उर्वरको एवं खादों के दीर्घकालीन प्रयोग के अंतर्गत एक टीपिक हैप्लूस्टेप्ट मृदा में जीवांश पदार्थ का निरुपण

CHARACTERIZATION OF SOIL ORGANIC MATTER UNDER LONG-TERM FERTILIZATION AND MANURING IN A TYPIC HAPLUSTEPT

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CERTIFICATE

This is to certify that the thesis entitled **“Characterization of soil organic matter under long-term fertilization and manuring in a Typic Haplustept”** 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. Debarup Das**, 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: 30-06-2012

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

In the intensively cultivated Indo-Gangetic Plains (IGP), deterioration of soil health in terms of depletion of soil organic carbon (SOC), sub-soil compaction and widespread multi-nutrient deficiencies, has emerged as one of the most critical constraints to the sustainability of important production systems followed in the region (Yadav *et al.* 1998c; Timsina and Connor 2001; Ladha *et al.* 2009). The IGP is heartland of rice-wheat system (RWS) - one of the world's most important and widely practiced production systems. At present, the area under RWS is estimated at 13.5 million ha in South Asian countries of India, Nepal, Bangladesh and Pakistan (Ladha *et al.* 2009). The RWS has been under stress showing a decline in factor productivity since 1990s, mostly due to management-induced soil problems (Yadav *et al.* 1998b; Saharawat *et al.* 2011). Within IGP, the problem is more acute in the high productivity areas of Trans-Gangetic Plains (TGP, representing Punjab and Haryana) and Upper Gangetic Plains (UGP, representing Delhi and Western Uttar Pradesh) (Yadav *et al.* 1998c), wherein 50% of India's total food grain is produced (Bhattacharyya and Pal 2003). Recent diagnostic surveys in the TGP and UGP revealed that the farmers use higher rates of fertilizers, especially N fertilizers, to achieve similar yields that were obtained earlier with relatively less fertilizer input, thus encouraging indiscriminate and unbalanced use of plant nutrients that would further deteriorate soil fertility besides aggravating environmental problems. These trends in fertilizer use could be reversed with restoration and improvement in SOC levels in these soils which are inherently low in SOC. The SOC plays a crucial role in determining physical, chemical and biological properties that control nutrient cycling and consequently overall soil quality and fertility (Gregorich *et al.* 1994). Therefore, the amount and quality of SOC in agricultural soils benefit both soil productivity and environmental quality.

Constant depletion of SOC has emerged as one of the major soil health concerns responsible for unsustainability of RWS (Dawe *et al.* 2000; Manna *et al.* 2005). With large scale adoption of intensive cropping, the long-term balance between additions of C from different sources and losses through different pathways is disrupted (Kong *et al.* 2005), often resulting in net depletion of SOC in tropical and sub-tropical climatic conditions owing to excessive losses of C under continuous cultivation. Hence, there is need to evolve/identify management practices which show potential for annual accretion of SOC, and improve overall soil health, besides supporting sustained high crop yields (Sleutel *et al.* 2006). The long-term experiments (LTEs) showed variations in SOC content under different soil climatic conditions and nutrient management (Nambiar 1995; Abrol *et al.* 2000). A decline in SOC upon long-term cultivation with nil or inadequate fertilizer application, and an increase in SOC with integrated nutrient management (INM) have been reported (Katyal *et al.* 2001; Singh and Wanjari 2009). Reviewing several LTEs that continued for 12 to 17 years in IGP, Yadav *et al.* (2000a; 2000b) also reported the advantageous effect of INM on SOC levels. They also underlined three very important observations out of the results of these LTEs: (i) at the sites initially low in SOC, continuous cropping and fertilization increased SOC levels even without use of organic manures; (ii) at the sites initially high in SOC, the levels could not be sustained even with INM; and (iii) SOC (Walkley-Black C, WBC) levels were often not related to the RWS productivity, across the LTE sites. These findings obviously suggested for studying nutrient management and cropping induced changes in SOC beyond determination of WBC in order to draw logical conclusion on the effect of nutrient management, as also to develop nutrient supply options that enhance the quality of organic matter along with the content.

SOC is considered to be comprised of a small labile or active pool with relatively high turnover rate, which greatly influences nutrient cycling for maintaining soil quality and productivity (Chan *et al.* 2001) and a large recalcitrant or passive pool with slower turnover rates (Krull *et al.* 2003), which is important from carbon sequestration point of view. From soil fertility point of view, adoption of procedures that can preferentially extract 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 (McLauchlan and Hobbie 2004). 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. But, Tirol-Padre and Ladha (2004) reported that C oxidized by $KMnO_4$ is not a reliable measure of labile C, and should be referred to as permanganate oxidisable C (PmOC) when used as a parameter for characterizing soil C. The labile C fraction comprises 5-30% of total SOC, and is considered more sensitive to changes in cultivation or management practices compared to total SOC content (Graham *et al.* 2002). Soil microbial biomass C (MBC) is another important labile fraction that mainly consists of bacteria and fungi and makes up 1-5% of SOC (Haynes 2005). Methods like chloroform fumigation-incubation and chloroform fumigation-extraction have been used widely to determining MBC content (Jenkinson and Ladd 1981). Results of a long-term (122 years) field experiment revealed that both the amount and functional composition of water- and sodium-pyrophosphate-soluble SOM fractions are affected by the type of crop cultivated and differences in fertilizer applications (Kaiser and Ellerbrock 2005). Long-term agricultural practices have been shown to enrich relatively stable components, dominated by aromatic structures, in SOM during its decomposition in tropical climate (Abe *et al.* 2009).

Hence, the present investigation was under taken using an LTE on RWS continuing since past eighteen years at the Project Directorate for Farming Systems Research (PDFSR), Modipuram, that comprises use of fertilizers alone and in conjunction with five organic inputs of varying chemical composition *viz.* FYM, sulphitation pressmud (SPM), greengram residue (GR), and cereal residues (CR) *i.e.* rice straw (RS) and wheat straw (WS). Following were the specific objectives of the investigation:

1. To study the effect of long-term use of fertilizers and manures on the soil organic carbon pools
2. To understand the quality of soil organic matter, and its relationship with available nutrients and crop yields under different nutrient supply options

2. BACKGROUND

Rice-wheat cropping system (RWS) is one of the largest agricultural production systems of the world, occupying around 13.5 million hectares of cultivated land in the Indo-Gangetic Plains (IGP) of India, Bangladesh, Nepal and Pakistan and several million hectares in China (Ladha *et al.* 2009). It is of utmost importance for food and livelihood security in South Asia (Gupta *et al.* 2003). The RWS is, however, under stress owing to indiscriminate use of fertilizers, tillage induced sub-surface compaction, excessive irrigation, decline in soil organic matter (SOM) contents and widespread multi-nutrient deficiency, raising concerns on its sustainability (Yadav *et al.* 1998; Rai *et al.* 2009). The SOM is known to be the nucleus of soil fertility having role in increasing nutrient availability, improving moisture retention characteristics, and improving soil physical health and microbial activity resulting in overall improvement in the crop productivity (Katyal *et al.* 2001). It is thus important to understand the role of nutrient management practices on changes in the quality and quantity of SOM, as also its relationship with available nutrients and crop yields, particularly under RWS wherein soil undergoes drastic changes due to frequent dry and wet tillage (Timsina and Connor 2001). Relevant literature on the above aspects is cited under the following heads:

2.1. Organic carbon stock of Indian soils

Soil organic carbon (SOC) is not only the central indicator of soil quality and health but also a major terrestrial pool for C, N, P, and S and it is strongly affected by agricultural management (Farquharson *et al.* 2003; Feichtinger *et al.* 2004). An increase in SOC improves soil physical properties, conserves soil moisture, and increases available nutrients leading ultimately to greater crop yields (Onemli 2004). On the other hand, a significant decline in SOC levels would decrease the productive capacity of agriculture by deterioration in soil physical properties and impairment of soil nutrient cycling mechanisms (Loveland and Webb 2003). Improving its level is pre-requisite to ensuring soil quality, future productivity, and sustainability (Katyal *et al.* 2001). 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 first comprehensive study on soil organic carbon (SOC) status in Indian soils was conducted by Jenny and Raychaudhuri (1960) on 500 soil samples collected from different cultivated fields and forests with variable rainfall and temperature patterns. But, the study was confined to the effects of climate on soil OC content rather than estimating the total organic carbon stock in the soils. The attempt made by Gupta and Rao (1994) in estimating OC stock was of significance in this context as they reported an OC stock of 24.3 Pg for the soils ranging from surface to an average subsurface depth of 44 to 186 cm, using the database of 48 soil series. The present day OC stock determinations are based on the method described by Batjes (1996), which involves calculation of SOC, multiplying SOC content, bulk density and thickness of horizon for individual soil profiles with thickness varying from 0 to 30, 0 to 50, 0 to 100 and 0 to 150 cm. Based on this method, SOC stock (in the first 30 to 150 cm soil depth) for different physiographic regions has been estimated as 7.89 to 18.31 Pg in the Northern Mountains, 3.28 to 10.53 Pg in the Great Plains dominated by alluvial soils, 3.64 to 13.34 Pg in the Peninsular India dominated by black soils and 2.24 to 10.90 Pg in coastal soils (NATMO 1980; Bhattacharyya *et al.* 2000). Another estimate in the western side of the Indian Peninsula revealed 0.44 Pg of SOC for the first 30 cm soil depth corresponding to the 1999 land-cover status (Krishnan *et al.* 2007). Soil OC stocks in the IGP were estimated as 0.63 and 2.00 Pg in the first 30 and 150 cm soil depth, respectively. This corresponds to about 6% of the total soil OC stock of India (Bhattacharyya *et al.* 2004), although the SOC stocks of Indian IGP contribute to less than 0.4% of the total SOC stock of all tropical regions. According to Velayutham *et al.* (2000), about 70% of Indian soils fall in the OC-deficient zone, based on the low content of top soil (< 1%; 0-30 cm). Based on the limited data set, it appears that the total SOC stock in the first 20 cm soils in the IGP has increased from 0.66 Pg in 1980s to 0.88 Pg in 2005 (Bhattacharyya *et al.* 2007). The Global Environmental Facility co-financed Soil Organic Carbon (GEFSOC) Modelling system predicted an estimated SOC stock for the Indian IGP of 1.27, 1.32 and 1.27 Pg for 1990, 2000 and 2030, respectively, in the top 20 cm of soil, although the trends of overall change in SOC stock assessed from the soil survey data indicated that the soils of the Indian IGP may store 1.1 Pg of C in 2030 (Bhattacharyya *et al.* 2007). Information on

SOC stock under prominent cropping systems or under different nutrient management options is, however, scarce.

2.2. Soil organic carbon (SOC) status under long-term rice-wheat cropping systems

Several studies have shown that conversion of forest lands to permanent cropping decreases the SOC stocks, rapidly in the initial years and at a slower rate thereafter, approaching a new equilibrium after 30 to 50 years (Mann 1986; Balesdent *et al*. 1988; Arrouays *et al.* 1995; Nieder and Benbi 2008). Decline in organic matter content of tropical soils due to continuous cultivation has also been reported (Brown and Lugo 1990; Lugo and Brown 1993). Rice-wheat system (RWS), the mainstay of food security in India, is now showing signs of fatigue with a decline in factor productivity (Yadav *et al.* 2000a; Gupta *et al.* 2003). The underlying reasons for decline or stagnation of crop yields are not precisely known, though it has been attributed to changes in quantity and quality of soil organic matter along with a gradual decline in the supply of soil nutrients, causing macro and micronutrient imbalances (Ladha *et al.* 2000). Bronson and Hobbs (1998) argued that SOC and N-supplying capacity of rice-wheat soils declined due to intensive cropping when little organic matter is returned. Nambiar (1994; 1995) reported that SOC in FYM-omitted treatments declined in some LTEs in India and that application of FYM was effective in building-up SOC and boosting crop yields. Analysis of a long-term experiment (LTE) at Pantnagar using simulation model has indicated that yield decline in rice is due to decline in SOC and total N (Timsina *et al.* 1997). In the major rice-wheat growing regions of north-western India, SOC has decreased from 0.5% in the 1960s to 0.2% in the late 1990s (Sinha *et al.* 1998). Studies by Bhandari *et al.* (2002) and Regmi *et al.* (2002) also attributed the decrease in productivity of the RWS, *inter alia*, to declining soil organic matter (SOM) content and decreased soil fertility. A 19-year old LTE in West Bengal showed that continuous cultivation without use of organic inputs significantly depleted total C content by 39-43% when compared with the addition of organic amendments (Ghosh *et al.* 2010). On the other hand, SOC was conserved or even increased in intensive double- and triple-crop irrigated rice systems in the lowland tropics with high temperatures and adequate soil moisture throughout the year (Cheng 1984; Dobermann and Witt 2000).

A study in southeast China on a red clay (Typic Plinthudults) revealed elevated soil C in the plough layer (0-15 cm) of 66 rice fields, with rice-cultivation time ranging from 2 to 100 years (Zhang and He 2004). A few other studies also favoured enhancement in SOC levels under submerged rice (Sahrawat *et al.* 2005).

A study was conducted in Punjab having a cropping intensity of 190% with RWS as the predominant system. Evaluation of soil data for 25 years (1981-82 to 2005-06) revealed that intensive agriculture resulted in improved SOC status (Benbi and Brar 2009). As a weighted average for the whole state, SOC increased from 2.9 g kg^{-1} in 1981-82 to 4.0 g kg^{-1} in 2005-06, an increase of 38%. Increased productivity of rice and wheat resulted in enhanced C sequestration in the plough layer by 0.8 t C ha^{-1} per ton of increased grain production. Soil organic C content in the surface layer (0-15 cm) in red soils of China increased gradually in the first 30 years of rice cropping, but decreased with the depth (Zhang and He 2004). The increase in organic C with years of rice cropping was the greatest during the 2-15 year period, and became smaller thereafter. The amount of organic C stored in rice soils is greater than upland soils, because of difference in biochemical processes and mechanisms mainly caused by flooding in the former case (Guo and Lin 2001). Both decomposition of amended organic materials and mineralization rates of native SOC are considerably retarded compared with those under aerobic conditions. Therefore, flooding has a tendency to enhance organic C accumulation in the soils (Zhang and He 2004). Analysing several LTEs on RWS across the Indian IGP, Yadav *et al.* (2000b) reported a decline in SOC content only in those LTEs where initial SOC was relatively higher, *e.g.* Pantnagar and Kalyani. In the LTEs with initially low SOC, intensive rice-wheat cropping and fertilization led to either maintenance or increase of SOC content.

2.3. Soil organic carbon (SOC) fractions

A small labile or active pool and a large recalcitrant or passive pool together constitute organic carbon in soil, with the former having relatively higher turnover rate than the later (Krull *et al*. 2003). Nutrient cycling and soil fertility are greatly influenced by this labile pool, which upon quick decomposition contributes to CO_2 flux to the atmosphere (Chan *et al*. 2001; Majumder *et al*. 2008). So, labile carbon pool serves well in characterizing the SOC status under different soil management practices including cropping systems and application of organic and inorganic sources of nutrients (McLauchlan and Hobbie 2004). The highly recalcitrant or passive pool is not suitable for the purpose as it alters very slowly by microbial activities (Weil *et al*. 2003). Included among the labile constituents are comminuted plant litter, macro-organic matter or light fraction, the living component or bio-mass, and non-humic substances that are not bound to mineral constituents (Theng *et al.* 1989). The most labile components of SOM include cellular contents such as carbohydrates, amino acids, peptides, amino sugars, and lipids, followed by less readily metabolized structural materials such as waxes, fats, resins, lignin, cellulose, and hemi-cellulose. Labile pools also contain some recalcitrant plant residues (Woomer *et al.* 1994). Stable organic constituents in the soil include humic substances and other organic macromolecules that are intrinsically resistant against microbial attack, or that are physically protected by adsorption on mineral surfaces or entrapment within clay and mineral aggregates (Theng *et al.* 1989).

One model structure, which has been used to represent multiple-pool SOM relationships, divides SOC into metabolic (turnover time 0.5 yr), active (turnover time 1.5 yr), structural (turnover time 3 yr), slow C (turnover time 25 yr), and passive soil C (turnover time 1000 yr) (Parton *et al.* 1988). The first three fall into the active fraction, which consists mainly of living microbial biomass plus some readily metabolizable organic compounds leached out of litter, roots, and recently dead microbes.

The approach of enhancing the oxidation of C as followed in most of the conventional methods used in SOC determination (Walkley and Black 1934; Nelson and Sommers 1982) may not be useful for assessing the effect of management practices (Chan *et al*. 2001). The adoption of procedures that can preferentially separate the labile pools from non-labile ones might be a useful approach for characterizing SOC and assessing its quality as affected by 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 conditions (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 (MBC), mineralizable C, oxidisable organic C fractions, and light-fraction C.

Labile SOM fractions such as the light-fraction, macro-organic matter or particulate C (Christensen 1986; Hussain *et al.* 1999), MBC (Sparling 1992; Yoshikawa and Inubushi 1995), mineralizable C (Franzluebbers *et al.* 1994), carbohydrates, and enzymes (Deng and Tabatabai 1996a; 1996b; 1997) are highly responsive to changes in C inputs to the soil, and will provide a measurable change before any such change in total organic matter (Gregorich and Janzen 1996). In contrast, the more stable (humified) pools are probably the more appropriate and representative fractions for C sequestration characterization (Cheng and Kimble 2001).

Fractionation of SOC, based on its susceptibility to oxidation with $KMnO_4$ solutions of various concentrations (33-333 m*M*), was introduced by Loginow *et al.* (1987) on the premise that microbiological decomposition of SOM is largely associated with an oxidation process of enzymatic character. Blair *et al.* (1995) modified the procedure using a single concentration of $KMnO_4$ (333 m*M*) as the oxidizing agent. Carbon, which is oxidized by $KMnO_4$ in 1 hour, was considered as labile, and the remaining C that is not oxidized, as non-labile. But, Tirol-Padre and Ladha (2004) reported that C oxidized by $KMnO_4$ is not a reliable measure of labile C, and should be referred to as permanganate oxidisable C (PmOC). The labile C fraction comprises 5-30% of total SOC, and is considered more sensitive to changes in cultivation or management practices compared to total SOC content (Graham *et al.* 2002).

Soil microbial biomass C (MBC) is another important labile fraction that mainly consists of bacteria and fungi, and makes up 1-5% of SOC (Haynes 2005). Methods like chloroform fumigation-incubation and chloroform fumigation-extraction have been used widely to determining MBC content (Jenkinson and Ladd 1981). Changes in the MBC can provide an early indication of longer-term trends in the TOC of soils (Powlson and Jenkinson 1981; Carter 1986; Powlson *et al.* 1987). The ratio of MBC to TOC, known as 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 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 SOM 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).

Particulate organic C (POC) has been shown to be a sensitive indicator of soil management effects on SOC and is considered to represent the slow pool of SOC (Cambardella and Elliott 1992; Elliott *et al.* 1996; Kelley *et al.* 1996; Del Galdo *et al.* 2003) with an intermediate turnover time between the active and passive pool (Parton *et al.* 1987). A combination of physical and chemical methods has been proposed (Zimmermann *et al.* 2007) to separate active (POC and dissolved organic C), slow (silt and clay associated C or stabilized in aggregates) and passive (oxidation-resistant C) SOM fractions analogous to the pools considered in RothC model (Coleman and Jenkinson 1999).

2.4. Chemical characterization of SOM

SOM is mainly formed of humus, and for chemical characterization it needs to be first extracted and then purified. Extraction of SOM with a dilute base works reasonably well, and separation of alkaline extract into humic acid (HA), fulvic acid (FA) and humin was first carried out by Sprengel (1826). The use of dilute alkali, however, has been criticized from time to time because it could alter SOM through hydrolysis and auto-oxidation (Stevenson 1982). On the other hand, a number of workers (Smith and Lorimer 1964; Schnitzer and Skinner 1968) have shown that there was little evidence to demonstrate that dilute alkali under an atmosphere of N_2 damaged or modified SOM. Some researchers (Kononova 1966; Schnitzer *et al.* 1981) have extracted SOM with a mixture of solvents such as 0.1 *M* NaOH and 0.1 *M* $Na_4P_2O_7$ solutions. Cameron *et al.* (1972) and Piccolo and Mirabella (1987) have suggested that 0.1 *M* NaOH solution extracts more high-molecular weight OM than does 0.1 *M* $Na_4P_2O_7$ solution at pH 7.

Extraction of humic substances by NaOH and $Na_4P_2O_7$ is popular because they generally extract large quantities of humic material in most soils (Stevenson 1994), and these amounts are sensitive to soil type (Olk 2006). The fractionation procedure aims to separate macro-OM via sieving or flotation and extraction of dissolved SOM (active pool) from humic material (fulvic acid, humic acid, humin fraction) and non-humic biomolecules of plant and microbial origin (Baldock and Nelson 2000). The fulvic acid fraction is soluble in alkali (*e.g.* 0.1*M* NaOH+0.1*M* $Na_4P_2O_7$) and soluble in acid (*e.g.* HCl), whereas the humic acid fraction is soluble in alkali and insoluble in acid (Stevenson 1994).

Fulvic acids are less-polymerized and have lower molecular weight as compared to humic acids, which have longer chains (Mukherjee and Ghosh 1984). Spectroscopic measurements in the different regions of the electromagnetic spectrum have been shown to provide valuable information about the nature of soil humic substances. The ratio of absorbances at 465 and 665 nm, referred to as E_4/E_6 ratio, has been widely used for characterization purposes. It is considered as an inverse index of particle size and aromaticity. The E_4/E_6 ratio of humic acids are usually <5.0; those for fulvic acids range from 6.0 to 8.5 (Stevenson 1982).

Long-term agricultural practices have been shown to enrich relatively stable components, dominated by aromatic structures, in SOM during its decomposition in tropical climate. It was also found that organic N composition was less affected by land use or management practice than organic C forms (Abe *et al.* 2009). Organic amendments found to cause major chemical changes in coarser soil organic fractions but very minor changes in the finer fractions due to the low turn-over and/or a greater homogeneity in the nature of the organic carbon entering the latter fractions (Sebastia *et al.* 2007). The semiquinone-type free radicals (spins), which are believed to be stabilized by condensed aromatic structures (Wikander and Norden 1988; Senesi 1990), have been associated with humification degree of soil humic substances (Martin-Neto *et al.* 1998; Bayer *et al.* 2000). Bayer *et al.* (2002) evaluated Long-term (5- and 9-year) effects of two tillage regimes (conventional tillage, CT; and no-tillage, NT) and two cropping systems (oat/maize and oat+vetch/maize+cowpea) on characteristics of humic acids (HAs) from surface layer (0 to 25 mm) of a sub-tropical Brazilian Paleudult soil. Generally, soil HA samples from conservation management systems with no soil disturbance (NT) and high crop residue addition (oat+vetch/maize+cowpea) showed lowest degree of humification, as demonstrated by lowest concentration of semiquinone-type free radicals, determined by electron spin resonance (ESR), and lowest total fluorescence (TF), which is proportional to area under fluorescence spectrum; however, cropping systems had less effect than tillage regimes on two spectroscopic parameters.

2.5. Nutrient management *vis-à-vis* SOC fractions and available N, P, S in rice-wheat system

For maintaining the productive potential of the RWS, it is imperative to enhance C input through return of crop residues and addition of organic manures (Timsina and Connor 2001). Accumulation of organic C in soil can be greatly influenced by input of crop residue or crop residue C (Dalal 1989; 1992; Follett *et al.* 1997; Lal 1997), but the amount of C sequestered in soil depends on the inherent level of organic C in soil (Hassink and Whitmore 1997; Thomson *et al.* 2006; Gulde *et al.* 2008). A study after 11 years of rice-wheat cropping with continuous application of farmyard manure (FYM), rice straw (RS), and fertilizer nitrogen (N) showed that application of FYM and RS increased SOC stocks in the surface soil by 33.7% over sole application of fertilizer N (Benbi *et al.* 2012). Conjoint use of FYM and RS along with fertilizer N caused the greatest (83.5%) increase in SOC stocks, and this combination could maintain SOC almost at the same level as for the uncultivated soil, indicating that this practice may help in maintaining the sustainability of RWS in the IGP (Benbi *et al.* 2012). Malhi *et al.* (2011) found that straw retention and N fertilizer application increased organic C and N, and generally the responses to management practices were more pronounced for light fraction organic C and N than total organic C and N. Similarly, in the IGP of West Bengal, MBC and mineralizable C increased with the addition of organic inputs *i.e.* FYM (7.5 t ha^{-1}), rice straw (10 t ha^{-1}) or green manure (8 t ha^{-1}) (Ghosh *et al.* 2010). Addition of organic residues with NPK fertilizers significantly increased the nutrient content of the soil. Continuous cropping decreased total C as well as its labile and non-labile fractions. The labile C fractions dominated in the near surface soil layers, but decreased significantly in the deeper layers where the recalcitrant C fraction dominated. The result has clearly shown that even in intensive cropping, application of NPK+organic amendments could build-up more C as compared to that of fallow and among the organic inputs, FYM proved more beneficial than rice straw or green manure (Ghosh *et al.* 2010). Sodhi *et al.* (2009) reported that after 10 rice–wheat cycles on a sandy loam soil of Punjab, application of rice straw compost at 2 t ha^{-1} along with fertilizers increased SOC and available N content significantly over control, and a further increase was registered with the use of rice straw compost at 8 t ha^{-1}. Sleutel *et al.* (2006) reported that manure and fertilizer application can increase the amount of OC present in free particulate organic matter, occluded particulate organic matter and mineral associated OM at the time scale of several decades. Studies on changes in SOC content due to continuous cropping and manuring under AICRP-LTFE revealed a decrease in SOC in unfertilized plot (control) by 41.5, 24.5, and 15.5% compared to initial values under rice-wheat-jute, soybean-wheat and sorghum-wheat system, respectively, whereas the treatments receiving NPK and NPK+FYM either maintained or improved the SOC over initial content Manna *et al.* (2005). In these experiments, active fractions of SOC *viz.*, water-soluble carbon and hydrolysable carbohydrates, soil MBC and MBN, dehydrogenase and alkaline phosphatase activity were improved significantly with the application of NPK or NPK+FYM over control. Hao *et al.* (2002) showed that the effects of manure application, tillage, crop rotation, fertilizer rate, and soil and water conservation farming on SOC pool were cumulative. Campbell *et al.* (2000; 2001) found that not only the SOC was increased by annual cropping and application of adequate fertilizer NP in semiarid south-western Saskatchewan, but SOC and total N, MBC, light fraction organic C and N, and mineralizable N generally had positive responses to fertilization. After 16 years of different fertilizer management treatments in wheat-corn-soybean rotation, Liu *et al.* (2005) found that the profile average SOC content (0-90 cm) was only 0.9%, 4.1%, and 8.6% higher for manure, fertilizers, and manure+fertilizers, respectively, than that with no fertilizer application (control) in the Chinese Mollisols. However, SOC at the 0-15 cm soil layer was 6.2%, 7.7%, and 9.3% higher with manure, fertilizers, and manure+fertilizers, respectively, than with no fertilizer application. These results indicated that the annual decline rate of SOC in the 0-15 cm layer without fertilizer was not very high (< 0.58%/yr). The results were similar to reports from LTEs in Denmark and England that revealed a slow change in SOC levels under temperate conditions in response to changes in different land uses (Christensen and Johnson 1997). Yang *et al.* (2003) further indicated that the SOC content could be maintained at a relatively stable level under sufficient fertilizer application even without return of manure or crop residues, and SOC content was increased with conjoint use of fertilizers and manures. Liu *et al.* (2005) also reported for the Chinese Mollisols that manure alone did not increase the N content in the soil profile compared to that of no-fertilizer application in the crop rotation. However, fertilizers and manure+fertilizers significantly increased N contents, especially at the 0-15 cm and 15-30 cm soil layers. Francioso *et al.* (2000) also reported that SOC and N differed significantly after 22 years for all treatments where in the amendments with cattle manure markedly increased the SOC and N contents, and the greatest reduction in SOC and N contents was in the unamended plots after 22 years. Applications of fertilizer N are often recommended to increase SOC, particularly on lands that have already experienced significant loss of SOC as a result of cultivation. Fertilization has been shown to increase the level of SOC within cropping systems (Bowman and Halvorson 1998; Campbell *et al.* 1999).

