*=0.05)	123	61	394	1417

Table 4.9. Fractions of oxidizable organic carbon in sub-surface (15-30 cm) soil as influenced by nutrient management practices

Treatment	Organic carbon fractions (mg kg^{-1})			
	Very labile carbon (C_{VL})	Labile carbon (C_L)	Less labile carbon (C_{LL})	Non-labile carbon (C_{NL})
Control	284	254	805	7267
NPK	392	359	630	6967
FYM	428	436	1098	6133
NPK+FYM	478	494	906	10933
SPM	516	430	1129	7067
NPK+SPM	554	465	1141	8700
NPK+ID	478	411	1193	7667
NPK+FYM+ID	523	531	904	12300
NPK+SPM+ID	593	501	720	10967
SEm (±)	16	14	32	288
LSD (*P*=0.05)	49	44	94	870

Table 4.10. Relationships of soil organic carbon fractions with mineral N and crop yields

Treatment	Correlation coefficients (r-values)			
	NH_4-N	NO_3-N	Wheat yield	Pigeonpea yield
TOC	0.72*	0.71*	0.74*	0.69*
WBC	0.87**	0.88**	0.86**	0.79*
MBC	0.83**	0.98**	0.82**	0.74*
LBC	0.96**	0.83**	0.86**	0.79*
POC	0.84**	0.82**	0.81**	0.74*
NH_4-N	1.00	0.79*	0.72*	0.64
NO_3-N	0.79*	1.00	0.71*	0.61
Wheat yield	0.72*	0.64	1.00	0.98**
Pigeonpea yield	0.64	0.61	0.98**	1.00

* Significant at *P*= 0.05, ** Significant at *P*=0.01

5. RESEARCH PAPER-II

Soil hydro-physical properties under different nutrient management practices, and their relationship with soil organic carbon fractions and yield under pigeonpea-wheat sequence

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Abstract

Soil physical degradation owing mainly to intensive cereal-cereal cropping, low organic matter input and excess traffic is one of the serious production constraints in several agriculturally important areas of the world including the Indo-Gangetic Plain region. The present investigation was therefore, undertaken to study the effect of different nutrient management practices involving the use of fertilizer NPK alone or in combination with FYM, sulphitation pressmud (SPM) or induced defoliation (ID, imposed in pigeonpea through foliar spray of 10% urea solution at physiological maturity) on soil hydro-physical properties of a Typic Haplustept under pigeonpea-wheat sequence, in a field experiment that continued for five years (2004-05 to 2008-09) at IARI, New Delhi. Application of fertilizer NPK at recommended rate to both the crops resulted in a significant increase in macro-aggregates, mean weight diameter, geometric mean diameter, water-stable aggregates and saturated hydraulic conductivity in surface soil compared with unfertilized-control. Supplementing fertilizer NPK with organic manures and/or ID brought further improvement in above hydro-physical properties. Conjoint use of fertilizers, organic manures and ID also decreased soil bulk density (0-15 cm) significantly over control. Effectiveness of organics and ID in improving soil physical environment was in the order: FYM>ID>SPM. The hydro-physical properties showed significant correlations with different soil organic carbon (SOC) fractions and crop yields.

Key words: Mean weight diameter; macro-aggregates; water-stable aggregates; bulk density; saturated hydraulic conductivity, pigeonpea-wheat, Typic Haplustept

5.1. Introduction

The fatigue in agricultural production noticed in the post-Green Revolution era, particularly after 1980s, is often linked to deterioration in soil health (Yadav *et al.* 2000; Swaminathan 2006). But when it comes to evaluating the effect of soil management or land uses on soil health, the studies mostly remain confined to soil fertility status. On the other hand, deterioration of soil physical properties under intensive cropping, more so in the rice-wheat dominated Indo-Gangetic Plain region, (IGPR) are posing serious problems to the productivity of non-rice crops (Boparai *et al.* 1992; Singh *et al.* 2005; Bhushan *et al.* 2007). In fact, soil compaction has emerged as a global problem and is an important form of physical land degradation (Hassan *et al.* 2007), caused mainly due to repeated use of heavy machinery, reduced use of organic manures, and ploughing at the same depth for many years (Flowers and Lal 1998). Compaction causes unfavourable changes in soil bulk density, porosity and penetration resistance (Soane *et al.* 1981), which results in restricted root growth that in turn may affect whole plant growth and yield (Jorajuria *et al.* 1997; Oussible *et al*. 1992).

Soil hydro-physical properties (Liu *et al.* 2000) are important for both crop growth and maintaining soil quality. Studies have shown that the organic matter has regulatory role over numerous physical soil features like pH, bulk density, hydraulic conductivity, aggregate stability, and erosion susceptibility. Loss of organic matter could cause soil aggregates to break down easily and accordingly become more erodible (Jastrow 1996). Parallel to the increases in soil organic matter, soil porosity increased, while bulk density and soil erodibility decreased (Cerda 1996). Use of organic manures improves soil structure (Choudhury and Ghildyal 1969) and aggregate stability (Sarkar and Rathore 1992) as well as moisture retention capacity (Bhagat and Verma 1991) and infiltration rate (Tiwari *et al.* 1998). However, effects of manures and plant residues on soil physical properties, particularly soil aggregates, depend on their decomposition, nutrient release rate, and the amount applied (Tian *et al.* 1995). Plant residues that decompose quickly will provide crops with a large amount of nutrients in early stage of crop growth, but may not have an effect on soil physical condition, whereas slowly decomposing plant residues and other organic materials will have effects opposite to the above (Tian *et al*. 1993).

The SOC plays a fundamental role in stabilization of soil aggregates and formation of pores (Oades 1984; Tisdall and Oades 1982). Decreasing SOC content usually leads to the degradation of soil physical properties, especially soil structural stability. The loss of structural stability leads to a reduction in the total porosity and changes in the pore size distribution. Consequently, the soils generally have smaller pores and a lower infiltration rate (Kemper *et al*.1988). A reduced infiltration rate may induce soil erosion by increasing runoff (Conde *et al*. 2007) resulting in a decrease in soil productivity (Descroix *et al*. 2001). Improvement in soil moisture retention capacity due to reduction of the soil bulk density, and an increase in soil porosity and specific surface area of soil particles is in fact a significant advantage of the inclusion of organic manures (Tarenitzky *et al.* 1999). Lado *et al*. (2004) found a significant interaction between aggregate size and organic matter content on sandy loam soil, in improving saturated hydraulic conductivity. Similarly, the increase in hydraulic conductivity resulting from the application of organic manure was directly related to the quantity of organic manures. Benbi *et al.* (1998) demonstrated that amending coarse-textured soils of Punjab with manure over the years increased SOC content and improved saturated hydraulic conductivity, water stable aggregates, and water retention under maize-wheat –fodder cowpea cropping system.

Pigeonpea-wheat is relatively new crop sequence, which came in to existence only in recent years with the development of extra-short duration varieties of pigeonpea. Hence, information on the effect of nutrient management practices involving chemical fertilizers and/or organic manures on soil physical parameters under this crop sequence is scarce, if not lacking altogether. The present investigation was, therefore, undertaken to study (i) the changes in soil hydro-physical properties under pigeonpea-wheat sequence as influenced by different nutrient management practices, and (ii) explore the relationship of these properties with SOC fractions and crop yields.

5.2. Materials and Methods

Soil samples for present investigation were collected from a field experiment that continued for five years (2004-05 to 2008-09) on a Typic Haplustept of IARI Research Farm, New Delhi. The details of the field experiment, soil sampling and analytical methods are given as under:

5.2.1 The experimental site

A field experiment on pigeonpea (*Cajanus cajan* L. Millsp.)-wheat (*Triticum aestivum* L.) sequence was established in 2004-05 on a Typic Haplustept of IARI Research Farm, New Delhi, which continued up to 2008-09. The experimental site (28^oN longitude, 77^oE latitude, and 250 m above mean sea level) represented the Upper Gangetic Plain (UGP) transect of the IGPR. This cropping area is characterized by irrigated, mechanized and input-intensive agriculture with rice-wheat as pre-dominant cropping system. Other crop sequences followed are maize-wheat, pearlmillet-wheat and pearlmillet-mustard. The climate of Delhi is sub-tropical semi-arid, with average annual rainfall of 651 mm. The sandy loam soil of the experimental field was mildly alkaline (pH 8.35) in reaction, and had an electrical conductivity of 0.26 dS m^{-1}. It contained 0.36% organic carbon (Walkley and Black 1934), 194 kg ha^{-1} alkaline-permanganate mineralizable N (Subbiah and Asija 1956), 13.7 kg ha^{-1} 0.5 *M* $NaHCO_3$-extractable P (Olsen *et al.* 1954), 232 kg ha^{-1} *N* NH_4OAc-extractable K (Hanway and Heidel 1952), and 7.2 mg kg^{-1} 0.15% $CaCl_2$-extractable S (Williams and Steinbergs 1959).

