CROPPING SYSTEM AND ANTECEDENT CARBON LEVEL EFFECTS ON SOIL ORGANIC MATTER AND NITROGEN DYNAMICS

Thesis

Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE
in
SOIL SCIENCE
(Minor Subject: Chemistry)

By

Samrat Ghosh
(L-2017-A-156-M)

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CERTIFICATE I

This is to certify that the thesis entitled, "**Cropping system and antecedent carbon level effects on soil organic matter and nitrogen dynamics**" submitted for the degree of M.Sc. in the subject of **Soil Science** (Minor subject: **Chemistry**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Samrat Ghosh (L-2017-A-156-M)** under my supervision and that no part of this thesis has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE II

This is to certify that the thesis entitled, "**Cropping system and antecedent carbon level effects on soil organic matter and nitrogen dynamics**" submitted by **Samrat Ghosh (L-2017-A-156-M)**to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of **Master of Science**, in the subject of **Soil Science** (Minor subject: **Chemistry**) has been approved by the Student's Advisory Committee along with External Examiner after an oral examination on the same.

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ABSTRACT

Land-use and agricultural management are known to impact organic matter and nitrogen (N) dynamics in soil. Besides climatic conditions, the effect of land-use and management depends on choice of the cropping sequence that governs the magnitude and composition of plant-derived carbon (C) input to soil, and the soil organic C status which is central to most of the physical, chemical and biological processes. Although the effect of cropping systems on soil organic carbon (SOC) and N dynamics is fairly documented, yet the information on their influence on soil C and N dynamics vis-à-vis antecedent C level is scanty. In the present study, impact of maize-wheat and soybean-wheat cropping in reference to continuous fallow, on total and labile pools of SOC and N dynamics in four soils of different antecedent C level was investigated. In soils of low to intermediate C level, cropped soils lost 11.7 to 21.6% C compared to continuous fallow, however, in a high C soil the cropped soils could maintain soil C status similar to fallow soil. However, compared to antecedent C stocks, the average soil C stocks in the plough layer (0-15 cm) under the three land-uses were improved (0.55 to 1.41 Mg ha^{-1}) in soil of low antecedent C level, but depleted (0.04 to 3.64 Mg ha^{-1}) in soil of high antecedent C level. Compared to fallow soils, the cropped soils had lower concentrations of water soluble (17.7 to 40.5%), hot water soluble (18.1 to 25%) and $KMnO_4$-oxidizable (16.5 to 29.2%) carbon. In soils of intermediate to high antecedent C level, cropped soils being lower (7.9 to 12.4%) in very labile pool and higher in recalcitrant pool (6.4 to 29.4%), had greater stabilization of soil C than continuous fallow. While both the cropping systems exhibited lower C mineralization (31 to 54%) than fallow in low to intermediated C levels, the two cropping systems revealed contrasting N mineralization kinetics in soils with intermediate to high C levels; maize-wheat exhibited higher (8.5 to 9.8%), but soybean-wheat showed lower (upto 8.1%) N mineralization compared to fallow. Maize-wheat influenced nitrification potential only in low C soil (19% higher than fallow) whereas soybean-wheat in intermediate C soil expressed opposite results to that in high C soil. Compared to fallow, soybean-wheat exhibited lower (8-14%) nitrification potential in medium C soil, but higher (17%) potential in high C soil. In conclusion, choice of a cropping sequence in a soil must consider the antecedent soil C status in predicting the magnitude and direction of changes in soil C and N pools.

Keywords: Antecedent soil C, C sequestration, water extractable pools of C, labile C, organic C fractions of different oxidizability, C and N mineralization, nitrification potential

Signature of Major Advisor **Signature of the student**

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ਸਾਰ-ਅੰਸ਼

ਜ਼ਮੀਨ ਦੀ ਵਰਤੋਂ ਅਤੇ ਖੇਤੀ ਪ੍ਰਬੰਧ ਮਿੱਟੀ ਵਿੱਚ ਜੈਵਿਕ ਮਾਦੇ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਗਤਿਆਤਮਕ ਉੱਪਰ ਪ੍ਰਭਾਵ ਲਈ ਜਾਣੇ ਜਾਂਦੇ ਹਨ। ਜਲਵਾਯੂ ਹਾਲਤਾਂ ਤੋਂ ਬਿਨਾਂ ਜ਼ਮੀਨ ਵਰਤੋਂ ਅਤੇ ਪ੍ਰਬੰਧ ਫ਼ਸਲੀ ਚੱਕਰ ਜੋ ਪੌਦਿਆਂ ਤੋਂ ਪ੍ਰਾਪਤ ਮਿੱਟੀ ਵਿੱਚ ਕਾਰਬਨ (C) ਅਤੇ ਜੈਵਿਕ ਕਾਰਬਨ (OC) ਪੱਧਰ ਜੋ ਜ਼ਿਆਦਾਤਰ ਭੌਤਿਕੀ, ਰਸਾਇਣਿਕ ਅਤੇ ਜੈਵਿਕ ਗਤੀਵਿਧੀਆਂ ਦਾ ਕੇਂਦਰ ਬਿੰਦੂ ਹੈ, ਦੀ ਸੰਰਚਨਾ ਅਤੇ ਮਾਪ ਨੂੰ ਸੰਚਾਲਿਤ ਕਰਦਾ ਹੈ। ਹਾਲਾਂਕਿ ਫ਼ਸਲੀ ਚੱਕਰ ਦਾ ਮਿੱਟੀ ਜੈਵਿਕ ਕਾਰਬਨ ਮਿੱਟੀ ਜੈਵਿਕ ਕਾਰਬਨ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਗਤਿਆਤਮਕ ਕਾਫੀ ਹੱਦ ਤੱਕ ਦਸਤਾਵੇਜ਼ ਕੀਤਾ ਹੋਇਆ ਹੈ, ਪਰ ਫਿਰ ਵੀ ਮਿੱਟੀ ਵਿੱਚਲੇ ਕਾਰਬਨ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਗਤਿਆਤਮਕ ਦਾ ਪਹਿਲਾਂ ਤੋਂ ਕਾਰਬਨ ਪੱਧਰ ਉੱਪਰ ਪ੍ਰਭਾਵ ਬਾਰੇ ਜਾਣਕਾਰੀ ਕਾਫੀ ਘੱਟ ਹੈ। ਮੌਜੂਦਾ ਅਧਿਐਨ ਵਿੱਚ ਮੱਕੀ-ਕਣਕ ਅਤੇ ਸੋਇਆਬੀਨ-ਕਣਕ ਫ਼ਸਲੀ ਚੱਕਰ ਦਾ ਖਾਲੀ ਜਗ੍ਹਾ ਦੇ ਸੰਦਰਭ ਵਿੱਚ ਮਿੱਟੀ ਜੈਵਿਕ ਕਾਰਬਨ ਦੇ ਕੁੱਲ ਅਤੇ ਲੇਬਾਈਲ ਭਾਗ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਗਤਿਆਤਮਕ ਚਾਰ ਵੱਖ-ਵੱਖ ਮਿੱਟੀਆਂ ਦੀਆਂ ਕਿਸਮਾਂ ਵਿੱਚ ਜਾਂਚਿਆ ਗਿਆ। ਘੱਟ ਤੋਂ ਦਰਮਿਆਨੇ ਕਾਰਬਨ ਪੱਧਰ ਵਾਲੀ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਸਲੀ ਮਿੱਟੀ ਵਿੱਚ ਖਾਲੀ ਜਗ੍ਹਾ ਦੀ ਬਜਾਏ 11.7 ਤੋਂ 21.6 ਪ੍ਰਤੀਸ਼ਤ ਕਾਰਬਨ ਦੀ ਕਮੀ ਆਈ ਹਾਲਾਂਕਿ ਉੱਚ ਕਾਰਬਨ ਵਾਲੀ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਸਲਾਂ ਅਧੀਨ ਮਿੱਟੀ ਵਿੱਚ ਕਾਰਬਨ ਪੱਧਰ ਖਾਲੀ ਜਗ੍ਹਾ ਦੇ ਬਰਾਬਰ ਬਰਕਰਾਰ ਰਿਹਾ। ਪਰ ਐਂਟੀਸੀਡੇਂਟ ਕਾਰਬਨ ਸਟੋਕ ਦੀ ਤੁਲਨਾ ਵਿੱਚ 0-15 ਸੈਂਟੀਮੀਟਰ ਤਹਿ ਵਿੱਚ ਔਸਤ ਕੁੱਲ ਕਾਰਬਨ ਤਿੰਨੇ ਹੀ ਜ਼ਮੀਨ ਵਰਤੋਂ ਵਿੱਚ ਘੱਟ ਐਂਟੀਡੀਟੇਂਟ ਕਾਰਬਨ ਪੱਧਰ ਵਿੱਚ (0.55 ਤੋਂ 1.41 ਮੈਗਾ ਗਰਾਮ ਪ੍ਰਤੀ ਹੈਕਟੇਅਰ) ਬਿਹਤਰ ਹੋਇਆ ਪਰ ਉੱਚ ਐਂਟੀਡੀਸੇਂਟ ਕਾਰਬਨ ਪੱਧਰ ਵਿੱਚ ਘਟਿਆ (0.04 ਤੋਂ 3.64 ਮੈਗਾ ਗਰਾਮ ਪ੍ਰਤੀ ਹੈਕਟੇਅਰ), 1 ਖਾਲੀ ਜ਼ਮੀਨਾਂ ਦੇ ਮੁਕਾਬਲੇ ਫ਼ਸਲੀ ਜ਼ਮੀਨਾਂ ਵਿੱਚ ਪਾਣੀ ਘੁਲਣਸ਼ੀਲ (17.7 ਤੋਂ 40.5 ਪ੍ਰਤੀਸ਼ਤ), ਗਰਮ ਪਾਣੀ ਵਿੱਚ ਘੁਲਣਸ਼ੀਲ (18.1 ਤੋਂ 25 ਪ੍ਰਤੀਸ਼ਤ) ਅਤੇ ਪੋਟਾਸ਼ੀਅਮ ਪ੍ਰਮੈਂਗਾਨੇਟ ਔਕਸੀਡਾਈਜੇਬਲ (16.5 ਤੋਂ 29.2 ਪ੍ਰਤੀਸ਼ਤ) ਕਾਰਬਨ ਘੱਟ ਸੀ। ਦਰਮਿਆਨੇ ਤੋਂ ਉੱਚ ਐਂਟੀਸੀਡੇਂਟ ਕਾਰਬਨ ਪੱਧਰ ਵਿੱਚ ਫ਼ਸਲੀ ਜ਼ਮੀਨ ਵਿੱਚ ਲੇਬਾਈਲ ਪੂਲ ਬਹੁਤ ਘੱਟ (7.9 ਤੋਂ 12.4 ਪ੍ਰਤੀਸ਼ਤ) ਅਤੇ ਰੀਕੈੱਲਸੀਟ੍ਰੈਂਟ ਪੂਲ (6.4 ਤੋਂ 29.4 ਪ੍ਰਤੀਸ਼ਤ) ਵਿੱਚ ਉੱਚ ਅਤੇ ਲਗਾਤਾਰ ਖ਼ਾਲੀ ਰਹਿਣ ਦੇ ਮੁਕਾਬਲੇ ਵੱਧ ਸਥਿਰ ਮਿੱਟੀ ਕਾਰਬਨ ਸੀ। ਖਾਲੀ ਨਾਲੋਂ ਦੋਨੋਂ ਫ਼ਸਲੀ ਚੱਕਰਾਂ ਵਿੱਚ ਘੱਟ ਕਾਰਬਨ ਖਣਿਜੀਕਰਣ (31 ਤੋਂ 54 ਪ੍ਰਤੀਸ਼ਤ) ਹੋਇਆ, ਦੋਨੇ ਫ਼ਸਲੀ ਚੱਕਰਾਂ ਵਿੱਚ ਨਾਈਟ੍ਰੋਜਨ-ਖਣਿਜੀਕਰਨ ਵਿੱਚ ਆਪਸੀ ਵਿਰੋਧਾਭਾਗ ਸੀ, ਮੱਕੀ-ਕਣਕ ਵਿੱਚ ਖਾਲੀ ਦੇ ਮੁਕਾਬਲੇ (8.5 ਤੋਂ 9.8 ਪ੍ਰਤੀਸ਼ਤ), ਪਰ ਸੋਇਆਬੀਨ-ਕਣਕ ਵਿੱਚ ਘੱਟ ਕਾਰਬਨ (8.1 ਪ੍ਰਤੀਸ਼ਤ) ਖਣਿਜੀਕਰਣ ਹੋਇਆ। ਮੱਕੀ-ਕਣਕ ਨੇ ਨਾਇਟ੍ਰੀਫਿਕੇਸ਼ਨ ਨੂੰ ਸਿਰਫ ਘੱਟ ਕਾਰਬਨ (19 ਪ੍ਰਤੀਸ਼ਤ ਜ਼ਿਆਦਾ ਖਾਲੀ ਨਾਲੋਂ) ਵਿੱਚ ਪ੍ਰਭਾਵਿਤ ਕੀਤਾ ਜਦਕਿ ਸੋਇਆਬੀਨ-ਕਣਕ ਨੇ ਦਰਮਿਆਨੀ ਕਾਰਬਨ ਮਿੱਟੀ ਵਿੱਚ 8-14 ਪ੍ਰਤੀਸ਼ਤ ਘੱਟ ਨਾਈਟ੍ਰੀਫਿਕੇਸ਼ਨ ਸਮਰੱਥਾ ਦਿਖਾਈ ਪਰ ਉੱਚ ਕਾਰਬਨ ਮਿੱਟੀ ਵਿੱਚ ਉੱਚ ਸਮਰੱਥਾ (17 ਪ੍ਰਤੀਸ਼ਤ) ਦਰਸਾਈ। ਸਿੱਟੇ ਵਜੋਂ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਸਲੀ ਚੱਕਰ ਦੀ ਚੋਣ ਨੂੰ ਪਹਿਲਾਂ ਤੋਂ ਮਿੱਟੀ ਕਾਰਬਨ ਪੱਧਰ ਨੂੰ ਮਿੱਟੀ ਵਿੱਚ ਮਿੱਟੀ ਕਾਰਬਨ ਅਤੇ ਨਾਈਟ੍ਰੋਜਨ ਪੂਲ ਵਿਚ ਤਬਦੀਲੀ ਦੀ ਦਿਸ਼ਾ ਜਾਨਣ ਲਈ ਜਰੂਰ ਧਿਆਨ ਵਿੱਚ ਰੱਖਣਾ ਚਾਹੀਦਾ ਹੈ।

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ਮੁੱਖ ਸਲਾਹਕਾਰ ਦੇ ਹਸਤਾਖਰ

ਵਿੱਦਿਆਰਥੀ ਦੇ ਹਸਤਾਖਰ

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Increasing concentration of greenhouse gases in the atmosphere is forcing global climate change. Despite global endeavors to mitigate atmospheric abundance of carbon dioxide (CO_2), its concentration in the atmosphere has been increasing and during 2014-2015 it increased at a rate (2.3 parts per million, ppm) higher than the previous decade (~2.08 ppm) (WMO 2014). Globally averaged concentration of CO_2 in 2015 reached 400 ± 0.1 ppm, indicating an increase of 44% over the pre-industrial level (Betts *et al* 2016). Agriculture contributes 5.1–6.1 Gt CO_2-eq yr^{-1}, which is 10 to 12% of total emissions (Smith *et al* 2007). Bidirectional soil-atmosphere interaction plays an important role in global carbon (C) cycle. Soil is the largest pool of actively cycling C in terrestrial ecosystem (Bolin and Sukumar 2000). Soil being potential source as well as sink of CO_2, C sequestration in soil is considered a suitable option for mitigating atmospheric CO_2 concentration (Nieder and Benbi 2008). A goal of "4 per mille" for C sequestration in global soils has been set to contain temperature increase within +1.5/2 °C by 2050: the threshold beyond which climate change would have a significant impact (Minasny *et al* 2017). This implies that C stocks in soil has to be increased by 0.4% annually through improved crop and land management practices that increase C input to soil or reduce soil respiration or both. Management practices that increase C input to soil include intensification of agriculture, conservation agriculture, residue recycling, balanced nutrition including fertilizer and manure, water management, growing of cover crops and involving diversified crop rotations (Benbi 2015). Though magnitude of C sequestration in soil is linearly related to C input yet the proportion of added C stabilized varies with climatic conditions, cropping system, soil texture and management practices (Nieder and Benbi 2008). In Indian agroecosystems, about 8 to 21% of the added C is sequestered in soil depending on soil and climatic conditions (Benbi *et al* 2012b).