In intensive cereal-cereal systems other than RWS, use of fertilizers and manure affected SOC content over the years substantially, as the SOC content and soil microbial activities in maize-wheat-forage cowpea system on a Typic Haplustept were enhanced with the use of NPK+FYM (Manjaiah and Singh 2001). The LTEs at different locations in the sub-tropical and tropical regions in India revealed that recommended dose of NPK either increased or at least maintained the SOC content over the initial values, whereas unbalanced (N or NP) and inadequate fertilizer (50% of the recommended NPK) use failed to do so (Swarup and Wanjari 2000; Yadav *et al*. 2000b). Studying the influence of long-term application of fertilizers and FYM on organic C fractions in a Typic Haplustept under maize-wheat-forage cowpea system, Rudrappa *et al.* (2006) reported that application of 150% of recommended NPK resulted in higher total organic C (TOC) (12.9 g C kg^{-1}) over either 50% of recommended NPK (9.3 g C kg^{-1}) or 100% of recommended NPK (10.0 g C kg^{-1}) in 0-15 cm soil layer. In this study also, NPK and FYM emerged as the most efficient nutrient supply option to accumulate largest amount of TOC. Data acquired from a 20-year LTE on wheat-maize cropping system on a loess soil of China revealed that integrated use of manure and NPK, was most effective for improving TOC and its labile pools, followed by NPK fertilizer+crop straw, and then NP (Yang *et al.* 2012). Mandal (2010) found that inclusion of organic manures, particularly FYM, in fertilization schedule was beneficial to improve SOC and mineral-N levels in pigeonpea-wheat sequence. Addition of pigeonpea leaflitter 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.

Extensive studies on the benefits of inclusion of legumes in crop sequences 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 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. 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, nodules and aboveground biomass are thus likely to release N faster than FYM or cereal crop residues incorporated to the soil.

Normally 95% of nitrogen (N) and sulphur (S) reside in organic matter (Stevenson 1982) and 60-80% of phosphorus (P) is of organic origin (Sanchez 1976). In several studies, mineralizable N was found to be linearly related to SOC content (Ferguson 1967; Zielke and Christenson 1986). 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 alone 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. The NO_3-N content in the soil at any given time depends upon the rate of formation, crop removal, leaching, volatilization, denitrification, addition of NO_3-N through fertilizers and organic manures and rate of mineralization (Giesenking 1975). Yadav and Singh (1991) reported that increasing rates of NPK application had a favourable influence on exchangeable NH_4-N in soil. In the treatments where N was applied only through fertilizers, soil NH_4-N content was low, although a positive effect of 50% and 75% N substitution through FYM or vermicompost was observed in terms of improved NH_4-N contents of the soil due to slow release and retention by soil (Duraisami *et al.* 2001).

As a result of adoption of nutrient management strategies that depended mainly on NPK fertilizers and largely ignore the replenishment of other nutrients through fertilizers or organic sources, a situation has arrived where application of nutrients like S actually decides the productivity level of intensive cropping systems, as also the response to NPK fertilizers under many situations (Singh 1999; Dwivedi *et al.* 2001b; Sahrawat *et al.* 2007). Presently, deficiencies of S are widespread (Tiwari *et al*. 2006), and recent estimates of All India Coordinated Research Project (AICRP) on Micro and Secondary nutrients and Pollutant Elements, indicate 41% of the soil samples are deficient in S (Shukla *et al*. 2012). Major factors leading to S deficiency are inherent low S content of the soil, coarse sandy texture, low organic matter content, and the conditions that favour leaching losses of available S (TSI 1994). Important management factors responsible for emergence of S deficiency are: (i) progressively greater removal of soil S owing to high production levels, (ii) negative S balances due to S removals exceeding S additions, and (iii) use of S-free fertilizers (Tandon 2011). Farmer participatory surveys undertaken in the IGP revealed that RWS producing, on an average, 3.92 t ha^{-1} rice and 3.95 t ha^{-1} wheat in a year removes annually about 331 thousand tones S from this region (Sharma 2003). On the other hand, application of S is generally ignored. Thus, increasing S deficiency in soil has emerged as one of the major causes for declining yields at the LTEs at some sites (Hobbs and Morris 1996; Swarup and Wanjari 2000). The available S content and magnitude of S deficiency in soils is often associated with SOC content. Dwivedi *et al.* (2001b) analysed a large number of soils from RWS fields in Western Uttar Pradesh, and reported a strong positive relationship between SOC and available S content. Also the extent of S deficiency was invariably smaller in soils with high SOC content. As organic S fraction of the soil is positively related to SOC (Takkar 1988; Pasricha and Sarkar 2009), and generally considered important donor pool of available S (Tripathi and Hazra 2000), lesser deficiencies are expected in soils with high organic C, or in those receiving organic manure along with fertilizers.

In RWS, the reactions that free fixed P under anaerobic conditions reduce the need to apply P to rice (Gill and Meelu 1983; Rekhi *et al.* 2000). Later studies, however, revealed the necessity of P application to both crops (Yadvinder-Singh *et al.* 2000). Increasing SOC levels may promote the reduction of Fe and hence solubilization of P (Sanyal and De Datta 1991; Timsina and Connor 2001). Likewise, incorporating rice straw into soil may depress P solubility and enhance its availability (Singh and Jones 1976). Verma *et al.* (2010) found that extent of improvement in extractable P content in soil was directly proportional to the amount of FYM applied under various treatments under soybean–wheat. They also reported that under RWS, different nutrient management treatments comprising of integrated and sole organic sources significantly improved the extractable P status of soil under puddled condition. Increased availability of P in puddled soil due to decrease in P sorption and increase in P diffusion has been documented (Singh *et al.* 2000). The mineralization of organic P plays important role in its availability in soils, especially in relatively high SOC soils. Transformation of added phosphatic fertilizers is also reported to be influenced by level of soil organic matter. Various researchers observed the increase in available phosphorus in soils due to addition of legume residues with or without fertilizers (Bairathi *et al*. 1974; Gupta *et al*. 1988; Dhillon and Dhillon 1991). Significant increase in available P content was also observed by application of inorganic fertilizer in combination with FYM (Das *et al*. 1991). Incorporation of green manure (*Sesbania*) generally increased the available P content of soils (Singh *et al*. 1981; Yadvinder-Singh *et al*. 1988; Yashpal *et al*. 1993).

2.6. Inter-relationships between SOC fractions and available nutrients

Studies in an LTE continuing since 1971-72 on a Typic Haplustept revealed that correlation between TOC and MBC was stronger (r = 0.90) than between particulate organic C (POC) and MBC (r = 0.82), whereas correlation between MBC and labile organic C was in between the above. Labile OC correlated better with POC than TOC

(Rudrappa 2004). Labile fractions 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).

It is not only the quantity of SOC that affects the availability of N, P, S and other nutrients, but the fertility status of soil has been reported to be influenced by quality of organic matter to a greater extent. Soil microbial biomass serves as a labile source or an immediate sink of C, N, P and S in soils (Diazravina *et al*. 1993; He *et al*. 1997; Dalal 1998; Chan and Heenan 1999). He *et al*. (2003) reported that available nitrogen in soils had highly significant positive correlation with both SOC (r=0.99) and soil MBC (r=0.97), while available P showed positive relationship only with soil MBC. The cycling of nutrient in soil of agricultural ecosystem varies with energy supply to and through soil biota. Soil microbial biomass is an important labile pool of C, N, P and S, and fluctuation in size and activity can significantly influence crop productivity (Rosswall and Paustian 1984; McGill *et al*. 1986). Coleman *et al*. (1983) observed that microbial biomass while comprising a relatively small pool of N, P, and S, may cycle these nutrients perhaps 8 to 10 times per year. The microbial biomass may typically comprise 0.5 to 24% of total phosphorus in mineral soils (Brookes *et al*. 1982; 1984). Although, a very few studies conclusively proved that $KMnO_4$-oxidizable carbon is far more sensitive than TOC to the changes in land uses and agricultural management practices, information on its relationships with the availability of N, P and S is non-existent, particularly under tropics.

A critical review of the available literature indicates knowledge gaps pertaining to the long-term effect of organic sources of diverse origin on the SOC fractions and availability of nutrients under RWS. Information on the quality of SOM under different nutrient supply options in agricultural production systems in general, and RWS in particular, is missing which needs to be generated.

3. MATERIALS AND METHODS

The investigation entitled *"Characterization of soil organic matter under long-term fertilization and manuring in a Typic Haplustept"* involved determination of important organic C pools and some quality parameters of soil organic matter, and studying their relationship with available nutrients and crop yields under different nutrient supply options in a long-term experiment (LTE). For this, an LTE with rice-wheat cropping system (RWS) continuing since 1993-94 at Project Directorate for Farming Systems Research (PDFSR), Modipuram (U.P.) was chosen. Post wheat harvest soil samples were collected from this field experiment after completion of eighteen cropping cycles. Subsequently, yield data as provided by PDFSR were used to draw the inferences as per the objectives of the investigation. Detailed description of materials used and methods followed for different studies are furnished hereunder:

3.1. The experimental site

A long-term experiment (LTE) was established in 1993-94 on a Typic Haplustept of the Research Farm of Project Directorate for Farming Systems Research (then Project Directorate for Cropping Systems Research), Modipuram, Meerut, India in order to study the long-term effect of different nutrient supply options on soil health and productivity of rice-wheat cropping system. Meerut (29^o 4′ N, 77^o 46′ E, 237 m above mean sea level), located in western part of Uttar Pradesh, represents an irrigated, mechanized and input-intensive cropping area of the Upper Gangetic Plain (UGP) transect of the Indo-Gangetic Plain region. The climate of Meerut is semi-arid subtropical, with dry hot summers and cool winters. The average monthly minimum and maximum temperatures in January (the coolest month) are 7.2^o C and 20.1^o C, respectively. The corresponding temperatures in May (the hottest month) are 24.2^o C and 39.8^o C, respectively. Average annual rainfall is 823 mm, and over 75% of this received through the southwest monsoon during July to September.

The soil of the experimental site was a sandy loam of Gangetic alluvial origin, very deep (> 2 m), well drained and with flat (about 1% slope) topography. Data on initial soil characteristics (0-15 cm depth) measured at the onset of the experiment during 1993-94 revealed that the soil was mildly alkaline in reaction (pH 7.98) and non-saline (EC

0.42 dS m^{-1}), and contained 0.41% organic C, 16.4 kg ha^{-1} available (0.05 *M* $NaHCO_3$-extractable) P, 96 kg ha^{-1} available (1*N* ammonium acetate extractable) K and 14.5 kg ha^{-1} available (0.15% $CaCl_2$-extractable) S. Prior to establishment of the experiment the site was generally managed under sugarcane-ratoon-wheat cropping system, and rice (puddled-transplanted)-wheat system was followed intermittently.

3.2. Treatments and crop management practices

The LTE comprises 11 treatments involving chemical fertilizers alone or in combination of different organic sources *viz.* farmyard manure (FYM), sulphitation pressmud (SPM), greengram residues (GR) and cereal *i.e.* rice or wheat residues (CR), and an unfertilized-control. The treatments are being evaluated on a permanent (undisturbed) layout of randomized block design with four replications. In the present investigation, however, 8 out of total 11 treatments and 3 replications were included as per details given in Table 3.1.

The plot size was 8 m x 8 m. The recommended NPK rates were 120 kg N, 26 kg P and 33 kg K ha^{-1} for both rice and wheat crops. Fertilizer N, P and K were applied through urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively, except NPKZnS treatment wherein single super phosphate (SSP) was used as P fertilizer in place of DAP to supply P and S (45 kg ha^{-1}) simultaneously. In NPKZn and NPKZnS treatments, 5 kg Zn ha^{-1} was applied through zinc sulphate to rice only. One-third of N and entire P, K, S and Zn were applied as basal dose as per treatment at the time of transplanting/sowing and remaining N was top-dressed in two equal splits at maximum tillering and panicle/ear emergence.

The quantities of organic inputs (FYM/SPM/CR) were pre-determined on the basis of their N content. FYM and SPM were incorporated in the soil one week before transplanting/sowing, whereas CR was incorporated 15-20 days before transplanting/sowing of the crops as per treatments. In the treatments involving GR, summer greengram was sown immediately after wheat harvest, and after pod-picking the residues (above ground biomass) was incorporated in the soil before puddling.

Table 3.1. Treatment details of the LTE chosen for organic C characterization studies

S. No.	Treatment Code	Treatment details	
		Monsoon (Rice)	Winter (Wheat)
1	Control (C)	Unfertilized	Unfertilized
2	NPKZn	Recommended N, P, K and Zn through fertilizers	Recommended N, P and K through fertilizers
3	NPKZnS	Recommended N, P, K, Zn and S through fertilizers	Recommended N, P, K and S through fertilizers
4	NPK+FYM	75% of recommended N, P and K through fertilizers + 25% substitution of recommended N through FYM	Recommended N, P and K through fertilizers
5	NPK+SPM	75% of recommended N, P and K through fertilizers + 25% substitution of recommended N through SPM	Recommended N, P and K through fertilizers
6	NPK+GR	75% of recommended N, P and K through fertilizers + incorporation of greengram residues after pod picking	Recommended N, P and K through fertilizers
7	NPK+GR+FYM	75% of recommended N, P and K through fertilizers + incorporation of greengram residues after pod picking	75% of recommended N, P and K through fertilizers + 25% substitution of recommended N through FYM
8	NPK+CR	75% of recommended N, P and K through fertilizers + 25% substitution of recommended N through wheat straw	75% of recommended N, P and K through fertilizers + 25% substitution of recommended N through rice straw

Each year, 25-day old seedlings of rice (cv. PR 106) were transplanted manually at 20 x 15 cm spacing in puddled plots during first week of July. After rice harvesting, wheat (cv. PBW 343) was sown in 20 cm rows during third week of November. Both crops were grown under assured irrigated conditions, and chemical weed control was adopted to maintain almost complete weed-free condition. The crops were harvested manually.

3.3. Collection, preparation and preservation of soil samples

Soil samples from three depths *i.e.* 0-7.5, 7.5-15 and 15-30 cm were collected following standard procedure from all plots of the three replications after completion of eighteen rice-wheat crop cycles in 2010-11. 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 the measurement of organic C stock in soil profile, additional samples from 30-45 and 45-60 cm were also taken. For determination of bulk density, soil cores were drawn from four depths *i.e.* 0-15, 15-30, 30-45 and 45-60 cm using a core sampler. Soil samples from all above depths were also collected from adjacent uncultivated area for determination of different parameters (Table 3.2) as done in the samples collected from the LTE.

3.4. Soil Analysis

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

Soil pH was determined in 1:2 soil-water suspension using combined electrode. The EC was determined in the supernatant of the same soil: water ratio on a conductivity bridge as per procedure given by Jackson (1973), and expressed as dS m^{-1}.

3.4.2. Soil physical properties

Bulk density

The core sampler was pushed into the soil to different depths (0-15, 15-30, 30-45 and 45-60 cm) in such a way that soil core is collected from the centre of each 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 dry soil by the volume of core used (Veihmeyer and Hendrickson 1948).

Table 3.2. Important parameters in the uncultivated soil (2011) adjacent to the LTE

Parameter	Soil depth		
	0-7.5 cm	7.5-15 cm	15-30 cm
$pH_{1:2}$	8.04	8.28	8.45
$EC_{1:2}$ (dS m^{-1})	0.20	0.13	0.11
Clay (%)	26.4	26.8	27.6
Silt (%)	17.2	19.6	17.2
Sand (%)	56.4	53.6	55.2
Textural class	Sandy loam	Sandy loam	Sandy loam
Total organic C (%)	1.21	1.06	0.81
Walkley-Black C (%)	0.45	0.39	0.28
Permanganate oxidisable C (g kg^{-1})	0.65	0.39	0.28
Microbial biomass C (mg kg^{-1})	162	146	73
Non-labile C (%)	0.76	0.67	0.52
Less labile C (g kg^{-1})	0.67	0.72	0.95
Labile C (g kg^{-1})	2.42	2.18	0.94
Very labile C (g kg^{-1})	1.38	1.00	0.94
E_4/E_6 ratio of fulvic acid	9.1	--	--
E_4/E_6 ratio of humic acid	5.1	--	--
NH_4-N (mg kg^{-1})	20.0	18.3	18.3
NO_3-N (mg kg^{-1})	21.5	12.2	6.10
Olsen P (kg ha^{-1})	19.3	15.2	8.60
Available S (kg ha^{-1})	10.6	12.2	7.4

Mechanical composition of soil

The per cent sand, silt and clay contents were determined by hydrometer method (Bouyoucos 1962), and soil texture was determined with the help of triangle as proposed by USDA (Brady 2002).

3.4.3. Soil organic carbon fractions

Total organic carbon

Total organic carbon was determined by automatic elemental analyser (vario EL, Elementar Analysensysteme GmbH, Hanau, Germany). Organic C was measured by adding one to two drops of 15% (w/v) HCl to 60 mg soil sample in a silver capsule to convert carbonates to CO_2. The sample in the silver capsule was then dried in an oven at 50 °C for about 2 h. The sample was sealed in the silver capsule and analysed for total organic carbon using the Vario EL, Elementar Analysensysteme GmbH.

Microbial biomass carbon

Microbial biomass carbon (MBC) was determined by fumigation-extraction method (Jenkinson and Ladd 1981). For this, 10 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 maintaining a soil: solution ratio of 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 at 120 °C 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 after stabilizing the trapped CO_2 as $BaCO_3$ by adding saturated $BaCl_2$ solution. 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 under:

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

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.

Permanganate-oxidisable organic carbon

The permanganate-oxidiasble organic carbon (PmOC) was determined following the procedure of Tirol-Padre and Ladha (2004). For this, 2.0 g of soil was taken in centrifuge tube and oxidized with 25 mL of 33 m*M* $KMnO_4$ by shaking on a mechanical shaker for 1 hour. The contents were centrifuged for 5 minutes at 4000 rpm, and 2.0 mL of supernatant was diluted to 50 mL with double distilled water (DDW). The absorbance of the samples and blanks was then measured at 565 nm wavelength on a spectrophotometer. The concentration of $KMnO_4$ from the samples and blanks was determined using the standard calibration curve. The amount of PmOC in the sample was computed as follows:

PmOC (g kg^{-1}) = [(m*M* Blank – m*M* Sample)* (50/2)* 25* 9] / [1000 (mL L^{-1})* weight of sample (g)]

Oxidizable organic carbon and its fractions

The content of oxidizable organic carbon (OOC) and its different fractions in the soil were estimated following procedure of Walkley and Black (1934) 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 distribution of TOC into the following four fractions of decreasing oxidizability as defined by Chan *et al*. (2001):

Fraction I (very labile, VLC)	: Organic C oxidizable under 6.0 mol L^{-1} H_2SO_4
Fraction II (labile, LC)	: Difference in OC oxidizable under 9.0 mol L^{-1} and that under 6.0 mol L^{-1} of H_2SO_4
Fraction III (less labile, LLC)	: Difference in OC 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, NLC): 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 finely ground soil samples as determined by the procedure of Walkley and Black (1934) was referred as Walkley and Black carbon (WBC).

3.4.4. Available nitrogen, phosphorus and sulphur in soil

Mineral nitrogen

Ammonium-N (NH_4-N) was estimated following the procedure given by Rowell (1994). A 10 g soil sample was extracted with 50 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, and then titrated with 0.01*N* H_2SO_4. Nitrate-N (NO_3-N) was estimated by distilling the same sample after adding 0.5 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 0.01*N* H_2SO_4.

Available phosphorus

The soil samples were extracted with 0.5 *M* $NaHCO_3$; pH 8.5 (Olsen *et al*. 1954). Phosphorus content in the extracts was determined by ascorbic acid method (Watanabe and Olsen 1965).

Available sulphur

Available sulphur was determined by extracting the soil sample with 0.15% $CaCl_2$ (Williams and Steinbergs 1959), and sulphur in the extracts was determined by turbidimetric method (Chesnin and Yien 1950).

3.4.5. Extraction of humic substances and determination of E_4/E_6 ratio

Before extraction of humic substances, the soil was decalcified with 0.05 *N* HCl and then air-dried after washing out excess acid with distilled water. Then 12 g of this airdry soil was taken in polypropylene centrifuge tubes and 120 mL of freshly prepared $Na_4P_2O_7$-NaOH solution (0.1 *N* with respect to both $Na_4P_2O_7$ and NaOH, pH 13) was added. The tubes were tightly capped and shaken for 1 hour on an orbital shaker to mix the contents well and left to stand until next morning. The next morning, the dark coloured supernatant solution was separated from the residual soil by centrifugation and filtration. This alkaline extract was then acidified with 2 *N* H_2SO_4 to pH 2 and allowed to stand at room temperature for 24 hours. Then the soluble material (fulvic acid) was separated from coagulate (humic acid) by centrifugation and filtration. The fulvic acid solution thus obtained was then passed through Amberlite IR-120 ion exchange resin in H-form thrice and per cent transmittance at 465 and 665 nm was measured. On the other hand, the humic acid from the filter paper was separated by dissolving it in 0.05 *N* NaOH, and C concentration of the solution was determined. The C concentration of the Na-humate solution was then adjusted to around 135 mg L^{-1}, and per cent transmittance at 465 and 665 nm was measured. The per cent transmittance was converted to absorbance reading using the following formula:

$$\text{Absorbance} = 2 - \log_{10} (\% \text{ transmittance})$$

The E_4/E_6 ratio was calculated by dividing absorbance at 465 nm by that at 665nm.

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 (VLC, LC and LLC) 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; Mandal 2010). Accordingly,

$$\text{Lability index (Li)} = (\text{VLC}/\text{TOC})*3 + (\text{LC}/\text{TOC})*2 + (\text{LLC}/\text{TOC})*1$$

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

Microbial quotient

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

Organic carbon stock

Organic carbon stock was computed using the following formula-

C stock (Mg ha^{-1}) = [TOC (%)/100] * bulk density (Mg m^{-3}) * depth (m) *10000 (m^{2} ha^{-1})

For the depth 0-15 cm, TOC was calculated by averaging the TOC of 0-7.5 and 7.5-15 cm.

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).

4.1. RESEARCH PAPER-I

Effect of long-term fertilization and manuring on soil organic carbon pools under rice-wheat cropping system on a Typic Haplustept

Abstract

Rice-wheat system (RWS) is under stress due to constant deterioration in soil health. Since soil organic C (SOC) is pivotal to almost all soil processes associated with soil health, the changes in SOC under continuous RWS as influenced by nutrient supply options need to be studied. We, therefore, collected soil samples after completion of 18 rice-wheat cycles from a long-term experiment continuing since 1993-94 on a Typic Haplustept of Project Directorate for Farming Systems Research, Modipuram. Treatments chosen for the study included use of fertilizers alone or in combination with organic sources *i.e.* FYM, sulphitation pressmud (SPM), greengram residue (GR) and cereal residue (CR *i.e.* rice or wheat straw), and an unfertilized-control. Total organic C (TOC) and its different fractions increased significantly with conjoint use of fertilizers and organics compared with control or sole fertilizer (NPKZn) treatment, and such treatment differences were more apparent in surface (0-7.5 cm) soil. Labile fractions like microbial biomass C (MBC) and permanganate oxidisable C (PmOC) were generally higher in treatments that received FYM, SPM or GR along with fertilizer NPK, whereas these labile fractions were much lower in NPK+CR treated plots. Oxidisable organic C (OOC) fractions measured as per modified Walkley-Black's procedure revealed that active pool (very labile+labile C) was much larger in FYM or GR+FYM treated plots, whereas passive pool (less labile+non-labile C) was larger under control and NPK+CR. Correlation studies revealed that the amount of MBC could be effectively predicted from Walkley-Black C (WBC) and PmOC, as highly significant linear relationship existed between these SOC fractions. On average, WBC, PmOC and MBC contributed 29 to 46, 4.7 to 6.6 and 1.16 to 2.40% towards TOC in surface (0-7.5 cm) soil layer. Comparison of SOC contents under different treatments with those under adjacent uncultivated land (treated as initial) also established the superiority of INM. Use of fertilizers alone (NPKZn or NPKZnS) either maintained different SOC fractions at initial level, or brought a marked increase in the same.