5.2.2. Treatments and crop management

The field experiment on pigeonpea-wheat cropping system (2004-05 to 2008-09) comprised 15 treatments which included fertilizer NPK, use of organics (FYM and SPM *i.e.* sulphitation pressmud) alone or in different combinations with NPK, induced defoliation (ID) in pigeonpea, and an unfertilized-control. The experiment was laid out in a randomized block design with three replications. However, only nine treatments were chosen for the present investigation *viz.* T_1: Unfertilized-control (Control); T_2: Soil test-based fertilizer NPK (NPK); T_3: T_2 + 10 t FYM ha^{-1} (NPK+FYM); T_4: 10 t FYM ha^{-1} alone (FYM); T_5: T_2 + 10 t SPM ha^{-1} (NPK+SPM); T_6 : 10 t SPM ha^{-1} alone (SPM); T_7 :

T_2 + Induced defoliation (ID) in pigeonpea (NPK+ID); T_8 : T_3 + ID (NPK+FYM+ID); T_9: T_5 + ID (NPK+SPM+ID).

The gross plot-size was 5 m × 3.5 m, and the layout remained undisturbed throughout experiment duration. Pigeonpea (cv. ICPL 88039) and wheat (cv. HD 2285) were sown each year in the first week of June and third week of November, respectively. These crops were harvested manually during first week of November and third week of April, respectively. The aboveground biomass was removed from the plots after recording the grain and stover/straw yields. Soil test-based N-P-K fertilizer rates were 25-26-33 kg ha^{-1} for pigeonpea and 150-26-50 kg ha^{-1} for wheat, which were applied through urea, diammonium phosphate and muriate of potash, respectively. Entire amount of NPK for pigeonpea, and one-third N and entire PK for wheat were applied basally at the time of sowing. Remaining N in wheat was top-dressed in two equal splits after first and third irrigation *i.e.* 25 and 70 days after sowing (DAS). Pigeonpea seed was also inoculated with *Rhozobium* culture obtained from Microbiology Division, IARI, New Delhi. In the treatments receiving 10 t ha^{-1} of organic manures annually, 2.5 t ha^{-1} of SPM or FYM to pigeonpea as per treatment was applied, and subsequent wheat received remaining 7.5 t manure ha^{-1}. Induced defoliation (ID) treatment in pigeonpea was imposed by spraying of aquous solution 10% (w/v) of urea on green foliage at physiological maturity of the crop. The ID treatment brought-in almost complete defoliation within a week time. Same varieties and management including rates of nutrient application, tillage *etc.* were followed during five years of experimentation.

5.2.3. Soil sampling and analysis

After completion of five cropping cycles, soil samples from two depths (*i.e.* 0-15 and 15-30 cm) were collected from four points in each plot. The sub-samples so obtained were mixed and bulked, and representative soil samples for each depth were drawn for chemical analysis. Each sample was divided into two parts: the first part was stored in a refrigerator for determination of microbial biomass carbon (MBC) and mineral-N contents, and the second part was processed for other analyses. Soil bulk density at both depths was determined in each plot after wheat harvest (2008-09) using core sampler (Veihmeyer and Hendrickson 1948). Saturated hydraulic conductivity of soil was measured using the same undisturbed soil cores. A constant head was maintained at 1 cm and saturated hydraulic conductivity was calculated using Darcy's equation:

$K_{sat} = Q/At \times L/H$

where, K_{sat} is saturated hydraulic conductivity (cm hr^{-1}), A the cross sectional area (cm^2), Q the amount of water passing (cm^3), t the time (hr), Q/At the water flux, and L/H the hydraulic head.

Aggregates of larger size (8.0-4.0 mm) were separated from soil by breaking large clods into smaller segments along natural cleavage and sieving to separate the aggregates that passed through 8 mm sieve and retained on a 4 mm sieve. The aggregates were separated using wet-sieving technique (Yoder 1936). After wet-sieving, aggregates from each sieve were transferred to a set of pre-weighed beakers, oven-dried at 60 °C until water evaporated and weighed. The mean weight diameter (MWD) and geometric mean diameter (GMD) were calculated as an index of aggregation (Van Bavel 1949; Kamper and Roseneau, 1986) using following formula:

$MWD=\sum xiwi$

where wi is the proportion of each aggregrate class in relation to whole, and xi the mean diameter of the class (mm)

$GMD =\exp [\sum (wi \log xi)/(\sum wi)$

where, wi is the weight of aggregrates (g) in a size class with an average diameter xi.

The aggregates larger than 0.2 mm were grouped as macro-aggregates and those smaller than 0.2 mm as micro-aggregates. Water-stable aggregates (%) were computed by adding different size fractions and expressing them as percentage of dry soil. The soil samples were analysed for pH and EC in 1:2 soil-water suspension (Jackson 1973), mechanical composition (Bouyoucos 1962) and mineral N content (Rowell 1994). Total organic carbon (TOC) was determined by wet-digestion (Snyder and Trofymow 1984), microbial biomass carbon (MBC) by fumigation-extraction (Jenkinson and Ladd 1981), labile carbon (LBC) by $KMnO_4$-oxidation (Blair *et al.* 1995), and particulate organic carbon (POC) as per Camberdella and Elliot (1992).

5.2.4 Statistical analysis

For treatment comparisons, ‘F-test’ was used, following the procedures of randomized block design (Gomez and Gomez 1984). Correlation coefficients were computed using SPSS programme (SPSS version 16).

5.3. Results

5.3.1. Mean weight diameter

Use of organic manures in combination with fertilizer NPK increased mean weight diameter (MWD) significantly over control in surface soil (Table 5.1). Of the two organic manures, MWD was invariably greater in the treatments receiving FYM than those receiving SPM. Increase in MWD due to ID was significant over NPK, and highest values of MWD were recorded under NPK+FYM+ID followed by NPK+SPM+ID. Similar treatment effects were registered in sub-surface soil (Table 5.2), although the MWD values were much smaller (0.40 to 0.50 mm) than those in surface soil (0.42-0.97 mm).

5.3.2. Geometric mean diameter

The treatment comparisons for geometric mean diameter (GMD) were almost similar to those for MWD, except that the values were relatively smaller in surface soil (0.38 to 0.62 mm) (Table 5.1). The GMD under fertilizer NPK was greater by 34% compared with control. Conjoint use of NPK+FYM+ID resulted in a further increase in GMD by 32% over NPK. The ID imposed over NPK in absence of FYM or SPM could improve the GMD by 11% compared with fertilizer NPK treatment. The treatment effects were less prominent in sub-surface soil, and the differences between treatments involving ID were also not significant (Table 5.2).

5.3.3. Soil aggregation

Unfertilized-control plots had only 30.9% macro-aggregate in surface soil, which were increased to 43.1% with the application of NPK at recommended rates (Table 5.1). Use of organic manures or ID brought further significant increase in macro-aggregates, and the extent of such increase was greater with FYM. Organic manures, applied alone could, however, not exhibit any benefit over fertilizer NPK. The positive effect of integrated nutrient supply (i.e. NPK+ Organics with or without ID was also apparent in sub-surface soil (Table 5.2), but the total macro-aggregates across the treatments were relatively lower than surface soil. A reverse effect of different treatments was recorded on micro-aggregates at both soil depths.

5.3.4. Water-stable aggregates

Percent water-stable aggregates (WSA) varied from 53.5 to 73.6 in surface soil, with lowest values under control and the highest under NPK+FYM+ID (Table 5.3). The corresponding percentage of WSA in sub-surface soil was 37.6 and 54.7, respectively (Table 5.4). Application of fertilizer NPK in absence of any organic manure also increased WSA significantly over control in both soil layers. Like macro and micro-aggregates, the WSA also did not change markedly when SPM or FYM was used alone *i.e.*, without fertilizer NPK.