Agroecosystems differ in C accretion potential, mainly because of differences in plant-mediated C return to the soil and the prevailing soil organic carbon (SOC) level that determines C saturation deficit. Rooting behavior of crops and moisture regimes during crop growth also influence SOC. Benbi and Brar (2009) showed that intensively cultivated rice-wheat systems in Punjab resulted in 38% improvement in SOC. Enhanced C sequestration was related to increased crop yields; one tonne increase in productivity of rice and wheat resulted in 0.85 Mg C sequestration ha^{-1}. Increasing rotation diversity such as from monoculture to continuous cropping or increasing cropping intensity can sequester 200±120 kg C ha^{-1} yr^{-1} (West and Post 2002). Besides plant mediated C input the external supply of C through organic amendments such as farmyard manure (FYM) and crop residue has a major influence on SOC build-up and its distribution among various C pools (Benbi *et al* 2012b).

Cropping systems besides impacting amount of organic C accumulation also influence its composition. For instance, agroforestry systems lead to greater C accumulation in labile pools than rice-wheat and maize-wheat systems in which dominant proportion of SOC is stored in less labile or recalcitrant pools (Benbi *et al* 2012a). Similarly, soils under rice-wheat and maize-wheat systems compared to sugarcane had higher proportion of SOC in recalcitrant forms (Benbi *et al* 2015). Soils under vegetable farming had higher amount of labile C as compared to soils under soybean-wheat system and fodder crops (Kalambukattu *et al* 2013). Legumes, important component of crop rotation and diversification, are known to increase soil organic matter level which in turn improves soil quality (Smith 2016). Unique characteristics leading to the favorable impact of legumes on soil is their ability to fix atmospheric N_2, release more root exudates, greater leaf litter fall and deep root system (Gregorich *et al* 2001). Inclusion of a legume in a cropping sequence significantly improves SOC content, which can be greater in surface soil compared to sub-surface soil (Venkatesh *et al* 2013). Due to higher production of root biomass (31% of above ground plant biomass), soybean based cropping systems add high amount of organic C to soil (Kundu *et al* 1997). The sequestered C is stabilized in different forms in soil, which can be quantified by physical, chemical and biological fractionation techniques (Popleau *et al* 2018). Different physical fractionation procedures involve size and density floatation techniques depending upon extent of protection inside the aggregates (Cambardella and Elliott 1993, Golchin *et al* 1994, Sollins *et al* 1996, DeGryze *et al* 2004, Benbi and Senapati 2010, Benbi *et al* 2012b). Chemical and biological fractionation involve extraction with various reagents ranging from distilled water to solutions of different salts to strong acids (Vance *et al* 1987, Blair *et al* 1995, Sparling *et al* 1998, Chantigny 2003, Benbi *et al* 2012b, Hopkins 2007) or oxidation with acid-aqueous solutions of variable strength (Chan *et al* 2001). The sensitivity of chemical and biological methods to discern management-induced changes in SOM has been studied for different soils and agro-ecosystems (Carter *et al* 1998, von Lutzow *et al* 2000). In Punjab, capability of these methods as sensitive indicators of changes in SOM has mainly been evaluated for rice-wheat and maize-wheat systems (Benbi *et al* 2015, Benbi *et al* 2012a). Information on changes in chemical and physical pools of SOC under a legume-based (soybean-wheat) cropping system vis-à-vis non-legume based (maize-wheat) system is generally lacking. It was hypothesized that amount and quality of C derived from a leguminous C_3 (soybean) plant will differ from a non-legumonous C_4 (maize) plant, which may differentially influence C stabilization in various SOC pools.

Soils have finite capacity to store C, which *inter alia*, depends on soil texture and existing SOC content (Benbi 2015). Results of long-term experiments in India have shown that in soils with high antecedent C level the SOC concentration declined as a result of cropping (Yadav *et al* 2000). The magnitude and rate of decline depended on cropping system and soil management. Though some studies have quantified C sequestration potential of different cropping systems (Kong *et al* 2005, Shrestha *et al* 2006, Varvel and Wilhelm 2011), yet the information on changes in amount and composition of SOC vis-à-vis antecedent C level is lacking. It is well-known that C and N cycles are interrelated and introduction of a legume in a crop rotation besides directly influencing changes in SOC may also exert its effect by impacting soil N dynamics (Nieder and Benbi 2008). Information on N dynamics in a legume based cropping system and their effect on soil C pools in Punjab soils is lacking. Therefore, the present study was conducted to enumerate the influence of a legume and a non-legume based cropping system on SOC and N dynamics under varying antecedent SOC levels. The specific objectives of the study were:

1. To study the effect of cropping system on organic matter and N dynamics in soils of different fertility.
2. To enumerate the effect of cropping system and antecedent SOC level on aggregation and C and N turnover in soil.

CHAPTER II

REVIEW OF LITERATURE

The literature pertinent to the present study entitled “Cropping system and antecedent carbon level effects on soil organic matter and nitrogen dynamics” is reviewed under the following heads-

2.1 Effect of organic manures and inorganic fertilizers on C and N dynamics in soil

2.2 Cropping system effects on C and N dynamics in soil

2.3 Antecedent C level effects on organic matter and N dynamics in soil

2.4 Depth distribution of SOC pools

2.1 Effect of organic manures and inorganic fertilizers on C and N dynamics in soil

Agricultural management practices that influence C sequestration in soil include application of organic amendments, residue recycling, adoption of agroforestry systems, selection of high biomass producing crops, elimination of summer or winter fallow, and changing from monoculture to rotation cropping (Benbi 2015). A number of studies have documented the favorable effects of organic manures and inorganic fertilizers on C and N dynamics in soil. Generally, organic manures lead to greater C stabilization in soil compared to inorganic fertilizers (Sodhi *et al* 2009, Benbi and Khosa 2014, Jha *et al* 2014). Depending on soil and climatic conditions, 8 to 21% of the C added through organic manures is stabilized in soil (Benbi *et al* 2012b); the proportion being higher in temperate than tropical climates. Greater C sequestration with organic manures may be attributed to C input through these sources and partial decomposition of organic manures prior to their application in the field. As a result of decomposition, organic C in manures is converted to recalcitrant form which gets stabilized with time. Therefore, their application to soil in different cropping systems enhances C sequestration potential per unit of time (Dick and Gregorich 2004).

Application of organic amendments such as FYM and rice straw for 11 years in rice-wheat system in northern India increased SOC by 34-84% in surface and 15-58% in sub-surface soil (Benbi *et al* 2015). Likewise, Banger *et al* (2010) reported increase in SOC concentration by 36% in 0-15 cm depth and by 18% in 15-30 cm depth after 16 years of FYM application in rice-cowpea system in a sandy loam soil in southern India. Application of FYM at 10 Mg ha^{-1} yr^{-1} for 25 years in rice-wheat system in China improved SOC concentration by 1.5 to 23% over N and NPK application (Yan *et al* 2007). Use of FYM and crop residues along with green manure leads to greater improvement in SOC level compared to their solitary application. In a study, the SOC concentration rose significantly by 6.8 to 12% with application of crop residues, FYM and green manure compared to application of inorganic fertilizers alone in pearl millet-wheat sequence (Goyal *et al* 1999). Application of compost and mineral fertilizers for 18 years in irrigated wheat-maize grown on a sandy loam soil significantly increased SOC status by 27 to 124% (Yu *et al* 2012). Rise in SOC status was higher in compost amended soils compared to mineral fertilizer treated soils.

Besides improving SOC stocks, organic amendments bring about changes in the composition of soil organic matter enumerated through physical, chemical and biological fractionation methods. In a silty loam soil in north China plain, long-term application of FYM for 15 years significantly increased hot water soluble C (HWSC) by 80 to 120% and $KMnO_4$-oxidizable C by 36 to 100% in 0-20 cm soil layer compared to soil receiving no amendment (Liang *et al* 2012). Similarly, application of compost in maize-wheat system for 22 years resulted in significant improvement in WSC, $KMnO_4$-oxidizable C and carbon management index by 23 to 153%, 31 to 113% and 34 to 120%, respectively compared to only N fertilization (Lou *et al* 2011). Long-term FYM application (30 Mg ha^{-1} $2yr^{-1}$) for 96 years in sugarbeet-spring barley-potato-winter wheat system resulted in 70% increase in $KMnO_4$ oxidizable C in 0-10 cm soil layer compared to soil not receiving FYM (Blair *et al* 2006). In an experiment in a loamy sand soil, bagasse ash application to wheat for four years under rice-wheat sequence had significantly improved HWSC by 72%, $KMnO_4$-oxidizable C by 31%, microbial biomass C by 27%, very labile pool of SOC by 60% and recalcitrant pool of SOC by 83% (Benbi *et al* 2017). In another study, comparing organic and conventional agriculture under rice-wheat sequence in a part of Indo-Gangetic Plain, it has reported that organic agriculture resulted in significantly higher SOC stock (by 2.2 Mg C ha^{-1}) at 0-15 cm depth compared to conventional management; coarse particulate organic C (*c*POC) and mineral associated organic C (MinOC) under organic management was 30 to 161% and 22 to 39% higher than conventional agriculture, respectively (Benbi *et al* 2018). Organic cultivation improved soil microbial biomass C (MBC) by 57 to 70% and mineralizable C (C_{min}) by 22 to 23% compared to conventional cultivation. The application of fertilizers and organic manures greatly influenced soil aggregation and C storage within aggregates (Benbi *et al* 2016). Long-term application of organic amendments viz. rice straw and FYM alone or in combination in a sandy loam soil significantly improved aggregate associated C in macro-aggregates compared to micro-aggregates in rice-wheat system (Benbi and Senapati 2010). The improvement in aggregate associated C in different size classes was greatest in soils receiving both FYM and rice straw. Similarly, in a 41 years study in sandy clay loam soil under rice-rice system, application of FYM significantly increased C density in different sized aggregates with greater effect on macro-aggregates (2-5 mm) than micro-aggregates (0-0.053 mm) (Tripathy *et al* 2014). Macro-aggregates contained 11.6 to 20.9% higher C than micro-aggregates. Conversely, during a study in paddy soils of China, significant decrease in macro-aggregate (2-0.25 mm) and micro-aggregate associated C with time was observed irrespective of organic or inorganic fertilizer application (Lee *et al* 2009).

Besides organic amendments, the inorganic fertilization also increases SOC content through greater plant mediated C input to soil resulting from higher amount of plant biomass and crop residues returned to soil. Sainju *et al* (2008) reported that N fertilization increased plant mediated C input to soil in cotton-maize and cotton-rye systems as a result of increased biomass production. In a 96 years long-term experiment, application of NPK resulted in SOC build-up by 6.1 to 26% compared to NP and NK application alone. However, there was no statistically significant difference between NP and NPK treatments (Blair *et al* 2006). In soybean-wheat system grown on a sandy loam soil, continuous application of NPK for 30 years led to 35.5% higher SOC concentration in surface soil (0-15 cm). The NP treatment alone resulted in significant rise in SOC status compared with NK but was statistically at par with NPK (Kundu *et al* 2007). Nitrogen fertilization at 270 kg N ha^{-1} has been reported to increase SOC stock in soils under continuous corn and corn-soybean systems (Wilson and Kaisi 2008). Application of P along with N significantly improved SOC compared to unfertilized soils. Conjoint use of both, organic as well as inorganic amendments may lead to greater SOC (73.8 to 93.2%) accretion compared to their individual application (Kundu *et al* 2007). Integrated use of organic and inorganic fertilizers leads to greater crop productivity and C sequestration and maintenance of soil health. Integrated nutrient management in paddy soil resulted in 40-60% increase in SOC level; higher SOC status was observed under continuous water logged than alternate wetting and drying condition (Yang *et al* 2005). Similarly, in another study, integrated nutrient management practices improved the SOC by 82% compared to soil not receiving any organic and inorganic amendment (Gong *et al* 2009).

A number of studies have enumerated the effect of integrated nutrient management on chemical pools of soil organic C. Labile pools of C are significantly improved by conjoint application of organic and inorganic fertilizers (Schulz *et al* 2011). Soils not receiving organic amendment showed decline in HWSC concentration by 25-32%, whereas in soils amended with organics, the HWSC was decreased by 50%. Significant increase in HWSC in 0-20 cm soil layer after 12 years of NPK+FYM application in a clay loam soil has been reported by Šimon (2008). However, application of NPK alone did not result in any change in HWSC. Similarly, organic manure application in conjunction with inorganic fertilizers significantly improved both the labile and recalcitrant fractions of SOC (Ding *et al* 2012). The magnitude of increase in recalcitrant fraction over control was higher than labile fraction indicating that, organic C sequestered through organic inputs was stabilized in recalcitrant pools. Concentration of all the four fractions of organic C of variable oxidizability viz. very labile, labile, less labile and recalcitrant were increased significantly by 50, 57, 44 and 22%, respectively, in surface soil (0-15 cm) after 5 years of NPK+FYM (at 15 Mg ha^{-1} yr^{-1}) application to rice-wheat system in sandy loam soil (Singh and Benbi 2018). In the same experiment, integrated nutrient management raised labile C by 306% compared to unfertilized control. Conjoint application of fertilizer and rice straw compost conjointly, increased SOC by 26 to 30% and $KMnO_4$-oxidizable C by 41 to 43% under rice-wheat system in a sandy loam soil (Sodhi *et al* 2009). In an experiment in sandy clay loam soil under 41 years rice-rice system, integrated use of NPK and FYM application resulted in significant increase in microbial biomass C (MBC) compared to control (Mohanty *et al* 2013).