Key words: Soil organic C fractions; organic C stock; integrated nutrient management; rice-wheat system; Typic Haplustept

4.1.1. Introduction

In the post-Green Revolution era, Indian agriculture encountered the problems of soil health deterioration, stagnation in food grain production and productivity growth rate, groundwater recession, *etc.* resulting in overall decline in factor productivity. Long-term soil fertility studies have shown that decline in soil organic matter (SOM) quantity and quality is one of the major factors for the productivity fatigue in the Indo-Gangetic plains (IGP) (Bhandari *et al.* 2002; Regmi *et al.* 2002; Ladha *et al.* 2003); accompanied with unbalanced and inadequate nutrient use, decreased nutrient supply, increase in sub-soil compaction and indiscriminate use of irrigation water (Yadav *et al*. 1998c; Ladha *et al.* 2003). Together, these factors have affected the most important and widely-practiced cropping system of the IGP *i.e*., rice-wheat cropping system (RWS), resulting in signs of stress (Yadav *et al.* 1998a). Studies revealed that organic C in the soils of major rice-wheat regions of north-western India has decreased from 0.5% in 1960s to 0.2% in the late 1990s (Sinha *et al.* 1998).

Soil organic carbon (SOC) plays a crucial role in improving soil physical properties, conserving water, and increasing available nutrient contents in soil, thus ultimately leading to greater crop yields (Bauer and Black 1994; Berzsenyi *et al.* 2000; Onemli 2004). With large scale adoption of intensive cropping, the long-term balance between additions of C from different sources and losses through different pathways is disrupted (Kong *et al.* 2005), often resulting in net depletion of SOC in tropical and sub-tropical climatic conditions owing to excessive losses of C under continuous cultivation. Studies have shown that besides manure or residue additions, SOC stocks are also affected by fertilization (Hartwig and Ammon 2002), cropping sequence (Kuo *et al.* 1997), duration and timings of ‘fallowing’ (Halvorson *et al.* 2002), *etc*. The two major pools of SOC *i.e.* actively cycling labile pool and relatively more stable resistant/recalcitrant pool vary in their residence time. The former, consisting of transitional materials between fresh plant residues and stabilized organic matter and with short turnover time of <10 years (Janzen *et al.* 1997), has loads of influence on nutrient cycling and thus maintenance of soil quality and its productivity. Contrarily, the later *i.e.* the resistant or passive pool is composed of humic substances and other complex products of biological degradation of plant and animal residues (Baldock and Nelson 2000), which impart the passive pool a highly recalcitrant nature and make it subject to slow microbial alteration (Sherrod *et al.* 2005). The SOC fractions like microbial biomass C (MBC), oxidisable organic C (OOC) (*i.e.* Walkley-Black C), $KMnO_4$ oxidisable organic C (PmOC), *etc*. could be used to detect changes in TOC at early stages of changes in management practices (Purakayastha *et al.* 2008; Gong *et al.* 2009), as these are the first to deplete upon cultivation or related perturbations (Sherrod *et al.* 2005).

Studying the sustainability of RWS in the IGP, Yadav *et al.* (2000a; 2000b) noticed significant changes in SOC contents consequent to long-term use of fertilizers alone or in combination with organic nutrient sources although the changes in SOC contents *per se* were not always corrected with the yield trends. This necessitated in depth studies on SOC pools so as to explain in pragmatic way the effect of management on SOC.

With the above background, the present study was undertaken in an on-going long-term experiment on a Typic Haplustept of Modipuram (Meerut) in order to study (i) the effect of long-term use of fertilizers and organic nutrient sources on SOC fractions under RWS, (ii) understand interrelationships between SOC fractions at different soil depths.

4.1.2. Materials and Methods

4.1.2.1 Experimental site and treatment details

Soil samples for the present investigation were collected from a long-term experiment (LTE) continuing since 1993-94 with rice (*Oryza sativa* L.)- wheat (*Triticum aestivum* L.) cropping system at the research farm of Project Directorate for Farming Systems Research (PDFSR), Modipuram, Meerut (29°40′N, 77°46′E, 237 m above mean sea level). The site is located in the Upper Gangetic Plain zone of the IGP, and represents mechanized and intensive cropping area. Detailed site characteristics including soil and climatic conditions are given in Chapter 3.

The LTE comprised 11 treatments involving different nutrient supply options and an unfertilized control, in a randomized block design with four replications. However, following eight treatments involving fertilizer alone or in combination with organic sources *i.e.*, farmyard manure (FYM), sulphitation pressmud (SPM), greengram residue (GR), cereal residue (CR) *i.e.* rice or wheat straw (RS or WS), and an unfertilized-control with three replications were selected for the present investigation:

Treatment code	Treatments*	
	Rice	Wheat
Control (C)	Unfertilized-control	Unfertilized-control
NPKZn	NPK+Zn	NPK
NPKZnS	NPK+Zn+S	NPK
NPK+FYM	NPK (75%)+FYM (25% N)	NPK
NPK+SPM	NPK (75%)+SPM (25% N)	NPK
NPK+GR	NPK (75%)+GR	NPK
NPK+GR+FYM	NPK (75%)+GR	NPK (75%)+FYM (25% N)
NPK+CR	NPK (75%)+WS (25% N)	NPK (75%)+RS (25% N)

* For detailed description of treatments, please refer to Table 3.1.

The plot-size was 8 m × 8 m. Each year, 25-day rice seedlings (cv. PR 106) were transplanted manually during first week of July. After rice harvesting, wheat (cv. PBW 343) was sown during third week of November. Fertilizer N, P, K and Zn were applied through urea, diammonium phosphate (DAP), muriate of potash (MOP) and zinc sulphate, respectively, except NPKZnS treatment wherein single superphosphate (SSP) was used as P fertilizer. One-third of N and entire P, K, S and Zn were applied as basal dose as per treatment at the time of transplanting/sowing and remaining N was top-dressed in two equal splits at maximum tillering and panicle/ear emergence. FYM and SPM were incorporated in the soil one week before transplanting/sowing, whereas CR was incorporated 15-20 days before transplanting/sowing of the crops as per treatments. In the treatments involving GR, summer greengram was grown after wheat harvest, and after pod-picking the residues (aboveground biomass) was incorporated in the soil before puddling. The crops were harvested manually and aboveground residues were removed from the plots.

4.1.2.2. Soil sampling and analysis

Soil samples from three depths *i.e.* 0-7.5, 7.5-15 and 15-30 cm were collected from all plots of three replications, after wheat harvest (2010-11) *i.e.* after completion of eighteen rice-wheat crop cycles. Each sample was divided into two parts: the first part was stored in a refrigerator for determination of MBC, and the second part was processed for other analyses. For the measurement of C stock in soil profile additional samples from 30-45 and 45-60 cm were also taken. Bulk density (BD) was determined in undisturbed soil cores drawn from four depths *i.e.* 0-15, 15-30, 30-45 and 45-60 cm using a core sampler.

The soil samples were analysed for pH and EC in 1:2 soil-water suspension (Jackson 1973) and mechanical composition of soil (Bouyoucos 1962). Undisturbed soil cores were used to measure BD of the soil (Veihmeyer and Hendrickson 1948). Total organic C (TOC) was determined by TOC Analyser model Vario EL (Elementar Analysensysteme GmbH), after removing inorganic C by HCl treatment, microbial biomass carbon (MBC) by fumigation-extraction method (Jenkinson and Ladd 1981) and permanganate oxidisable carbon (PmOC) by $KMnO_4$-oxidation method (Tirol-Padre and Ladha 2004). 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, VLC): Organic C oxidizable under 6.0 mol L^{-1} H_2SO_4

Fraction II (labile, LC) : 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, LLC) : 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, NLC): Residual organic C after oxidation with 12.0 mol L^{-1} H_2SO_4 when compared with TOC.

4.1.2.3. Computations and statistical analysis

A lability index for SOC was computed by expressing the amounts of each of the three labile pools namely VLC, LC and LLC as fractions of TOC, and 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; Mandal 2010) as follows:

Lability index (Li) = (VLC/TOC)*3+ (LC/TOC)*2+ (LLC/TOC)*1

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

Microbial quotient was computed as the ratio of MBC to TOC. SOC stock (Mg ha^{-1}) was computed by multiplying SOC content (%TOC divided by 100), soil bulk density (Mg m^{-3}), soil depth (m) and area for one hectare *i.e.* 10000 (m^2).

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).

4.1.3. Results and Discussion

4.1.3.1. Soil pH and electrical conductivity

The soil of the LTE site was mildly alkaline at the onset of the experiment. Soil after 18 crop cycles ranged between 7.92 and 8.37 (mean 8.15) in 0-7.5 cm soil layer; the mean pH across the treatments at 7.5-15 cm and 15-30 cm depth was 8.25 and 8.31, respectively (Table 4.1.1). Averaged across the treatments, soil EC was 0.22, 0.18 and 0.16 dS m^{-1} at 0-7.5, 7.5-15 and 15-30 cm depth, respectively (Table 4.1.2). Both pH and EC generally remained unaffected due to nutrient management treatments.

Table 4.1.1. Effect of nutrient supply options on soil pH in rice-wheat system

Treatment	$pH_{1:2}$ at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	8.37	8.39	8.39
NPKZn	8.19	8.23	8.40
NPKZnS	8.22	8.25	8.31
NPK+FYM	8.12	8.18	8.32
NPK+SPM	8.01	8.12	8.22
NPK+GR	8.22	8.33	8.30
NPK+GR+FYM	8.15	8.30	8.29
NPK+CR	7.92	8.21	8.29
Mean	8.15	8.25	8.31
LSD (*P*=0.05)	NS	NS	NS
SEd±	0.43	0.42	0.47

Table 4.1.2. Effect of nutrient supply options on soil electrical conductivity (EC) in rice-wheat system

Treatment	EC (dS m^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	0.22	0.18	0.15
NPKZn	0.23	0.16	0.14
NPKZnS	0.25	0.19	0.16
NPK+FYM	0.23	0.19	0.15
NPK+SPM	0.26	0.20	0.17
NPK+GR	0.20	0.17	0.17
NPK+GR+FYM	0.21	0.18	0.15
NPK+CR	0.20	0.19	0.16
Mean	0.22	0.18	0.16
LSD (*P*=0.05)	NS	0.02	NS
SEd±	0.02	0.01	0.01

4.1.3.2. Soil bulk density

The mean soil BD at 0-15, 15-30, 30-45 and 45-60 cm depth was 1.52, 1.66, 1.68 and 1.73 Mg m^{-3}, respectively indicating an increase in BD with increasing soil depth (Table 4.1.3). As the soil compaction increases with depth in puddled soils (Gajri *et al.*

1992; Dwivedi *et al.* 2003), the increase in BD observed in the present case is explainable. Treatment effects on soil BD were significant ($p<0.05$) in 0-7.5 cm soil layer only, wherein BD was highest (1.70 Mg m^{-3}) under unfertilized-control. Use of organics like FYM, GR or CR along with fertilizer brought significant decrease in BD, that was as low as 1.40 Mg m^{-3} under NPK+GR+FYM or NPK+CR. Between the treatments receiving sole fertilizers, BD under NPKZnS was lower than that under NPKZn, although the differences between these treatments, or those between sole fertilizers and control were not significant. These results corroborated with those recorded under AICRP-LTFE, wherein use of 10-15 t FYM ha^{-1} yr^{-1} along with NPK brought reduction in soil BD in different soils (Nambiar 1994; Swarup and Wanjari 2000). Positive effect of FYM, cereal straw or legume litter recycling on soil BD reduction under RWS and other cropping systems has been documented earlier (Bellaki *et al*. 1998; Singh *et al.* 2005; Hati *et al.* 2006). Soil BD normally does not change significantly due to NPK treatments; however, there could be a marginal reduction due to increase in biomass production with consequent increase in below ground root mass recycling (Bharadwaj and Omanwar 1992).

Table 4.1.3. Soil bulk density (BD) as influenced by long-term use of fertilizers, organic manures and crop residues

Treatment	BD (Mg m^{-3}) at different soil depths			
	0-15 cm	15-30 cm	30-45 cm	45-60 cm
Control	1.70	1.77	1.79	1.85
NPKZn	1.64	1.70	1.71	1.76
NPKZnS	1.57	1.69	1.71	1.76
NPK+FYM	1.43	1.61	1.63	1.67
NPK+SPM	1.55	1.70	1.70	1.76
NPK+GR	1.42	1.60	1.63	1.72
NPK+GR+FYM	1.40	1.52	1.59	1.64
NPK+CR	1.40	1.65	1.65	1.69
Mean	1.52	1.66	1.68	1.73
LSD (*P*=0.05)	0.19	NS	NS	NS
SEd±	0.09	0.09	0.08	0.09

4.1.3.3. Total organic carbon

Total organic carbon (TOC) content at different soil depths was significantly affected by the nutrient supply options (Table 4.1.4). On average, TOC content was highest (1.35%) in top (0-7.5 cm) soil and the lowest (0.32%) at 45-60 cm soil depth. Among treatments TOC under control and sole fertilizer treatments was statistically similar, whereas integrated nutrient options, except NPK+GR, increased the TOC significantly over control in 0-7.5 cm soil layer. The TOC in 0-7.5 cm soil under integrated nutrient supply, except NPK+GR and NPK+SPM, was even greater than sole fertilizer treatments. At other soil depths also, TOC under these treatments was significantly greater than control, although the differences were not as spectacular as in the top soil.

Table 4.1.4. Total organic C (TOC) under different nutrient supply options in rice-wheat system

Treatment	TOC (%) at different soil depths				
	0-7.5 cm	7.5-15 cm	15-30 cm	30-45 cm	45-60 cm
Control	1.15	0.96	0.67	0.59	0.27
NPKZn	1.22	1.10	0.74	0.64	0.28
NPKZnS	1.24	1.13	0.80	0.70	0.30
NPK+FYM	1.42	1.30	0.88	0.96	0.38
NPK+SPM	1.35	1.24	0.81	0.70	0.30
NPK+GR	1.30	1.23	0.75	0.70	0.28
NPK+GR+FYM	1.52	1.34	0.92	0.83	0.40
NPK+CR	1.60	1.32	0.79	0.65	0.31
Mean	1.35	1.20	0.79	0.72	0.32
LSD (*P*=0.05)	0.17	0.14	0.11	0.09	0.04
SEd±	0.08	0.06	0.05	0.04	0.02

At all soil depths, TOC content in control decreased over uncultivated soil after eighteen years of rice-wheat cropping (Fig. 4.1.1). On the other hand, treatments like NPK+FYM and NPK+GR+FYM had a positive impact on TOC content over uncultivated soil at all five soil depths, and the extent of increase in TOC under these treatments was from 9 to 57% and 14 to 43%, respectively. Results thus indicated that the C inputs through different organic sources as also through the root biomass increased the TOC with the passage of time. Similar results of increased TOC with the use of fertilizers and organics have been reported elsewhere (Olsson *et al.* (2005); Su *et al.* 2006; Lou *et al.* 2011). Further estimation of root biomass and rhizodeposition under different nutrient supply options would provide a better explanation to the treatment effects on TOC in future.

4.1.3.4. Soil organic C stock

The SOC stock varied under different treatments from 26.9 to 30.8, 17.7 to 21.2, 15.7 to 23.3 and 7.21 to 9.82 Mg ha^{-1} at 0-15, 15-30, 30-45 and 45-60 cm soil depth, respectively (Table 4.1.5). The SOC stock decreased markedly with increasing soil profile depth irrespective of treatments. The higher SOC stock in the surface as compared to deeper soil layers may possibly be associated with C inputs through organic sources.

Table 4.1.5. Effect of long-term fertilization and manuring on soil organic C (SOC) stock in rice-wheat system

Treatment	SOC stock (Mg ha^{-1}) at different soil depths			
	0-15 cm	15-30 cm	30-45 cm	45-60 cm
Control	26.9	17.7	15.7	7.60
NPKZn	28.6	19.0	16.5	7.47
NPKZnS	27.9	20.3	17.9	8.02
NPK+FYM	29.2	21.2	23.3	9.43
NPK+SPM	30.2	20.6	17.7	7.98
NPK+GR	27.0	18.1	17.1	7.21
NPK+GR+FYM	30.1	21.0	19.8	9.82
NPK+CR	30.8	19.5	16.1	7.80
Mean	28.8	19.7	18.0	8.17
LSD (*P*=0.05)	3.83	3.41	2.72	1.27
SEd±	1.86	1.66	1.32	0.62

Alike TOC contents, the stocks were generally greater under integrated nutrient management (INM), except NPK+GR, compared with control or sole fertilizer treatments, but at 0-15 cm depth the differences between control and NPK+CR could attain statistical significance only. At other depths also, INM appeared superior to fertilizer alone in enhancing SOC stock. Data on SOC stock for entire profile depth of 0-60 cm (Fig. 4.1.2) revealed that the SOC stock under NPK+FYM and NPK+GR+FYM was greater by 22 and 19% over control, and by 16 and 13% over NPKZn. The results are in concurrence with the earlier studies showing that increase in C stock is directly linked to the amount and quality of organic residues (Rasmussen *et al.* 1980), and manuring and fertilization (Hartwig and Ammon 2002).

4.1.3.5. Walkley and Black carbon

Use of fertilizer NPK at soil test-based recommended rate along with Zn or Zn+S increased Walkley and Black carbon (WBC) at 0-7.5 cm depth by 0.13% and 0.18%, respectively compared to control (0.34%) (Table 4.1.6). Use of organic inputs along with NPK increased WBC by 0.22 to 0.37% over control, with highest increase recorded under NPK+GR+FYM. Similar treatment effect on WBC was registered at 7.5-15 cm depth, although the magnitude of increase due to fertilizers or INM over control was smaller (0.07 to 0.22%).

Table 4.1.6. Walkley-Black C (WBC) content of soil as influenced by long-term nutrient management under rice-wheat system

Treatment	WBC (%) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	0.34	0.29	0.24
NPKZn	0.47	0.36	0.24
NPKZnS	0.52	0.44	0.26
NPK+FYM	0.64	0.50	0.26
NPK+SPM	0.59	0.46	0.25
NPK+GR	0.56	0.43	0.24
NPK+GR+FYM	0.71	0.51	0.28
NPK+CR	0.60	0.46	0.26
Mean	0.55	0.43	0.25
LSD (*P*=0.05)	0.07	0.06	NS
SEd±	0.03	0.03	0.02

Differences in treatments at the third soil depth (15-30 cm) were not significant. Also the WBC content declined sharply with soil depth irrespective of treatments. Compared with uncultivated soil, continuous rice-wheat cropping either maintained or increased WBC in different treatments especially in surface (0-7.5 cm) layer, and the magnitude of such build-up in WBC was obviously greater in INM treatments (Fig. 4.1.3). Multi-location LTEs involving intensive cereal-based systems in the sub-tropical and tropical regions revealed that application of NPK at locally recommended rates either increased or at least maintained WBC contents *vis-à-vis* initial contents at most locations (Singh and Wanjari 2009). Use of organics brings further improvement in WBC (Yadav *et al.* 2000b). Greater improvement in WBC with FYM as compared to SPM observed in the present case was due to the fact that SPM is not as rich C source as FYM (Mandal 2010).

4.1.3.6. Permanganate oxidisable carbon

Permanganate oxidisable carbon (PmOC) is considered as a labile C fraction in soil. In the present study, PmOC ranged between 0.58 and 1.01 g kg^{-1} (mean 0.78 g kg^{-1}) in 0-7.5 cm soil, 0.40 and 0.83 g kg^{-1} (mean 0.63 g kg^{-1}) in 7.5-15 cm soil, and 0.27 and 0.41 g kg^{-1} (mean 0.32 g kg^{-1}) in 15-30 cm soil (Table 4.1.7). Treatments receiving FYM, GR and SPM showed significantly greater PmOC contents compared with control or NPKZn in top two soil layers. Among the INM treatments, PmOC was lowest under NPK+CR, compared to uncultivated soil, an increase in PmOC was noted in 0-7.5 and 7.5-15 cm soil mostly under FYM, GR and SPM treated plots (Fig. 4.1.4).

Table 4.1.7. Permanganate oxidisable C (PmOC) at different soil depths as influenced by long-term nutrient supply in rice-wheat system

Treatment	PmOC (g kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	0.58	0.40	0.29
NPKZn	0.66	0.52	0.27
NPKZnS	0.70	0.59	0.29
NPK+FYM	0.84	0.78	0.36
NPK+SPM	0.87	0.65	0.32
NPK+GR	0.84	0.65	0.32
NPK+GR+FYM	1.01	0.83	0.41
NPK+CR	0.75	0.65	0.30
Mean	0.78	0.63	0.32
LSD (*P*=0.05)	0.09	0.07	0.05
SEd±	0.04	0.03	0.02

Literature on effect of nutrient management on PmOC as oxidized with 33*mM* $KMnO_4$ in present case is scarce. However, studies with 333 mM $KMnO_4$ oxidizable organic C (referred as labile C by Blair *et al.* 1995) revealed that the changes in this fraction depended on the amount and nature of organic source added (Mtambanengue and Mapfuno 2008), long-term use of 15 t FYM ha^{-1} yr^{-1} along with NPK brought substantial increase in labile C compared with NPK treatments on Typic Haplustept (Rudrappa *et al.* 2006).

4.1.3.7. Microbial biomass carbon

Microbial biomass carbon (MBC) fraction in surface soil layer (0-7.5 cm) ranged between 135 mg kg^{-1} in control to 366 mg kg^{-1} in NPK+GR+FYM (Table 4.1.8). In general, treatment effects on MBC followed trends similar to PmOC and the lowest MBC was noticed in NPK+CR amongst the INM treatments.

Table 4.1.8. Effect of nutrient supply options on microbial biomass C (MBC) at different soil depths

Treatment	MBC (mg kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	135	133	87
NPKZn	148	141	88
NPKZnS	186	158	87
NPK+FYM	340	248	88
NPK+SPM	256	167	153
NPK+GR	290	216	179
NPK+GR+FYM	366	264	196
NPK+CR	186	183	140
Mean	239	189	127
LSD (*P*=0.05)	29	24	15
SEd±	13	11	7

Goyal *et al.* (1999) reported that application of organic manures along with fertilizers led to increased MBC, as the organics supplied readily decomposable organic matter in addition to increased root biomass and root exudates. Microbial biomass C and LBC are considered more sensitive to change in management practices than TOC or other fractions of SOC (Graham *et al.* 2002; Haynes 2005), and the increase in MBC due to INM is supported by several workers (Rudrappa *et al.* 2006; Mandal 2010). In the present study, surface soil exhibited higher MBC compared to lower soil depths primarily due to addition of leftover crop residues and root biomass in the topsoil, as also observed by Gupta *et al.* (1994).

Compared to adjacent uncultivated soil, MBC changes were meagre in control or fertilizer treated plots (Fig. 4.1.5). Integrated nutrient supply, however, brought marked improvement in MBC at different soil depths.

Microbial quotient (MQ) computed as ratio of MBC to TOC ranged from 0.9 to 2.9% under different treatments (Fig. 4.1.6a). The MQ values in different soil layers were generally greater under treatments that included organic materials, particularly FYM, GR, and SPM. The MQ values were highest (2.4%) in treatments receiving FYM or GR+FYM along with NPK in 0-7.5 cm, which in fact indicated the advantage of these nutrient management options in improving the relative proportion of MBC for each unit of TOC. Compared to uncultivated soil, only the treatments having FYM or GR or FYM+GR with NPK showed positive change in MQ in all three soil depths (Fig. 4.1.6b). These results are in concurrence with Brookes *et al.* (1984) and Rudrappa *et al.* (2006). Microbial biomass C having a competitively rapid turnover rate may provide an early indication of long-term trends in the TOC contents (Powlson and Jenkinson 1981; Powlson *et al.* 1987).

4.1.3.8. Oxidizable organic carbon fractions

The oxidizable organic carbon (OOC) was grouped into 4 fractions *viz.* very labile (VLC), labile (LC), less labile (LLC) and non-labile (NLC) as proposed by Chan *et al*. (2001), and the data on the same are presented in Tables 4.1.9a to 4.1.9d. Averaged across the treatments, different OOC fractions in the 0-7.5 cm soil were in the order: LLC (1.00 g kg^{-1}) < VLC (1.71 g kg^{-1}) < LC (2.81 g kg^{-1}) < NLC (7.99 g kg^{-1}). Similar order of OOC fractions was recorded in other soil depths also. There is a deviation from the order reported by Chan *et al.* (2001) under different pasture species in Australian soils. Variation in the rate of decomposition of crop residues, type of FYM and different climatic conditions may be responsible for differences in the size of carbon pools as observed in the present case. Application of CR with NPK significantly increased NLC content over other treatments in 0-7.5 cm soil and over control and sole fertilizer treatments in 7.5-15 cm soil layer.

Table 4.1.9a. Long-term effect of nutrient supply options on very labile C (VLC) content of soil in rice-wheat system

Treatment	VLC (g kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	1.02	0.91	0.86
NPKZn	1.18	0.72	0.58
NPKZnS	1.91	1.28	0.94
NPK+FYM	2.09	1.90	0.94
NPK+SPM	1.94	1.82	0.93
NPK+GR	1.75	1.61	0.83
NPK+GR+FYM	2.51	2.09	1.15
NPK+CR	1.31	1.13	0.96
Mean	1.71	1.43	0.90
LSD (*P*=0.05)	0.22	0.18	0.11
SEd±	0.10	0.08	0.05

Table 4.1.9b. Long-term effect of nutrient supply options on labile C (LC) content of soil in rice-wheat system

Treatment	LC (g kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	1.71	1.52	0.98
NPKZn	2.08	1.83	0.98
NPKZnS	2.23	2.24	1.15
NPK+FYM	3.36	2.38	1.21
NPK+SPM	3.24	2.11	1.12
NPK+GR	3.16	2.23	1.21
NPK+GR+FYM	3.69	2.42	1.26
NPK+CR	3.02	2.28	0.96
Mean	2.81	2.13	1.11
LSD (*P*=0.05)	0.43	0.34	0.16
SEd±	0.20	0.15	0.07

The LLC fraction followed almost similar trends as NLC, and was highest under NPK+CR. The contents of LC and VLC were, however, greater in nearly all soil layers under INM treatments that included FYM, GR or SPM (Tables 4.1.9a and 4.1.9b). Also, variable extent of change in different fractions over the uncultivated soil were recorded (Figs 4.1.7a to 4.1.7d), which further indicated the significance of nature of organic materials in modifying the OOC fractions over time.