5.3.5. Bulk density

The bulk density (BD) of surface soil was highest (1.69 Mg m^{-3}) under unfertilized-control, which was decreased with fertilizer NPK application, though the difference was statistically not significant (Table 5.3). Use of FYM alone or in combination with NPK, however, brought significant reduction in soil BD, and the lowest value (1.43 Mg m^{-3}) was registered under NPK+FYM+ID treatment. The BD under NPK+ID was also significantly lower than control, but statistically similar to NPK. Treatment effects in sub-surface layer were not significant (Table 5.4).

5.3.6. Saturated hydraulic conductivity

Conjoint use of fertilizer NPK with FYM, SPM or ID increased saturated hydraulic conductivity (K_{sat}) of surface soil significantly over control or sole NPK treatment (Table 5.3). The K_{sat} values under NPK (0.56 cm hr^{-1}) were also significantly higher than those recorded under control (0.46 cm hr^{-1}). Changes in K_{sat} were greater in FYM treatments compared with those involving SPM. In surface soil also, similar treatment effect were recorded (Table 5.4), although the K_{sat} values were lower than the surface soil.

5.3.7. Relationship of hydro-physical properties with yield and SOC fractions

Different hydro-physical properties in surface soil showed highly significant and positive correlations with each other, except soil bulk density (BD) which had negative correlation with MWD, GMD, macro-aggregates, WSA and K_{sat} (Table 5.5). The coefficients of correlation (r-values) between micro-aggregates and other parameters (except BD) were also negative. The relationship between different hydro-physical properties and wheat yield was significant and positive, except for BD and micro-aggregates wherein a negative relationship was registered. The r-values between hydro-physical properties (MWD, GMD and macro-aggregates) and pigeonpea yield were also significant, but the relationship was not a strong as in case of wheat yield. Linear relationship of wheat yield with BD and macro-aggregates is illustrated in Fig. 5.1. Almost similar kinds of relationships between different parameters were registered in sub-surface soil (Table 5.6). At this depth, correlations of BD with GMD, and micro- and macro-aggregates was not significant.

Coefficients of correlation given in Table 5.7 showed a significant relationship between different hydro-physical properties and soil organic carbon (SOC) fractions, except that between WSA and TOC. Also the relationship was positive in all the cases, except that in case of BD which was negatively correlated with the SOC fractions. Linear relationships between macro-aggregates and different SOC fractions are depicted in Fig. 5.2.

5.4 Discussion

The results of the present investigation revealed substantial increase in soil aggregation and stability of the aggregates consequent to the use of organic manures along with fertilizer NPK (Tables 5.1 to 5.4). Increase in water-stable aggregates (WSA) is known to be associated with soil organic matter content that increases with the use of balanced fertilization alone or in combination with organic manure (FYM) (Kanwar and Prihar 1962). Benbi *et al.* (1998) reported that application of FYM for 20 years in a maize-wheat-fodder cowpea cropping sequence increased WSA of all sizes, and the total WSA by 12% over control. Of the several theories proposed on the role of organic matter in stabilizing soil aggregates (Martin 1971; Cheshire 1979; Tisdall and Oades 1982; Jastrow 1996), the generally accepted one is that the release of polysaccharides and organic acids during decomposition of organic sources plays a key role in stabilization of soil macro-aggregates. Since polysaccharides and organic acids do not spread far from the site of production, freshly added residues function as nucleation sites for the growth of fungi and other soil microbes (Puget *et al.* 1995; Angers and Giroux 1996; Jastrow 1996), leading to binding of residues and soil particulates into macro-aggregates. The beneficial effect of balanced fertilization on soil aggregation might also be ascribed to (i) the role played by phosphate ions in binding of soil particles (Sivasamy 1982), and (ii) the large amount of residues produced in the fertilized plots (Ravindra *et al.* 1985). Mean weight diameter (MWD) and geometric mean diameter (GMD), computed as indices to quantity the changes in soil aggregation status in the present case, were invariably greater when FYM and ID were used along with NPK. This could be due to combined effect of better crop growth, addition of more residues through leaf litter and organic matter input through FYM. Positive relationship between soil organic C and aggregation observed in the present study have also been substantiated by other researchers (Oades 1984; Acharya *et al.* 1988; Benbi *et al.* 1998). Soil compaction as a result of increase in bulk density (BD) of surface and sub-surface soil layers has emerged as a major physical constraint in intensive agriculture (Soane *et al.* 1981), as the compaction-induced soil degradation affects about 68 million hectares of land globally (Flowers and Lal 1998). Integration of the nutrient inputs of different origin and composition *i.e.* fertilizers, organic manures and ID as attempted in the present study caused significant reduction in soil BD compared with unfertilized-control and even the fertilizer NPK treatment. Further, a negative relationship between soil BD and wheat yields (Table 5.5), and a significant increase in yields due to above treatments indicated that a reduction in soil BD owing to inclusion of manures and ID in fertilization schedule played an important role in yield enhancement. In fact, the literature suggested that the deleterious effect of soil compaction is often more pronounced on yield than other crop growth parameters (Hassan *et al.* 2007). Reduction in wheat grain yield to the extent of 38% due to soil compaction has been reported (Ishaq *et al*. 2001). The present findings pertaining to positive role of organics used along with fertilizer NPK in reducing soil BD are corroborated by other studies in the IGPR and elsewhere (Khaleel *et al.* 1981; Haynes and Naidu 1998; Swarup and Wanjari 2000; Hati *et al.* 2006). The reduction in BD in these studies was, by and large, attributed to higher soil organic matter content, better aggregation and increased root growth in the fertilizer and manure treated plots. Treatment effects on soil BD were not significant in sub-surface soil (Table 5.4), possibly because of a sharp reduction in SOC content at this depth compared with the surface soil.

Fertilizer NPK applied at recommended rates increased significantly the saturated hydraulic conductivity (K_{sat}) over control, and inclusion of organic manures and/or ID brought further improvement in K_{sat} (Tables 5.3 and 5.4). The increase in K_{sat} under conjoint use of NPK and organics might be attributed to the improvement in aggregate stability, organic matter content, biological activity (Bellaki *et al.* 1998). An increase in K_{sat} from 0.56 cm hr^{-1} under NPK to as high as 0.81 cm hr^{-1} under NPK+FYM+ID in 0-15 cm soil layer might also be due to possible increase in effective pore volume owing to increased aggregation (Flowers and Lal 1998). The K_{sat} decreased considerably in all the treatments with an increase in soil depth, which was probably due to increased compaction leading to reduced effective pore volume (Hati *et al.* 2006).

5.5 Conclusion

The foregoing results revealed that conjoint use of fertilizer NPK at soil test-based recommended rate and organic manures, particularly FYM, helped in improving soil physical environment in terms of increasing soil aggregation, stability of aggregates and saturated hydraulic conductivity, and decreasing soil bulk density. Induced defoliation in pigeonpea appeared a promising technique in modifying different hydro-physical parameters and NPK+FYM coupled with ID was actually emerged as the best nutrient management option.