Carbon and nitrogen dynamics in soil are associated with each other. Besides bringing about changes in soil C pools, organic and inorganic fertilization influence soil N dynamics. One ton increase in organic C in one ha soil through inorganic fertilizer application simultaneously improved the indigenous soil N status (0-15 cm) by 4.75 kg (Benbi and Chand 2006). There are several studies documenting the effect of organic and inorganic fertilization, applied alone or conjointly, on total soil N and plant available pools viz. mineralizable N, NH_4^+-N and NO_3^--N in soil (Benbi and Richter 2002, Ideriah *et al* 2008, Aulakh *et al* 2000, Singh and Aulakh 2001, Gupta and Laik 2002). Inorganic fertilization alone or conjointly with FYM, urban compost or poultry manure significantly increased total N, hydolysable N, non-hydrolysable N and mineralizable N in both surface as well as sub-surface soils (Tabassum *et al* 2010). About 3-6% and 2-5% of total N was mineralized in surface and sub-surface soil, respectively. Application of FYM at 15 t ha^{-1} for five years, in combination with fertilizer N, in maize-wheat system on a sandy loam soil has resulted in increase in prevailing NO_3^--N concentration in soil by 19-30 kg ha^{-1} at 180 m soil profile (Benbi *et al* 1993). In a short-term experiment with maize-wheat sequence on a sandy loam soil, 6 years mulch application with different rates of N fertilizer increased the soil NO_3^--N content by 33 to 42 kg ha^{-1} (Sandhu *et al* 1992). Long-term balanced fertilization (100% NPK) and FYM application for 22 years in maize-wheat-cowpea fodder sequence increased soil N and SOC by 12 to 28% and 30 to 110%, respectively, compared to initial (Benbi and Biswas 1997). Apparent N recovery was improved by 32 to 64%. Application of FYM and compost resulted in 8 to 25% build-up in soil N as compared to inorganic fertilization alone (Yusuf *et al* 2007). In a 7 years rice-wheat sequence followed on sandy loam soil, rice-straw, FYM and their conjoint application resulted in 37, 77 and 90% increase in total soil N, respectively (Benbi and Senapati 2010). In a saline-sodic soil, total N rose significantly upon application of pistachio residues as a source of organic matter (Neshat *et al* 2011). An incubation study with different types of hydromorphic soils treated with organic wastes have reported a significant decrease in total inorganic N (NO_3^- + NH_4^+) over first two weeks which was increased thereafter (Iwegbue *et al* 2011). In three different soils, 1.9 to 46.9% of total N was mineralized after 58 days of incubation. Besides mineralization, total N in soil is decreased for NO_3^- leaching. With increase in rate of inorganic N fertilizer application in soil, NO_3^- leaching increases significantly and conenctration of total soil N decreases (Benbi 1990, Benbi *et al* 1991). In a study, 50% NPK application led the lowest whereas 150% NPK application caused the highest NO_3^- leaching in soil (Benbi 2017). Loss of NO_3^--N under rice-wheat can account for

10-15% of applied N (Benbi 2017).

Majority of total N in various organic manures is bound organically that must be converted to inorganic forms before it becomes available to plants. Therefore, N mineralization is an important process influencing N availability to plants (Balkcom *et al* 2009). Mineralization and immobilization processes in soil are greatly influenced by organic and inorganic fertilization. In a laboratory study conducted with a surface soil drawn from rice-wheat sequence, organic manure application significantly improved cumulative N mineralized and N mineralization potential of soil (Bhat *et al* 2018). The rate of N mineralization was higher in recommended fertilizer plus FYM treated soil by 32, 46 and 77% at 15, 25, and 35 ^{0}C, respectively, compared to soil receiving no amendment (Bhat *et al* 2018). In an experiment under maize-wheat system in a loam soil, conjoint use of poultry manure and urea (50:50) resulted in the highest N mineralization (85% of total N within 6 days of incubation) compared to their individual application (Abbasi and Khaliq 2016). Similarly, application of organic manure, rice straw and inorganic fertilizers in maize-wheat system significantly influenced gross N mineralization rate, which was correlated with SOC and total N in soil. However, in rice-wheat sequence, incorporation of crop residues of preceding wheat crop lead to higher immobilization of inorganic N (Singh *et al* 2004). Another experiment also has reported linear correlation between N mineralization and SOC level (Haer and Benbi 2003). For one g of organic C in soil, amount of N mineralized was 9 mg. In a 112 days of incubation study with 15 different benchmark soils from Punjab, cumulative N mineralization was 2.7 to 8% of soil organic N which varied between 8.2 to 75.6 mg N kg^{-1} soil (Haer and Benbi 2003). In an experiment with three cropping sequences (continuous corn, corn-soybean-corn-soybean, and com-oats-meadow-meadow) receiving different rates of N-fertilizer, rate of nitrification in soil varied between 22.2 to 67.8% with relatively higher rate under higher N fertilizer application (Tabatabai 1992).

2.2 Cropping system effects on organic matter and N dynamics in soil

Cropping systems differ in quantity, quality, time and placement of plant mediated C return to soil. Therefore, diverse cropping systems under similar management may lead to variation in the level of C sequestration in soil. In an eight years study with 10 cropping systems on an alluvial loamy sand soils of northern India, the maize based cropping systems resulted in significant increase in SOC concentration compared to rice, cotton and groundnut based cropping systems by 15.9 to 28.4%, 26 to 29% and 29.8 to 43.8%, respectively, at 0-15 cm depth (Brar *et al* 2015). Shrestha *et al* (2006) also reported that in silty loam soils of Nepal, maize-based cropping systems viz. maize-potato and maize-wheat resulted in 11.6 to 42.6% higher SOC than rice-potato and rice-wheat systems after 50 years of cropping. Also, rice-wheat system significantly improved SOC status compared to rice-vegetables and rice-sugarcane cropping systems by 23.6 and 106%, respectively. They further reported that rice-wheat system, compared to rice-tobacco and rice-mustard systems, resulted in significant improvement in SOC status (5.4 to 9.4 g kg^{-1}). In a study on application of different organic and inorganic amendments, rice-rice-fallow system in practice for 29 years resulted in 112 to 133% increase in SOC concentration as compared to maize-maize-fallow system in practice for 24 years (Yan *et al* 2013). Compared to upland soils, paddy soil had higher C sequestration rate. However, a study based on five long-term experiments (7-36 years) involving five rice-based cropping systems and four crop management practices (including a fallow management) showed that all rice based cropping systems resulted in SOC depletion over time compared to continuous fallow (Mandal *et al* 2007).

Inclusion of a legume within a cropping sequence, may affect its soil C sequestration potential. In a 19 years study on a silty clay loam soil, continuous corn, soybean-corn and continuous soybean cropping sequences were reported to show differential C sequestration (Varvel and Wilhelm 2011). Highest SOC build-up in 0-15 cm layer was in soils under continuous-corn (36.6 Mg ha^{-1}) followed by soybean-corn (34.1 Mg ha^{-1}) and continuous soybean (32.5 Mg ha^{-1}) systems. In another study for 20 years in silty loam soils of U.S. under soybean-winter wheat/ green manure, corn-soybean and continuous corn systems, continuous corn resulted in significant increase in SOC concentration, which was 21% higher over soybean-corn system (Sanford *et al* 2012). Crop successions of wheat/soybean/oat/soybean/ oat + vetch/maize/radish had resulted in 10.8% and 4.8% significant increase in SOC concentration compared to soybean/wheat succession and wheat/soybean/oat/soybean succession, respectively, in a clay loam soil of southern Brazil (Ferreira *et al* 2013). Among 10 different land use systems viz. rainfed wheat-control, rainfed wheat-legume, rainfed wheat-fallow, irrigated wheat-control, irrigated wheat-legume, irrigated wheat-fallow, conventional wheat-tomato, conventional maize-tomato, legume maize-tomato and organic maize-tomato in practice for 10 years in Yolo silt loam and Rincon silty clay loam soils, organic maize-tomato system resulted in highest improvement in SOC status while irrigated wheat-control and legume maize-tomato system showed lowest soil C sequestration. Other cropping systems (except irrigated wheat-legume and irrigated wheat-fallow systems) resulted in decline in SOC level with time, the highest depletion being in rainfed wheat-control system (Kong *et al* 2005). In another study in sandy clay loam soil, soybean-lentil and soybean-pea and soybean-wheat systems resulted in variable increase in SOC status. The trend of C sequestration observed was soybean-lentil > soybean-pea > soybean-wheat systems (Bhattacharya *et al* 2009). Cropping involving alfalfa (corn-oat-alfalfa) resulted in higher SOC stock compared to cropping systems without alfalfa (continuous corn and corn soybean) (Russel *et al* 2005). After 9 years of practicing continuous alfalfa, millet-potato-wheat, millet-wheat-potato and millet-fallow-peas systems in silty clay loam soil, SOC concentration under different cropping systems followed the order: continuous alfalfa ≥ millet-wheat-potato ≥

millet-fallow-peas ≥ millet-potato-wheat (Wang *et al* 2009).

While crops differ in SOC accretion potential, the distribution of accumulated C in physical and chemical SOC pools is also altered. Major proportion of sequestered C in soils under maize-wheat and rice-wheat is stabilized into recalcitrant forms and mineralizable C was significantly higher in soils under rice-wheat compared to maize-wheat system (Benbi *et al* 2015). Less labile and recalcitrant fractions together constituted 63% of SOC in rice-wheat compared to 40% in maize-wheat in sandy loam soils of northern India (Benbi *et al* 2012a). Martrins *et al* (2009) compared four summer cropping sequences viz. maize monocrop, soybean monocrop, soybean-maize and rice-bean/cotton-bean and reported that macro-aggregates of size 1.0-2.0 mm and micro-aggregates of size <0.25 mm were associated with highest and lowest C density, respectively. Maize monocrop had highest SOC content in aggregates of diameter 2.0-6.3 mm.

Soil organic matter dynamics and nutrient cycling are closely related. Besides influencing C dynamics, different crops have differential effect on soil N dynamics. In a long-term experiment with different N fertilization for 11 years in clay loam soil in Canada, corn-soybean-wheat and continuous corn systems resulted in highest and lowest increase, respectively, in SOC and total N in 0-20 cm soil layer (Congreves *et al* 2017). A long-term study for 36 years with five cropping sequences viz. a 9 years rotation (corn–wheat–corn–wheat–corn–wheat–alfalfa–alfalfa–alfalfa), two 2-year successions (corn–wheat and sugarbeet–wheat), continuous corn and continuous wheat systems, all receiving variable manure and N fertilization rates showed that different cropping systems and fertilization had significant effect influencing the soil C and N stock (Triberty *et al* 2016). After initial decline for 18 years in all systems, the steepest rise in SOC and total N was observed in 9 years sequence and continuous wheat while slowest rise was observed in sugarbeet-wheat system. Poplar based agroforestry system resulted in significantly higher amount of total N in soil as compared to rice-wheat and maize-wheat systems (Benbi *et al* 2012a).

In silty clay loam and silty loam soils in U.S, a study with four cropping systems viz. continuous corn, corn–soybean, corn–soybean–wheat, and continuous soybean over conventional tillage and no-tillage reported highest total N observed to be in corn–soybean–wheat system (Zuber *et al* 2015). A 10 years study on four no-till based cropping systems viz. continuous corn, corn–winter wheat, corn–winter wheat–grain sorghum, corn–winter wheat–grain sorghum–soybean practiced under limited irrigation in silty loam soils showed SOC and total N to increase with time in all the systems (Halvorson and Schlegel 2012) and continuous corn and corn–winter wheat– grain sorghum–soybean systems resulted in highest and lowest rate of SOC and total N change in soil, respectively. Another study with four long-term (17 years) no-till cereal and legume-based cropping systems viz. bare soil without cropping, oat/maize sequential cropping, lablab+maize intercropping and pigeon pea+maize intercropping followed on a native grassland showed that during the period of conventional cultivation, C and N stock decreased by 22% and 14% (0-17.5 cm soil layer), respectively and with N fertilization, legume based cropping systems resulted in significant increase but, oat/maize sequential cropping resulted in no change in soil C and N stock with time (Diekow *et al* 2005).

2.3 Antecedent C level effects on C and N dynamics in soil

Effect of different agricultural management practices on C dynamics in soil is modulated by existing SOC concentration. From a long-term experiment on rice-wheat system for 15 years at six different locations, Yadav *et al* (2000) reported that in soils having antecedent organic carbon level greater than 6.5 g kg^{-1}, a significant decrease in SOC occurred with time while in soils with SOC concentration less than 5.0 g kg^{-1} a significant increase in organic C was recorded. Available N content showed a declining trend at all locations except the one receiving 100% NPK application. Similarly, in another long-term fertilizer experiment at three different locations under rice-wheat double cropping system receiving eighteen soil fertility combinations, significant rise in SOC concentration was observed over time in soils having SOC level less than 0.40% while it decreased significantly in soils having SOC level greater than 0.75% (Yadav *et al* 1998). Soil organic carbon, at different locations, tended to get stabilized between 0.60 and 0.65%.

Variation in C mineralization, a biologically active pool of SOC, occurs depending upon SOC status and proportion of a particular C fraction available in soil. In a laboratory incubation experiment under rice-wheat sequence in practice for 20 years, C mineralization kinetics of rice straw (RS), rice straw compost (RSC), rice-straw-derived biochar, rice-husk (RH), rice husk ash (RHA), and FYM amended soils was associated with initial decomposable and recalcitrant pools of SOM (Benbi and Yadav 2015). Carbon mineralization was greater in RS and RH treated soil compared to FYM, biochar, RSC, and RHA amended soil. A study conducted at 10 sites (four croplands, one grassland and five forest) reported that soils with higher SOC status showed higher temperature sensitivity (Q_{10}) to decomposition, while lower SOC containing soils showed lower Q_{10} values (Zheng *et al* 2009). Soils with higher SOC status were also associated with higher amount of labile C.

Irrespective of the cropping systems, soil antecedent C level affects the distribution of SOC among different soil particle size fractions. Based on three long-term field experiments (an organic amendment experiment, a fertilization and rotation experiment and a tillage experiment) in clay loam soil in US, it was reported that SOC concentrations, in all the particle size fractions, was significantly related to soil C status. A significant increase in sand associated SOC resulted only when the prevailing bulk soil SOC concentration exceeded 30 g C kg^{-1} soil (Yang *et al* 2016). It was further reported that up to 98% of the SOC was associated with the silt and clay sized fractions when bulk soil SOC was less than 20 g C

kg^{-1} soil and it was only 70–80% of SOC when bulk soil C content was greater than 30 g C kg^{-1}. Similarly, results of another study showed that cropping systems and management practices could sustain SOC only when the antecedent SOC level was greater than a critical value (2.9 Mg ha^{-1}) indicating prevailing SOC level to be an important factor affecting C dynamics in soil (Mandal *et al* 2007).