Table 4.1.9c. Long-term effect of nutrient supply options on less labile C (LLC) content of soil in rice-wheat system

Treatment	LLC (g kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	0.63	0.44	0.53
NPKZn	1.41	1.05	0.81
NPKZnS	1.03	0.92	0.54
NPK+FYM	0.95	0.72	0.42
NPK+SPM	0.75	0.64	0.41
NPK+GR	0.70	0.50	0.32
NPK+GR+FYM	0.87	0.56	0.38
NPK+CR	1.64	1.15	0.68
Mean	1.00	0.75	0.51
LSD (*P*=0.05)	0.11	0.11	0.06
SEd±	0.05	0.05	0.03

Table 4.1.9d. Long-term effect of nutrient supply options on non-labile C (NLC) content of soil in rice-wheat system

Treatment	NLC (g kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	8.13	6.73	4.30
NPKZn	7.49	7.43	5.03
NPKZnS	7.23	6.83	5.33
NPK+FYM	7.80	7.97	6.17
NPK+SPM	7.62	7.93	5.57
NPK+GR	7.40	8.00	5.07
NPK+GR+FYM	8.17	8.33	6.40
NPK+CR	10.07	8.63	5.27
Mean	7.99	7.73	5.39
LSD (*P*=0.05)	0.98	0.95	0.72
SEd±	0.46	0.44	0.34

The lability index (LI) computed by adding the proportions of the OOC fractions of variable lability to the TOC revealed the highest values of LI under NPK+GR+FYM followed by the NPK+FYM, NPK+SPM and NPK+GR, indicating that these treatments maintained relatively higher amount of C in active (*i.e.* labile + very labile) pools compared with sole fertilizer treatments or unfertilized-control at 0-7.5 and 7.5-15 cm soil depths (Fig. 4.1.8). 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, the VLC and LC fractions may prove useful indices to detect small changes in SOC due to management. More detailed studies are needed to evaluate the utility of these fractions *vis-à-vis* other labile fractions like MBC and PmOC.

4.1.3.9. Contribution of different SOC fractions to TOC

The contribution of WBC and PmOC to TOC under different treatments in 0-7.5 cm soil varied from 29 to 46 and 4.7 to 6.6%, respectively (Fig.4.1.9a to 4.1.9b). The corresponding proportion of these fractions in 7.5-15 cm soil was 30 to 39 and 4.2 to 6.2%, and in 15-30 cm soil was 29 to 36 and 3.6 to 4.5%, respectively (Fig. 4.1.2b). Proportion of WBC to TOC was higher in case of conjoint use of NPK and organic sources compared to control and NPKZn in 7.5-15 and 15-30 cm soil layers, but it was less as compared to control in the upper most layer (0-7.5 cm). The treatments receiving FYM or GR+FYM along with NPK supported higher proportion of WBC per unit of TOC in all three depths. Other INM treatments were inconsistent over depth with respect to contribution of WBC towards TOC. The contribution of PmOC was also greater in INM treatments except NPK+CR over control or NPKZn in 0-7.5 and 7.5-15 cm soil layers. However, proportion of PmOC to TOC was more or less similar across the treatments in 15-30 cm depth.

Considering all the three depths, contribution of NLC, LLC, LC and VLC towards TOC under different treatments was 53.5 to 70.8, 4.04 to 11.8, 11.6 to 24.4, and 6.6 to 16.5%, respectively. The passive pools (LLC+ NLC) showed relatively higher proportion (70.1%) than active (VLC+LC) pool *i.e.* 29.9%. This is again in contrary to Parton *et al.* (1992) who showed passive pools in range of 30 to 40% using crop modeling approaches. On the other hand, Majumder *et al.* (2007) showed a large proportion of passive pools

(63%) in different NPK and FYM treatments. Such variations in the results are explainable in view of large variability in the composition of organic materials, cropping systems, climate and soil conditions.

4.1.3.10. Inter-relationships between SOC fractions

Positive and significant ($p<0.01$) correlations were observed between WBC, VLC, LC and PmOC at 0-7.5 and 7.5-15 cm soil depths (Tables 4.1.10a to 4.1.10c). At these soil depths, TOC was also positively and significantly correlated with WBC, NLC, LC and PmOC. The relationships between different fractions at 15-30 cm depth were generally inconsistent. Highly significant relationship of WBC with MBC and PmOC (Figs. 4.1.11a and b), and between PmOC and MBC (Fig. 4.1.11c) suggested the possibility of predicting PmOC from WBC, and MBC from WBC or PmOC at 0-7.5 cm and 7.5-15 cm soil depths. Similarly, LC and VLC could also be helpful in predicting MBC (Fig. 4.1.11d and e). Positive correlations between WBC and labile fractions of SOC have also been reported earlier (Rudrappa *et al.* 2006; Majumder *et al.* 2007; Mandal 2010).

Table 4.1.10a. Inter-relationships between SOC fractions in 0-7.5 cm soil layer

Treatment	Correlation coefficients (r-values)							
	TOC	WBC	NLC	LLC	LC	VLC	PmOC	MBC
TOC	1.00							
WBC	0.67^{**}	1.00						
NLC	0.69^{**}	0.08	1.00					
LLC	0.35	0.06	0.52^{*}	1.00				
LC	0.61^{**}	0.87^{**}	0.08	-0.12	1.00			
VLC	0.37	0.76^{**}	-0.22	-0.37	0.72^{**}	1.00		
PmOC	0.57^{**}	0.87^{**}	-0.03	-0.22	0.86^{**}	0.82^{**}	1.00	
MBC	0.40	0.80^{**}	-0.15	-0.38	0.85^{**}	0.84^{**}	0.86^{**}	1.00

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

Table 4.1.10b. Inter-relationships between SOC fractions in 7.5-15 cm soil layer

Treatment	Correlation coefficients (r-values)							
	TOC	WBC	NLC	LLC	LC	VLC	PmOC	MBC
TOC	1.00							
WBC	0.74**	1.00						
NLC	0.69**	0.40	1.00					
LLC	0.01	-0.03	0.09	1.00				
LC	0.68**	0.67**	0.54**	.096	1.00			
VLC	0.62**	0.76**	0.44*	-0.53**	0.62**	1.00		
PmOC	0.80**	0.85**	0.56**	-0.16	0.78**	0.80**	1.00	
MBC	0.70**	0.70**	0.51*	-0.34	0.70**	0.79**	0.87**	1.00

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

Table 4.1.10c. Inter-relationships between SOC fractions in 15-30 cm soil layer

Treatment	Correlation coefficients (r-values)							
	TOC	WBC	NLC	LLC	LC	VLC	PmOC	MBC
TOC	1.00							
WBC	0.30	1.00						
NLC	0.92**	0.20	1.00					
LLC	-0.35	-0.15	-0.37	1.00				
LC	0.56**	0.15	0.57**	-0.72**	1.00			
VLC	0.48*	0.54**	0.51*	-0.53**	0.33	1.00		
PmOC	0.53**	0.22	0.54**	-0.54**	0.43*	0.67**	1.00	
MBC	0.31	0.09	0.32	-0.55**	0.33	0.48*	0.54**	1.00

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

4.1.4. Conclusion

The foregoing results clearly underline the significance of conjoint use of fertilizers and organic nutrient sources in sustaining and improving SOC levels under

RWS. Among organics, FYM and GR were comparatively more effective in increasing the labile pools of SOC, whereas incorporation of CR *i.e.* rice or wheat straw mostly added non-labile fraction of SOC. Results further suggest that in the areas where regular green manuring is not possible for one or the other reason, incorporation of residues of short duration summer greengram after pod-picking could be an alternative option to improve soil health by increasing labile SOC and also by decreasing soil BD. Further investigations are needed to evaluate the active OOC fractions *vis-à-vis* other labile SOC fractions for detecting management induced changes in SOC.

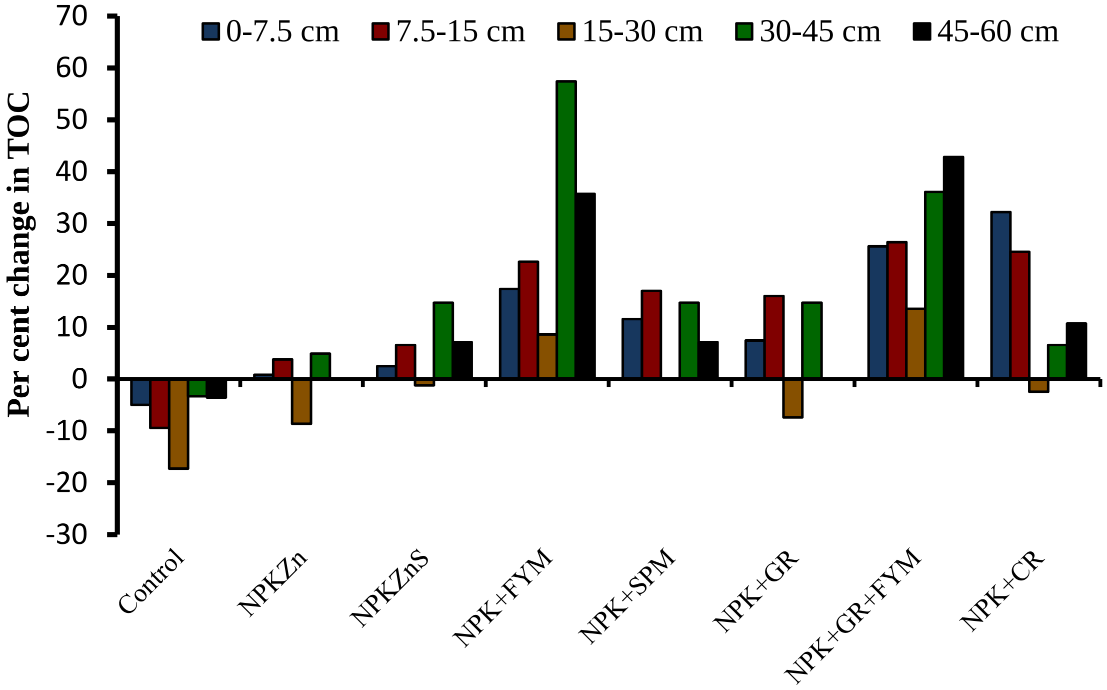


Fig. 4.1.1. Per cent change in TOC over uncultivated soil after 18 rice-wheat crop cycles

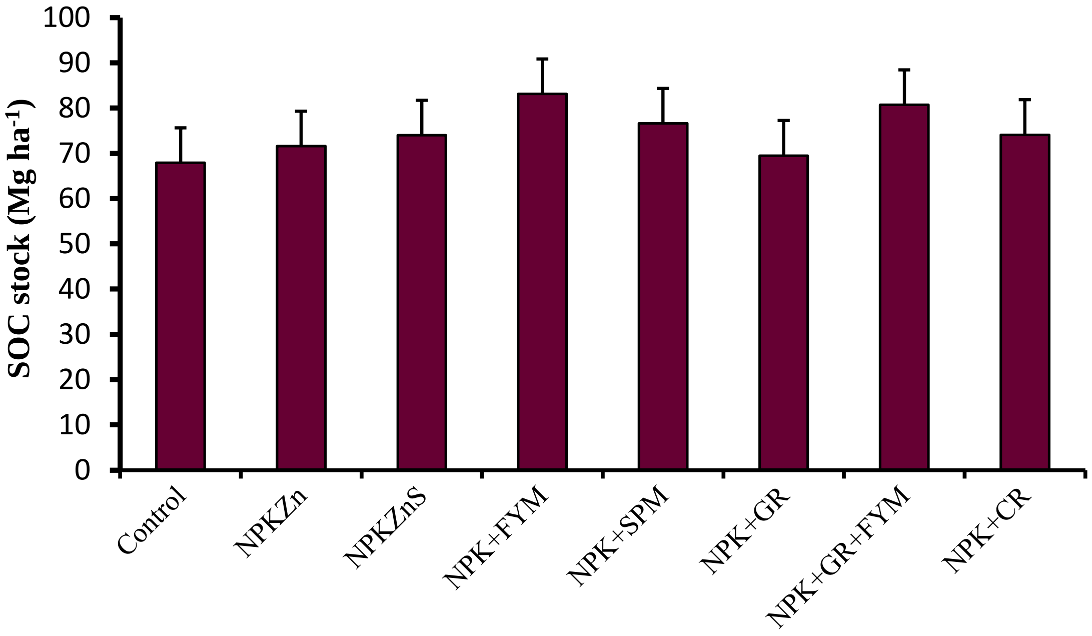


Fig. 4.1.2. Effect of long-term fertilization and manuring on SOC stock (0-60 cm soil depth) in rice-wheat system, error bars indicate LSD (p=0.05).

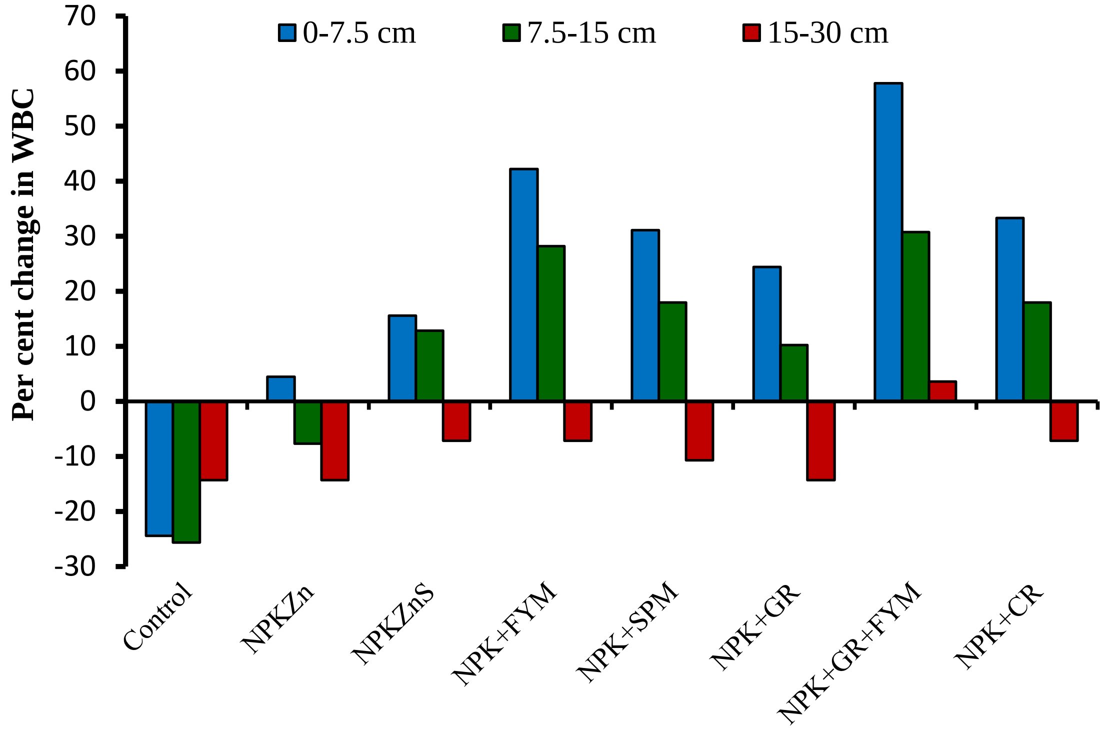


Fig. 4.1.3. Per cent change in WBC over uncultivated soil after 18 rice-wheat crop cycles

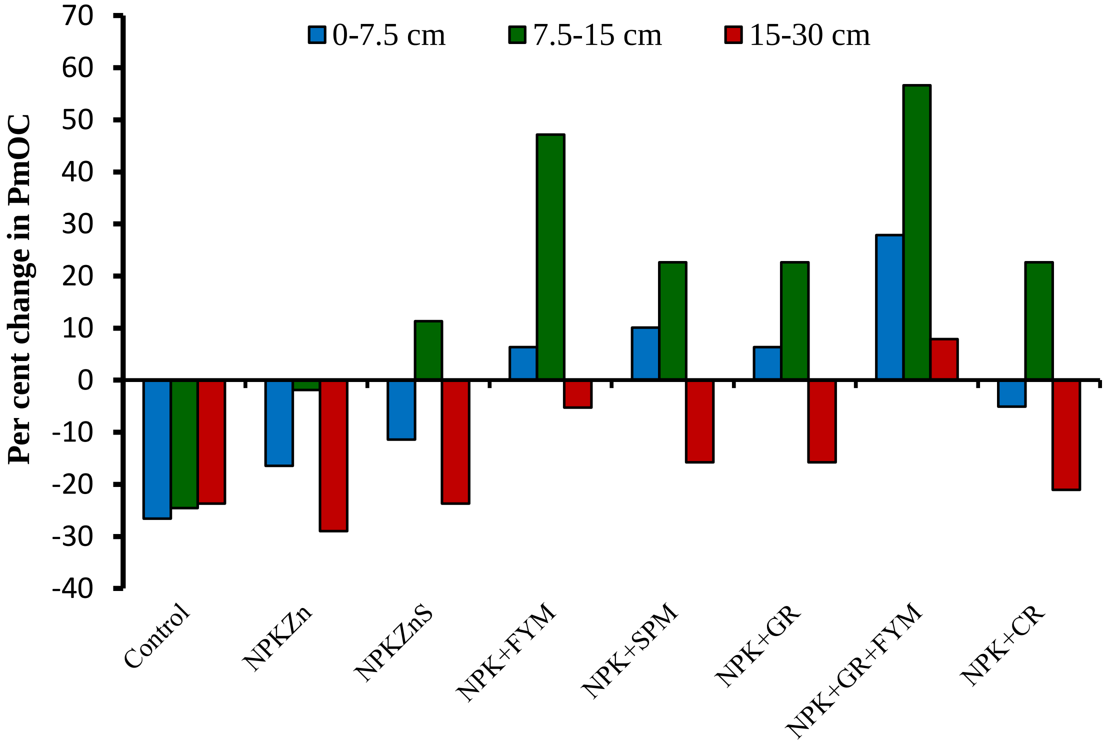


Fig. 4.1.4. Per cent change in PmOC over uncultivated soil after 18 rice-wheat crop cycles

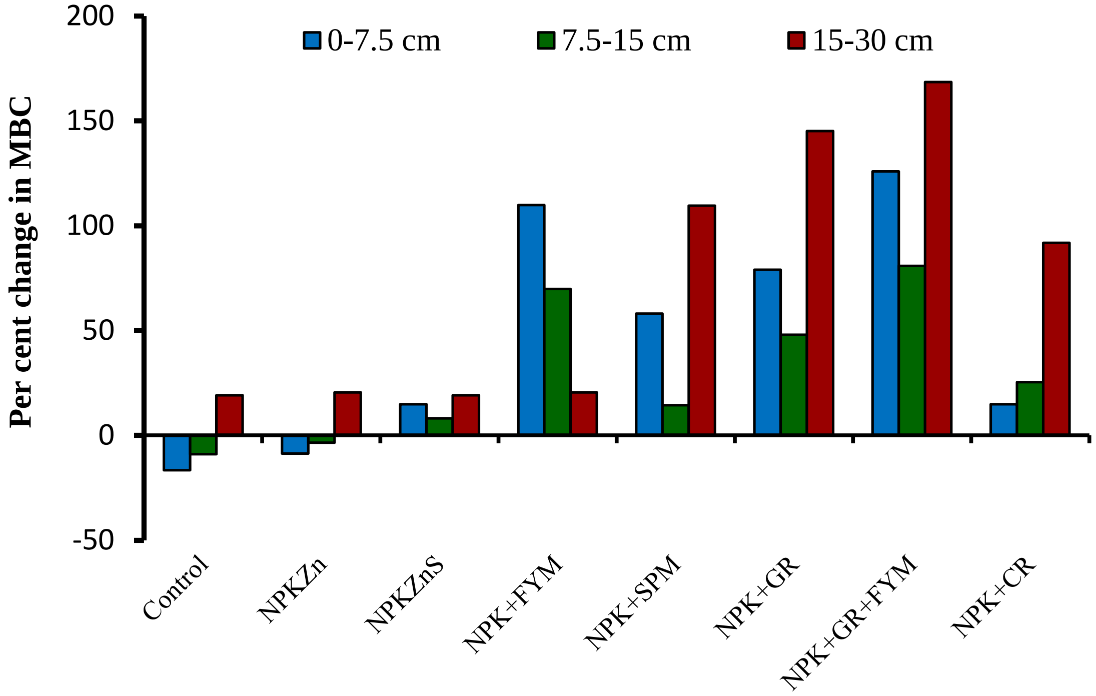


Fig. 4.1.5. Per cent change in MBC over uncultivated soil after 18 rice-wheat crop cycles

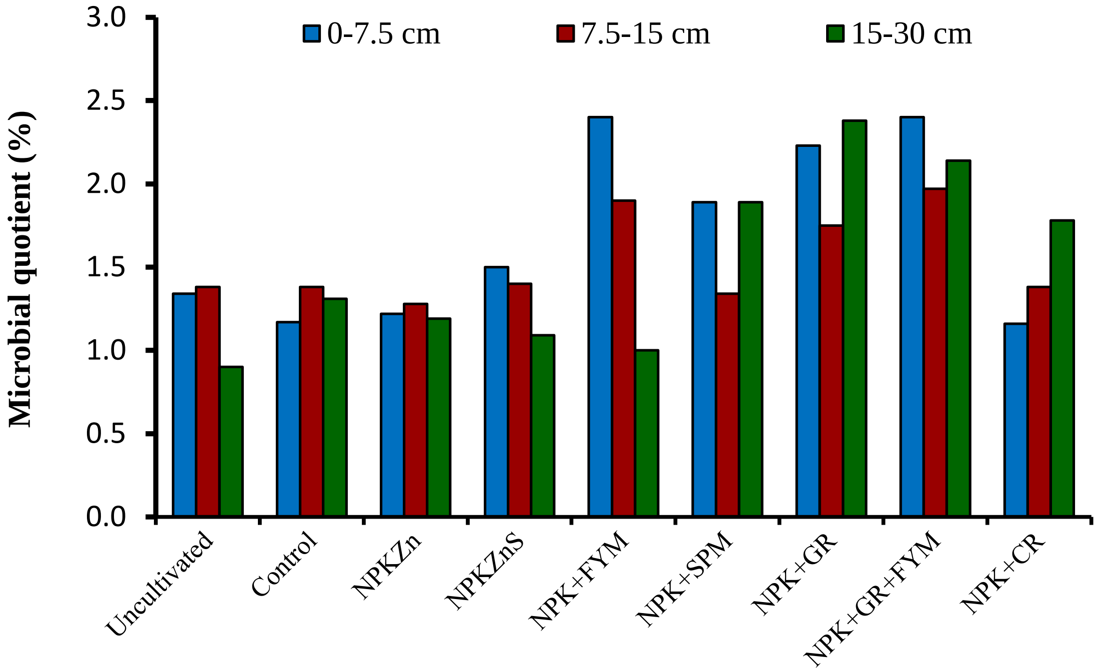


Fig. 4.1.6a. Microbial quotient (%) under different nutrient supply options and soil depths in rice-wheat system

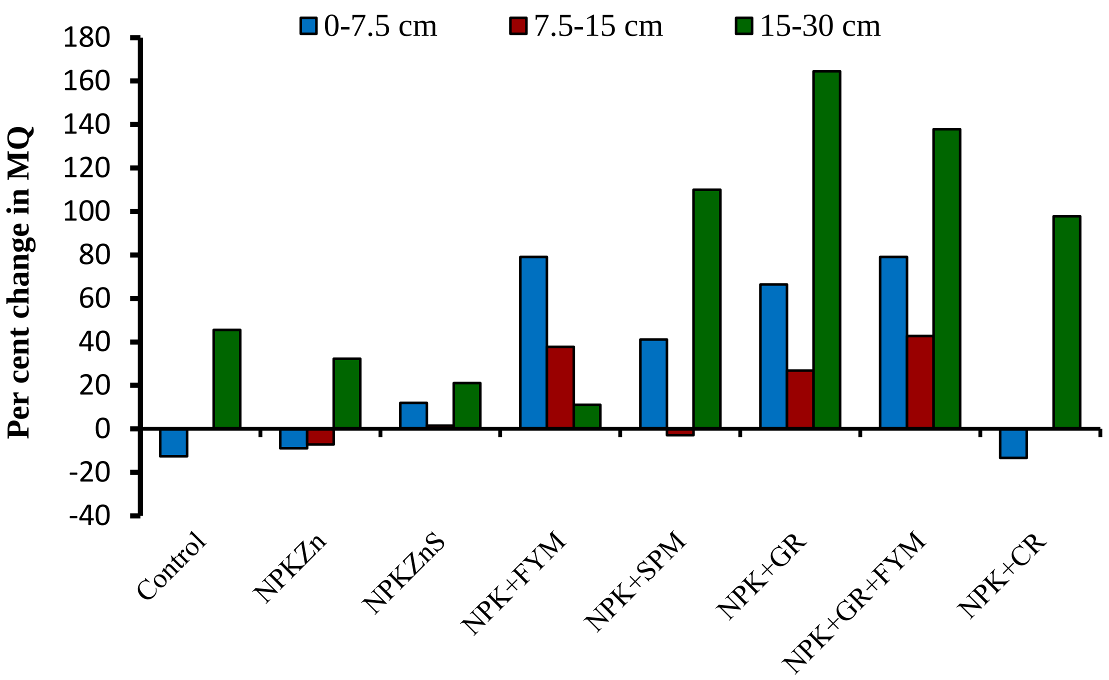


Fig. 4.1.6b. Per cent change in MQ over uncultivated soil after 18 rice-wheat crop cycles

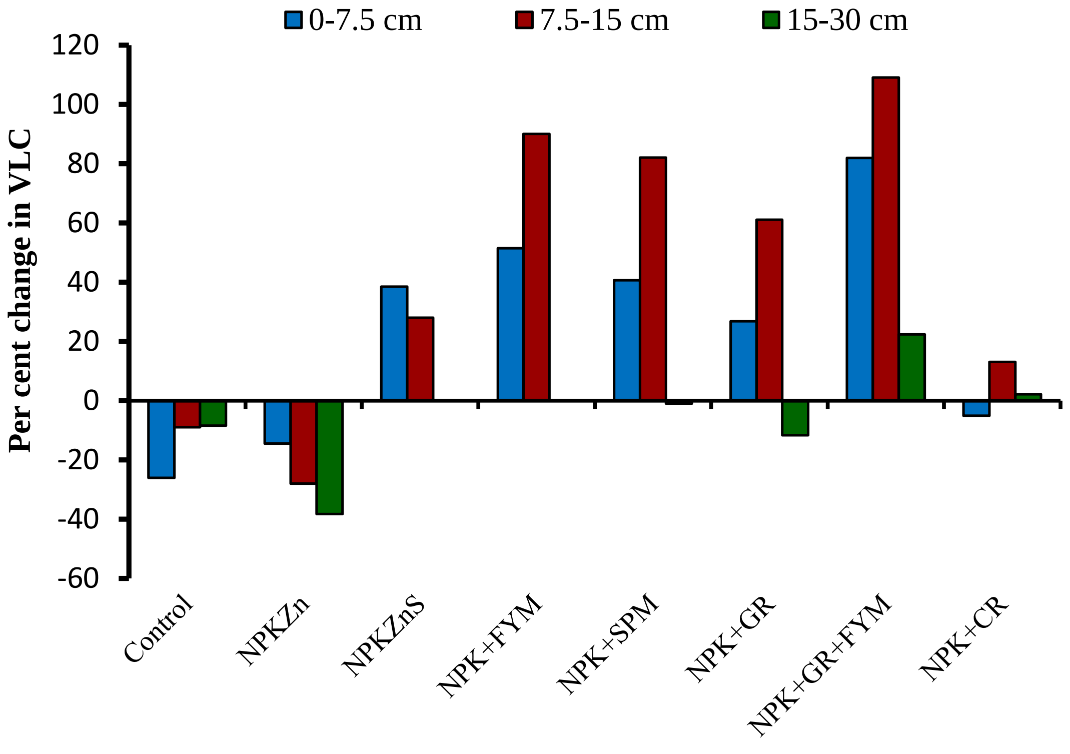


Fig. 4.1.7a. Per cent change in VLC over uncultivated soil after 18 rice-wheat crop cycles