Table 5.1. Hydro-physical properties in surface (0-15 cm) soil as influenced by nutrient management practices

Treatment	Hydro-physical properties			
	MWD (mm)	GMD (mm)	Macro-aggregates (%)	Micro-aggregates (%)
Control	0.42	0.38	30.9	69.1
NPK	0.53	0.47	43.1	56.9
FYM	0.65	0.50	44.3	55.7
NPK+FYM	0.89	0.57	53.2	46.8
SPM	0.50	0.48	42.3	57.7
NPK+SPM	0.67	0.51	47.8	52.2
NPK+ID	0.72	0.52	54.2	45.8
NPK+FYM+ID	0.97	0.62	59.1	40.9
NPK+SPM+ID	0.79	0.56	54.2	45.8
SEm (±)	0.01	0.02	1.3	1.3
LSD (*P*=0.05)	0.03	0.05	4.0	4.0

Table 5.2. Hydro-physical properties in sub-surface (15-30 cm) soil as influenced by nutrient management practices

Treatment	Hydro-physical properties			
	MWD (mm)	GMD (mm)	Macro-aggregates (%)	Micro-aggregates (%)
Control	0.40	0.34	25.30	74.7
NPK	0.43	0.40	32.6	67.4
FYM	0.46	0.44	33.2	66.8
NPK+FYM	0.47	0.48	41.4	58.6
SPM	0.42	0.46	36.9	63.1
NPK+SPM	0.45	0.47	38.8	61.2
NPK+ID	0.47	0.50	40.9	59.1
NPK+FYM+ID	0.50	0.52	42.7	57.3
NPK+SPM+ID	0.50	0.47	39.0	61.0
SEm (±)	0.02	0.02	2.0	1.6
LSD (*P*=0.05)	0.05	0.06	5.0	4.7

Table 5.3. Effect of nutrient management practices on water-stable aggregates (WSA), bulk density (BD), and saturated hydraulic conductivity (K_{sat}) in surface soil

Treatment	Hydro-physical properties		
	WSA (%)	BD (Mg m^{-3})	K_{sat} (cm hr^{-1})
Control	53.5	1.69	0.46
NPK	62.9	1.57	0.56
FYM	64.6	1.52	0.59
NPK+FYM	72.3	1.46	0.78
SPM	53.0	1.59	0.58
NPK+SPM	64.2	1.56	0.60
NPK+ID	71.3	1.51	0.61
NPK+FYM+ID	73.6	1.43	0.81
NPK+SPM+ID	65.0	1.48	0.65
SEm (±)	2.2	0.04	0.01
LSD (*P*=0.05)	6.7	0.13	0.03

Table 5.4. Effect of nutrient management practices on water-stable aggregates (WSA), bulk density (BD), and saturated hydraulic conductivity (K_{sat}) in sub-surface soil

Treatment	Hydro-physical properties		
	WSA (%)	BD (Mg m^{-3})	K_{sat} (cm hr^{-1})
Control	37.6	1.82	0.34
NPK	49.4	1.70	0.45
FYM	48.3	1.69	0.46
NPK+FYM	50.3	1.65	0.62
SPM	43.0	1.77	0.46
NPK+SPM	45.8	1.74	0.49
NPK+ID	48.5	1.77	0.51
NPK+FYM+ID	54.7	1.66	0.68
NPK+SPM+ID	49.5	1.68	0.54
SEm (±)	1.6	0.03	0.01
LSD (*P*=0.05)	4.8	NS	0.02

Table 5.5. Coefficients of correlation (r-values) between hydro-physical properties in surface soil and crop yields

Treatment	Correlation coefficients (r-values)								
	MWD	GMD	Macro-aggregate	Micro-aggregate	WSA	BD	K_{sat}	Wheat yield	Pigeonpea yield
MWD	1.00								
GMD	0.96**	1.00							
Macro-aggregates	o.93**	0.97**	1.00						
Micro-aggregates	-0.92**	-0.96**	-1.00**	1.00					
WSA	0.89**	0.83**	0.87**	-0.87**	1.00				
BD	-0.95**	-0.97**	-0.95**	0.95**	-0.88**	1.00			
K_{sat}	0.95**	0.94**	0.86**	-0.87**	0.81**	0.92**	1.00		
Wheat yield	0.75*	0.79*	0.85**	-0.85**	0.71*	-0.73*	0.67*	1.00	
Pigeonpea yield	0.68*	0.72*	0.77*	-0.77*	0.65	-0.65	0.63	0.98*	1.00

* Significant at *P*= 0.05 level, ** Significant at *P*=0.01 level

Table 5.6. Correlations coefficient (r-values) between hydro-physical properties in sub-surface soil and crop yields

Treatment	Correlation coefficients (r-values)								
	MWD	GMD	Macro-aggregate	Micro-aggregate	WSA	BD	K_{sat}	Wheat yield	Pigeonpea yield
MWD	1.00								
GMD	0.81**	1.00							
Macro-aggregates	0.79*	0.97**	1.00						
Micro-aggregates	-0.79*	-0.97**	-1.00**	1.00					
WSA	0.85**	0.75*	0.76*	-0.75**	1.00				
BD	-0.74*	-0.53	-0.57	0.57	-0.87**	1.00			
K_{sat}	0.84**	0.85**	0.87**	-0.89**	0.78*	-1.00**	1.00		
Wheat yield	0.76*	0.73*	0.82**	-0.82**	0.72*	-0.58	0.75*	1.00	
Pigeonpea yield	0.66	0.63	0.75*	-0.75*	0.67*	-0.57	0.69*	0.98*	1.00

* Significant at *P*= 0.05 level, ** Significant at *P*=0.01 level

Table 5.7. Correlation coefficients (r-values) between hydro-physical properties and, SOC fractions in surface soil

Treatment	Correlation coefficients (r-values)				
	TOC	WBC	MBC	LBC	POC
MWD	0.87**	0.95**	0.97**	0.91**	0.95**
Macro-aggregates	0.81**	0.93**	0.96**	0.93**	0.88**
WSA	0.64	0.82**	0.84**	0.82**	0.74*
BD	-0.81**	-0.92**	-0.94**	-0.84**	-0.87**

* Significant at *P*= 0.05 level, ** Significant at *P*=0.01 level

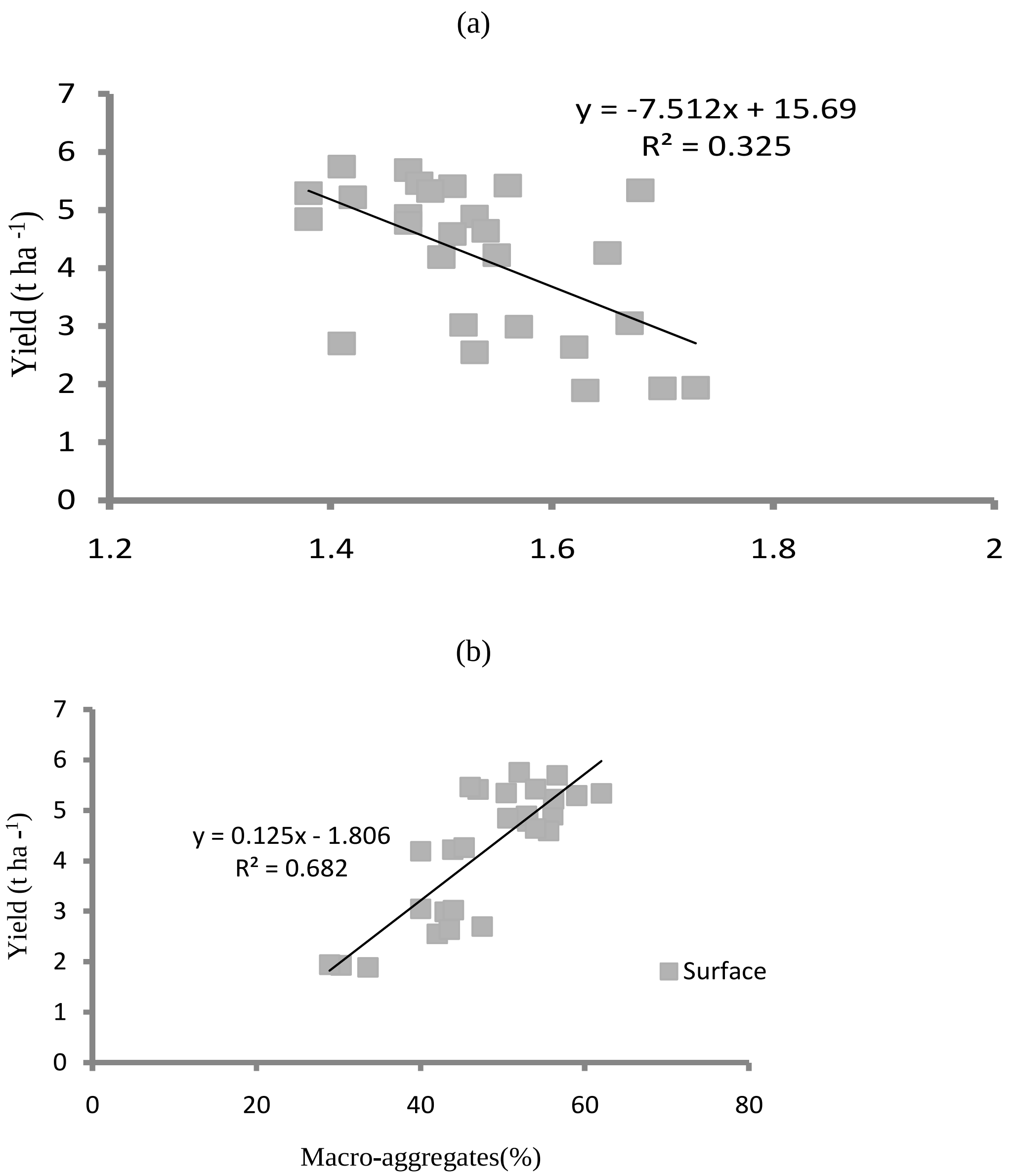

Fig. 5.1. Scatter diagrams showing linear relationship of wheat yield with (a) soil BD, and (b) macro-aggregates in surface (0-15 cm) soil