2.4 Depth distribution of SOC pools

Movement of SOC to deeper soil layers, vertical mixing by different soil organisms and decrease in SOC decomposition in deeper layers affects the depth-distribution (Gill and Burke 2002). Lesser amount of fresh organic matter in deeper soil layers does not provide enough energy to soil microbes; it causes lesser decomposition of organic matter at greater depth which thereby affect its distribution (Fontaine *et al* 2007). Average SOC, total N, labile C and particle size fraction-associated C were observed to be significantly higher in surface soil (0-15 cm) compared to sub-surface soil (15-30 cm) in a 17 years study involving manure and inorganic fertilizer application under rice-cowpea system in sandy loam soil in southern India (Banger *et al* 2009). Addition of more plant biomass and root exudates resulted in higher SOC in surface soil because most of the root biomass of wheat and maize are confined within this depth. Similarly, in another study, on application of FYM and rice straw alone or in combination, 11 years of rice-wheat sequence in sandy loam soils resulted in variable increase in SOC concentration in two soil depths (Benbi *et al* 2012b). Increase in SOC, on application of these organic amendments, was higher in surface (0-7.5 cm) than in sub-surface (7.5-15 cm) soil. Coarse and fine particulate organic matter (*c*POM and *f*POM) showed similar trend. The organic C pools in various density fractions showed significant increase in both the soil depths and followed the order mineral associated organic C (MinOC) > heavy fraction organic C (HFOC) > light fraction organic C (LFOC) > intra-aggregate associated C (iLFOC), but the magnitude of increase was higher in surface compared to sub-surface soil but, cumulative C mineralization was higher in sub-surface compared to surface soil. Another 5 years study under rice-wheat system in loamy soils involving application of different organic amendments showed variable increase in SOC, total water stable aggregates (WSA) and these aggregates associated C in surface (0-7.5 cm) and sub-surface (7.5-15 cm) soils (Benbi *et al* 2016). Variable increase in SOC concentration at different depths has also been reported in another experiment involving organic and inorganic fertilization for 8 years on soybean-wheat system in a silty clay loam soil in India (Bhattacharyya *et al* 2009). Soil organic carbon concentration, due to integrated use of amendments, was significantly higher at 0-15, 15-30 and 30-45 cm soil depths but the magnitude of increase was highest in surface soil. Enumerating C turnover kinetics, with the help of C^{13} signature, in 1m profile-depth under 0-10 years of maize after wheat cultivation in a loamy soil, it was reported that highest proportion of maize-derived SOC was observed in 15 cm soil depth which then decreased in

50 and 100 cm soil depths (Rasse *et al* 2006).

Variable distribution pattern of SOC in soil profile in different land use systems has been reported in several studies. In a long-term experiment, a study estimating SOC stock under plantation with native tree species established on a degraded pasture system revealed that the C stock was much higher in surface soil and decreased 3.2 to 3.5 times with soil depth (Jiménez *et al* 2007). Similarly, in another study in northern India, SOC stock showed significant rise with age (1-11 years) under *Populus deltoides* plantations and decreased with soil depth (Arora *et al* 2014). Similarly, a study under poplar and corn systems in south-eastern Spain showed that apart from high SOC stock under poplar system compared to corn system in both surface (0-20 cm) and sub-surface soil (20-100 cm), surface soil under poplar was characterized by more labile pool of C whereas sub-surface soil by more recalcitrant pool (Sierra *et al* 2013). The presence of recalcitrant substances viz. tannin, lignin, suberin etc. in deeper layers were ascribed to root decomposition. Different land use systems viz. cultivated soil (maize-wheat system), grassland, forest land and eroded land resulted in significant changes in SOC in both the surface and sub-surface soils (Saha *et al* 2011). Soil organic carbon among different land uses followed the order grassland > forest > cultivated land > eroded land in surface soil whereas the trend was forest > eroded land > cultivated land > grass land in sub-surface soil. Similarly, another study reported decrease in SOC with increasing soil depth under diverse land-use systems and the decrease was significantly different across vertical soil profile (Wang *et al* 2010). Variation in inorganic C in soil did not follow a similar trend to SOC (Reeder *et al* 2004). In northern Belgium, vertical SOC distribution pattern under different land use systems with different soil texture and soil drainage conditions was reported based on a quantitative model. Increase in soil depth resulted in significant decrease in SOC content near the surface of dry silty loamy cultivated soil but under dry to moderately grassland soil, a small increase in SOC status was observed (Meersmans *et al* 2009). Increase in inorganic C with increasing soil depth was also reported by Wissing *et al* (2010) and Mi *et al* (2008). Increase in soil inorganic C with depth in different land uses viz. cropland, shrub land, meadow and forest was because of leaching and SOC accumulation.

CHAPTER III

MATERIALS AND METHODS

The present investigation entitled "Cropping system and antecedent carbon level effects on soil organic matter and nitrogen dynamics'' comprised field and laboratory studies. In the field, the effect of maize-wheat, soybean-wheat and continuous fallow on carbon (C) and nitrogen (N) dynamics was studied in four soils of different antecedent organic carbon level. Kinetics of nitrogen mineralization and nitrifying potential of soils drawn from field plots were studied in laboratory incubation experiments under controlled conditions.

3.1 Description of field experiment

Field experiments involving maize-wheat, soybean-wheat and continuous fallow have been in progress since kharif, 2015 on four soils of different fertility at research farm of Department of Soil Science, Punjab Agricultural University, Ludhiana (30°56 N, 75°52 E and 247 m above mean sea level). In the semi-arid sub-tropical monsoonal climate, annual rainfall in the experimental site ranges between 296 and 593 mm of which greater than 70% occurs during the monsoon months (July to September). Mean monthly maximum and minimum temperature during the experimental years ranged from 17.2 to 39.8 and 7.1 to 28.6 °C, respectively (Fig 3.1). The experimental soils were sandy loam (60% sand and 17% clay) in texture and classified as Typic Ustorthents (USDA 1999).

The experimental soils varied in fertility, primarily in soil organic C which was created as a consequence of a long-term experiment on rice-wheat system conducted at the site during 1999 to 2015. The previous experiment included four main treatments viz. i) incorporation of rice straw in wheat, ii) application of farmyard manure (FYM) in rice along with incorporation of rice straw in wheat, iii) FYM application in wheat, and iv) application of inorganic fertilizers only without any organic amendments. Sixteen years continuous application of organic amendments resulted in creation of four levels of SOC. These soils are hence after referred to as Soil 1, Soil 2, Soil 3 and Soil 4, respectively (Table 3.1). Soil 1 had low antecedent C, Soil 2 and Soil 3 were medium or intermediate in antecedent C level and Soil 4 had high antecedent C. The present experiment was initiated in May 2015 after discontinuing all the previous treatments. On each soil three land-uses viz. maize-wheat and soybean-wheat cropping systems and continuous fallow were laid out in a split plot design. The four soils of different fertility were treated as main plots and three land-uses (maize-wheat, soybean-wheat and continuous fallow) as sub-plots of size 99 m^2 (30 m x 3.3 m).

Each year before sowing maize and soybean the field was tilled 4 times with disc harrow and planked twice. Maize was sown during the last week of May to first week of June each year at a seed rate of 18 kg ha^{-1} maintaining a row-row and plant to plant spacing of 60 and 20 cm, respectively. A total of 4 to 6 irrigations, with canal or groundwater, were applied over entire crop growth period based on the visual inspection of the field. Round-up, Atrataf and Landis were used for weed control and Decis for controlling shoot borer. Maize was harvested manually in the first or second week of October. Soybean was seeded in the first fortnight of June at 60-70 kg ha^{-1} with row to row spacing of 45 cm. Prior to seeding soybean seeds were treated with Bradyrhizobium at the rate of 200g per 30 kg seeds. A total of 3 to 4 irrigations were applied over the full crop growth season. Weeds were controlled using Steak, Rogor etc. and Ekalux was used for controlling hairy catterpiller. Soybean was harvested manually during last week of October to first week of November. Land preparation for wheat after maize or soybean was similar to that followed in maize. Wheat was sown around 15th November at 100 kg ha^{-1} in rows 20 cm apart. A total of 3 to 4 irrigations, with canal or groundwater, were applied over the entire crop growth season. For control of weeds the field was sprayed with Topik and Algrin; yellow rust was controlled by spraying Tilt. Wheat was harvested manually in last week of April. Each crop was fertilized at university recommended rates of fertilizer N, P and K (Table 3.2). In continuous fallow plots, shredder was used to control weeds and irrigation was frequently applied to maintain soil moisture conditions similar to that in the cropped plots.

Table 3.1 Details of organic and inorganic fertilizers applied to four soils during 1999-2015 to rice-wheat and 2015-18 to maize-wheat and soybean-wheat

Soil	Kharif 1999 to Rabi 2014-15 Organic amendments#	Kharif 2015 to rabi 2017-18
Soil 1	No organic amendment	Recommended rates of fertilizer NPK to each crop in maize-wheat and soybean-wheat rotation
Soil 2	FYM to rice	
Soil 3	Rice straw incorporation in wheat	
Soil 4	Rice straw incorporation in wheat + FYM to rice	

Along with organic amendments recommended doses of N, P and K fertilizers were applied to each crop in rice-wheat rotation

Table 3.2 Varieties and rates of fertilizers applied to different crops

Crop	Variety	Fertilizer application (kg ha^{-1})		
		N	P_2O_5	K_2O
Maize	P 3401	120	60	30
Soybean	SL 958	30	60	0
Wheat	HD 2967	120	60	0

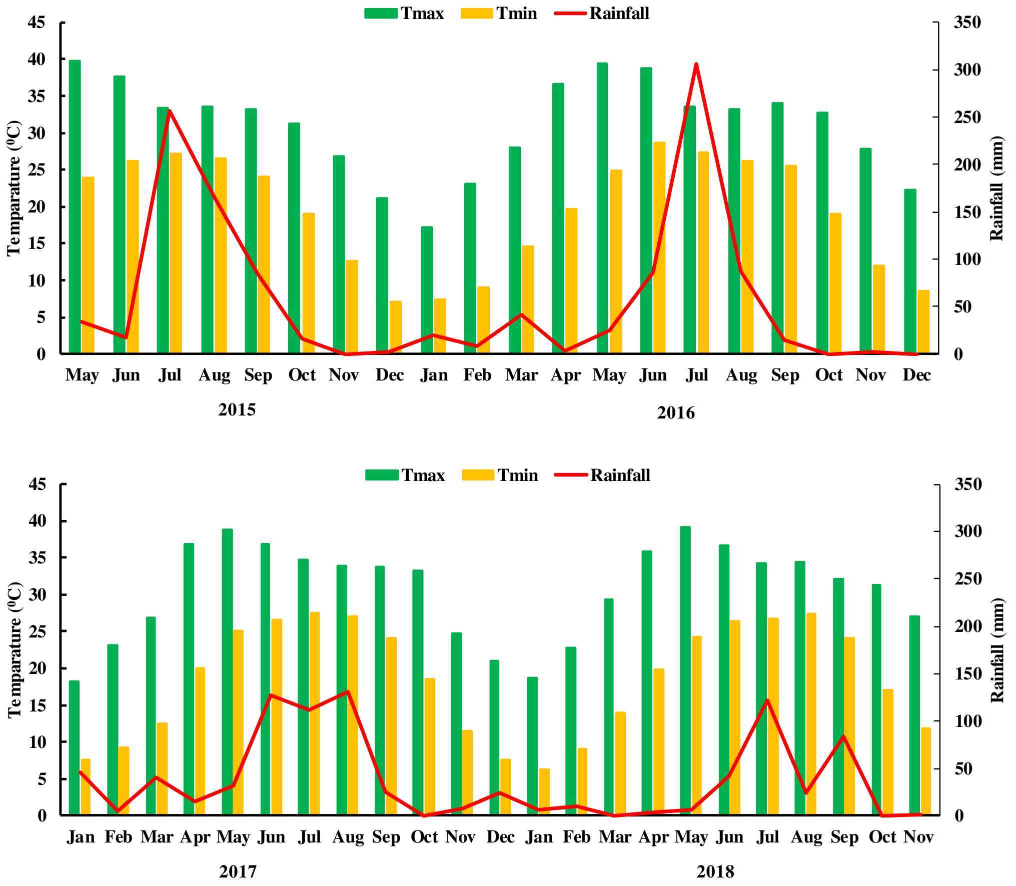


Fig 3.1 Mean monthly maximum and minimum temperature and rainfall during the experimental period (May, 2015 to Nov, 2018)

3.2 Soil sample collection and preparation

Collection of soil samples was done from three replicates of each treatment (cropped and fallow) in May, 2018 when the harvesting of wheat was over. The samples were collected with a metal tube (6 cm diameter) at 0-7.5, 7.5-15, 15-30, 30-45 and 45-60 cm depths. Each sample of soil was made by compositing soils collected from ten spots within a plot. The soil samples were kept open at room temperature for air drying and all visible roots and organic debris were removed. The samples were ground with the help of wooden pestle and mortar and sieved through 2-mm sieve and sieved samples were stored in plastic containers prior to analysis. The soil samples were analysed for pH, electrical conductivity (EC), mineral N, available P, available K, and soil texture as per the standard methods (Table 3.3). Methods for determination of soil physical properties (bulk density and water stable aggregates) and different pools of soil organic C and N are detailed in the following section. For estimating land-use effect on C sequestration in soil, archived soil samples collected in May, 2015 were processed and analysed for total organic carbon (TOC).

Table 3.3 Details of methods used for determination of general soil properties

Soil properties	**Method**
pH	1:2 soil:water suspension using a glass electrode pH meter (Elico, model LI 120) (Jackson 1967)
Electrical conductivity (EC)	supernatant of 1:2 soil:water solution using an electrical conductivity meter (Elico, model CM180)
Mineral N	Extracting with 2N KCl (1:2 soil:extractant) followed by steam distillation of the filtered extract using MgO powder for NH_4^+-N and then Devarda's alloy for NO_3^--N (Page *et al* 1982).
Available P	Extracting with 0.5M $NaHCO_3$ (pH 8.5) (1:20 soil:extractant) by shaking for half an hour (Olsen *et al* 1954) followed by colorimetric determination of P concentration at 760 nm wavelength with a spectrophotometer (Thermoscienticfic, model spectronic 20D+) using ascorbic acid method (Murphy and Riley 1962).
Available K	Extracting with neutral normal Ammonium acetate (1:5 soil:extractant) by shaking for five minutes followed by concentration determination using flame photometer (Elico, model CL 361) (Merwin and Peech 1951).
Soil texture	International pipette method (Gee and Bauder 1986)

3.3 Soil analysis

3.3.1 Soil physical properties

3.3.1.1 Bulk density: Bulk density (D_b) was measured at all the five soil depths with metallic cores having 8 cm inner diameter and 7.5 cm height. Within a plot, samples were taken in duplicates for each of the first two depths (viz. 0-7.5 and 7.5-15 cm). As the core was 7.5 cm in height, core sample at 15-30 cm was taken twice, once at first half of the depth (for 15-22.5 cm) and next at remaining half of the depth (for 22.5-30 cm). The samples were taken in duplicate and thus, a total of four samples were collected at 15-30 cm depth. Likewise, core samples were also taken at 30-45 and 45-60 cm depths. The collected soil samples were oven-dried at 105 °C for 24 hours and D_b ($Mg\ m^{-3}$) was calculated as:

$$D_b = \frac{W_s}{V_t}$$

Where, W_s is soil weight (Mg) and V_t is the core volume (m^3)

3.3.1.2 Water stable aggregates: Wet sieving technique given by Yoder (1936) was used for aggregate size distribution. Air-dried soil clods of 4-8 mm size were spread uniformly on the topmost sieve of a nest of sieves having pore diameters 2.0, 1.0, 0.5, 0.25, 0.106 and 0.053 mm. The height of water in the tank was raised so that it just touches the uppermost sieve of the nest and slaking of soil samples in the sieves was done for 30 min. The nest of sieves was moved up and down for 30 minutes with the help of a pulley arrangement at 30 cycles per minute. Water stable aggregates held on each sieve were collected separately and oven-dried at 60 °C. The water stable aggregates of each size were weighed and expressed as percentage of the total soil weight taken for analysis. Aggregates of different sizes were grouped into two main classes viz. macro-aggregates (MacA, >2.0-0.25 mm) and micro-aggregates (MicA, 0.25-0.053 mm). Macro-aggregates further had two classes viz. coarse macro-aggregates (CMacA, >2.0 mm) and meso-aggregates (MesoA, 2.0-0.25 mm). Micro-aggregates also had two classes viz coarse micro-aggregates (CMicA, 0.25-0.106 mm) and fine micro-aggregates (FMic, 0.106-0.053 mm) (Benbi *et al* 2016). Total water stable aggregates (WSA) were estimated by summing up all the aggregate size classes. Mean weight diameter (MWD) of aggregates was computed as:

$$\text{MWD (mm)} = \frac{\sum_{i=1}^{n} X_i W_i}{\sum_{i=1}^{n} W_i}$$

Where, n indicates the number of size fractions, X_i and W_i represent the mean diameter of the ith sieve and the weight of aggregates (g) retained on that sieve, respectively (Van Bavel 1950).