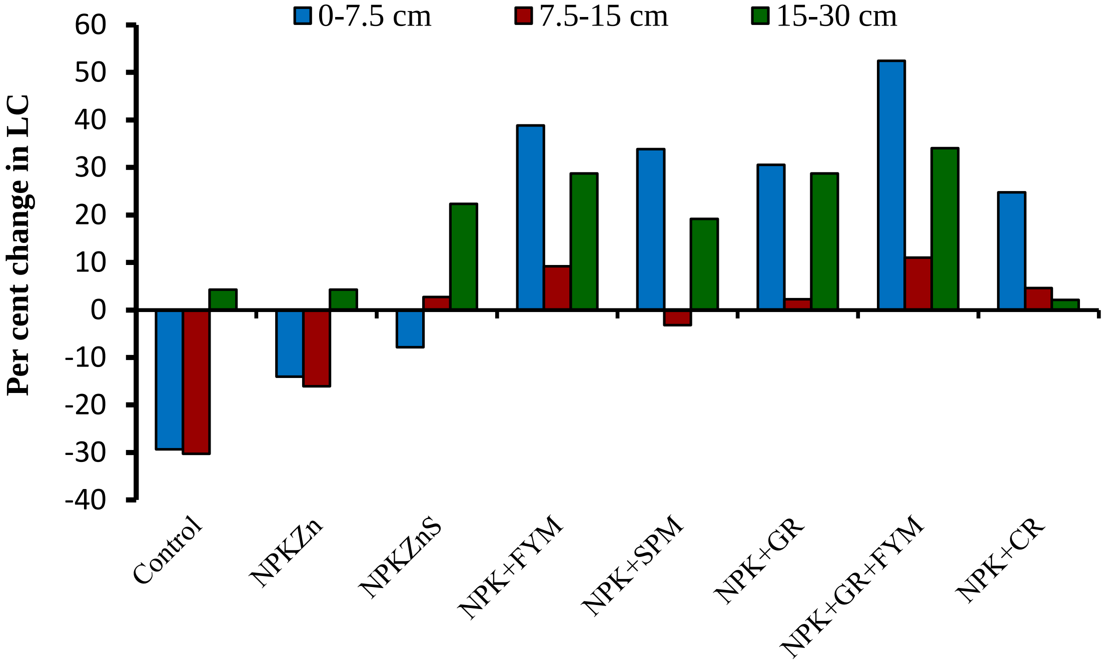


Fig. 4.1.7b. Per cent change in LC over uncultivated soil after 18 rice-wheat crop cycles

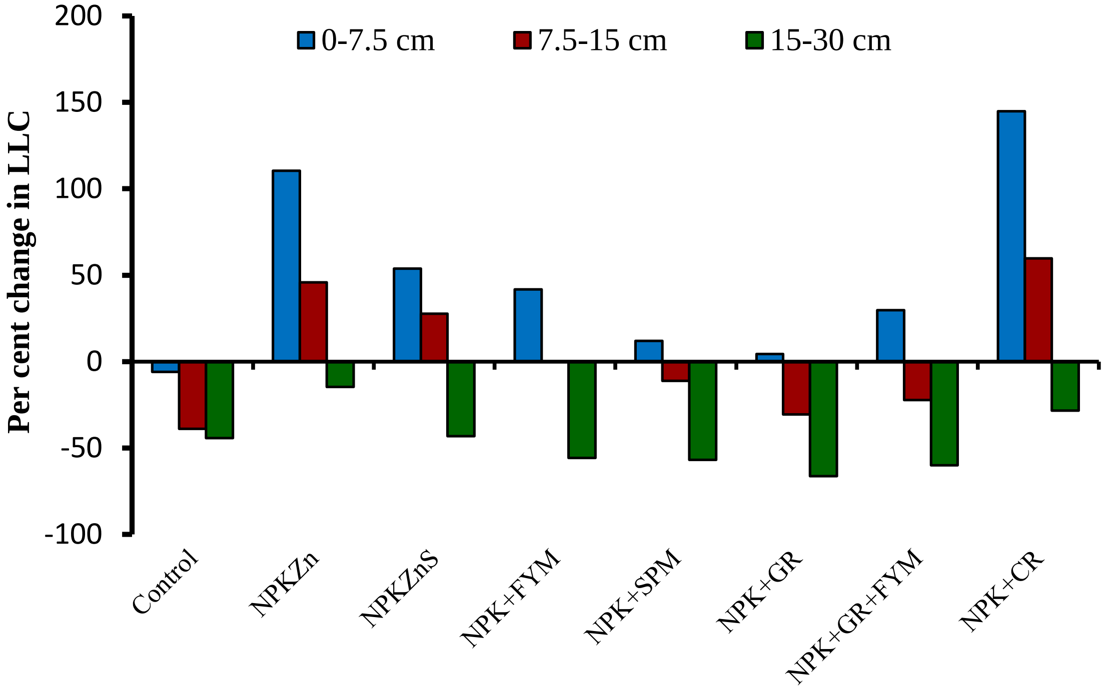


Fig. 4.1.7c. Per cent change in LLC over uncultivated soil after 18 rice-wheat crop cycles

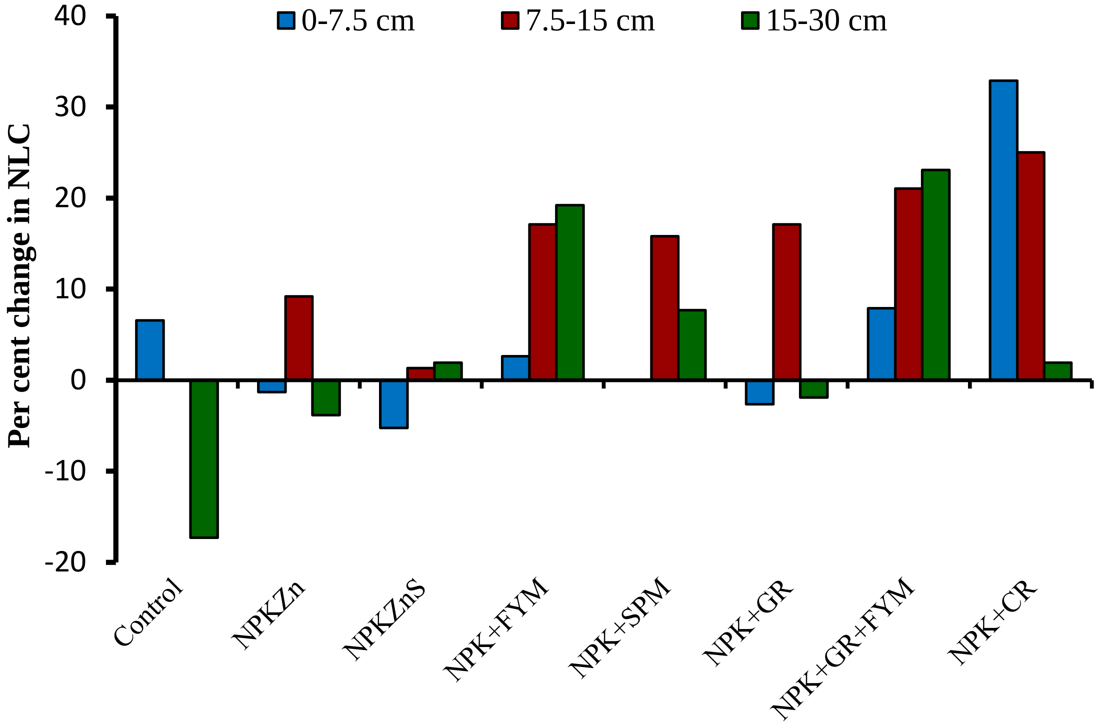


Fig. 4.1.7d. Per cent change in NLC over uncultivated soil after 18 rice-wheat crop cycles

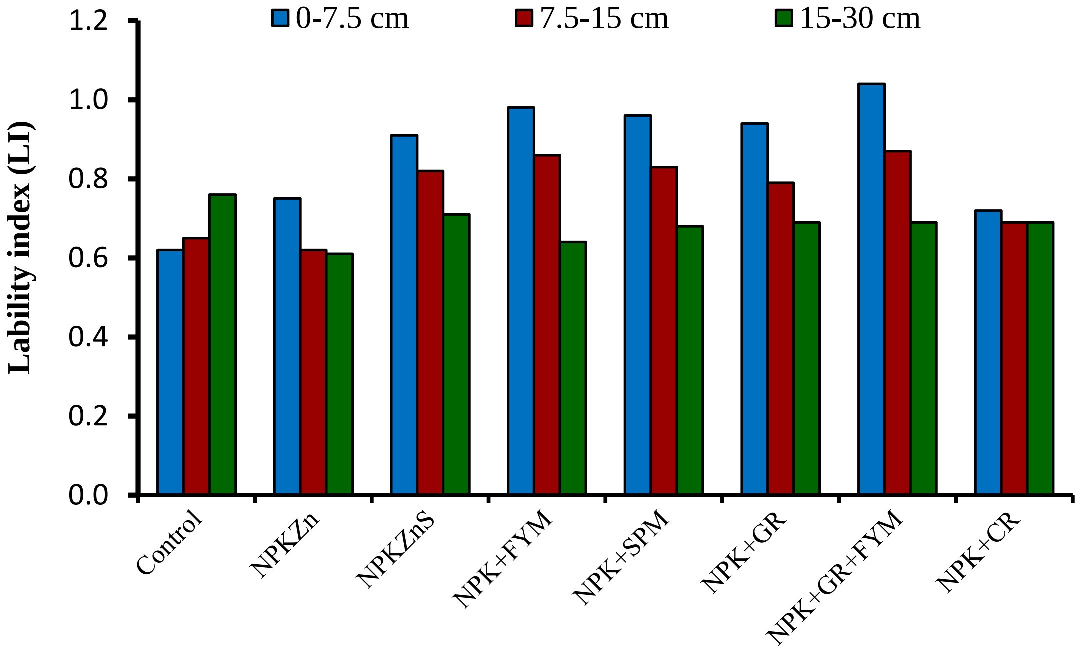


Fig. 4.1.8. Lability index (LI) under different nutrient supply options and soil depths

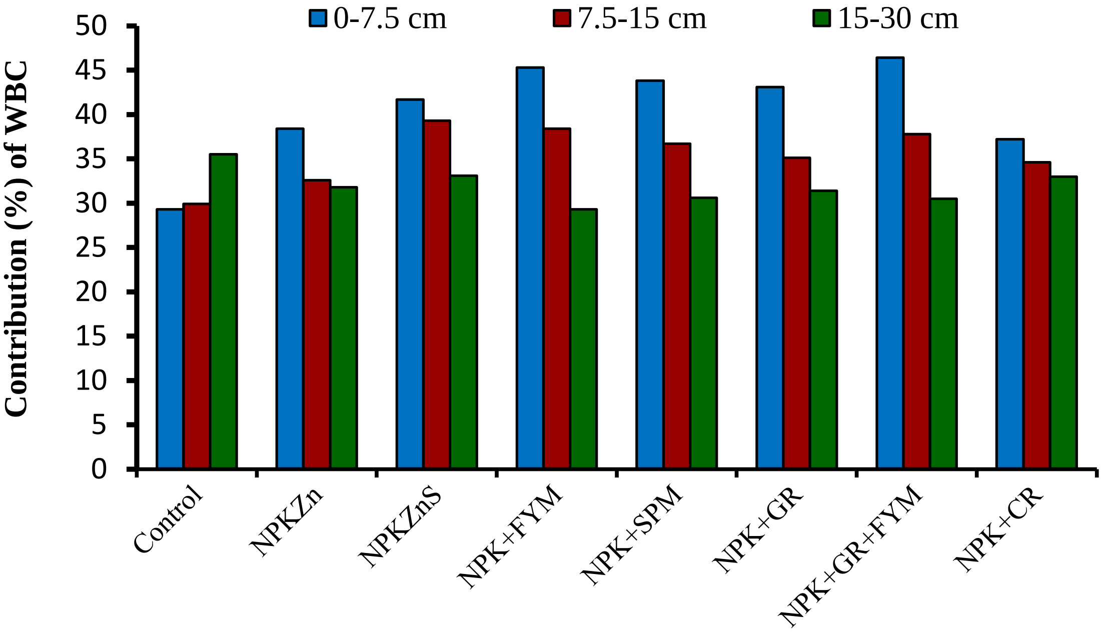


Fig. 4.1.9a. Per cent contribution of WBC to TOC under different nutrient supply options and soil depths

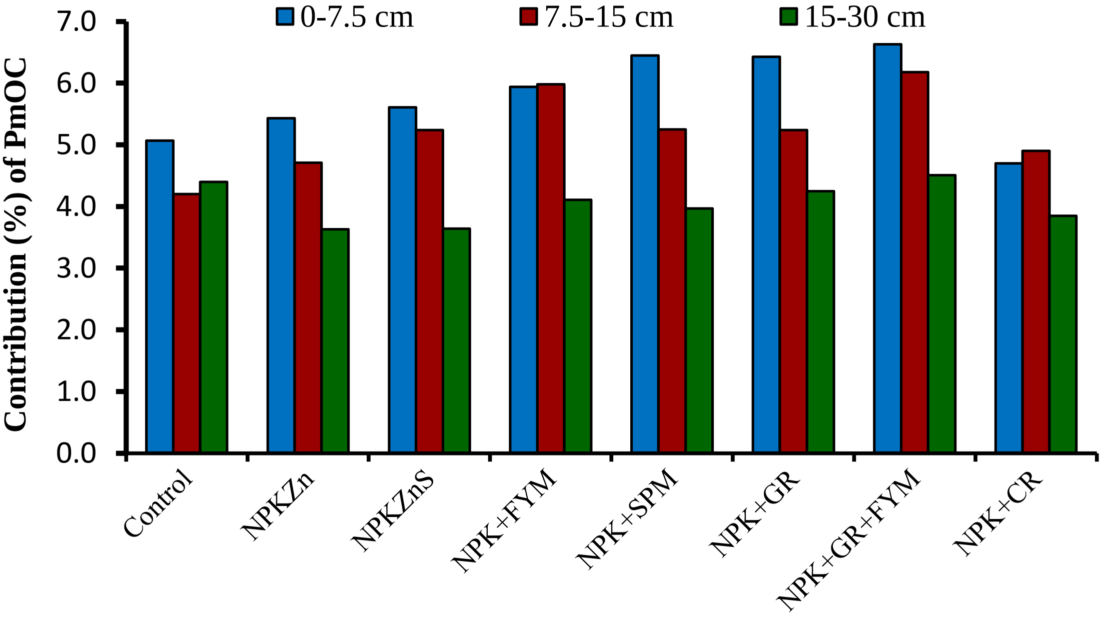


Fig. 4.1.9b. Per cent contribution of PmOC to TOC under different nutrient supply options and soil depths

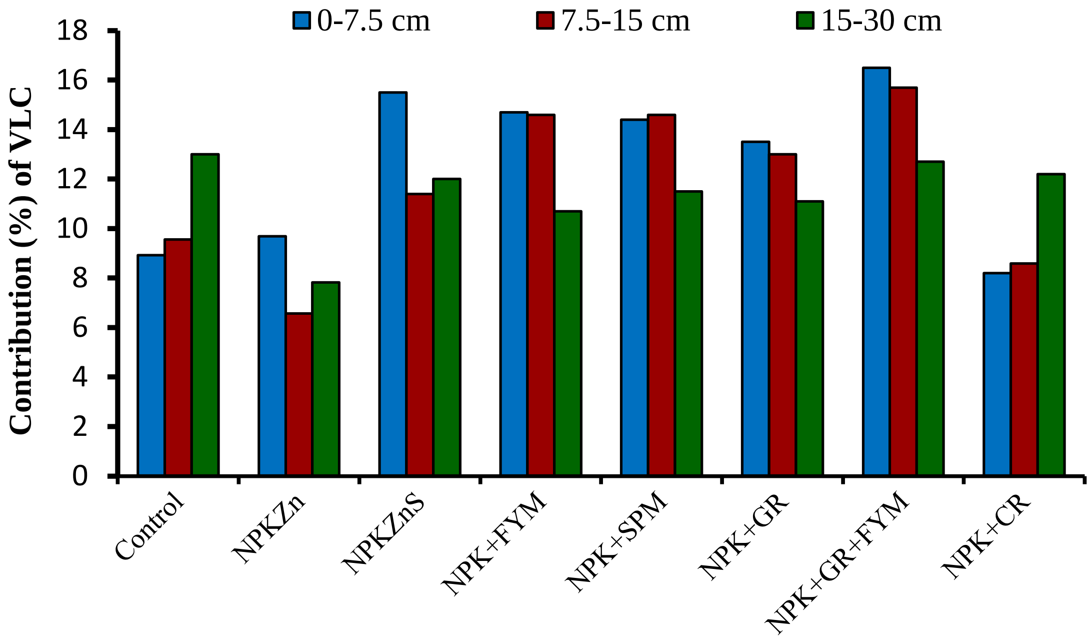


Fig. 4.1.10a. Per cent contribution of VLC to TOC under different nutrient supply options and soil depths

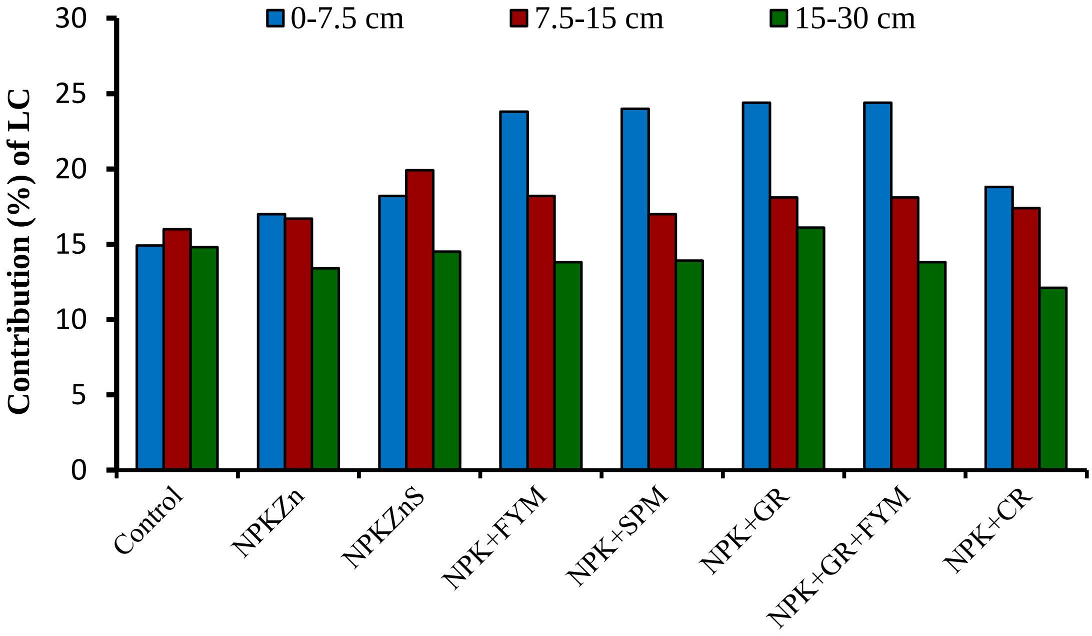


Fig. 4.1.10b. Per cent contribution of LC to TOC under different nutrient supply options and soil depths

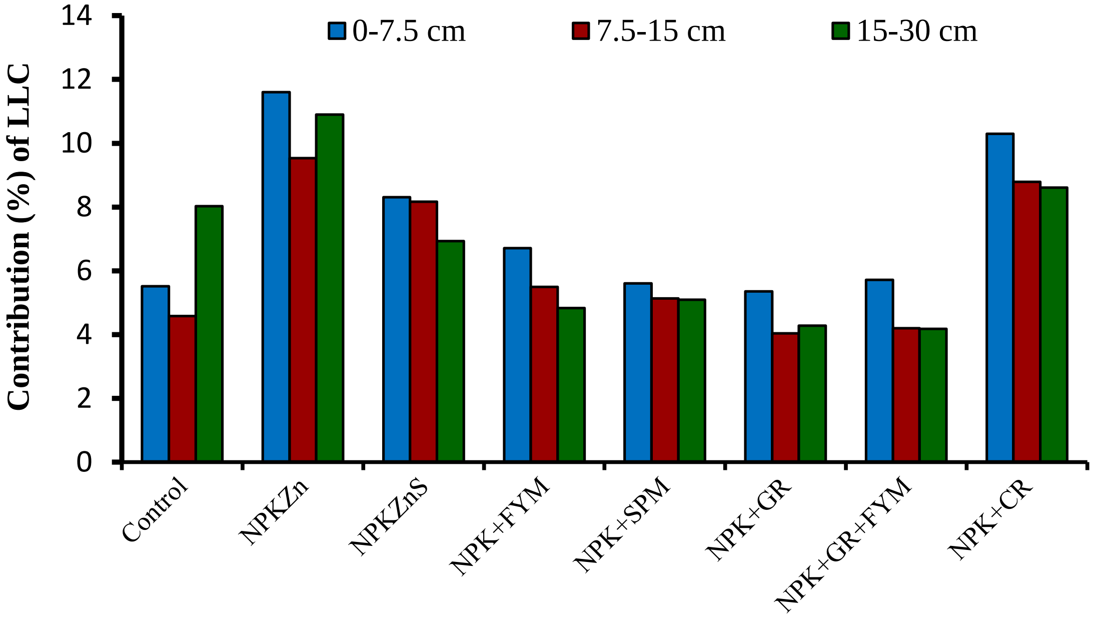


Fig. 4.1.10c. Per cent contribution of LLC to TOC under different nutrient supply options and soil depths

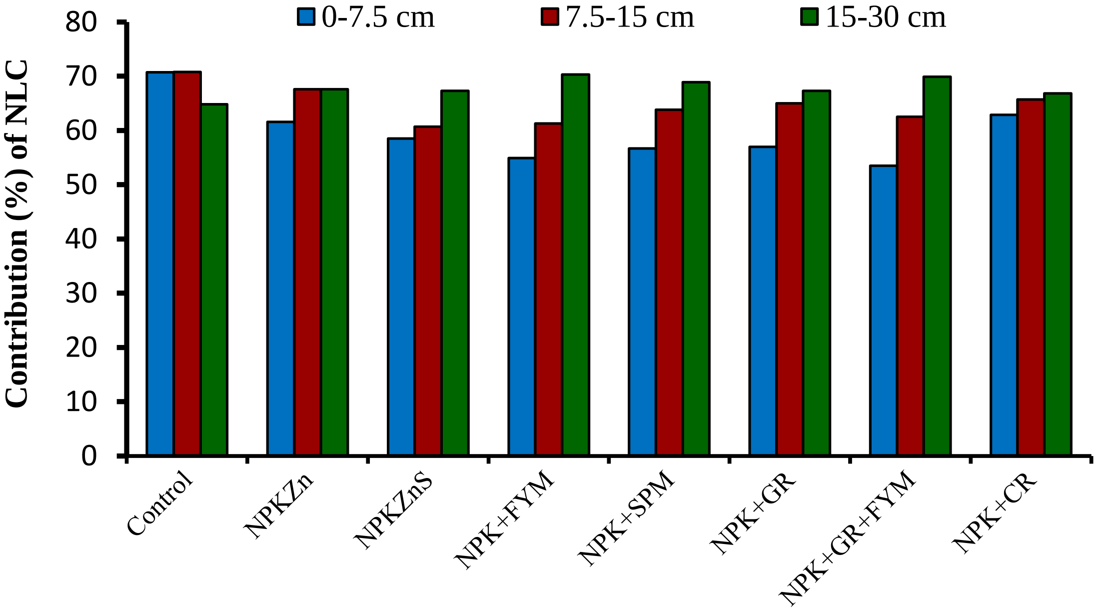


Fig. 4.1.10d. Per cent contribution of NLC to TOC under different nutrient supply options and soil depths

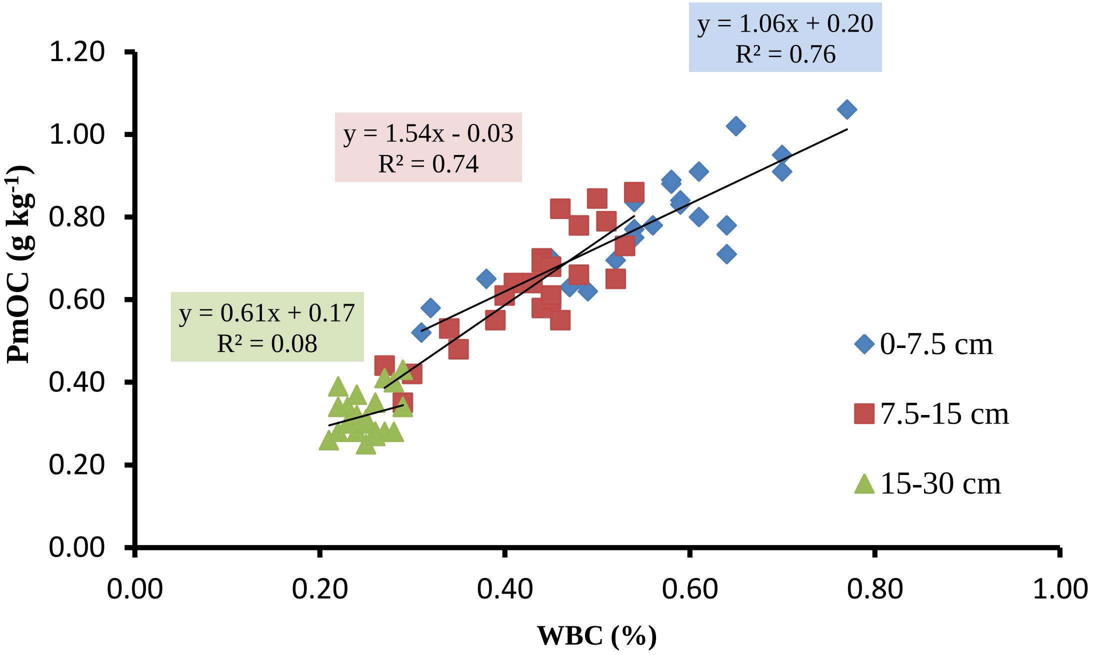


Fig. 4.1.11a. Scatter diagram showing relationship between WBC and PmOC at different soil depths