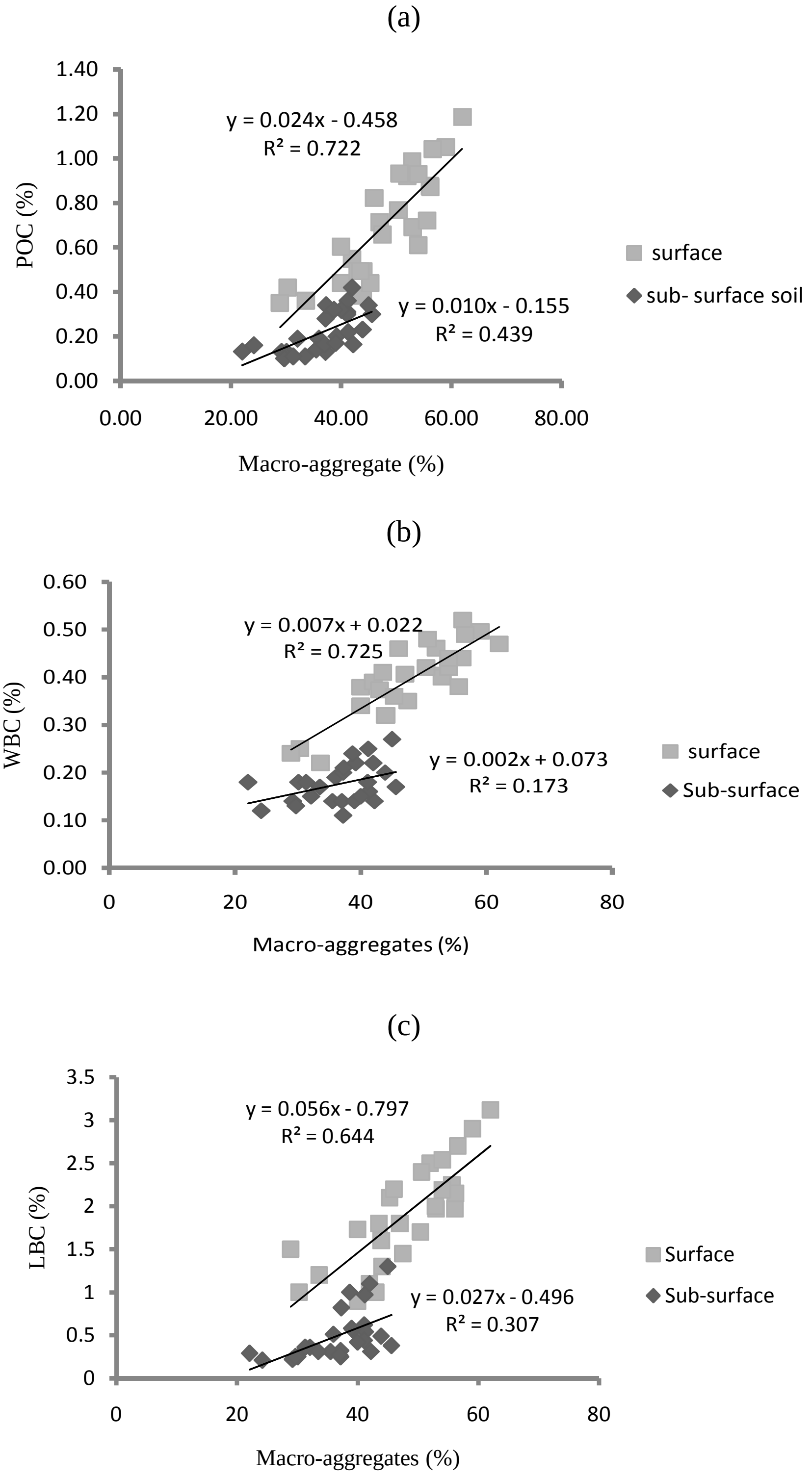

Fig. 5.2. Linear relationship of macro-aggregates with (a) particulate organic carbon (POC), (b) Walkley and Black carbon (WBC), and (c) labile carbon (LBC) in surface and sub-surface soil

6. DISCUSSION

Majority of the soils of India, especially those in the IGPR are inherently low in organic matter and N content (Yadav *et al.* 2000b), but may support high productivity with better nutrient management options. A desirable nutrient management practice would be one that sustains reasonably high levels of yield and soil fertility status, especially soil organic carbon (SOC) stocks (Sleutel *et al.* 2006). Soil organic matter is rightly considered the nucleus of soil health. In the present investigation, different nutrient management practices were evaluated in pigeonpea-wheat sequence on a sandy loam (Typic Haplustept) in terms of their effect on SOC fractions, mineral N content, hydrophysical properties and crop yields. Changes in total organic C (TOC) due to fertilizer NPK over unfertilized-control or those due to organics (FYM or SPM) alone over NPK were not significant, even after completion of five cropping cycles (Table 4.2). This is explainable since changes in TOC are generally large and more apparent when natural ecosystems are converted to arable farming (Katyal *et al.* 2001; Dhaliwal 2003). Soil management practices within agriculture systems, on the other hand, bring too small changes in TOC content of the soil to be measured over short-term because of large quantity of background organic matter already present in the soil (Elliot 1986). Thus, a marked change in soil TOC owing to usual fertilizer use practices is not expected during the short period of five years. The increase in TOC content of soil (0-15 cm depth) as observed under conjoint use of fertilizers and organics in the present case may be attributed to recycling of additional roots, above ground residues and stubble due to higher biomass production in these treatments, in addition to the C added through manures (Manjaiah and Singh 2001; Majumder *et al.* 2008). The values of TOC and all other SOC fractions were greater in surface (0-15 cm) than sub-surface (15-30 cm) soil across the treatments, obviously due to higher residue recycling and other biological activities confined to this soil layer (Gupta *et al*. 1994; Potter *et al.* 1998). Compared to NPK treatment there were no significant changes in TOC in case of induced defoliation (ID), which is due to lower C/N ratio of leaves leading to rapid mineralization and subsequent loss of C as CO_2. Walkley and Black C (WBC) was more sensitive than TOC to changes in nutrient management, due to the fact that dichromate method adopted for determination of MBC uses the heat of dilution or minimal heating which does not allow complete oxidation of organic matter in soil, although the most reactive form of organic carbon are converted to CO_2 (Page *et al*. 1982). Significant increase in WBC due to NPK fertilization over control as noticed in this study is substantiated with long-term studies, which showed advantage of balanced fertilizer use in improving WBC content at several sites in the IGPR (Yadav *et al.* 2000; Swarup and Wanjari 2000). Greater improvement in soil WBC content in FYM treated soils than SPM observed in the present case is because SPM is not as rich carbon source as FYM. The proportion of WBC to TOC in our case ranged between 17 and 22% in different treatments, which is very low compared to generally reported values. In earlier studies involving different land uses and management practices, WBC on average accounted for 25.4% of TOC (Verma 2006). Chemical recalcitrance of residues (*i.e.* higher lignin and polyphenol contents), physical recalcitrance (*i.e.* aggregate-led protection) and organo-mineral complexation may provide some explanation to such a low recovery of WBC. This aspect, however, that needs to be further investigated.