Calculation of aggregate ratio was done as:

$$\text{Aggregate ratio} = \frac{[\%\ macro\ aggregates > 0.25\ mm]}{[\%\ micro\ aggregates < 0.25\ mm]}$$

3.3.2 Chemical pools of soil organic carbon and nitrogen

3.3.2.1 Total organic carbon: For determination of total organic C (TOC), soil samples were ground with the help of a pestle and mortar and then passed through 0.25 mm sieve. Dry combustion method with CHN Elemental analyzer (Elementar, model Vario EL III Cube) was followed to determine total C (TC) in the samples. Inorganic C was determined by Puri's method (Puri 1949). Inorganic C (IC) was generally absent except in a few samples where it was present upto 0.07%. Then, total organic carbon (TOC) was obtained by subtracting the inorganic carbon (IC) from total carbon estimated by CHN analyser (TC-IC).

3.3.2.2 Water soluble carbon: Method described by Benbi *et al* (2015) was used for determination of water soluble carbon (WSC). In a 50 ml centrifuge tube, 10 g soil sample was weighed and 20 ml of double distilled water was put in it. The soil-water mixture was shaken for 5 minutes and centrifuged at 5000 rpm for 10 minutes. The solution was filtered through Whatman no.1 filter paper and 5 ml of aliquot was taken in a 250 ml Erlenmeyer flask. Then, 5 ml of 0.07 N potassium dichromate, 10 ml concentrated sulfuric acid and 5 ml phosphoric acid were added to it. The solution was kept in an oven at 150 °C for half an hour and after cooling, 20 ml double distilled water was added to it. Then, it was titrated against 0.01 N ammonium iron (II) sulfate hexahydrate (FAS) standard solution using 5 to 6 drops of diphenylamine indicator. FAS consumed was recorded and WSC was calculated as:

$$\text{WSC (mg kg}^{-1}) = \text{vol. of } K_2Cr_2O_7 \text{ consumed x CF x } \frac{20}{Vol.\ aliquot} \text{ x } \frac{1000}{wt.\ of\ soil}$$

$$= \frac{(V_b - V_s) \times 0.01}{0.07} \times (3 \times 0.07) \times \frac{20}{Vol.\ of\ aliquot} \times \frac{1000}{wt.\ of\ soil}$$

Where, V_b and V_s represent the volume of FAS consumed for titration of blank and samples, respectively and CF represents conversion factor to C.

3.3.2.3 Hot water soluble carbon: Method proposed by Schulz *et al* (2003) was used for determination of hot water soluble C (HWSC). Twenty g soil sample was weighed in 250 ml conical flask and 100 ml distilled water was added. The solution was subjected to mild boiling on reflux condenser for one hour; cooled to normal room temperature immediately using a water bath and 5-6 drops of 49% magnesium sulphate were added for quick sedimentation. The supernatant solution was collected carefully in a centrifuge tube and centrifuged at 3000 rpm for 10 minutes. Ten ml of aliquot was taken in a 250 ml Erlenmeyer flask. Then, 10 ml of 0.2 N chromosulfuric acid was added and the mixture was kept at 125° C for 20 minutes in an oven. The mixtures were cooled and titrated against 0.2 M ferrous ammonium sulphate (FAS) using 5 drops of indicator (0.2 g N-phenylicanthranilic acid + 0.2 g sodium carbonate) solution. It follows the reaction:

$$K_2Cr_2O_7 + 4H_2SO_4 + C = Cr_2(SO_4)_3 + K_2SO_4 + CO_2 + 4H_2O + O_2$$

Amount of HWSC was calculated as:

$$\text{HWSC (mg kg}^{-1}\text{)} = \text{vol. of } K_2Cr_2O_7 \text{ consumed} \times \text{CF} \times \frac{100}{Vol.\ of\ aliquot} \times \frac{1000}{wt.\ of\ soil}$$

$$= \frac{(V_b - V_s) \times 0.2}{0.2} \times (3 \times 0.2) \times \frac{100}{Vol.\ of\ aliquot} \times \frac{1000}{wt.\ of\ soil}$$

$$= (V_b - V_s) \times 300$$

Where, V_b and V_s represent the volume of FAS used for titrating blank and soil samples, respectively and CF represents conversion factor to C.

3.3.2.4 Potassium permanganate-oxidizable carbon ($KMnO_4$-C): Method proposed by Blair *et al* (1995) was used for determination of potassium permanganate-oxidizable C. In a 50 ml centrifuge tube, 3 g soil sample was taken; 25 ml of 33 mM $KMnO_4$ was added to it and was shaken on a reciprocal shaker for 6 hours. After shaking, centrifugation was done at 2000 rpm for 5 minutes. 2 ml aliquot was pipetted into 50 ml volumetric flasks and diluted to the full volume up to mark. A blank was prepared in a similar manner. Then, the absorbance of prepared samples and blank were measured on a double-beam spectrophotometer at 565 nm. $KMnO_4$ concentration was estimated from a standard calibration curve. The overall reaction is:

$$4Mn^{+7} \longrightarrow 4Mn^{+4} \quad \text{(reduction)}$$

$$3C^{0} \longrightarrow 3C^{+4} \quad \text{(oxidation)}$$

$$\text{The amount of } KMnO_4\text{-C (mg kg}^{-1}\text{)} = \frac{(\text{mM}_{\text{blank}} - \text{mM}_{\text{sample}}) \times (\text{dilution factor}) \times V \times 9}{1000 \times \text{wt of soil (g)}} \times 10^3$$

where, the dilution factor is 50/2, V is volume of standardized $KMnO_4$ added to soil samples and 9 is conversion factor for calculating mg C from mM $KMnO_4$ consumed.

From the concentration of $KMnO_4$ oxidizable C, carbon management index (CMI) was calculated by the procedure outlined by Blair *et al* (1995). Total organic C in fallow plots of Soil 4 was taken as reference -

$$\text{Carbon management index (CMI)} = \text{CPI x LI x 100}$$

Where, CPI represents Carbon pool index and LI indicates the Lability index. Calculation of CPI and LI was done as:

$$\text{CPI}= \frac{TOC_{treated}}{TOC_{reference}}$$

$$\text{LI}= \frac{L_{treated}}{L_{reference}}$$

Where, L is lability of carbon that is:

$$L = \frac{Content\ of\ Labile\ C\ (KMnO_4\ oxidizable\ C)}{Content\ of\ non\ Labile\ C\ (TOC - KMnO_4\ oxidizable\ C)}$$

Where, TOC and labile C are expressed in g kg^{-1}

3.3.2.5 Organic C fractions of different oxidizability: Walkley and Black's (1934) method modified by Chan *et al* (2001) was used to determine TOC-fractions of different oxidizability. Four fractions of decreasing oxidizability/ lability were separated adding 5, 10 and 20 ml of concentrated sulphuric acid (H_2SO_4) separately to three flasks containing 2 g soil and 10 ml of 1 N $K_2Cr_2O_7$ in each. The three different solutions having $K_2Cr_2O_7$ to H_2SO_4 ratio 1:0.5, 1:1 and 1:2 corresponded to 12 N, 18 N and 24 N H_2SO_4, respectively. These fractions oxidized were categorized as very labile, labile, less labile and recalcitrant.

Very labile C (C_{VL}) = organic carbon (OC) oxidizable under 12 N H_2SO_4
Labile C (C_L) = OC oxidizable under 18 N H_2SO_4 - OC oxidizable under 12 N H_2SO_4
Less labile C (C_{LL}) = OC oxidizable under 24 N H_2SO_4 - OC oxidizable under 18 N H_2SO_4
Recalcitrant C (C_R) = TOC - OC oxidizable under 24 N H_2SO_4

For calculation of lability Index (LI), three labile fractions viz. C_{VL}, C_L and C_{LL} were expressed as proportion to TOC; multiplied by weightages of 3, 2 and 1, respectively, (given empirically on the basis of their ease of oxidation) and added (Datta *et al* 2015).

$$\text{Lability Index} = \frac{C_{VL}}{C_{total}}\ x\ 3 + \frac{C_L}{C_{total}}\ x\ 2 + \frac{C_{LL}}{C_{total}}\ x\ 1$$

3.3.2.6 Aggregate associated carbon (AAC): Different sized soil aggregates were oven dried at 60 °C and were ground to < 0.25 mm. Dry combustion method with CHN analyser (Elementar, model Vario EL III Cube) was used to determine C concentration in aggregates (g kg^{-1} aggregate). Carbon preservation capacity (CPC) of aggregates was calculated as:

$$\text{CPC (g kg}^{-1}\text{ soil)} = \frac{(\text{Aggregate associated C in g kg}^{-1})_i \text{ x (\% of Water stable aggregate)}_i}{100}$$

Where, ‘i’ denotes the size of sieve.

3.3.2.7 Total N: Soil samples for determination of total N were ground with the help of a pestle and mortar and passed through 0.25 mm sieve. Total N in the samples was determined by dry combustion method using CHN Elemental analyzer (Elementar, model Vario EL III Cube).

3.4 Laboratory experiments

Laboratory incubation experiments were conducted to study C and N mineralization kinetics and nitrification potential of soils drawn from maize-wheat, soybean-wheat systems and continuous fallow plots. Collection of soil samples was done at 0-7.5 and 7.5-15 cm depths in each plot (cropped and fallow) after the harvest of wheat in May, 2018. Each sample of soil was made by compositing soils collected from five spots within a plot. Soil samples were immediately rushed to the laboratory, passed through 2 mm sieve and kept at temperature below 4 °C until the initiation of laboratory experiments.

3.4.1 Mineralizable Carbon

Determination of mineralizable C was done following aerobic incubation at 25 °C temperature and field capacity moisture (Hopkins 2007). Fifty g fresh soil sample was weighed in a 250 ml conical flask and water was added to bring the soil to field capacity moisture which was maintained for the entire incubation period. During the incubation period, the CO_2 evolved was absorbed in 0.1 N NaOH solution kept in a vial hung inside the flask with a thread. The flask was sealed entirely with silicon corks to prevent any loss of evolved CO_2. Samples were kept in incubation for 64 days at 25±1 °C. Frequent change of alkali (inside the flasks) by fresh one was needed. It was changed every day, at one day interval, at two days interval and at three days interval during 1st, 2nd, 3rd and thereafter, upto 64 days of incubation, respectively. The CO_2 trapped in NaOH was precipitated using $BaCl_2$ and the excess NaOH was titrated against 0.1 N HCl in presence of phenolphthalein indicator. The reactions involved are:

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

$$NaOH + HCl \rightarrow NaCl + H_2O$$

The amount of CO_2 evolved was calculated as:

$$\text{C Mineralization (mg CO}_2\text{ kg}^{-1}) = 0.5 \text{ x } [(\frac{V_{NaOH} \text{ x } N_{NaOH}}{1000}) - (\frac{V_{HCl} \text{ x } N_{HCl}}{1000})] \text{ x } \frac{44000 \text{ x } 1000}{wt.\ of\ soil}$$

$$\text{C mineralization rate (mg CO}_2\text{ kg}^{-1}\text{ day}^{-1}) = \frac{\text{C Mineralization (mg CO}_2\text{ kg}^{-1})}{\text{incubation time (day)}}$$

Where, V_{NaOH} and V_{HCl} is volume of NaOH and HCl, respectively and N_{NaOH} and N_{HCl} is the normality of NaOH and HCl, respectively.

Basal soil respiration (BSR) was computed by averaging the C mineralization rate of the last two days of the incubation period because soils then reached to their stable values of

CO_2 evolution.

3.4.2 Mineralizable nitrogen

Potentially mineralizable N in soil was determined by conducting long-term aerobic incubation at 25 °C temperature and field capacity moisture. Thirty g fresh soil sample was weighed in a plastic bottle. Required amount of moisture to bring to field capacity was added to the sample and maintained throughout the incubation period. Incubations were done for 7, 14, 28, 42 and 56 days. The soil samples were shaken with 2M KCl solution (in 1:10 soil:extractant ratio) for 1 hr and filtered using a filter paper (Whatman no. 1). Steam distillation method (Page *et al* 1982) was used to determine the mineral N concentration (NH_4^++ NO_3^-) in the filtrates. Total amount of N mineralized (NH_4^++ NO_3^-) at different times was determined by subtracting initial mineral N concentration (at zero day) from the concentration after incubation.

3.4.3 Nitrification potential

Nitrification potential of soils was determined by short-term incubation method following static analysis approach (Schmidt and Belser 1982). Fifty g fresh soil samples were taken in plastic bottles in two sets. To one set, called amended soil, 1 ml ammonium sulphate solution (25 mg ml^{-1}) was added and the soil was wetted to field capacity. Other set of bottles was also wetted to field capacity but ammonium sulphate solution was not added. The soils were incubated at 25 °C for 14 and 28 days separately. The soil moisture was maintained at field capacity by frequently weighing the bottles and replenishing the water lost. At the end of an incubation period, both amended and control soils were analysed for NO_3-N content by extracting them with 2 N KCL followed by steam distillation of the filtrate using MgO powder and Devarda's alloy (Page *et al* 1982). Soils amended with $(NH_4)_2SO_4$ provided nitrification potential.