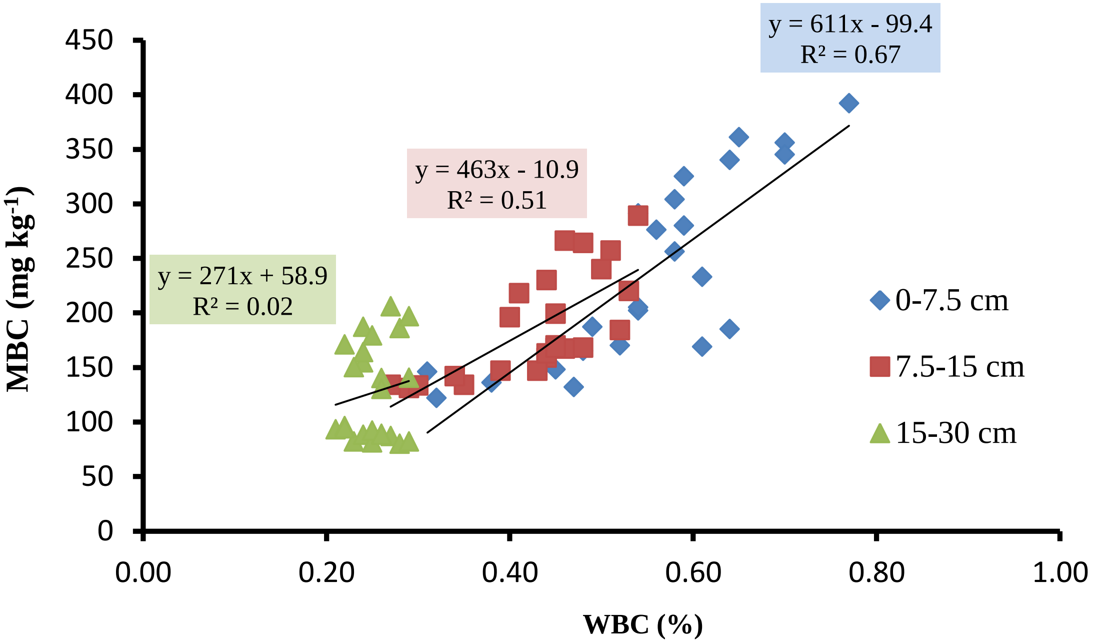


Fig. 4.1.11b. Scatter diagram showing relationship between WBC and MBC

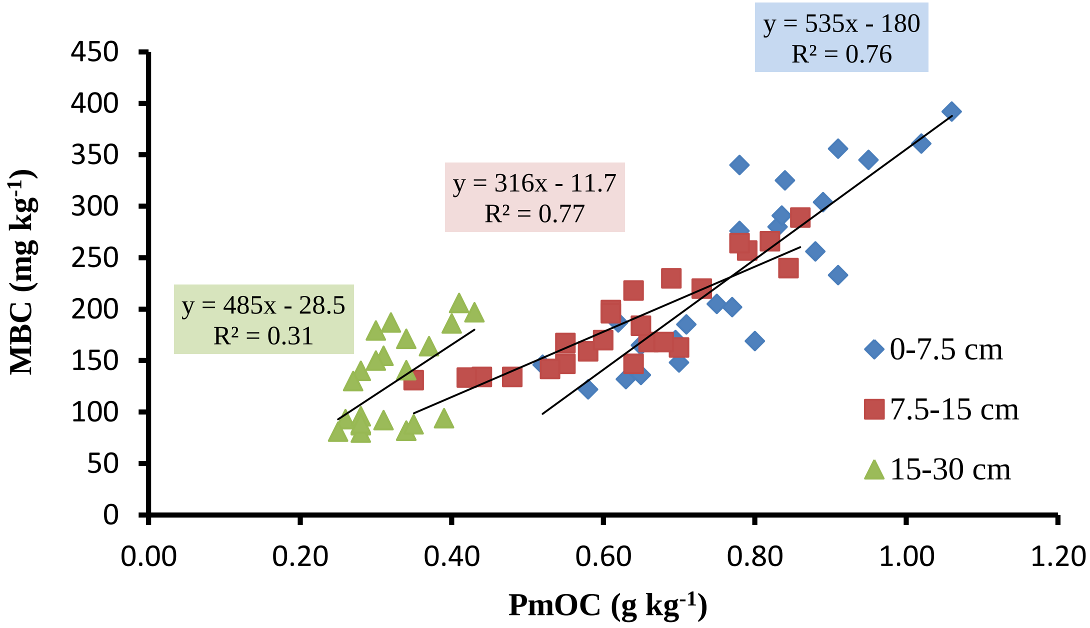


Fig. 4.1.11c. Scatter diagram showing relationship between PmOC and MBC

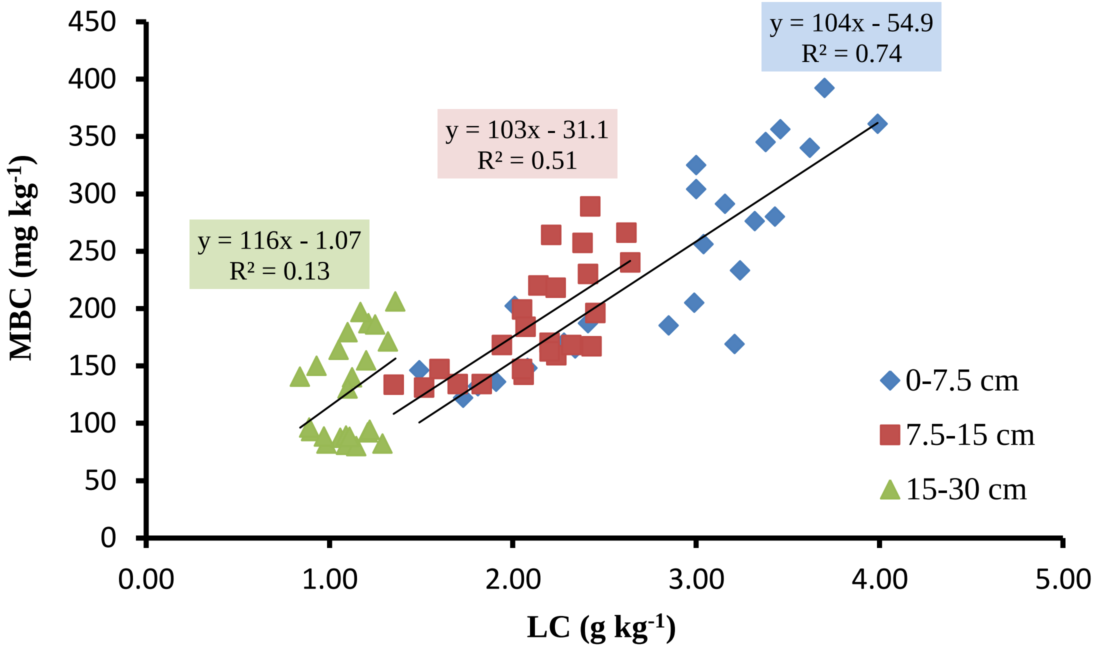


Fig. 4.1.11d. Scatter diagram showing relationship between LC and MBC

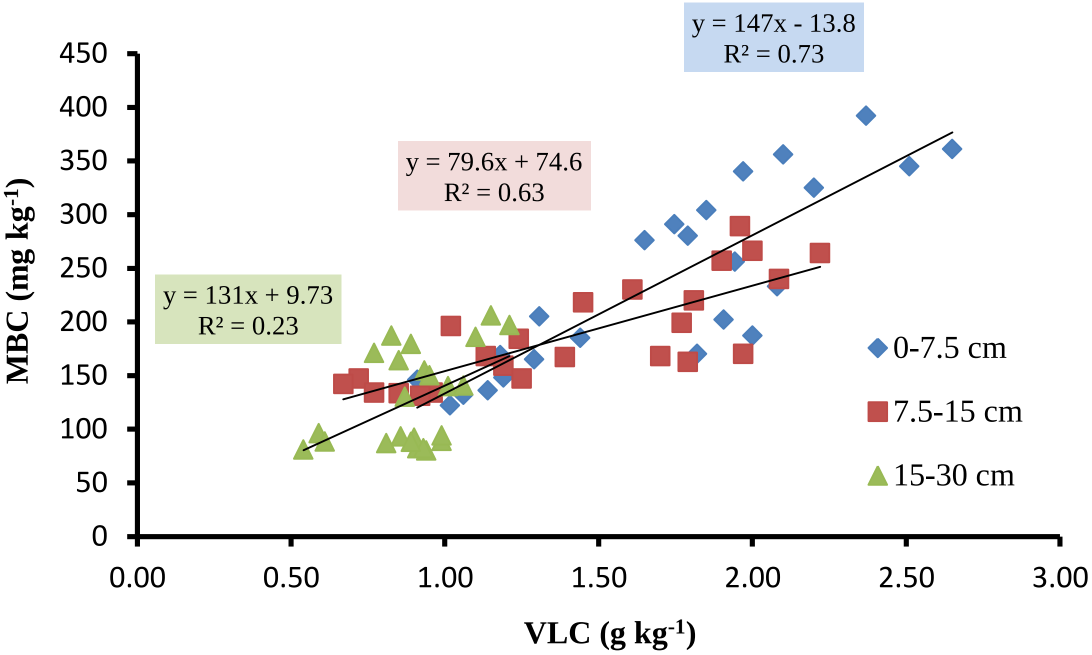


Fig. 4.1.11e. Scatter diagram showing relationship between VLC and MBC

4.2. RESEARCH PAPER-II

Quality of soil organic matter, and its relationship with available nutrients and crop yields under different nutrient supply options

Abstract

Effect of nutrient management on the quality of soil organic matter (SOM) and its relationship with nutrient availability and rice-wheat yields are relatively less researched areas. We, therefore, undertook an investigation to understand the impact of INM on SOM quality and to find out its relevance to nutrient availability and crop productivity, using an on-going long-term experiment (LTE) established in 1993-94 on a Typic Haplustept at PDFSR, Modipuram. Results indicated an increase in E_4/E_6 ratio of fulvic acid (FA) with continuous cropping and integrated use of NPK and organics like FYM, sulphitation pressmud (SPM) and greengram residue (GR). The INM options, except NPK+CR (cereal residues), also increased mineral N, Olsen-P and available S contents over sole fertilizer treatments. Highest grain yields of rice (6.32 t ha^{-1}) and wheat (5.77 t ha^{-1}) were obtained in SPM treated plots, followed by 6.02 and 5.28 t ha^{-1}, respectively under NPKZnS plots. Available nutrient contents and active SOC to TOC ratio especially in top soil (0-7.5 cm) showed highly significant relationship with grain yields. The E_4/E_6 ratios of FA and HA were, however, poorly correlated with available nutrients and crop yields.

Key words: E_4/E_6 ratio, mineral N, Olsen-P, available S, rice-wheat yields, long-term experiment, Typic Haplustept

4.2.1. Introduction

Soil organic matter (SOM) is known to serve as a soil conditioner, nutrient source, substrate for microbial activity, preserver of environment and major determinant for sustaining or increasing agricultural productivity (Schnitzer 1981). Importance of SOM content for maintenance of soil fertility, soil quality and production sustainability has been emphasized over the time (Stevenson 1994; Reeves 1997; Lal *et al.* 1998, Gallantini *et al.* 2006; Verma *et al.* 2010). Post-Green revolution agriculture in India witnessed several constraints referred to as second generation problems which threatened the sustainability of agriculture system as a whole. Among soil related problems, depletion of quantity and quality of SOM, emergence and expansion of multi-nutrient deficiencies and tillage induced subsoil compaction emerged as major threats to crop yields and factor productivity.

Rice-wheat systems (RWS) practiced over 13.5 million ha in the IGP is the mainstay of food and nutritional security, employment and income to millions of stable holders including farmers, traders and entrepreneurs (Timsina and Connor 2001). In IGP rice is grown in wet (monsoon) season after intensive dry and wet tillage (puddling) followed by wheat in the dry (winter) season after intensive dry tillage. This dry-wet transition leads to several physical, chemical and biological changes in soil characteristics that affect nutrient dynamics and also crop response to applied nutrients, (Hegde and Dwivedi 1992) and when grown with inadequate nutrient inputs leads to nutrient mining and severe yield losses. Declining use of organic manures further aggravate the problem (Hegde and Dwivedi 1993).

Integrated nutrient management (INM) involving combinations of organic and inorganic sources increase functionality of humic substances (Hayes 1989); leads to gradual reworking of SOM by soil microorganisms and various chemical reactions (Zech *et al.* 1997) that ultimately resul in higher grain yield and biomass yield (Rasmussen and Collins 1990). Literature shows an integrated fertilization increases SOM level (Paustian *et al.* 1992; Bowman and Halvorson, 1998); enhances soil quality (Herrick and Wander 1998; Seybold *et al.* 1998) and improves crop yields and sustainability (Yadav 2000b; Rivero *et al.* 2004; Bi *et al.* 2009). Information on the effect of INM on the quality of SOM and available nutrient contents, and the relationships of SOM quality with available nutrients and crop yields under RWS is scanty although the same is of utmost practical significance. We, therefore, undertook the present study in an LTE to understand these aspects in a pragmatic manner.

4.2.2. Materials and Methods

Soil samples for present investigation were collected from an on-going long-term field experiment on rice-wheat system that was established during 1993-94 on a Typic Haplustept of the research farm of Project Directorate for Farming Systems Research (PDFSR), Modipuram (U.P.). The details of the field experiment, soil sampling and analytical methods are given as under:

4.2.2.1. Site characterization

An LTE on rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) system was established in 1993-94 on a Typic Haplustept of PDFSR Farm, Modipuram, Meerut (U.P.), which completed 18 years in 2010-11. The experimental site (29^o 4′ N, 77^o 46′ E, 237 m above mean sea level) represented the Upper Gangetic Plain (UGP) transect of the IGP which is considered an intensively cropped and high productivity zone. Rice-wheat and sugarcane-ratoon-wheat are the pre-dominant cropping systems of the area. The climate of Modipuram is sub-tropical semi-arid, with average annual rainfall of 823 mm. At the onset of the LTE (1993-94), the sandy loam soil of the experimental field was mildly alkaline (pH 7.98) in reaction, and had an electrical conductivity of 0.42 dS m^{-1}. It contained 0.41% Walkley-Black C (WBC), 16.4 kg ha^{-1} 0.05 *M* $NaHCO_3$ extractable-P, 96 kg ha^{-1} 1 *N* ammonium acetate extractable-K and 14.5 kg ha^{-1} 0.15% $CaCl_2$ extractable-S. Thus, the site was initially non-saline, low in SOC, medium in available P, and low in available K and S contents.

4.2.2.2. Treatment details

The LTE comprised 11 treatments which included fertilizer NPKZn, NPKZnS, substitution of a part of seasonal N demand through organics (FYM, SPM *i.e.* sulphitation pressmud, GR *i.e.* greengram residue, CR *i.e.* cereal residue) applied in monsoon or winter seasons, and an unfertilized-control. The experiment was laid out in a randomized block design with four replications. The present investigation, however, utilized eight out of total 11 treatments as per details given in Table 3.1 of Chapter 3. The performance of five organic sources namely FYM, SPM, GR and CR (rice/wheat straw) applied along with fertilizer NPK continuously in 18 rice-wheat crop cycles was evaluated *vis-à-vis* sole fertilizer input and control.

Puddled transplanted rice (cv. PR 106) during monsoon and wheat (cv. PBW 343) during winter were grown under assured irrigation conditions. Recommended rate of fertilizers for rice as well as wheat were 120-26-33 kg N-P-K ha^{-1}, although 5 kg Zn ha^{-1} to rice and 45 kg S ha^{-1} to wheat were also applied as per treatments. Entire quantity of P, K, S and Zn as per treatment were applied as basal dose at the time of transplanting/sowing. Fertilizer N, on the other hand, was applied in three equal splits at transplanting/sowing, tillering and panicle/ear emergence. The quantities of FYM, SPM and CR were predetermined on the basis of their N content. FYM and SPM were incorporated in the soil one week before transplanting/sowing, whereas CR was incorporated 15-20 days before transplanting/sowing of the crops. In the treatments involving GR, short duration variety of summer greengram was sown immediately after wheat harvest, and after pod-picking the residues (aboveground biomass) was incorporated in the soil before puddling.

4.2.2.3. Soil sampling and analysis

Soil samples from three depths *i.e.* 0-7.5, 7.5-15 and 15-30 cm were collected following standard procedure from all plots of three replications of the LTE after completion of eighteen rice-wheat cycles 2010-11. Each sample was divided into two parts: the first part was used for determination of mineral N, and the second part was processed for other analyses *viz.* extraction of fulvic and humic acid for determination of E_4/E_6 ratio, and determination of available P and S contents. Soil samples from all three depths were also collected from adjacent uncultivated area for determination of all above parameters.

Fulvic and humic acid were extracted from the 0-7.5 cm soil samples using freshly prepared $Na_4P_2O_7$-NaOH solution, and E_4/E_6 ratio of the same was determined (Kononova 1966). Mineral N, Olsen-P and available S were determined for all three depths. Mineral N was determined by steam distillation after extracting with 2 *M* KCl (Rowell 1994), Olsen-P (P extracted with 0.05*M* $NaHCO_3$; Olsen *et al.* 1954) was determined by ascorbic acid blue colour method (Watanabe and Olsen 1965), and available S was determined by turbidimetric method (Chesnin and Yien 1950) after extraction with 0.01*M* $CaCl_2$ solution (Williams and Steinbergs 1969). Yield data of rice and wheat were obtained from PDFSR.

4.2.2.4 Statistical analysis

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

4.2.3. Results and Discussion

4.2.3.1. E_4/E_6 ratio of fulvic and humic acid

The E_4/E_6 ratio is the ratio of optical density of fulvic acid (FA) or humic acid (HA) solutions at 465 nm and 665 nm. It is considered as an inverse index of particle size and aromaticity of soil organic matter (SOM) (Ghosh *et al.* 2009). The E_4/E_6 ratio of fulvic acid (FA) varied from 10.6 to 14.2 with a mean of 12.2 under different treatments at 0-7.5 cm soil depth (Table 4.2.1). The mean ratio was higher than the adjacent uncultivated soil (9.1) which indicated lower degree of humification of the transient fractions of SOM with continuous cultivation (Skjemstad *et al.* 1986). Among the nutrient supply options, ratios of FA under INM treatments involving FYM, GR or GR+FYM were invariably greater than control, sole fertilizer or NPK+CR which may be attributed to the presence of less-humified metabolic components of the organic manures in this fraction as well as highly reactive organic matter with small sized aliphatic molecules (Stevenson 1994). On the other hand, E_4/E_6 ratio for humic acid (HA) ranged from 3.77 to 4.41 with a mean of 4.04 under different treatments and was invariably lower than that in the uncultivated soil (E_4/E_6 ratio of 5.07). Compared with control and sole fertilizer treatments, E_4/E_6 ratio of HA was significantly greater under INM treatments, particularly those involving FYM, SPM and CR. The E_4/E_6 ratios of FA and HA and their changes over time depend on type of organic manure (Rivero *et al.* 2004), period of cultivation (McGill *et al.* 1981), soil texture, climate, and other soil properties (Choppin and Allard 1985).

Table 4.2.1. Effect of long-term fertilization and manuring on E_4/E_6 ratio of humic and fulvic acid in rice-wheat system

Treatment	E_4/E_6 ratio	
	Fulvic acid	Humic acid
Control	11.1	3.78
NPKZn	11.5	3.90
NPKZnS	10.9	3.77
NPK+FYM	14.2	4.19
NPK+SPM	12.1	4.19
NPK+GR	13.1	3.78
NPK+GR+FYM	13.8	4.41
NPK+CR	10.6	4.33
Mean	12.2	4.04
LSD (*P*=0.05)	1.02	0.20
SEd±	0.49	0.10

4.2.3.2. Mineral N content

The NH_4-N and NO_3-N contents of 0-7.5 cm soil layer varied from 16.3 to 32.6 mg kg^{-1} (mean 26.3 mg kg^{-1}) (Table 4.2.2a), and from 21.8 to 46.3 mg kg^{-1} (mean 33.4 mg kg^{-1}) (Table 4.2.2b). The contents were lowest under control, which increased significantly with fertilizer (NPKZn or NPKZnS) application. Inclusion of organic manures like FYM and SPM brought further increase in both NH_4-N and NO_3-N over the sole fertilizer treatments. Among organic sources, CR and GR were not effective in enhancing NH_4-N over fertilizer treatments (Table 4.2.2a). The NO_3-N contents in plots treated with CR or GR were also lower compared with those receiving SPM or FYM (Table 4.2.2b). Treatment effect on NH_4-N at other soil depths was not very much pronounced, although NH_4-N in the top layer was greater than the sub-surface layers. On the other hand, treatment effect on profile distribution of NO_3-N suggested interesting trends. Whereas NO_3-N content at 15-30 cm depth in sole fertilizer treated plots was higher than the top (0-7.5 cm) soil, a reverse was true in INM treatments. Compared with uncultivated soil, mineral N generally increased with fertilization and manuring (Fig. 4.2.1a & b). Earlier studies in Typic Haplustept of New Delhi also revealed a significant effect of nutrient management practices on soil N content, and the mineral N contents were invariably higher under INM compared with fertilizer alone (Verma *et al.* 2010).

Table 4.2.2a. Effect of nutrient supply options on NH_4-N content of soil

Treatment	NH_4-N (mg kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	16.3	14.2	14.2
NPKZn	26.6	20.6	23.6
NPKZnS	29.4	19.9	20.8
NPK+FYM	30.2	23.9	24.1
NPK+SPM	32.6	22.2	21.8
NPK+GR	25.0	20.0	20.9
NPK+GR+FYM	30.2	22.4	24.9
NPK+CR	20.1	22.1	17.2
Mean	26.3	20.7	20.9
LSD (*P*=0.05)	2.80	2.60	2.40
SEd±	1.40	1.20	1.10

Table 4.2.2b. Effect of nutrient supply options on NO_3-N content of soil

Treatment	NO_3-N (mg kg^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	21.8	25.9	14.3
NPKZn	27.1	25.5	31.4
NPKZnS	27.1	26.0	29.8
NPK+FYM	39.8	27.4	16.2
NPK+SPM	46.3	34.4	19.5
NPK+GR	36.0	24.1	10.8
NPK+GR+FYM	38.5	25.9	15.6
NPK+CR	30.5	25.4	14.5
Mean	33.4	26.8	19.0
LSD (*P*=0.05)	3.46	3.30	2.50
SEd±	1.68	1.50	1.10

The LTEs with cereal-cereal system other than rice-wheat in different agro-ecologies have also supported an increase in mineral N owing to balanced use of fertilizer or conjoint use of fertilizer and organics (Singh and Wanjari 2009). As SPM is a rich source of plant nutrients compared with other organics included in the present study, relatively greater NH_4-N and NO_3-N under SPM treated plots is explainable, as also recorded earlier in a pigeonpea-wheat system (Mandal 2010). Greater retention of NO_3-N in surface soil owing to improvement in soil physical conditions and SOC content, as recorded under INM plots in the present study has been documented in sandy loam soil of IGP (Dwivedi *et al.* 2003; Singh *et al.* 2005).

4.2.3.3. Olsen-P content

Olsen-P content under different treatments varied from 12.1 to 38.9 kg ha^{-1} in 0-7.5 cm, 10 to 26.5 kg ha^{-1} in 7.5-15 cm and 7.1 to 13.5 kg ha^{-1} in 15-30 cm soil layer with mean contents of 27.5, 19.8 and 10.7 kg ha^{-1}, respectively (Table 4.2.3). In top soil layer, use of fertilizers alone increased Olsen-P content significantly over control, although, the highest Olsen-P was reported in the NPK+SPM treatment; at other soil depths, the treatment effects are not as spectacular as in top soil, yet NPK+SPM appeared superior to other treatments in augmenting Olsen-P content. When compared with uncultivated soil, a marked increase in Olsen-P content at all soil depths was recorded in sole fertilizers or INM treatments except under NPK+CR (Fig. 4.2.2).

Table 4.2.3. Long-term effect of nutrient management on Olsen P content of soil

Treatment	Olsen P (kg ha^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	12.1	10.6	7.1
NPKZn	33.5	23.0	12.0
NPKZnS	29.4	20.3	11.5
NPK+FYM	31.0	22.0	11.5
NPK+SPM	38.9	26.5	13.4
NPK+GR	26.4	19.7	10.8
NPK+GR+FYM	32.6	22.7	12.2
NPK+CR	15.8	13.4	7.0
Mean	27.5	19.8	10.7
LSD (*P*=0.05)	3.60	2.60	1.50
SEd±	1.60	1.20	0.69

A decline in Olsen-P under control compared with uncultivated/initial soil is obvious due to continuous P removal by the crops, as also reported earlier (Yadav *et al*. 2000b; Dwivedi *et al.* 2003). Relatively smaller Olsen-P content under NPK+CR is ascribed to low annual P inputs through cereal residue containing very low P (Hegde and Dwivedi 1993).

4.2.3.4. Available S

Available S content across the treatments were 16.8 kg ha^{-1} in 0-7.5 cm, 13.2 kg ha^{-1} in 7.5-15 cm and 8.8 kg ha^{-1} in 15-30 cm soil layer (Table 4.2.4). Inclusion of S in the recommended fertilizer schedule *i.e.* NPKZnS resulted in significantly higher available S content compared to NPKZn or control in all soil layers.