The labile C (LBC) and microbial biomass C (MBC) were significantly greater in surface soil treated with NPK+organics compared with sole NPK. The extent of increase in these fractions of SOC differed in accordance with the nature of organic C input (Table 4.2). While increase in MBC was more closely associated with FYM treatments, LBC was affected more by to ID. These fractions are considered more sensitive to change in management practices than TOC or other fractions of SOC (Blair *et al.* 1995; Conteh *et al.* 1999; Graham *et al.* 2002; Haynes 2005), and the present findings on the positive effect of LBC and MBC contents are supported by several workers (Buchnan and King 1992; Ismail *et al.* 1994; Graham *et al.* 2002; Rudrappa *et al.* 2006). Since organic manures add substantial amount of organic matter to the soil, $KMnO_4$ extracted higher amounts of LBC from manure/fertilizer treatments than control (Fig 4.2), as this reagent extracted relatively younger organic compounds including labile humic materials and polysaccharides (Conteh *et al.* 1999; Haynes 2005). Relatively greater increase in LBC due to ID is also explainable, as the pigeonpea leaf-litter added through ID was an easily decomposable (narrow C/N ratio) material which led to a faster change in LBC compared with SPM and FYM. Recent studies by Verma *et al.* (2010), in fact, suggested LBC as a more sensitive and consistent index of labile pool of SOC compared with MBC. Similarly, significant increase in particulate organic C (POC) under NPK or NPK +organics treatments over unfertilized-control (Table 4.2) may be attributed to greater amount of fresh plant residues in these treatments (Gregorich and Janzen 1996). This fraction, primarily composed of plant debris with a recognizable cellular structure, fungal hyphae, spores, faunal skeleton *etc*. (Spycher *et al*. 1983; Skjemstad *et al.* 1990), has a short turn-over time and thus serves as an important source of carbon and nutrients.

Determination of oxidizable SOC fractions using modified Walkley and Black method (Chan *et al*. 2001) and their categorization into different lability groups also gave interesting results. Whereas organic manures (FYM and SPM) brought greater increase in labile (C_L) and less labile (C_{LL}) fractions, pigeonpea leaf-litter addition through ID resulted in greater increase in very libile (C_{VL}) fractions (Table 4.8). The higher lability of SOC in ID treatments could help in explaining significant wheat yield responses to ID over NPK despite relatively small C inputs (compared with C inputs through FYM or SPM). Further grouping of oxidizable organic C fractions into active (C_{VL} + C_L) and passive (C_{LL} + non-labile C *i.e.* C_{NL}) pools as suggested by Mandal *et al.* (2008) revealed that the active pool had highly significant linear relationship with wheat yield and mineral N content of the surface soil (Fig. 4.12).

Although the proportion of SOC in active pool under different treatments in the present study was smaller than that reported by Chan *et al.* (2001) for pasture system in Australia, the oxidizable organic C fractions especially C_{VL} and C_L, may prove useful index for detecting small changes in SOC owing to management, which might otherwise go unnoticed. Further detailed studies under different soils and cropping systems are needed to evaluate the sensitivity of these fractions *vis-à-vis* others like MBC (Jenkinson and Ladd 1981) and LBC (Blair *et al.* 1995).

Induced defoliation (ID) in pigeonpea imposed by way of foliar spray of 10% urea solution at the physiological maturity of the crop attempted in this investigation was a non-conventional approach of legume residue (leaf-litter) recycling. Although, genetic improvements in recent years led to shortening of pigeonpea duration, making possible to grow it in rotation with wheat (*i.e.* pigeonpea-wheat annual crop sequence), the ESD varieties of pigeonpea retain substantial amount of green foliage at maturity (Sheldrake 1974). As much of the N retained in the non-grain portion of the crop remains confined to the green leaves containing about 4% N (Sheldrake and Narayanan 1979), defoliation and subsequent incorporation of these leaves at maturity may increase residual benefit to the subsequent wheat crop. The ID resulted in of 1.2 to 1.4 t ha^{-1} additional leaf-litter recycling over the natural senescence in other (non-ID) treatments. Substantial increase in soil mineral N contents particularly in surface layer under ID (Fig. 4.9) is very much expected, for the additional leaf litter recycled in this treatment not only added about 50 kg N ha^{-1} but also the N and other nutrients contained therein were possibly released faster (due to narrow C/N ratio) compared with FYM and SPM. Studies on the effect of ID on crop yield and soil properties are not many, yet limited available literature (Chauhan *et al.* 2001) supported the findings of this investigation. Highest wheat yields and mineral N contents were registered under NPK+SPM+ID, although most of the SOC fractions were highest under NPK+FYM+ID. These contradictions are also explainable because SPM is a rich nutrient source, whereas annual carbon inputs were relatively higher in treatments involving FYM.

So far as the hydro-physical properties of soil are concerned, most of them are directly or indirectly related to soil organic matter contents. The present investigation revealed substantial increase in soil aggregation and their stability consequent to the use of organic manures along with fertilizer NPK (Tables 5.1 to 5.4). Increase in water-stable aggregates (WSA) is known to be associated with soil organic matter content which increases with the use of balanced fertilization alone or in combination with FYM (Kanwar and Prihar 1962). Our findings are in accordance to those of Benbi *et al.* (1998) who reported that application of FYM for 20 years in a maize-wheat-fodder cowpea cropping sequence increased WSA of all sizes. Of the several theories proposed on the role of organic matter in stabilizing soil aggregates, the generally accepted one is that the release of polysaccharides and organic acids during decomposition of organic sources plays a key role in stabilization of soil macro-aggregates (Martin 1971; Cheshire 1979). Since polysaccharides and organic acids do not spread far from the site of production, freshly added residues function as nucleation sites for the growth of soil microbes (Puget *et al.* 1995; Angers and Giroux 1996; Jastrow 1996), leading to binding of residues and soil particulates into macro-aggregates. The beneficial effect of balanced fertilization on soil aggregation might also be ascribed to (i) the role played by phosphate ions in binding of soil particles (Sivasamy 1982), and (ii) the large amount of residues produced in the fertilized plots (Ravindra *et al.* 1985). Mean weight diameter (MWD) and geometric mean diameter (GMD), computed as indices to quantity the changes in soil aggregation status in the present case, were invariably greater when FYM and ID were used along with NPK. This could be due to combined effect of better crop growth, addition of more residues through leaf-litter and organic matter input through FYM. Positive relationship between soil organic C and aggregation observed in the present study are also in line with the findings of of some other researchers (Oades 1984; Acharya *et al.* 1988; Benbi *et al.* 1998). Soil compaction as a result of increase in bulk density (BD) of surface and sub-surface soil layers has emerged as a major physical constraint in intensive agriculture (Soane *et al.* 1981), as the compaction-induced soil degradation affects about 68 million hectares of land globally (Flowers and Lal 1998). Integration of the nutrient inputs of different origin and composition *i.e.* fertilizers, organic manures and ID involved in the present study caused significant reduction in soil BD compared with unfertilized-control and even the fertilizer NPK treatment. Further, a negative relationship between soil BD and wheat yields (Table 5.5), and a significant increase in yields due to above treatments indicated that a reduction in soil BD owing to inclusion of manures and ID in fertilization schedule played an important role in enhancing crop yields. The deleterious effect of soil compaction that increase BD is often more pronounced on yield than on other crop parameters (Hassan *et al.* 2007), so much so that reduction in wheat grain yield to the extent of 38% due to soil compaction has been reported (Ishaq *et al*. 2001). The present findings pertaining to positive role of organics used along with fertilizer NPK in reducing soil BD support other studies conducted in the IGPR and elsewhere (Khaleel *et al.* 1981; Haynes and Naidu 1998; Swarup and Wanjari 2000; Hati *et al.* 2006). The reduction in BD in these studies was, by and large, attributed to higher soil organic matter content, better aggregation and increased root growth in the fertilizer and manure treated plots. However, the treatment effects on soil BD were not significant in sub-surface soil (Table 5.4), possibly because of a sharp reduction in SOC content at this depth compared with the surface soil.