3.5 Collection of shoot and root samples

At the maximum vegetative growth stages of each crop viz. maize, soybean and wheat, shoot samples representative of all the plants within a given plot were taken from each plot and was put in paper bags. After air drying for about 1.5-2 hours, fresh weights were taken. Then these samples were kept in an oven at 60 °C for further drying and dry weights were recorded.

Root sampling was done at the maximum growth stages of each crop. For wheat crop, a metallic tube of 6 cm diameter and for soybean and maize crops, that of 8 cm diameter were used. Root samples for all the crops were taken at 0-15, 15-30 and 30-60 cm depths. At a particular depth in wheat, one sample exactly beneath the plant and two samples ($core_1$) each of which taken at either side of the plant (first sample) in a direction perpendicular to other rows were taken. The two samples taken beside the plants were mixed for every respective depth. At each depth in maize and soybean fields, two more samples ($core_2$) were taken at the outward sides of core$_1$ samples in a similar manner and mixed similarly. From all samples soil was removed with continuous flow of water and the roots were washed properly. After taking the fresh weights, these were kept in an oven at 60 °C for drying and dry weights were taken. Total root biomass at a given depth was calculated as:

Root biomass (t ha^{-1}) = $A \times 10^{-6} \times 10^{4} \times$ depth (m)

Where, $A = \frac{\text{Sum of dry root wt. in samples taken beneath and beside a plant } (g)}{\text{Total vol. of the soil samples taken for root sampling } (m^3)}$

At maturity, straw and grain yield data per m^2 area were recorded and calculated on per ha basis.

3.5.1 Root and shoot C partitioning: Well dried clean samples of root, straw and grain were ground with a grinder and total organic C concentrations were determined using CHN analyser (Elementar, model Vario EL III Cube). The ratio of total C (Mg ha^{-1}) in shoot (straw+grain) and root (0-60 cm depth) was calculated.

3.6 Statistical analysis

Statistical analysis of data was done using analysis of variance technique (ANOVA) following split-plot design. The significance of differences of treatment means and their interactions was tested at 5% ($P \leq 0.05$) level of probability using OPSTAT (http://14.139.232.166/opstat/) (Sheoran *et al* 1998). Data regarding root to shoot biomass and C partitioning for each crop were analyzed using one-way analysis of variance (ANOVA) applied to individual crop. For testing the significance of means of carbon management index (CMI) between land-uses, data were analysed using one-way ANOVA applied at individual soil.

CHAPTER IV

RESULTS AND DISCUSSION

The results of the study entitled "Cropping system and antecedent carbon level effects on soil organic matter and nitrogen dynamics'' have been reported and discussed under the following headings and sub-heads:

4.1 Effect of antecedent soil organic C level on shoot and root biomass of crops
4.2 Effect of maize-wheat, soybean-wheat and fallow on soil chemical properties
4.3 Effect of maize-wheat, soybean-wheat and fallow on soil physical properties
4.4 Effect of maize-wheat, soybean-wheat and fallow on chemical pools of C and N
4.5 Effect of maize-wheat, soybean-wheat and fallow on biological pools of C and N

4.1 Effect of antecedent soil organic C level on shoot and root biomass of crops

Antecedent C level had significant effect on shoot and root biomass and root to shoot ratio of maize, soybean and wheat. Shoot biomass of all the three crops was highest in Soil 4 and lowest in Soil 3 except for wheat following soybean. Shoot biomass of wheat following soybean was lowest in Soil 1 (Table 4.1). Root biomass of wheat (in both the crop rotations) was not significantly influenced by antecedent C level. However, root biomass of maize and soybean was higher in soil with lowest C level (Soil 1) compared to other soils. Root to shoot biomass ratio of maize, soybean and wheat ranged from 0.16 to 0.43, 0.18 to 0.27 and 0.09 to 0.13, respectively (Table 4.1). The root to shoot ratio recorded in the present study are consistent with published results. In Soil 1, maize and soybean crops had the highest root to shoot ratios (0.43 and 0.27, respectively). Several studies have reported that root to shoot ratios of crops under different climatic and soil conditions ranged from 0.09 to 0.22 for wheat (Izaurralde *et al* 1992, Campbell and de Jong 2001), 0.12 to 0.35 for maize (Zan *et al* 2001, Kisselle *et al* 2001) and 0.10 to 0.12 for soybean (House *et al* 1984, Marvel *et al* 1992). In soil with lowest antecedent C level, relatively higher root to shoot ratio of maize and soybean was because of higher root biomass in this soil compared to other soils. This suggests that because of low soil fertility, there was greater root proliferation to meet nutrient requirement of the crop.

Carbon content of grain, straw and root of different crops are presented in table 4.2. Carbon contents of grain, straw and root of individual crops did not vary with soil fertility and ranged from 40.6 to 48.5% for grain, 41.7 to 44.0% for straw and 37.7 to 39.1% for roots. Aboveground plant-C stocks (t ha^{-1}) in maize and wheat were significantly higher (by 52.6 and 19.0 to 26.6%, respectively) in soil with high antecedent C (Soil 4) compared to the soil with low antecedent C (Soil 1). However, aboveground-C in soybean was almost similar in all the soils (Table 4.3). In maize and soybean crops, significantly higher (86 to 116% and 22 to 61%, respectively) amount of C was stored in belowground root biomass in Soil 1 compared to other soils. Wheat root-C did not differ significantly with soil fertility. The root to shoot-C ratio in wheat did not vary significantly with soil fertility. However, root to shoot ratio of maize was 90 to 171% higher and that of soybean was 43% higher in soil with lowest fertility (Soil 1) compared to other soils (Table 4.3).

Table 4.1 Aboveground and below ground plant biomass (t ha^{-1}) of maize, soybean and wheat in four soils

	Maize-wheat		Soybean-wheat		
Soil	Maize	Wheat	Soybean	Wheat	Mean
			Shoot biomass		
S 1	8.38^{bc}	10.03^{bc}	5.12^{ab}	9.37^{b}	8.08
S 2	10.30^{ab}	11.23^{ab}	5.90^{ab}	11.50^{ab}	9.74
S 3	7.64^{c}	9.40^{c}	4.85^{b}	10.63^{ab}	8.13
S 4	11.94^{a}	11.92^{a}	6.15^{a}	11.85^{a}	10.47
Mean	9.43	10.65	5.51	10.84	
LSD$_{Soil}$ (0.05)	2.63	1.81	1.09	2.37	
			Root biomass		
S 1	3.57^{a}	1.35^{a}	1.37^{a}	1.21^{a}	1.87
S 2	1.91^{b}	1.12^{a}	1.05^{ab}	1.16^{a}	1.31
S 3	1.65^{b}	1.23^{a}	0.85^{b}	1.09^{a}	1.20
S 4	1.91^{b}	1.03^{a}	1.12^{ab}	1.15^{a}	1.30
Mean	2.26	1.18	1.10	1.15	
LSD$_{Soil}$ (0.05)	S:0.63	C: NS	0.429	NS	
			Root : shoot		
S 1	0.43^{a}	0.13^{a}	0.27^{a}	0.13^{a}	0.24
S 2	0.19^{b}	0.10^{ab}	0.18^{a}	0.10^{b}	0.14
S 3	0.22^{b}	0.13^{a}	0.18^{a}	0.10^{b}	0.16
S 4	0.16^{b}	0.09^{b}	0.18^{a}	0.10^{b}	0.13
Mean	0.25	0.11	0.20	0.11	
LSD$_{Soil}$ (0.05)	S:0.06	C:0.04	NS	0.02	

NS=Not Significant

Table 4.2 Carbon content (%) in different plant parts of maize, soybean and wheat crops

Crop	Grain	Straw	Root
Maize	42.2	42.9	37.8
Soybean	48.5	44.0	39.1
Wheat	40.6	41.7	37.7

Table 4.3 Carbon stored (t ha^{-1}) in above ground and below ground plant biomass of maize, soybean and wheat in four soils

Cropping system	Maize-wheat		Soybean-wheat		
Soil	Maize	Wheat	Soybean	Wheat	Mean
			Shoot C		
S 1	3.34^{bc}	4.14^{bc}	2.31^{ab}	3.87^{b}	3.42
S 2	4.40^{ab}	4.65^{a}	2.67^{ab}	4.76^{ab}	4.12
S 3	3.26^{c}	3.88^{c}	2.20^{b}	4.39^{ab}	3.44
S 4	5.10^{a}	4.93^{ab}	2.78^{a}	4.90^{a}	4.43
Mean	4.03	4.40	2.49	4.48	
LSD$_{Soil}$ (0.05)	1.12	0.74	0.49	0.97	
			Root C		
S 1	1.35^{a}	0.51^{a}	0.54^{a}	0.46^{a}	0.71
S 2	0.72^{b}	0.42^{a}	0.41^{ab}	0.44^{a}	0.50
S 3	0.62^{b}	0.46^{a}	0.33^{b}	0.41^{a}	0.46
S 4	0.72^{b}	0.39^{a}	0.44^{ab}	0.43^{a}	0.50
Mean	0.85	0.45	0.43	0.43	
LSD$_{Soil}$ (0.05)	0.23	NS	0.16	NS	
			Root C: shoot C		
S 1	0.38^{a}	0.12^{a}	0.23^{a}	0.12^{a}	0.21
S 2	0.17^{b}	0.09^{ab}	0.16^{b}	0.09^{b}	0.13
S 3	0.20^{b}	0.12^{a}	0.16^{b}	0.09^{b}	0.14
S 4	0.14^{b}	0.08^{b}	0.16^{b}	0.09^{b}	0.12
Mean	0.22	0.10	0.18	0.10	
LSD$_{Soil}$ (0.05)	0.05	0.03	0.07	0.01	

NS=Not Significant

Proportion of total plant C stored in root and shoot depended on soil's antecedent fertility level. In maize, 73 to 88% of total plant C was stored in shoot and 12 to 27% in roots. Similarly, in soybean shoot and roots stored 81 to 87% and 13 to 19% of total plant C, respectively. In wheat, slightly higher proportion of total plant C was stored in shoot (89 to 93%) compared to other crops. Wheat roots stored 7 to 11% of total plant C. Proportion of total plant C stored in below ground biomass of all crops was relatively higher in soil with high fertility (Soil 4) compared to that in soils with low to intermediate fertility (Soil 1 to Soil 3). The variation in the root to shoot C storage ratio of crops grown in different soils may be attributed to differences in root to shoot biomass. In soil with high antecedent C level, the crop roots represented a higher proportion of total plant C storage compared to other soils. This suggests that, compared to low and intermediate fertility soils, high fertility of soil diverted greater proportion of fixed C towards roots. The differences in root C stocks in relation to crop and soil impacted C return to soil and thus, C sequestration is discussed in section 4.4.1.

4.2 Effect of maize-wheat, soybean-wheat and fallow on soil chemical properties

4.2.1 Soil pH

The soils were neutral to alkaline in reaction. In surface soil (0-7.5 cm), soil pH ranged between 7.01 to 7.91 (Table 4.4). Averaged across cropping systems, the soils differed significantly in pH. The order of pH in different soils was Soil 3 > Soil 1 > Soil 4 > Soil 2. Differences in pH of these soils could be ascribed to the effect of long-term management prior to the current experiment. Long-term application of FYM in Soil 2 resulted in lowest soil pH, which was maintained even after three years of cessation of organic fertilization. Kumar and Singh (2010) and Srikanth *et al* (2000) have also reported decrease in soil pH upon application of FYM for several years because of production of organic acids and release of CO_2 during organic matter decomposition resulting in decrease in soil pH.

Table 4.4 Depth distribution of pH in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF)

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	7.72^{b}	7.99^{b}	8.15^{b}	7.94^{b}	7.98^{a}
S2	7.01^{d}	7.24^{d}	7.76^{c}	7.71^{c}	7.70^{b}
S3	7.91^{a}	8.12^{a}	8.24^{a}	8.11^{a}	7.97^{a}
S4	7.37^{c}	7.57^{c}	8.10^{b}	7.95^{b}	7.90^{a}
Land use					
MW	7.49^{ab}	7.71^{a}	8.02^{b}	7.89^{b}	7.86^{b}
SW	7.48^{b}	7.73^{a}	8.11^{a}	7.91^{ab}	7.87^{ab}
CF	7.55^{a}	7.76^{a}	8.06^{ab}	7.99^{a}	7.93^{a}
LSD (0.05)					
S	0.11	0.11	0.12	0.17	NS
CS	NS	NS	0.06	NS	NS
S*CS (S same)	0.13	0.11	0.13	0.21	NS
S*CS (CS same)	0.15	0.14	0.15	0.24	NS

S=Soil CS=Cropping System NS=Not Significant

In Soil 1 and Soil 3, maize-wheat cropping resulted in significantly higher soil pH (by 2.9 and 2%, respectively) than continuous fallow (Fig 4.1). On the contrary, in Soil 2 and Soil 4, maize-wheat significantly lowered soil pH (by 4.5 and 3.7%, respectively) compared to continuous fallow. Except Soil 4, in the other three soils, soybean-wheat and continuous fallow were statistically at par in soil pH. In Soil 4, soybean-wheat system had significantly lower soil pH than continuous fallow. The use of ammonium forming fertilizers has been reported to acidify soils (Belay *et al* 2002, Silva *et al* 2009, Saha *et al* 2008) due to nitrification of ammonium (Watanabe *et al* 2015). Significantly lower soil pH under maize-wheat in Soil 2 and Soil 4 compared to continuous fallow was possibly due to N fertilizer application through urea. Makinde *et al* (2009) and Ayeni *et al* (2012) also reported significant decrease in soil pH in maize based and other cropping systems with high N fertilization. Since the fertilizer N use in soybean was small compared to maize-wheat it did not show change in pH. These results are in line with the findings of Monsefia *et al* (2014) who also reported no change in soil pH after two cycles of soybean-wheat cropping.