Table 4.2.4. Long-term effect of nutrient management on available S content of soil

Treatment	Available S (kg ha^{-1}) at different soil depths		
	0-7.5 cm	7.5-15 cm	15-30 cm
Control	13.2	10.1	6.7
NPKZn	10.9	8.6	7.6
NPKZnS	29.3	23.5	11.6
NPK+FYM	14.7	10.1	7.8
NPK+SPM	26.3	22.6	14.3
NPK+GR	13.4	9.6	7.6
NPK+GR+FYM	15.1	11.7	7.8
NPK+CR	11.2	9.5	7.2
Mean	16.8	13.2	8.80
LSD (*P*=0.05)	2.20	1.70	1.10
SEd±	1.00	0.80	0.50

Alternatively use of SPM along with NPK also increased available S content of soil over control as well as over uncultivated soil (Fig. 4.2.3). Interestingly, available S under NPKZn plot was significantly smaller compared to control indicating excessive mining of S from native S reserves due to continuous neglect of S replenishment. In fact, removal of S under intensive cropping in far excess amount compared to its replenishment through different sources is the major reason of widespread S deficiencies in Indian soils in general (TSI 1994; Tandon 2011), and in the IGP particularly (Dwivedi *et al.* 2001b). Since organic S fractions in the soil is positively related to organic matter status (Pasricha and Sarkar 2009) and generally considered important donor pool to available S (Tandon 1991), lesser deficiencies are expected in the soils containing high SOC or in those receiving organic manure periodically. Significant contribution of SPM in improving soil S content is ascribed to higher S content compared to organic sources evaluated in the present study.

4.2.3.5. Grain yield

Rice and wheat yields under control were 1.72 and 1.42 t ha^{-1}, respectively. Use of fertilizer NPKZn at recommended rate produces an additional yield of 2.58 t rice ha^{-1} and 2.79 t wheat ha^{-1} (Fig. 4.2.4). Inclusion of S further increased rice and wheat yields over NPKZn by 1.72 and 1.07 t ha^{-1}, respectively. Highest grain yield of both the crops were recorded under NPK+SPM. Among INM options, the yield was significantly lower under NPK+CR. Increase in rice and wheat yields under INM has been documented earlier (Bhandari *et al.* 2002; Yadvinder-Singh 2004). LTEs across the IGP have shown yield decline in RWS due to unbalanced NPK fertilization and emerging deficiencies of S and micronutrients (Cassman *et al.* 1995; Yadav *et al.* 1998a). The yield decline can however be reversed by addressing the nutrient deficiencies through adequate fertilization and inclusion of organics (Hegde and Dwivedi 1992; Singh and Wanjari 2009; Dwivedi *et al.* 2001a).

4.2.3.6. Relationship of E_4/E_6 ratio of fulvic and humic acid with available nutrients and grain yield

The relationships of E_4/E_6 ratios of fulvic acid (FA) and humic acid (HA) with available nutrients, active SOC pool and rice and wheat yields were computed (Table 4.2.5). The relationship was, in general, inconsistent, except that between the FA or HA ratio and NO_3-N content (R^2-values 0.36 and 0.30, respectively), which could not attain statistical significance. However, a little bit stronger relationship was recorded between the FA or HA ratio and active SOC pool (R^2-values 0.46 and 0.40, respectively). Further studies are needed on this aspect to explain these poor relationships.

Table 4.2.5a. Relationship of E_4/E_6 ratio of fulvic acid (FA) with available N, P, S and grain yield

	Parameters (y)	Equation	R^2
E_4/E_6 Ratio of FA (x)	NH_4-N (mg kg^{-1})	y = 1.93x + 2.87	0.23
	NO_3-N (mg kg^{-1})	y = 3.46x - 8.64	0.36
	Olsen P (kg ha^{-1})	y = 2.76x - 6.05	0.19
	Available S (kg ha^{-1})	y = -0.67x + 24.9	0.02
	Rice yield (t ha^{-1})	y = 0.27x + 1.56	0.07
	Wheat yield (t ha^{-1})	y = 0.34x + 0.36	0.13
	Active SOC pool (g kg^{-1})	y = 0.54x + 2.09	0.46

Table 4.2.5b. Relationship of E_4/E_6 ratio of humic acid (HA) with available N, P, S and grain yield

	Parameters (y)	Equation	R^2
E_4/E_6 Ratio of HA (x)	NH_4-N (mg kg^{-1})	y = 5.43x + 4.35	0.07
	NO_3-N (mg kg^{-1})	y = 16.2x - 32.2	0.30
	Olsen P (kg ha^{-1})	y = 5.90x + 3.59	0.03
	Available S (kg ha^{-1})	y = -3.79x + 32.1	0.02
	Rice yield (t ha^{-1})	y = 1.58x - 1.52	0.09
	Wheat yield (t ha^{-1})	y = 1.41x - 1.21	0.08
	Active SOC pool (g kg^{-1})	y = 2.60x + 5.99	0.40

4.2.3.7. Interrelationships between grain yield and available nutrients and active SOC to TOC ratio

Grain yield of both rice and wheat was significantly and positively correlated with mineral N, Olsen-P and available S at 0-7.5 cm soil depth mostly at 1% level of significance (Table 4.2.6a). However, at lower depths *i.e.,* 7.5-15 and 15-30 cm, parameters other than NO_3-N showed significantly positive correlation with rice and wheat grain yields (Tables 4.2.6b & 4.2.6c).

Linear relationships drawn between grain yields and available nutrients at 0-7.5 cm soil depth indicated that NH_4-N could account for 61% and 73% variability in rice and wheat yields, respectively, whereas, 46% of yield variability in both rice and wheat could be explained by NO_3-N (Fig. 4.2.5). Similarly the relationships of yield with Olsen-P and available S are also illustrated as a scatter diagram (Fig. 4.2.6). The ratio of active SOC (VLC+LC; Tables 4.1.9a and b of Chapter 4.1) to TOC (Table 4.1.4 of Chapter 4.1) in 0-7.5 cm soil layer correlated well with mineral N content and grain yield of rice and wheat (Fig. 4.2.7), indicating its suitability to be used as an index of the quality of SOC.

Table 4.2.6a. Interrelationships between grain yield and available nutrients at 0-7.5 cm soil depth

Treatment	Correlation coefficients (r-values)					
	Rice yield	Wheat yield	NH_4-N	NO_3-N	Olsen P	Available S
Rice yield	1.00					
Wheat yield	0.90^{**}	1.00				
NH_4-N	0.75^{**}	0.84^{**}	1.00			
NO_3-N	0.63^{**}	0.64^{**}	0.65^{**}	1.00		
Olsen P	0.63^{**}	0.73^{**}	0.88^{**}	0.61^{**}	1.00	
Available S	0.52^{*}	0.47^{*}	0.54^{**}	0.23	0.44^{*}	1.00

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

Table 4.2.6b. Interrelationships between grain yield and available nutrients at 7.5-15 cm soil depth

Treatment	Correlation coefficients (r-values)					
	Rice yield	Wheat yield	NH_4-N	NO_3-N	Olsen P	Available S
Rice yield	1.00					
Wheat yield	0.90^{**}	1.00				
NH_4-N	0.61^{**}	0.60^{**}	1.00			
NO_3-N	0.32	0.30	0.28	1.00		
Olsen P	0.61^{**}	0.71^{**}	0.53^{**}	0.50^{*}	1.00	
Available S	0.54^{**}	0.46^{*}	0.05	0.54^{**}	0.40	1.00

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

Table 4.2.6c. Interrelationships between grain yield and available nutrients at 15-30 cm soil depth

Treatment	Correlation coefficients (r-values)					
	Rice yield	Wheat yield	NH_4-N	NO_3-N	Olsen P	Available S
Rice yield	1.00					
Wheat yield	0.90**	1.00				
NH_4-N	0.51*	0.60**	1.00			
NO_3-N	0.14	0.14	0.22	1.00		
Olsen P	0.56**	0.66**	0.78**	0.33	1.00	
Available S	0.62**	0.56**	0.16	0.33	0.52*	1.00

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

4.2.4. Conclusion

The study indicated positive effect of balanced and integrated use of plant nutrients in improving mineral N, Olsen-P and available S contents of soil. In view of increasing scarcity of FYM for competitive uses of cattle dung, organic resources like SPM and GR could be used to restore soil fertility and crop yields. SPM, a by-product of sugar industry approached a valuable input not only for partial substitution of fertilizer N, but also for increasing N and S availability in soil, and sustaining high yield levels over the years. Poor relationship of E_4/E_6 ratios of SOM with different parameters as recorded in the present case needs to be explained through more detailed studies in the quality of SOM in future.

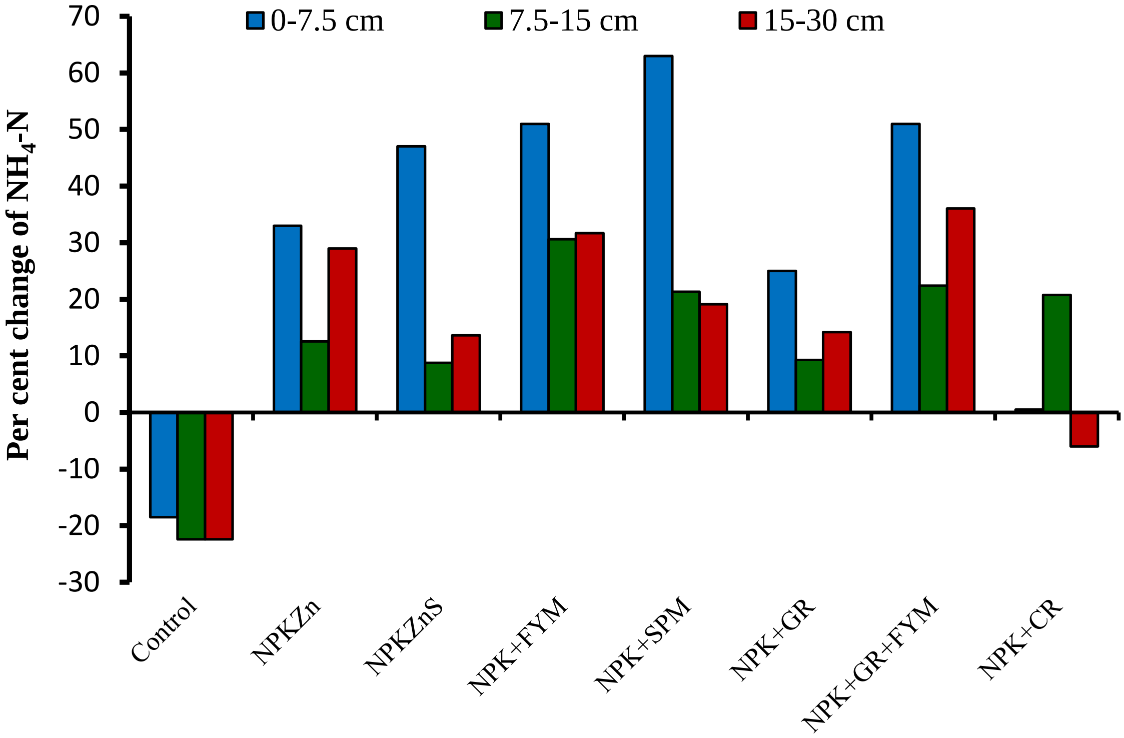


Fig. 4.2.1a. Per cent change in NH_4-N over uncultivated soil after 18 rice-wheat crop cycles

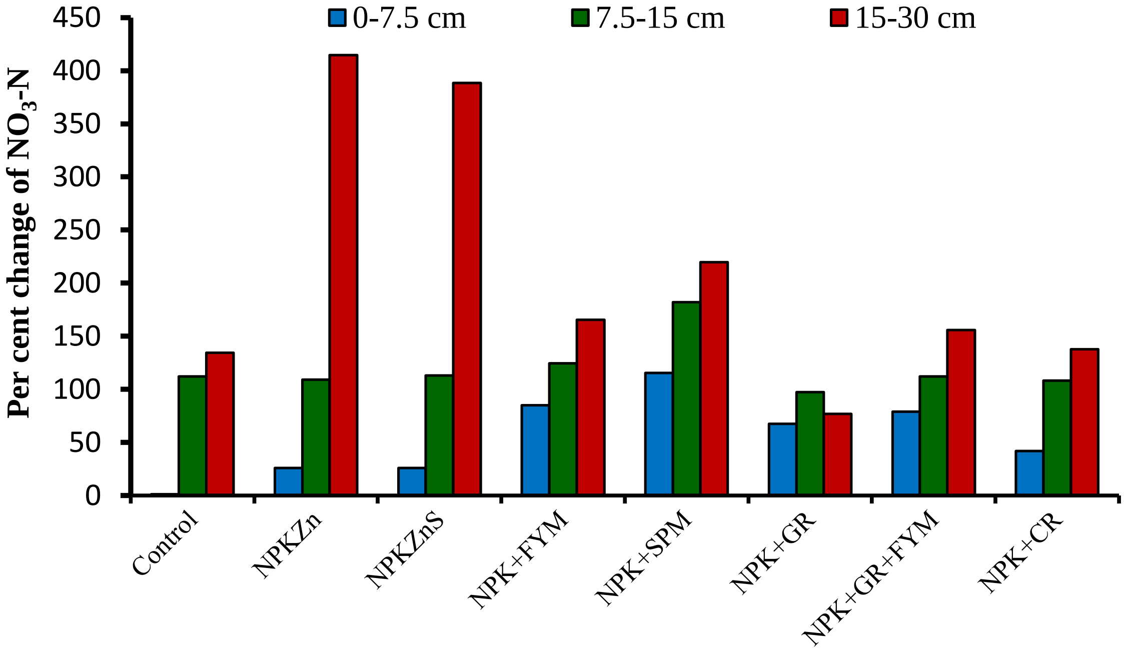


Fig. 4.2.1b. Per cent change in NO_3-N over uncultivated soil after 18 rice-wheat crop cycles

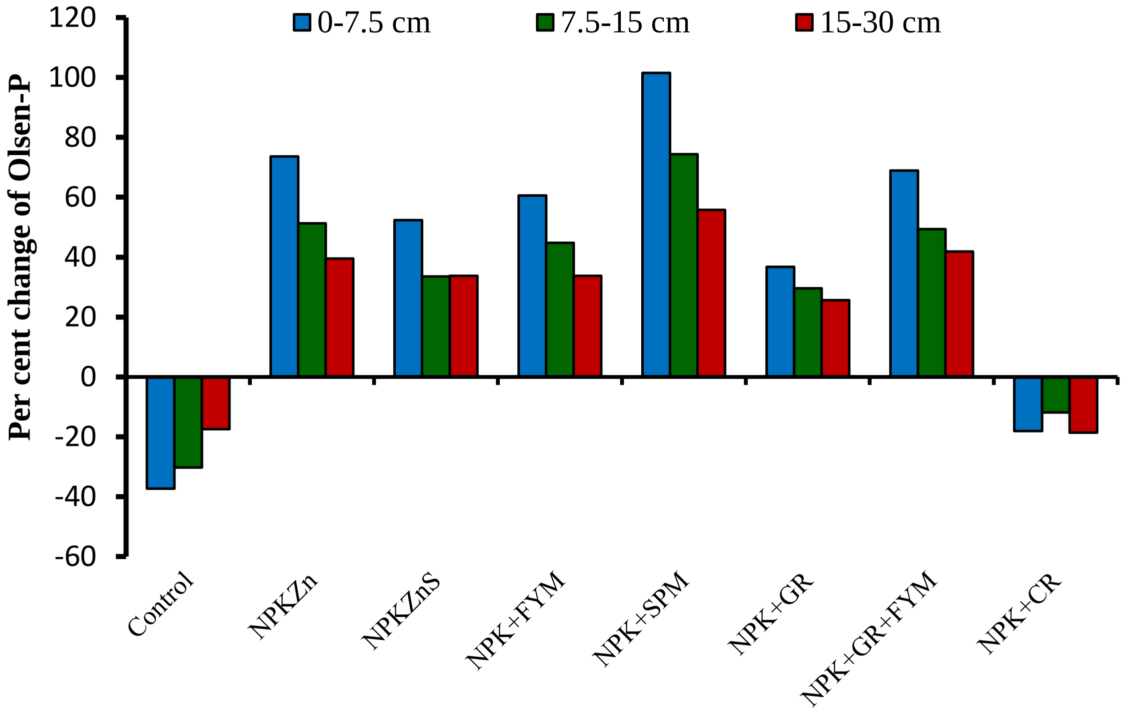


Fig. 4.2.2. Per cent change in Olsen-P over uncultivated soil after 18 rice-wheat crop cycles

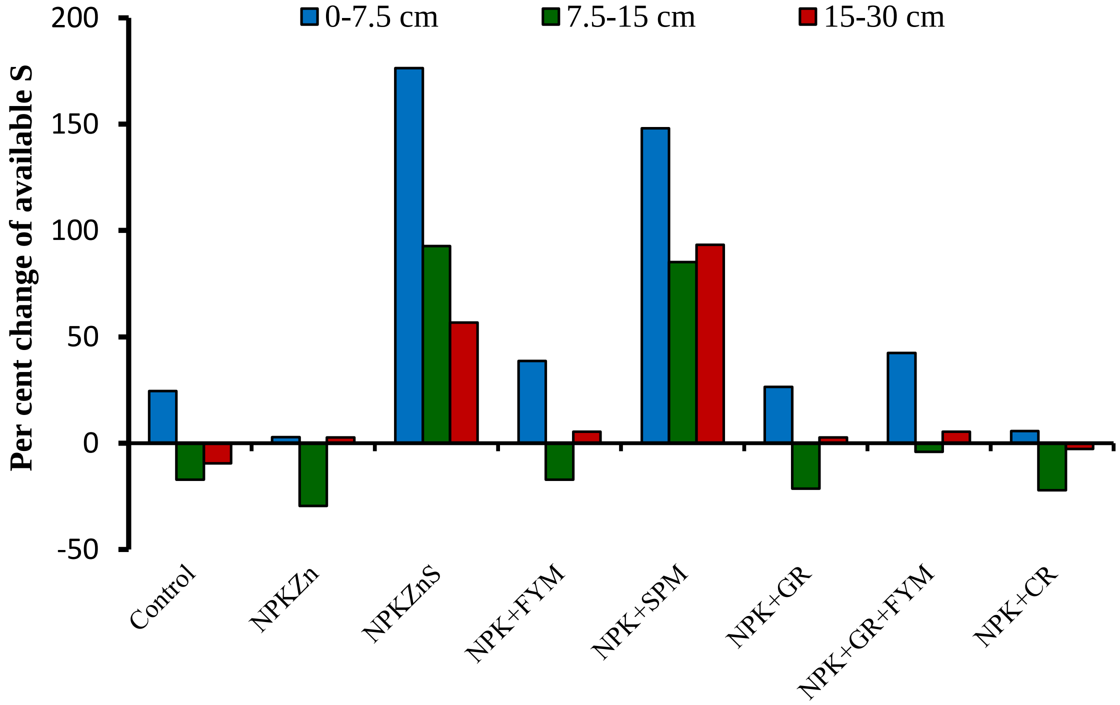


Fig. 4.2.3. Per cent change in available S over uncultivated soil after 18 rice-wheat crop cycles

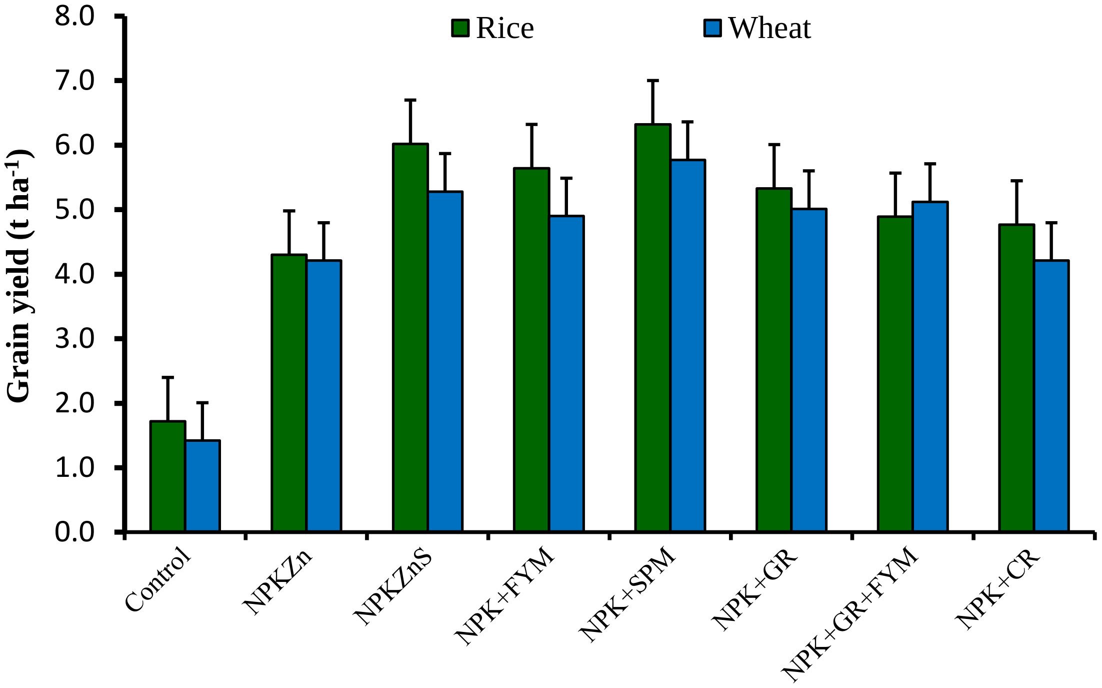


Fig. 4.2.4. Grain yields of rice and wheat (2010-11) under long-term fertilization and manuring. Error bars indicate LSD ($p=0.05$)

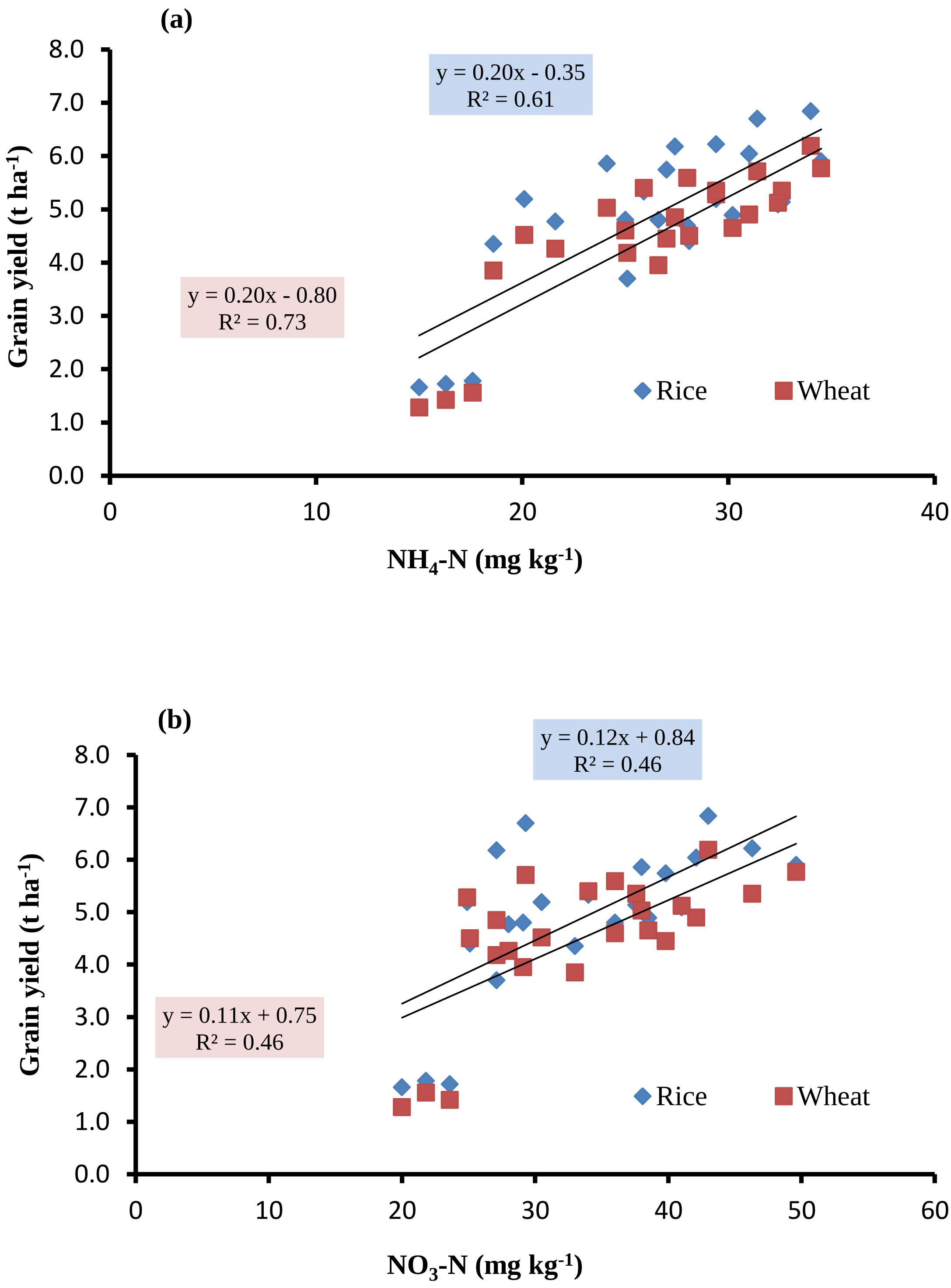
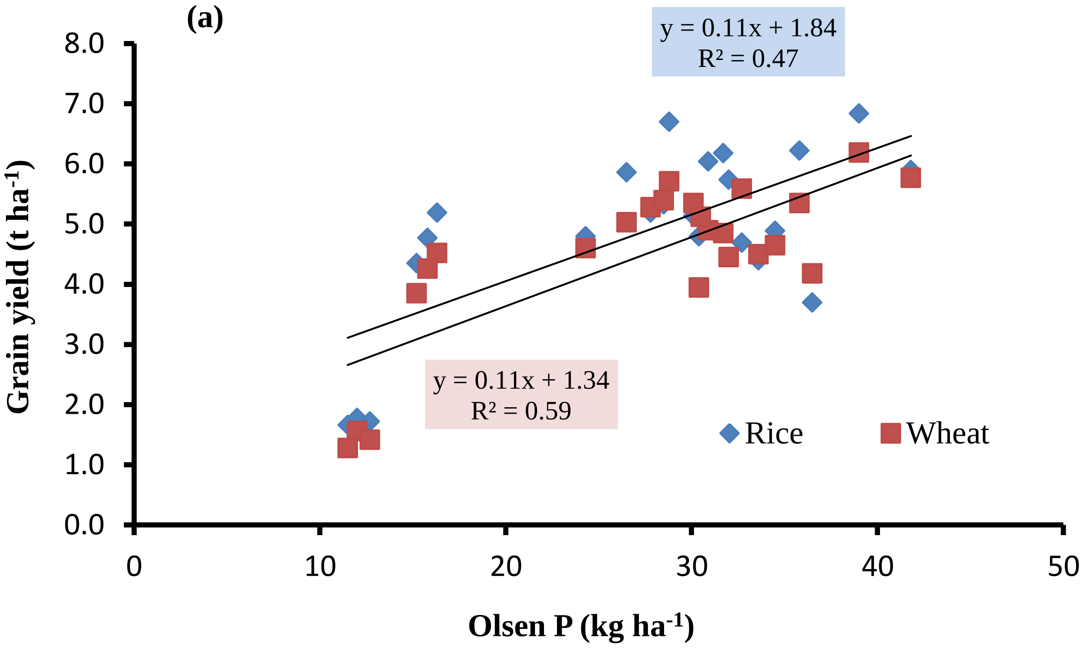