Fertilizer NPK applied at recommended rates increased significantly the saturated hydraulic conductivity (K_{sat}) over control, and inclusion of organic manures and/or ID brought further improvement in it (Tables 5.3 and 5.4). The increase in K_{sat} under conjoint use of NPK and organics might be attributed to the improvement in aggregate stability, organic matter content, and biological activities as explained by Bellaki *et al.* (1998). An increase in K_{sat} from 0.56 cm hr^{-1} under NPK to as high as 0.81 cm hr^{-1} under NPK+FYM+ID in 0-15 cm soil layer might also be due to possible increase in effective pore volume owing to increased aggregation (Flower and Lal 1998). The K_{sat} decreased considerably across the treatments with an increase in soil depth, which was probably due to increased compaction leading to reduced effective pore volume (Hati *et al.* 2006), which in turn might restrict water availability to crop plants.

7. SUMMARY AND CONCLUSION

The fatigue in agricultural production and productivity growth rates observed in the post-Green Revolution era is considered to be an outcome of dwindling soil health owing to intensive cereal-cereal cropping ignoring the basic principles of crop rotation, low organic matter input, indiscriminate use of fertilizers and irrigation water, and excessive tillage. Decline in soil organic carbon (SOC), deterioration in physical properties and emergence of multi-nutrient deficiencies are the major soil health concerns posing serious challenge to sustainable crop production. These problems are more acute in the Trans- and Upper Gangetic Plain transects (representing Punjab, Haryana, Delhi and western Uttar Pradesh) of the Indo-Gangetic Plain Region (IGPR). Where rice-wheat is the predominant cropping system. With the development of extra-short duration varieties of pigeonpea, it has become possible to grow this crop in sequence with wheat, thus providing an opportunity of crop diversification in these areas. There is, however, need to evaluate different nutrient management options in terms of changes in soil parameters and annual productivity under this new crop sequence. Integrated nutrient supply and crop diversification with inclusion of legumes may help to restore the soil health, but the same are not widely adopted. Hence, the present investigation was undertaken to study the effect of different nutrient management practices involving sole or conjoint use of fertilizers and manures on SOC fractions, mineral N and hydro-physical properties in a pigeonpea-wheat sequence, using a field experiment that continued for five years (2004-05 to 2008-09) on a Typic Haplustept at IARI Research Farm, New Delhi. In addition to fertilizer NPK and two manures *i.e.* FYM and sulphitation pressmud (SPM), effect of induced defoliation (ID) imposed in pigeonpea by foliar spray of 10% (w/v) urea solution at physiological maturity was also evaluated. Soil samples from surface (0-15 cm) and sub-surface (15-30 cm) layers were collected after completion of five crop cycles, and analysed for different SOC fractions, mineral N and hydro-physical properties. The results are summarized as under:

- Under pigeonpea-wheat crop sequence followed for five years on a Typic Haplustept, the TOC across the treatments varied from 1.73 to 2.32%, MBC from 174 to 410 mg kg^{-1}, LBC from 1.23 to 2.72 mg g^{-1}, POC from 0.38 to

1.04% and WBC from 0.30 to 0.50% in surface soil. Corresponding contents in sub-surface soil were relatively smaller.

- Soil test-based NPK fertilization did not improve TOC over unfertilized-control, but increased other SOC fractions significantly in 0-15 and 15-30 cm soil layers.
- Conjoint use of organic manures and fertilizer NPK resulted in higher SOC fractions compared with fertilizer alone, and the extent of such increase was greater in case of FYM compared with SPM.
- NPK+ID did not contribute much to TOC, but increased the LBC, MBC and WBC fractions by 82, 46 and 14%, respectively over NPK treatment. Highest values of different SOC fractions were recorded under NPK+FYM+ID closely followed by NPK+SPM+ID**.**
- Fractionation of oxidizable OC in to different lability pools helped detecting small changes in SOC due to nutrient management practices. Accordingly, ID treatments showed highest values of very labile C (C_{VL}), whereas other pools (labile, less labile and non- labile C) were greater under FYM or SPM treatments.
- IPNS increased significantly the TOC associated with macro-aggregates in surface and sub-surface layers, whereas the effect of nutrient supply options on micro-aggregates was not equally apparent.
- Carbon management index (CMI) was computed to evaluate the treatment effects vis-à-vis control on the changes in SOC stocks. Highest CMI was recorded under NPK+FYM+ID, followed by NPK+FYM, and NPK+SPM+ID. The CMI for NPK+ID was greater than NPK.
- Contribution of WBC, MBC and LBC towards TOC in different treatments was in the range of 17 to 22, 1.0 to 1.8 and 6.7 to 11.8%, respectively.
- Different SOC fractions were positively and significantly correlated with each other in both the soil layers. Highly significant positive correlation were registered between wheat yield and SOC fractions viz. WBC, MBC, LBC and POC in surface soil.

- Macro-aggregate size fractions in surface soil were only 30% under control, which were increased to 43% with NPK, 53% with NPK+FYM and up to 59% with NPK+FYM+ID. Treatment effect was less prominent in 15-30 cm layer.
- Water-stable aggregates, MWD, GMD and saturated hydraulic conductively in 0-15 cm soil layer were improved significantly due to IPNS over sole NPK, but the differences between IPNS options were not significant.
- Surface soil BD was highest (1.67 Mg m^{-3}) under control, which decreased (1.57 Mg m^{-3}) significantly with NPK application. Treatments involving FYM or SPM with ID further decreased the BD values. Differences for sub-surface layer were, however, not significant.
- Organic manures applied alone were not as effective as their conjoint use with fertilizers in influencing soil hydro-physical properties. Also, FYM applied along with NPK, with or without ID, was more effective than SPM in modifying the hydro-physical properties.
- Different hydro-physical properties were inter-correlated significantly and positively, except BD that had negative correlation with other properties. SOC fractions were also significantly correlated with hydro-physical properties.

Based on the findings of the present investigation, following conclusions could be drawn:

i) Deterioration in SOC levels and soil physical environment in high productivity areas of the IGPR can be reversed with the conjoint use of soil test-based fertilizers and organic manures, particularly FYM. Sulphitation pressmud (SPM), on the other hand, serves as a good nutrient source to enhance crop yields.

ii) Induced defoliation proved to be a unique management option to improve SOC fractions, especially labile ones, mineral N and hydro-physical properties of the soil, that ultimately culminated in to increased annual productivity of pigeonpea-wheat sequence. It is of particular significance in view of severe shortage of conventional manures, and competitive uses of other organic sources and crop residues.

iii) Scientifically sound explanations need to be provided for the very low proportion of WBC to TOC recorded in the present study. The factor of 1.3 conventionally used for conversion of WBC in to TOC seems to under-estimate, the TOC in the soils of IGPR, and may necessitate a revision. Data sets on the recovery of WBC vis-à-vis TOC for diverse soil types and cropping systems need to be generated for this purpose.

iv) Further detailed studies are needed to standardize and compare the modified Walkley and Black method of oxidizable organic C fractionation as proposed by Chan *et al.* (2001), for it is simpler and appears more sensitive to detect small changes in SOC due to management practices.

SOIL ORGANIC CARBON FRACTIONS, MINERAL N AND HYDRO-PHYSICAL PROPERTIES UNDER DIFFERENT NUTRIENT MANAGEMENT PRACTICES IN PIGEONPEA-WHEAT SEQUENCE

ABSTRACT

Decline in soil organic carbon (SOC), deterioration in physical properties and widespread nutrient deficiencies are considered major threats to the sustainable agriculture. The severity of these problems is greater in intensively-cropped areas of the Indo-Gangetic Plain region. Management strategies like integrated nutrient supply and crop diversification with inclusion of legumes may have potential to restore the soil health. Hence, in the present investigation an attempt has been made to study the effect of different nutrient management practices involving sole or conjoint use of fertilizers and manures on SOC fractions, mineral N and hydro-physical properties in a pigeonpea-wheat sequence, using a field experiment that continued for five years (2004-05 to 2008-09) on a Typic Haplustept at IARI Research Farm, New Delhi. In addition to fertilizer NPK and two manures *i.e.* FYM and sulphitation pressmud (SPM), effect of induced defoliation (ID) imposed in pigeonpea by foliar spray of 10% (w/v) urea solution at physiological maturity was also evaluated. Soil samples from surface (0-15 cm) and sub-surface (15-30 cm) layers were collected after completion of five crop cycles, and analysed for different SOC fractions, mineral N and hydro-physical properties.