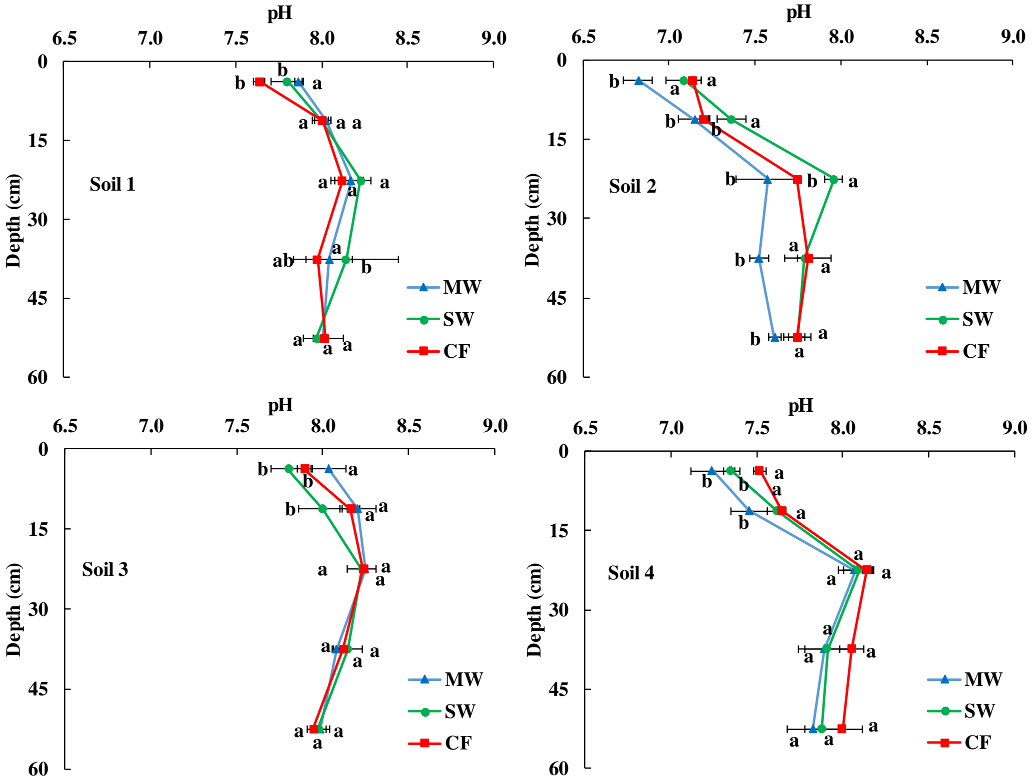


Fig 4.1 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of soil pH in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

Soil pH increased with depth upto 30 cm (Fig 4.1). Thereafter, soil pH decreased gradually and mean soil pH ranged between 7.7 and 7.98 at 45-60 cm depth. Cropping and continuous fallow did not influence soil pH significantly below 0-7.5 cm depth in all soils except Soil 2. Slight increase in soil pH below 7.5 cm was possibly because of leaching of bases and basic cations viz. Ca^{2+}, Mg^{2+} etc. from surface soil, to mainly 15-30 cm soil layer, and also due to decrease in organic C concentration (Sekhon *et al* 2009).

4.2.2 Electrical conductivity

Electrical conductivity (EC) in all the soils was within the permissible limit (< 0.80 dS m^{-1}) and ranged between 0.30 to 0.45 dS m^{-1} in the surface layer (Fig 4.2). Electrical conductivity did not change significantly between soils as well as cropping systems.

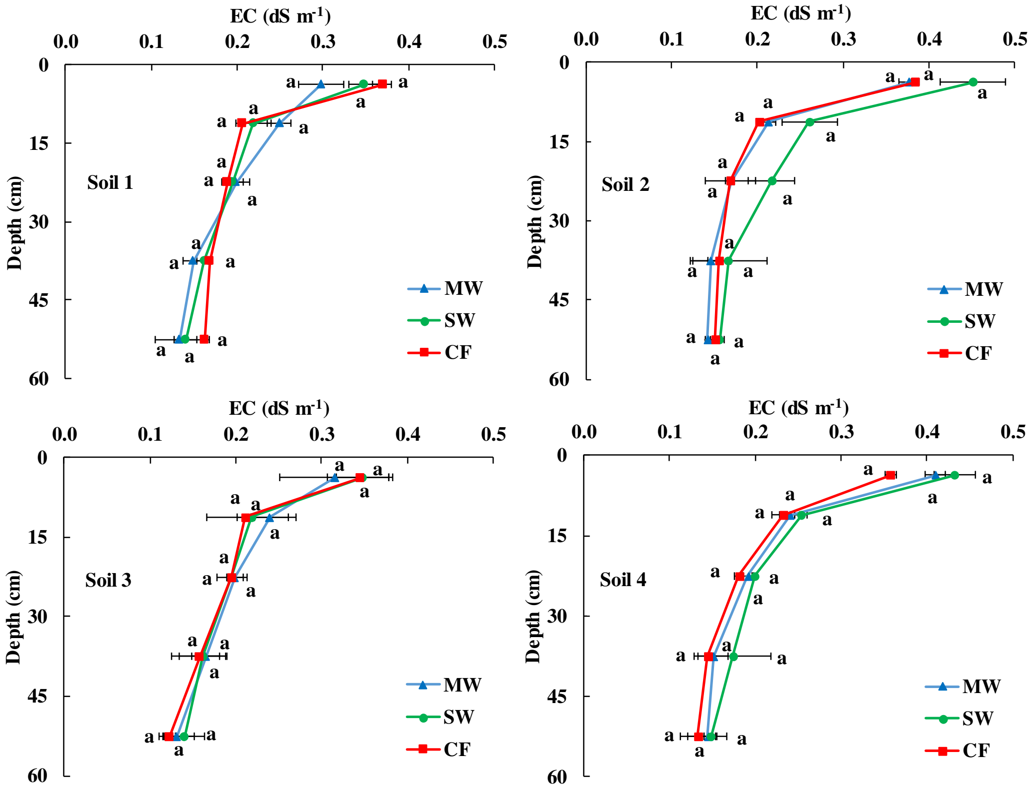


Fig 4.2 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of soil electrical conductivity in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

Electrical conductivity indirectly indicates the total concentration of soluble salts which is a direct measure of salinity. These results comply with Villamil and Nafziger (2015) who reported that application of organic amendments did not affect soil EC. With increase in soil depth, EC decreased gradually in all soils and a greater decrease was observed at 7.5-15 cm (Fig 4.2). Cropping and continuous fallow did not influence soil EC at lower depths.

4.2.3 Mineral N

Averaged across land-uses mineral N concentration (NH_4^++NO_3^-) in 0-7.5 cm surface soil ranged from 25.0 to 40.8 mg kg^{-1} (Table 4.5). Soil 2 had significantly higher mineral N (by 23%) than Soil 1. The other two soils viz. Soil 3 and Soil 4 were at par in mineral N and had 24 and 15% lower mineral N, respectively, compared to Soil 1. Cropping sequence and continuous fallow did not influence mineral N concentration in soils (Fig. 4.3). The highest concentration of mineral N in Soil 2 receiving historic application of FYM, is attributed to its

Table 4.5 Mineral N concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	32.9^{b}	40.2^{b}	30.1^{bc}	24.6^{b}	17.5^{c}
S2	40.8^{a}	45.7^{a}	28.8^{c}	23.7^{b}	22.2^{ab}
S3	25.0^{c}	32.8^{c}	34.9^{a}	28.0^{ab}	19.6^{bc}
S4	27.8^{c}	43.2^{ab}	32.8^{ab}	29.4^{a}	25.2^{a}
Land use					
MW	34.8^{a}	38.3^{b}	33.6^{a}	28.9^{a}	20.3^{a}
SW	35.4^{a}	43.6^{a}	31.3^{ab}	25.0^{b}	20.7^{a}
CF	24.6^{b}	39.4^{ab}	30.0^{b}	25.3^{ab}	22.4^{a}
LSD (0.05)					
S	3.8	NS	NS	NS	NS
CS	3.7	NS	NS	2.3	NS
S*CS (S same)	NS	NS	5.1	NS	8.4
S*CS (CS same)	NS	NS	5.9	NS	9.4

S=Soil CS=Cropping System NS=Not Significant

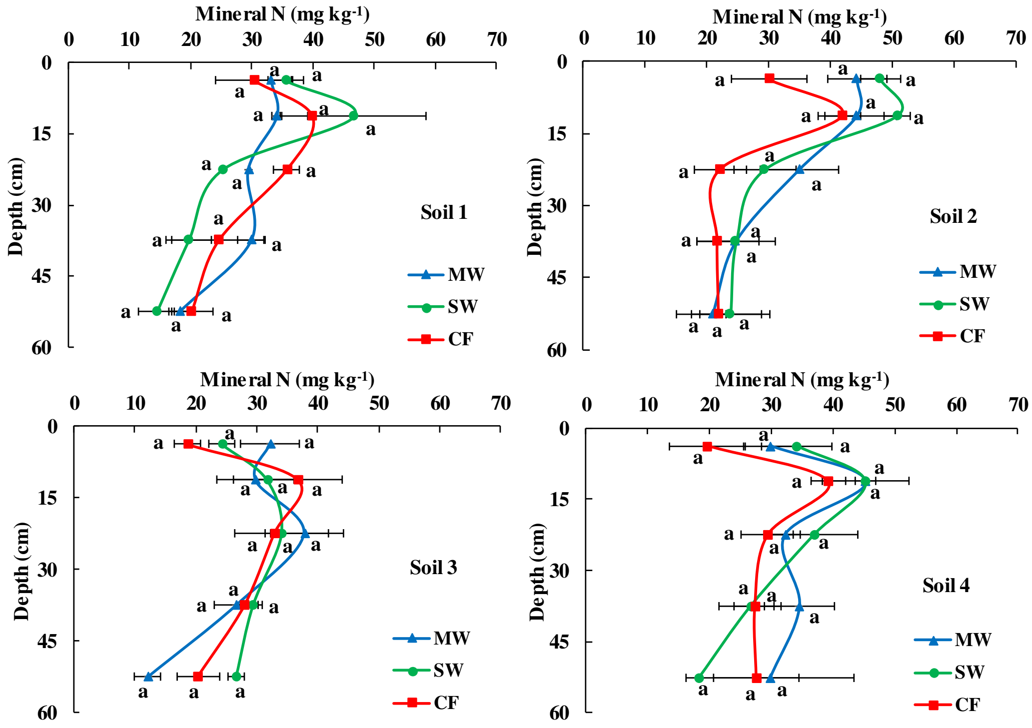


Fig 4.3 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth-distribution of mineral N in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

highest N mineralization potential (91.5 mg kg^{-1}) compared to other soils. Increased mineral N concentration because of greater mineralization of organic sources such as FYM has also been reported earlier (Sharma *et al* 2000, Tabassum *et al* 2010, Verma *et al* 2012). Highest mineral N concentration under soybean-wheat system in Soil 2 was attributed to the stimulation effect of FYM for higher biological N_2 fixation by soybean leading to increase in soil N (Moharana 2012) (Fig 4.3).

With increase in soil depth, mineral N increased at 7.5-15 cm depth. Below 7.5-15 cm depth, it decreased gradually and on an average ranged from 17.5 to 25.2 mg kg^{-1} at 45-60 cm depth (Fig 4.3). Cropping systems did not influence mineral N in sub-surface soil layers. The sub-surface soils had comparatively low mineral N than the surface layer, probably because of less accumulation of organic matter in this layer. The lower amount of mineral N in the sub-soil in the organic amended plots could also be due to its favorable effect on retardation of NO_3^--N movement to the lower layers (Biswas and Benbi 1997). The decrease in mineral N content with soil depth had also been reported by Sheeba and Chellamuthu (1999), Reddy *et al* (2003) and Tabassum *et al* (2010).

4.2.4 Available P

Available P concentration in surface soils (0-7.5 cm) ranged between 10.6 to 38.4 mg kg^{-1} (Table 4.6). Averaged across cropping sequences, available P concentration was highest in Soil 4 followed by Soil 2 and Soil 3 and least in Soil 1. The highest P concentration in Soil 4 may be attributed to the combined application of rice straw (6 t ha^{-1} yr^{-1}) and FYM

Table 4.6 Available P concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	10.6^d	6.5^d	5.5^b	5.7^c	4.5^c
S2	35.2^b	30.8^b	15.4^a	10.5^b	5.6^b
S3	12.2^c	8.7^c	4.1^c	3.3^d	1.8^d
S4	38.4^a	34.8^a	16.1^a	11.3^a	7.4^a
Land use					
MW	23.5^b	18.8^b	10.0^b	7.9^a	4.9^a
SW	24.3^a	20.9^a	10.7^a	7.5^a	4.7^a
CF	24.5^a	20.9^a	10.0^b	7.8^a	4.9^a
LSD (0.05)					
S	1.4	1.5	1.3	1.1	0.6
CS	1.4	1.6	1.2	1.0	0.5
S*CS (S same)	1.4	1.6	1.3	1.1	0.6
S*CS (CS same)	1.4	1.5	1.2	1.0	0.5

S=Soil CS=Cropping System NS=Not Significant

(10 t ha^{-1} yr^{-1}) for 16 years. The two organic sources viz. FYM and rice straw containing 0.22 and 0.1% P, respectively, supplied about 23 kg P ha^{-1} yr^{-1} which resulted in increased soil P status. Besides direct addition of P through organic amendments, these could have also resulted in solubilization of native P in soil through release of organic acids from organic matter decomposition (Tolanur and Bandanur 2003). Singh *et al* (2007) reported that addition of organic amendments maintained high level of available P in soils. Reddy *et al* (2000) also reported that combined use of manure and fertilizer proved better to raise available P concentration than their solitary application in a Vertisol. Because of application of fertilizer P during the last three years the differences in soil P status among different soils were maintained. Cropping systems in soil of intermediate fertility (Soil 2 and Soil 3) differed significantly from continuous fallow in available P concentration (Fig. 4.4). Available P concentration, in Soil 2 was significantly lower (by 6.4%) under maize-wheat and in soil 3 was significantly lower (by 20%) under both maize-wheat and soybean-wheat than fallow (Table 4.6). In the other three soils, cropped and fallow plots did not differ in available P concentration.

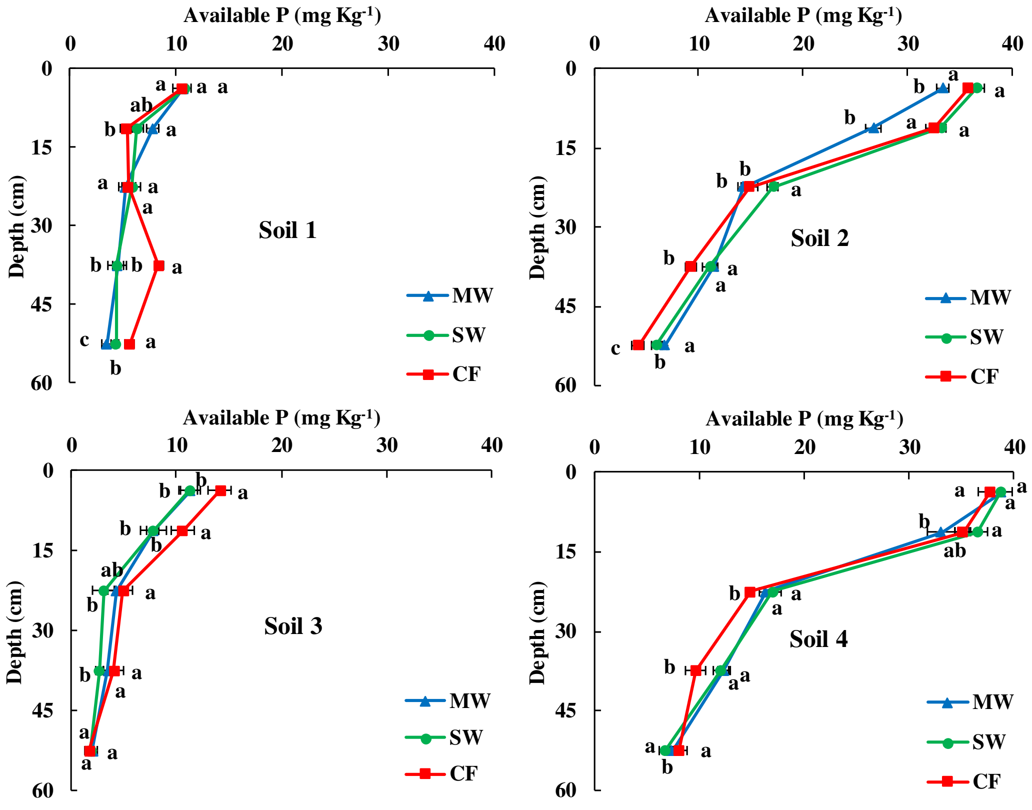


Fig 4.4 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of available P in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

Available P concentration in soil decreased gradually with depth (Fig 4.4). The decrease was small in the low fertility Soil 1 (Fig 4.4). In soils of intermediate (Soil 2 and Soil 3) and high (Soil 4) fertility, decrease in available P was greater at 15-30 cm depth, but thereafter the decline was gradual. Cropping systems did not influence available P concentration below 7.5 cm soil depth. Maranguit *et al* (2017) also observed decrease in available P with increasing depth. Bharti and Sharma (2017) had also reported decline in available P with depth in maize-wheat sequence. The decrease in available P concentration with depth was because of greater accumulation of organic matter in the surface soil than sub-surface soil.