Fig. 4.2.5. Relationships of (a) NH_4-N and (b) NO_3-N in 0-7.5 cm soil layer with grain yields of rice and wheat



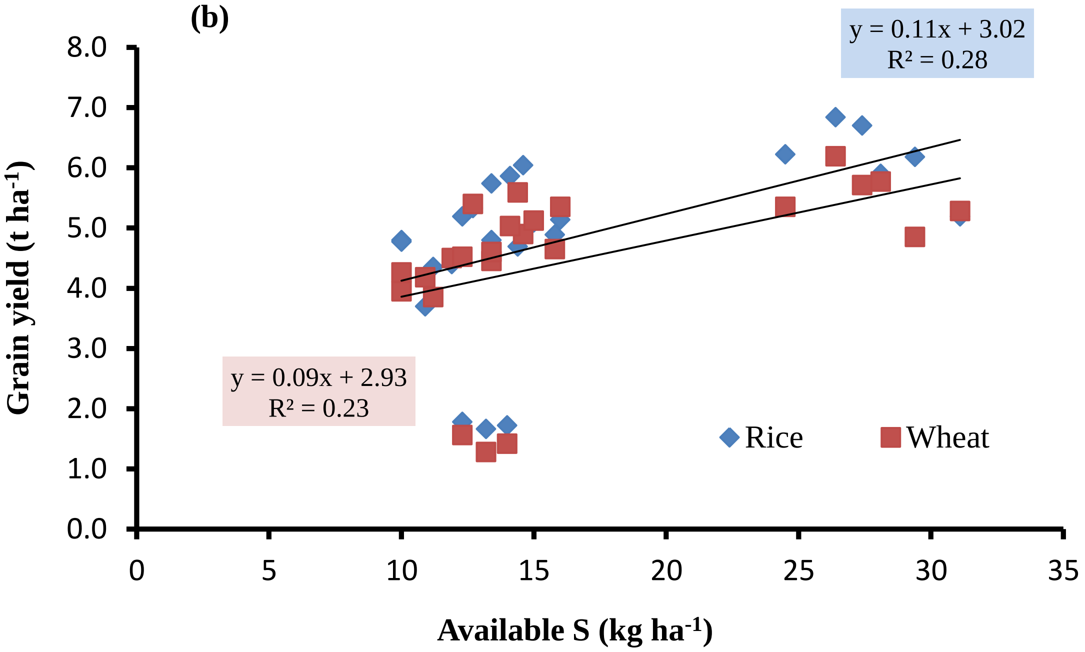
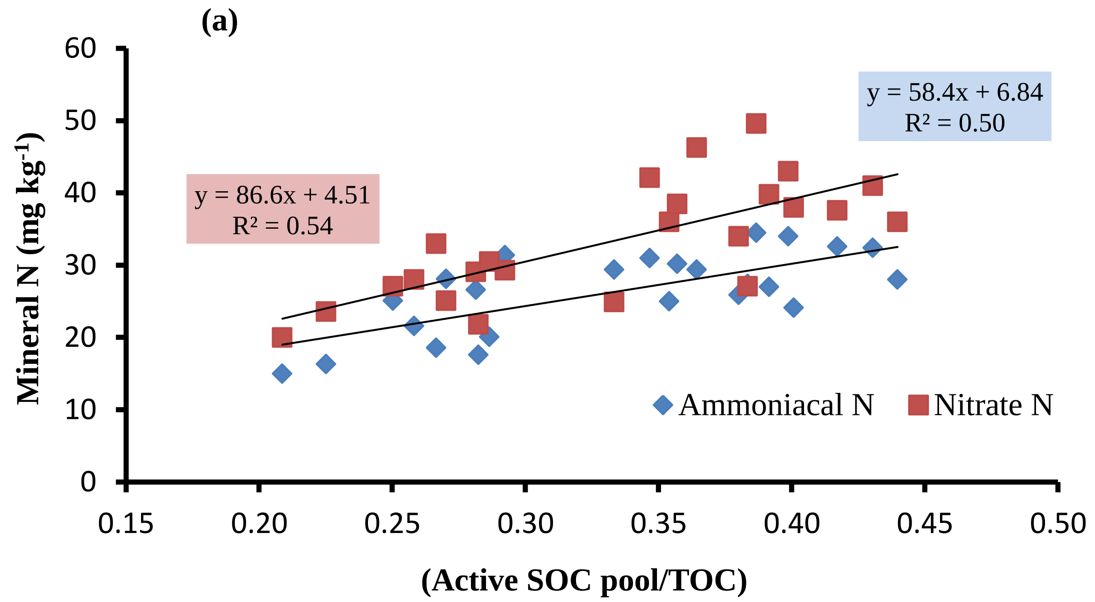


Fig. 4.2.6. Relationships of (a) Olsen-P and (b) available S in 0-7.5 cm soil layer with grain yields of rice and wheat



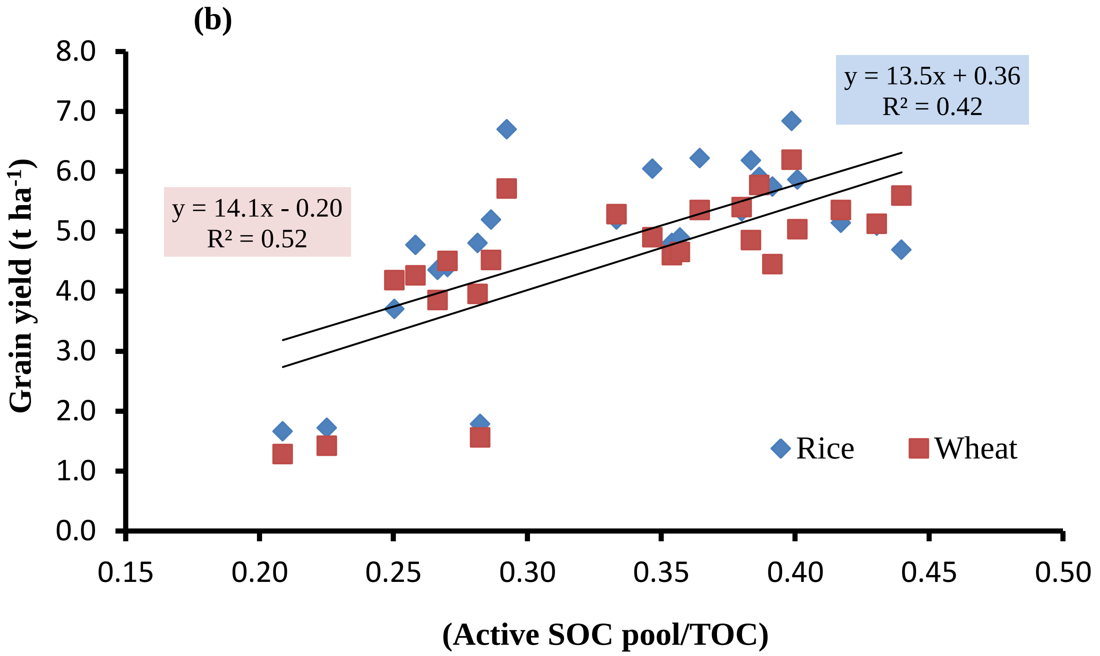


Fig. 4.2.7. Scatter diagram showing relationship of active SOC to TOC with (a) mineral N in 0-7.5 cm soil and (b) grain yields of rice and wheat

5. DISCUSSION

Improving SOM is crucial for sustenance of soil health and agricultural productivity. It is however, difficult in tropical regions (representing most Indian soils), for the contents decline with decreasing rainfall (Katyal and Sharma 1991) and also with an increase in temperature (Jenny and Raychaudhuri 1960). The soils of IGP, where RWS is predominantly practiced, are generally low in SOM and can support high yield levels with judicious fertilization and manuring only (Yadav *et al.* 1998b). Majority of the soils belong to arid and semiarid climate and rarely exhibit organic C levels exceeding 0.6% (Virmani *et al.* 1982), whereas the soils of temperate environments have SOC levels ranging between 1.2 and 2.5%. (Lal and Kang 1982) reviewing SOM management in tropical soils, underlined the necessity of at least four times organic inputs in tropical than in temperate environments to maintain the native SOM levels. Changes in SOC contents of soil due to nutrient management under intensive cropping systems including RWS are generally positive and greater when organic manures are included in fertilization schedules compared to those with fertilizers alone (Hegde and Dwivedi 1992; Singh and Wanjari 2009). Findings of the present investigation corroborate with these earlier reports. Further, results of the present study do not support the contention that SOC levels get depleted consequent to use of fertilizers. In fact, the SOC contents showed a build-up particularly in top soil even without inclusion of organics, provided adequate and balanced fertilizer input was ensured (Table 4.1.6).

Analysis of data of a LTE conducted at six locations in the IGP and one location in the Central Highland and Plateau region of India suggested that SOC levels at the locations containing high initial SOC could not be maintained even with INM involving use of FYM, green manure or crop residues (Yadav *et al.* 2000b). On the other hand, SOC levels increased with the use of fertilizers alone in the locations having low SOC at the initiation of the LTE. As the study site in the present case contained low initial SOC, the effect of different nutrient supply options on SOC and its fractions was generally positive. Yet, a few observations need to be underlined and discussed. The TOC and WBC contents under NPK+CR in the top soil (Tables 4.1.4 and 4.1.6) were either similar or greater than other INM treatments. But the crop productivity under NPK+CR was significantly lower than other INM options. Yadav *et al.* (2000b) also reported poor performance of cereal residues at most of the LTE locations, except Kalyani and Sabour located in the Eastern India. They linked the performance of CR with moisture availability for its decomposition. In the eastern part of IGP (lower and middle Gangetic plains), incorporation of CR 3-4 weeks prior to rice transplanting coincides with the onset of monsoon, thus facilitating proper decomposition of CR. However, at other locations, particularly those falling in northwest India (including the present study site), moisture scarcity during peak summers prior to rice transplanting may not allow proper decomposition of CR and rather enhance N immobilization at early rice growth due to presence of undecomposed CR, leading to poor performance of NPK+CR treatment. Another explanation lies in the distribution of TOC in different fractions. Despite high TOC content under NPK+CR, the labile pool including PmOC and MBC were much lower compared with other INM treatments. Also the active pool of OOC comprising VLC and LC was relatively lower under NPK+CR leading to low nutrient availability.

The results discussed above also suggest that fractionation of TOC may possibly not offer sound explanation to the treatment effects, and there is need to study quality *i.e.* chemical characteristics of SOM. The E_4/E_6 ratio of humic and fulvic acid measured in the present case varied amongst the treatments (Table 4.2.1). Nonetheless, there ratios did not exhibit any consistent relationship with available nutrients or with rice and wheat yields. Had there been analysis of other quality parameters (like functional groups), some of the treatment effects could have been explained in a better way. Future SOC research should invariably include detailed chemical characterization of SOM. There is also need to revisit the laboratory protocols recommended for determination of quality parameters of SOM.

Non-judicious use of fertilizers by the farmers practicing RWS is a norm rather than exception, mostly due to unawareness regarding soil fertility status and crop nutrient demand. As both component crops of RWS are exhaustive feeders of plant nutrients, any negligence in fertilizer use will not only causes yield loss but also prove detrimental to soil fertility (Tiwari *et al.* 2006). Higher crop yields under NPKZnS and NPK+SPM registered in the present study despite higher SOC content of other INM treatments, clearly indicated the importance of adequate nutrient supply in sustaining high yield levels of RWS. Diagnostic surveys conducted in the high productivity area of IGP indicated that farmers have started using greater than recommended rates of fertilizers (especially N fertilizers) in order to attain the same yield levels that were obtained earlier with relatively less fertilizer input. Such indiscriminate use of N would further enhance the mining of nutrients other than N, besides causing serious environmental implications. On the other hand, balanced and integrated use of plant nutrients improved the yields as also restored soil fertility by increasing the availability of plant nutrients as recorded in the present case. The findings of the present LTE also highlighted the significance of addressal of secondary (S) and micronutrient (Zn) deficiencies, suggesting that the meaning of balanced fertilization has changed now and it is no longer confined to NPK only.

6. SUMMARY AND CONCLUSION

Deterioration of soil health in terms of declining quantity and quality of soil organic matter (SOM), emergence and expansion of multinutrient deficiencies, and subsoil compaction has emerged as one of the serious causes of stagnation and decline in factor productivity, threatening the overall sustainability of important agricultural production systems. Non-judicious use of plant nutrients, low use of organic inputs and excessive tillage are major management-related problems responsible for above undesirable trends, particularly under rice-wheat cropping systems. Nutrient supply options that enhance addition and accretion of soil organic carbon (SOC) need to be identified. We, therefore, studied the long-term changes in SOC fractions, some quality parameters of SOM and nutrient availability as influenced by different nutrient supply options in rice-wheat cropping systems in a long-term experiment established during 1993-94 on a Typic Haplustept at PDFSR, Modipuram. Treatments chosen for the study comprised the use of fertilizers alone or combined use of fertilizer NPK along with organic sources of varying composition and origin (FYM, SPM, green gram residue and cereal residues), and an unfertilized-control. The results are summarized as under:

The results are summarized as under:

- Highest TOC content (1.60%) was recorded in 0-7.5 cm soil under NPK+CR, although the TOC stock (0-60 cm soil depth) in the INM treatments followed the order NPK+FYM > NPK+FYM+GR > NPK+SPM > NPK+CR.
- In top soil, bulk density was highest under control. Fertilizers applied in combination with organics decreased soil bulk density substantially with the lowest values in FYM or GR treated plots. Bulk density increased with soil depth, and treatment effect was also masked.
- The SOC fractions *viz.* WBC, MBC and PmOC were generally greater in treatments receiving FYM or FYM+GR along with NPK. Contribution of these SOC fractions towards TOC varied, and was generally greater in 0-7.5 cm soil layer as also under INM treatments. On average, WBC, PmOC and MBC contributed 29 to 46, 4.7 to 6.6 and 1.16 to 2.40% towards TOC.

- Among the oxidisable organic C fractions, active pool (LC+VLC) was relatively larger under conjoint use of fertilizers and organics. The passive pool (NLC+LLC), on the other hand, was larger under NPK+CR, NPKZn and control.
- The parameters like TOC, WBC, PmOC, MBC, LC and VLC showed, in general, considerable positive change over uncultivated soil in the treatments receiving organics along with NPK, whereas the same parameters changed negatively under control.
- Contribution of oxidisable organic C fractions towards TOC content generally followed the order NLC > LC > VLC > LLC. At different soil depths, most of the SOC fractions registered significant and positive correlation with each other and with TOC content.
- E_4/E_6 ratio of FA and HA varied from 10.6 to 14.2 and 3.77 to 4.41 in different treatments. This ratio was, in general, higher under INM. But, E_4/E_6 ratio did not correlate well with available nutrients or crop yields.
- INM helped retaining higher contents of NO_3-N in upper soil layer, whereas a reverse was true in case of sole fertilizer treatments. Available P and S contents were greater under treatments receiving these nutrients regularly through fertilizer or fertilizer+organics.
- Both mineral N and Olsen P increased substantially over uncultivated soil in all the treatments receiving fertilizer NPK, whereas increase in available S over uncultivated soil was observed only in two treatments *viz*. NPKZnS and NPK+SPM.
- Grain yield of rice and wheat was significantly higher over unfertilized-control in all the treatments receiving nutrients through fertilizers or fertilizer+organics. Highest yield of both crops were recorded with NPK+SPM.
- Available nutrient (NH_4-N, NO_3-N, Olsen P and Available S) content of the soil correlated well with rice and wheat yields. Also, bigger the active pool of SOC, higher was the mineral-N content and crop yields.

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

- Conjoint use of NPK and organics, particularly FYM and greengram residue not only increased the SOC content in rice-wheat system, but also the active pool (labile C + very labile C) of SOC.

- Active pool of SOC could be successfully used as an index to predict the availability of N in soil.
- Soil organic C accumulated with continuous use of cereal residues (CR) was dominated with non-labile and less labile C, which could be a reason for relatively low yields under NPK+CR.
- Detailed studies on the quality of soil organic matter need to be undertaken to explain the relationship of SOC with nutrient availability and crop yields.

CHARACTERIZATION OF SOIL ORGANIC MATTER UNDER LONG-TERM FERTILIZATION AND MANURING IN A TYPIC HAPLUSTEPT

ABSTRACT

Soil health deterioration, particularly decline in soil organic carbon (SOC) content, is considered as a major constraint for sustainability of agriculture in the intensively cropped Indo-Gangetic Plain region. The present investigation was, therefore, undertaken to study the long-term effect of fertilizers and manures on SOC pools and quality of soil organic matter, and their relationship with available nutrients and crop yields under rice-wheat cropping system. For this, soil samples were collected during 2010-11 from a long-term experiment continuing since 1993-94 on a Typic Haplustept at Project Directorate for Farming System Research, Modipuram and analysed for different parameters.

Total organic C (TOC) and its different fractions increased significantly with integrated use of fertilizers and organic sources compared with control or sole fertilizer (NPKZn) treatment, particularly at 0-7.5 cm soil depth. Labile fractions like microbial biomass C (MBC) and permanganate oxidisable C (PmOC) were generally higher in treatments that received farmyard manure (FYM), sulphitation pressmud (SPM) or greengram residue (GR) along with fertilizer NPK, whereas these fractions were much lower in NPK+ cereal residue (CR) treatment. Oxidisable organic C fractions measured as per modified Walkley-Black’s procedure revealed that active pool (very labile C+labile C) was much larger in NPK+FYM or NPK+GR+FYM treated plots, whereas passive pool (less labile C+non-labile C) was larger under control and NPK+CR. Correlation studies revealed that the amount of MBC could be effectively predicted from Walkley-Black C and PmOC, as highly significant linear relationship existed between these SOC fractions. On average, WBC, PmOC and MBC contributed 29 to 46, 4.7 to 6.6 and 1.16 to 2.40% towards TOC in 0-7.5 cm soil layer. Use of fertilizers alone (NPKZn or NPKZnS) either maintained different SOC fractions at initial level, or brought a marked increase in the same.

The E_4/E_6 ratio of fulvic acid (FA) increased with continuous cropping and integrated use of NPK and organics like FYM, and GR. The INM options, except NPK+CR, also increased mineral N, Olsen-P and available S contents over sole fertilizer treatments. Highest grain yields of rice (6.32 t ha^{-1}) and wheat (5.77 t ha^{-1}) were obtained in NPK+SPM treatment, followed by NPKZnS with 6.02 and 5.28 t ha^{-1} yield of these crops, respectively. Available nutrient contents and active SOC to TOC ratio, especially in top soil (0-7.5 cm), showed highly significant positive relationship with grain yields. The E_4/E_6 ratios of FA and HA were, however, poorly correlated with available nutrients and crop yields.

उर्वरको एवं खादों के दीर्घकालीन प्रयोग के अंतर्गत एक टीपिक हैप्लूस्टेप्ट मृदा में जीवांश पदार्थ का निरुपण

सारांश

मृदा स्वास्थ में गिरावट, विशेषतः मृदा जैव–कार्बन की मात्रा का ह्रास, सिंधु–गंगा के मैदानी क्षेत्रों में टिकाऊ खेती के लिए एक प्रमुख समस्या मानी जाति है। अतः वर्तमान शोध के अंतर्गत धान–गेहूँ फसल प्रणाली में उर्वरकों एवं खादो में दीर्घकालीन प्रभाव का मृदा जैव– कार्बन अंशो तथा जीवांश पदार्थ की गुणवत्ता, एवं पोषक तत्वों के उपलब्धता स्तर व फसलों की उपज के साथ इसके सह–संबंधो का अध्ययन किया गया। इसके लिए कृषि प्रणाली परियोजना निदेशालय, मोदीपुरम् में टीपिक हैप्लूस्टेप्ट मृदा पर 1993–94 से चल रहे एक दीर्घकालीन प्रयोग से वर्ष 2010–11 में मृदा नमूने एकत्र करके उनका विभिन्न घटकों के लिए विश्लेषण किया गया।

नियंत्रित अथवा केवल उर्वरक (एन.पी.के.जिंक) की तुलना में उर्वरको एवं जैविक स्रोत्रों के समेकित प्रयोग से कुल जैव–कार्बन एवं इसके विभिन्न अंशों, विशेषतः ऊपरी 0–7.5 सेमी. मृदा में सार्थक वृद्धि हुई। सक्रिय (लैबाइल) अंशो जैसे कि सूक्ष्मजैवीय बायोमास कार्बन (एम.बी.सी.) एवं परमैग्नेट–ऑक्सीकरण योग्य कार्बन (पी एम. ओ. सी.) की मात्रा एन.पी.के. के साथ गोबर की खाद, गन्ने की मैली अथवा मूंग के अवशेष प्रयुक्त होने वाले उपचारों में अधिक थी, जबकि एन.पी.के. + धान्य अवशेष उपचारित मृदा में इन सक्रिय अंशो की मात्रा अपेक्षाकृत काफी कर रही। वॉकले–ब्लैक की संशोधित विधि से मापे गए ऑक्सीकरण योग्य जैव–कार्बन अंशों में से सक्रिय अंश (लैबाइल + वेरी लौबाइल कार्बन) की एन. पी. के. + गोबर की खाद तथा एन.पी.के + मूंग अवशेष + गोबर की खाद वाले प्लाटो में अधिक मात्रा थी, जबकि नियंत्रित तथा एन.पी.के. + धान्य अवशेष प्रयुक्त प्लाटो में निश्क्रिय (लेस लैबाइल + नान लेस लैबाइल कार्बन) अंश की प्रचुरता देखी गई। सह–सबंध अध्ययनों से स्पष्ट हुआ कि वॉकले – ब्लैक कार्बन (डब्लू.बी.सी.) अथवा पीएम. ओ. सी. के द्वारा एम.बी.सी की मात्रा का आकलन संभव है, क्योकि इन जैव–कार्बन अंशो के बीच सीधा सार्थक संबंध पाया गया। 0–7.5 सेमी. मृदा परत में टी.ओ.सी. के लिए डब्लू.बी.सी. पीएम.ओ.सी. तथा एम.बी.सी. का औसत योगदान क्रमशः 29 से 46, 4.7 से 6.6 एवं 1.16 से 2.40 प्रतिशत रहा। केवल उर्वरकों के प्रयोग से विभिन्न जैव–कार्बन अंश या तो प्रारम्भिक स्तर पर बने रहे अथवा उनमें वृद्धि हुई।

लगातार खेती अथवा एन.पी.के. एवं गोबर की खाद या मूंग अवशेषों के समेकित प्रयोग से फल्विक अम्ल के E_4/E_6 अनुपात में वृद्धि हुई। समेकित पोषक तत्व प्रबंधन विकल्पों से एन.पी.के. + धान्य अवशेष को छोडकर, केवल उर्वरक प्रयोग की तुलना में खनिज नाइट्रोजन, ऑल्सन–फॉस्फोरस तथा उपलब्ध गंधक की मात्रा में वृद्धि हुई। धान (6.32 टन प्रति हे.) व गेहूँ (5.77 टन प्रति हे.) की अधिकतम उपज एन.पी.के. + गन्ने की मैली उपचार के अंतर्गत प्राप्त हुई, जबकि इन फसलों की क्रमशः 6.02 एवं 5.28 टन प्रति हे. उपज के साथ केवल उर्वरक (एन.पी.के.जिंक गंधक) उपचार दूसरे स्थान पर रहा। ऊपरी (0–7.5 सेमी) मृदा में पोषक तत्वों की उपलब्ध मात्रा तथा जैव–कार्बन के सक्रिय अंश/टी.ओ.सी. अनुपात का फसलों की उपज से धनात्मक व सार्थक सह–संबंध पाया गया। हालांकि फल्विक अथवा हयूमिक अम्ल के E_4/E_6 अनुपात तथा उपलब्ध पोषक तत्वों व उपज के बीच नगण्य सह–संबंध रहा।

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APPENDIX

Abbreviations used in the Thesis

BD	:	Bulk density
CR	:	Cereal residue
EC	:	Electrical conductivity
FA	:	Fulvic acid
FYM	:	Farmyard manure
GEFSOC	:	Global Environmental Facility co-financed Soil Organic Carbon
GR	:	Greengram residue
HA	:	Humic acid
IGPR	:	Indo-Gangetic Plain region
INM	:	Integrated nutrient management
LC	:	Labile carbon
LI	:	Lability index
LLC	:	Less labile carbon
LSD	:	Least square difference
LTE	:	Long-term experiment
MBC	:	Microbial biomass carbon
MQ	:	Microbial quotient
NLC	:	Non-labile carbon
OOC	:	Oxidisable organic carbon
PDFSR	:	Project Directorate for Farming Systems Research
PmOC	:	Permanganate oxidisable carbon
POC	:	Particulate organic carbon
RS	:	Rice straw
RWS	:	Rice-wheat cropping system
SOC	:	Soil organic carbon
SOM	:	Soil organic matter
SPM	:	Sulphitation pressmud

TGP : Trans-Gangetic Plain
TOC : Total organic carbon
UGP : Upper-Gangetic Plain
VLC : Very labile carbon
WBC : Walkley and Black carbon
WS : Wheat straw