Conjoint use of soil test-based fertilizer NPK and organics increased significantly different SOC fractions, macro-aggregate associated C, and mineral N compared with sole NPK or unfertilized-control, although the extent of increase varied in accordance with the nature of organic inputs. Whereas FYM and SPM used along with NPK brought significant increase in relatively stabilized SOC fractions like Walkley and Black C (WBC) and particulate organic C (POC), the magnitude of increase in microbial biomass C (MBC) and labile C (LBC) was greater under ID. By and large, highest values of different SOC fractions were obtained under NPK+FYM+ID treatment. The proportion of WBC, MBC and LBC towards TOC in 0-15 cm soil varied from 17 to 22, 1.0 to 1.8 and 6.7 to 11.8 %, respectively. The

corresponding figures for 15-30 cm soil depth were relatively lower. The SOC fractions were significantly correlated with each other, particularly in 0-15 cm soil depth, and also with mineral N and wheat yield.

Use of organic manures, especially FYM, with fertilizer NPK improved soil aggregation, as evident by a significant increase in macro-aggregates, mean weight diameter, geometric mean diameter and water-stable aggregates, over NPK or control. The treatment effect was generally consistent in sub-surface (15-30 cm) soil also. Compared with NPK, soil bulk density was reduced significantly with the conjoint use of organics and NPK. The bulk density was lowest under NPK+FYM+ID. The hydro-physical properties showed a positive and significant relationship with crop yields, except bulk density (0-15 cm) which had negative relationship with yield.

अरहर-गेहूँ फसल क्रम में विभिन्न पोषक तत्व प्रबंधन विकल्पों का मृदा जैव-कार्बन अंशों, खनिज नाइट्रोजन एवं जल-भौतिकीय गुणों पर प्रभाव

सारांश

मृदा जैव-कार्बन स्तर में कमी, जल-भौतिकीय गुणों में गिरावट तथा पोषक तत्वों की विस्तृत कमी टिकाऊ कृषि के लिए बड़ी चुनौती मानी जाती हैं। ये समस्याऐं सिन्धु-गंगा के मैदानी क्षेत्रों के सघन कृषि वाले क्षेत्रों में अधिक गम्भीर हैं। प्रबन्धन उपायों जैसे समन्वित पोषक तत्व प्रदाय एवं दलहन समावेशित फसल विविधीकरण द्वारा मृदा स्वास्थ्य का पुनरुत्थान सम्भव है।

अत: वर्तमान शोध कार्य के अन्र्तगत अरहर-गेहूँ प्रणाली में मृदा जैव-कार्बन के अंशों, खनिज नाइट्रोजन एवं जल-भौतिकीय गुणों पर विभिन्न पोषक तत्व प्रबन्धन विकल्पों जिनमें केवल उर्वरक अथवा उर्वरकों व खाद का मिला-जुला प्रयोग शामिल था, के प्रभाव का अध्ययन करने का प्रयास किया गया है। इसके लिए भारतीय कृषि अनुसंधान संस्थान, नई दिल्ली के अनुसंधान फार्म की टीपिक हेप्लूस्टेप्ट मृदा पर पिछले पाँच वर्षो (2004-05 से 2008-09) से चल रहे फील्ड एक्सपेरीमेंट का उपयोग किया गया। उर्वरक एन.पी.के. एवं दो खादों (गोबर की खाद तथा एस.पी.एम. अर्थात सल्फीटेशन प्रैसमड) के अतिरिक्त कृत्रिम पतझड़ (आई.डी.) जिसमें अरहर की फसल पर परिपक्वता की अवस्था आने पर 10% (भा./आ.) यूरिया घोल का छिड़काव कर सम्पूर्ण पतझड़ किया गया, के प्रभाव का मूल्यांकन भी किया गया। पाँच फसल क्रम पूरा होने पर मृदा की सतह (0-15 से.मी.) तथा अधोसतह (15-30 से.मी.) से नमूने एकत्र किये गये तथा विभिन्न जैव-कार्बन अंशों, खनिज नाइट्रोजन तथा जल-भौतिकीय गुणों के लिए उनका विश्लेषण किया गया।

केवल उर्वरक प्रयोग अथवा उर्वरक-रहित नियन्त्रित मृदा की अपेक्षा मृदा परीक्षण आधारित उर्वरकों एवं खादों के मिले-जुले प्रयोग से विभिन्न मृदा जैव-कार्बन अंशों, मैक्रोएग्रीगेट्स-संलग्न कार्बन तथा खनिज नाइट्रोजन की मात्रा में वृद्धि पायी गई, यद्यपि यह वृद्धि दर खादों की किस्म के अनुसार भिन्न-भिन्न थी। जहाँ एक ओर गोबर की खाद तथा एस.पी.एम. के उर्वरक-संग प्रयोग से अपेक्षाकृत स्थायी कार्बन (पी.ओ.सी.) की मात्रा में वृद्धि हुई वहीं दूसरी ओर सूक्ष्मजैवी बायोमास कार्बन (एम.बी.सी.) तथा सक्रिय (लेबाइल) कार्बन (एल.बी.सी.) की मात्रा कृत्रिम पतझड़ (आई.डी.) के अन्र्तगत अधिक पाई गई। प्राय: विभिन्न एस.ओ.सी. अंशों की अधिक मात्राऐं एन.पी.के. + गोबर की खाद + आई.डी. उपचार के अन्र्तगत पाई गई। कुल जैव-कार्बन (टी.ओ.सी.) में डब्लू.बी.सी., एम.बी.सी. तथा एल.बी.सी. के पारस्परिक योगदान ऊपरी मृदा (0-15 से.मी.) में क्रमश: 17-22, 1.0-1.8 तथा 6.7-11.8 प्रतिशत रहे जबकि नीचे की मृदा (15-30 से.मी.) में यह योगदान कुछ निम्न स्तर पर था। एस.ओ.सी. अंशों में विशेष रूप से सतही मृदा (0-15 से.मी.) में अच्छा सह-सम्बन्ध पाया गया। साथ ही एस.ओ.सी. अंशों तथा खनिज-नाइट्रोजन व गेहूँ की उपज के बीच भी अच्छा सम्बन्ध मिला।

केवल एन.पी.के. अथवा नियन्त्रित उपचारों की अपेक्षा कार्बनिक खादों, विशेष रूप से गोबर की खाद का प्रयोग उर्वरक एन.पी.के. के साथ करने पर मृदा एग्रीगेशन में सुधार हुआ जैसा कि मैक्रोएग्रीगेट्स, औसत भार व्यास (मीन वेट डायमीटर), ज्यामितीय औसत व्यास तथा जल स्थायी एग्रीगेट्स में हुई वृद्धि से प्रमाणित होता है। यह प्रभाव आमतौर पर 15-30 से.मी. गहरी मृदा में भी बना रहा। केवल एन.पी.के. की अपेक्षा खादों व उर्वरक एन.पी.के. के मिले जुले प्रयोग से मृदा स्थूल घनत्व (बल्क डैंसिटी) में कमी हुई। सबसे कम स्थूल घनत्व एन.पी.के. + गोबर की खाद + आई.डी. उपचारित मृदा में पाया गया। बल्क डैंसिटी को छोड़कर (जिसका उपज के साथ ऋणात्मक सम्बन्ध रहा), शेष सभी जल-भौतिकीय गुणों तथा उपज के बीच धनात्मक सम्बन्ध पाया गया।

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Appendix

Abbreviations used in the Thesis

BD : Bulk density

C_{L} : Labile carbon

C_{LL} : Less labile carbon

CMI : Carbon management index

C_{NL} : Non-labile carbon

C_{VL} : Very labile carbon

ESD : Extra-short duration

FYM : Farmyard manure

GMD : Geometric mean diameter

ID : Induced defoliation

IGPR : Indo-Gangetic Plain region

K_{sat} : Saturated hydraulic conductivity

LBC : Labile carbon

LI : Lability index

LSD : Least square difference

MaTOC : Macro-aggregate associated TOC

MBC : Microbial biomass

MiTOC : Micro-aggregate associated TOC

MQ : Microbial quotient

MWD : Mean weight diameter

OOC : Oxidizable organic carbon

POC : Particulate organic carbon

SOC : Soil organic carbon

SPM : Sulphitation pressmud

TGP : Trans-Gangetic Plain

TOC : Total organic carbon

UGP : Upper-Gangetic Plain

WBC : Walkley and Black carbon

WSA : Water-stable aggregates