4.2.5 Available K

Available K concentration varied greatly among soils and on an average ranged from 80.6 to 147.6 mg K kg^{-1} in surface soil (0-7.5 cm) (Table 4.7). The available K concentration in soils followed the order Soil 4 > Soil 2 > Soil 3 > Soil 1. Dissimilar concentration of available K in various soils may be attributed to differences in previous management involving rice straw and FYM application along with inorganic fertilization. Soil 4, which had been fertilized with rice straw and FYM for 16 years contained the highest concentration of available K. Application of rice straw (2.66% K) at 6 t ha^{-1} yr^{-1} and FYM (1.55% K) at 10 t ha^{-1} yr^{-1} added about 15 and 16 kg K ha^{-1} yr^{-1}, respectively. Thus, available K concentration in

Table 4.7 Available K concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depth

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	80.6^{d}	45.8^{d}	34.2^{b}	19.6^{c}	15.6^{d}
S2	118.3^{b}	58.9^{c}	43.3^{a}	23.1^{b}	23.2^{a}
S3	114.0^{c}	61.2^{b}	33.8^{b}	18.3^{c}	16.1^{c}
S4	147.6^{a}	76.8^{a}	42.1^{a}	25.0^{a}	21.6^{b}
Land use					
MW	113.2^{b}	60.8^{b}	38.9^{a}	22.0^{a}	21.8^{a}
SW	76.5^{c}	45.1^{c}	32.6^{b}	19.6^{b}	16.3^{b}
CF	155.7^{a}	76.2^{a}	43.5^{a}	22.9^{a}	19.4^{c}
LSD (0.05)					
S	2.0	1.8	5.2	1.6	0.9
CS	1.0	2.0	5.9	1.2	0.3
S*CS (S same)	2.25	1.8	NS	2.5	0.7
S*CS (CS same)	2.63	2.0	NS	2.5	1.0

S=Soil CS=Cropping System NS=Not Significant

soils previously amended with organic sources was higher than the unamended Soil 1 even after 3 years of cessation of the use of these amendments. The highest available K concentration in Soil 4 was due to the greatest amount of organic matter application to it. In long-term experiments on alfisols, Srinivasarao *et al* (2010) also reported that application of organic manures enriched the available K forms in soil.

Available K concentration in soils under maize-wheat and soybean-wheat was significantly lower than fallow soil (Table 4.7 and Fig 4.5). However, the extent of decrease depended on the existing soil fertility and the cropping sequence. Soils under maize-wheat had 12 to 33% lower available K concentration than fallow in contrast to 37 to 61% under soybean-wheat sequence in different soils. Greater depletion of soil K under soybean-wheat could be because of nil fertilizer K application in the sequence as opposed to addition of 30 kg K_2O ha^{-1} yr^{-1} in maize-wheat sequence. Therefore, K requirements of soybean and wheat were met from soil K supply. Plant species differ in their K uptake and use efficiency (Dessougi *et al* 2002, Trehan and Sharma 2002, Zhang *et al* 2007). The size of the root system, the physiology of uptake and the ability of plants to increase K solubility in the rhizosphere by exudation of organic compounds govern the uptake of K from soil (Steingrobe

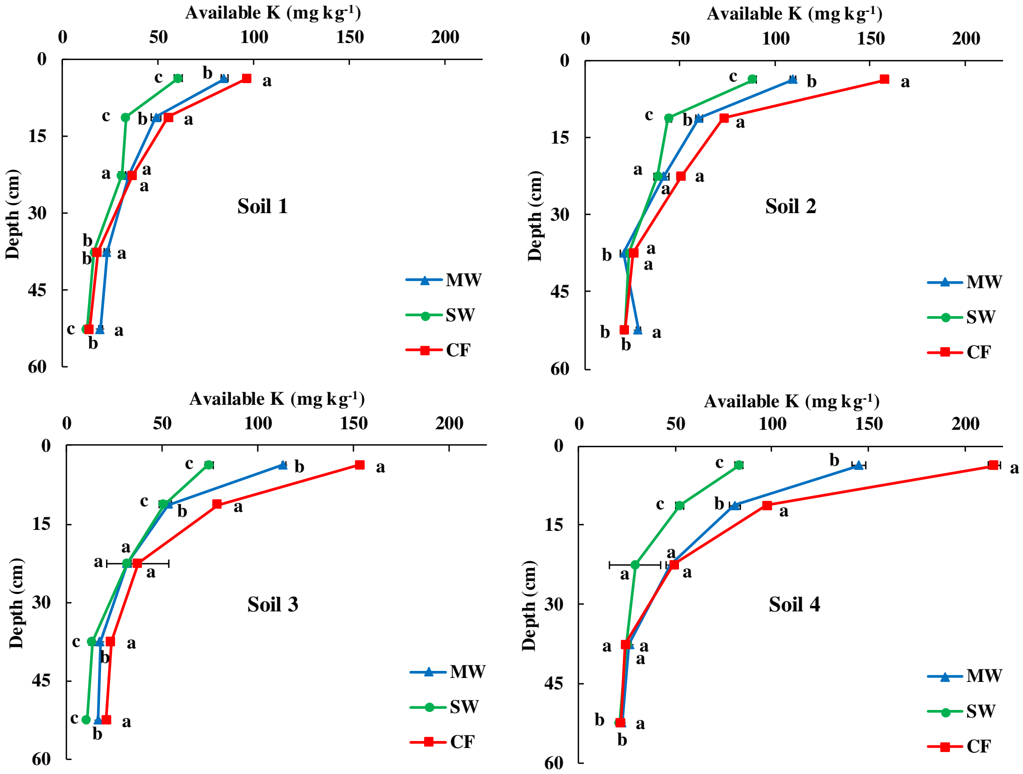


Fig 4.5 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of available K in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

and Claassen 2000, Rengel and Damon 2008). Besides plant factors, the uptake of potassium also depends upon soil fertility (Xie 2000). Plant K uptake is generally higher in K rich soils than in soils low in K (Xie 2000, Zhang *et al* 2009). Available K concentration in soil declined gradually upto 30 cm depth and thereafter, it remained almost unchanged (Fig 4.5). Cropping systems differed significantly in available K concentration upto 15 cm depth beyond which there was no significant difference. Accumulation of K from surface to lower depths might have nullified the differences between three land-uses.

4.3 Effect of maize-wheat, soybean-wheat and fallow on soil physical properties

4.3.1 Bulk Density

Bulk density of surface soil (0-7.5 cm) ranged from 1.63 to 1.72 Mg m^{-3} (Table 4.8). Only Soil 4 showed significantly lower bulk density compared to other soils. For a given soil, the cropping systems and continuous fallow did not influence soil bulk density significantly. Long-term historic application of FYM and rice straw in Soil 4 resulted in lowest bulk density. Microbial decomposition products from these organic inputs acted as binding agents which improved soil aggregation and total porosity and thus, decreased soil bulk density (Mishra and Sharma 1997). Mulumba and Lal (2008), Pervaiz *et al* (2009), Jordán *et al* (2010) also observed significantly reduced soil bulk density and increased porosity in soils receiving straw. Similarly, Mosaddeghi *et al* (2000) and Khan *et al* (2010) reported 1 to 5%

Table 4.8 Bulk density (Mg m^{-3}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	1.72^{a}	1.78^{a}	1.77^{a}	1.72^{b}	1.72^{a}
S2	1.68^{a}	1.80^{a}	1.78^{a}	1.77^{a}	1.70^{b}
S3	1.72^{a}	1.79^{a}	1.78^{a}	1.74^{ab}	1.73^{a}
S4	1.63^{b}	1.70^{b}	1.72^{b}	1.73^{b}	1.69^{b}
Land use					
MW	1.68^{ab}	1.74^{b}	1.76^{a}	1.74^{a}	1.73^{a}
SW	1.66^{b}	1.75^{b}	1.75^{a}	1.75^{a}	1.72^{a}
CF	1.72^{a}	1.80^{a}	1.77^{a}	1.73^{a}	1.68^{b}
LSD (0.05)					
S	0.03	0.05	NS	0.03	NS
CS	0.04	0.03	NS	NS	0.01
S*CS (S same)	NS	NS	NS	NS	NS
S*CS (CS same)	NS	NS	NS	NS	NS

S=Soil CS=Cropping System NS=Not Significant

decrease in bulk density due to application of FYM in soils. Both farmyard manure and straw application had individual effects on soil physical properties (Zhang *et al* 2014).

With increase in soil depth, soil bulk density increased at 7.5-15 cm depth. At 15-30 cm depth, soil bulk density was almost same as in 7.5-15 cm or it increased slightly. Below 15-30 cm depth, bulk density decreased gradually (Fig 4.6). In cropped soils, use of machinery for tillage operations compacted the soil in 7.5-15 and 15-30 cm soil layers leading to increase in bulk density. These results comply with Czyż (2004) who conducted an experiment on seven different textured soils with different crop rotations and reported 2.6 to 13.8% higher bulk density in tractor tilled compared to conventionally tilled soils. Horn *et al* (1998) reported increased bulk density in soil with increase in number of wheeling events. Elaoud and Chehaibi (2011) reported that in a sandy clay soil, the bulk density was increased by 9.0 to 14.7% compared to initial state with increase in number of passes by tractor.

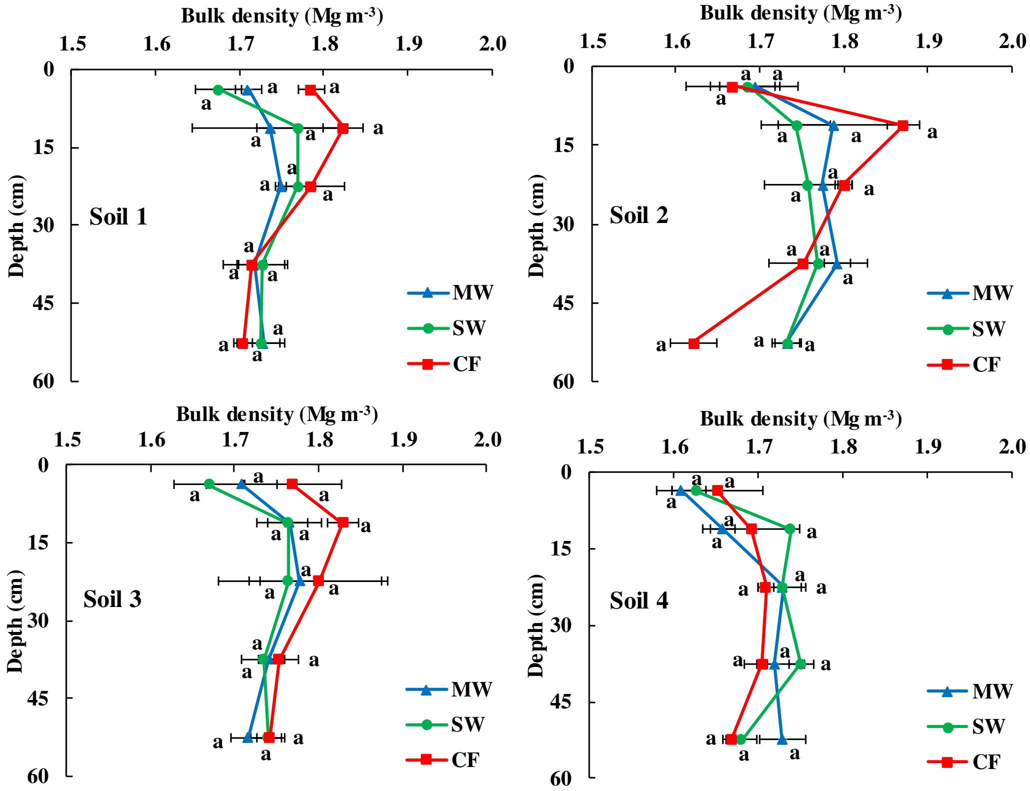


Fig 4.6 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of soil bulk density in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

4.3.2 Water stable aggregates

4.3.2.1 Total water stable aggregates

Total water stable aggregates (WSA) in the surface soil (0-7.5 cm) ranged from 82.4 to 89.2% (Table 4.9). Soil 1 had significantly lower amount of total water stable aggregates than the other soils. There was no significant effect of cropping and fallow on proportion of total WSA. The proportion of total WSA did not vary considerably in the lower layers. It ranged from 83.7 to 92.0% in 7.5-15 cm depth and from 81.6 to 92.5% in 15-30 cm depth (Table 4.9).

Table 4.9 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on total water stable aggregates at different depths

Soil	MW	SW	CF	Mean
			Depth = 0-7.5 cm	
S 1	84.6	82.4	86.9	84.6^{b}
S 2	89.0	86.3	87.6	87.6^{a}
S 3	89.2	85.3	86.4	87.0^{a}
S 4	88.3	84.8	88.2	87.1^{a}
Mean	87.8^{a}	84.76^{b}	87.3^{a}	
LSD (0.05)	S:1.9	CS:1.7	S*CS (S same): NS	S*CS (CS same): NS
			Depth = 7.5-15 cm	
S 1	89.6	83.7	92.0	88.4^{a}
S 2	88.6	89.3	90.4	89.5^{a}
S 3	84.6	84.8	85.9	85.1^{b}
S 4	89.9	89.3	87.6	88.9^{a}
Mean	88.2^{ab}	86.8^{b}	89.0^{a}	
LSD (0.05)	S:2.4	CS:2.1	S*CS (S same): NS	S*CS (CS same): NS
			Depth = 15-30 cm	
S 1	85.3	90.7	88.9	88.3^{ab}
S 2	89.9	92.5	84.6	89.0^{a}
S 3	88.0	87.8	87.2	87.7^{b}
S 4	90.3	90.2	81.6	87.4^{b}
Mean	88.4^{b}	90.3^{a}	85.6^{c}	
LSD (0.05)	S:1.1	CS:1.0	S*CS (S same): 2.2	S*CS (CS same): 2.4

S=Soil CS=Cropping System NS=Not Significant

4.3.2.2 Aggregate size distribution

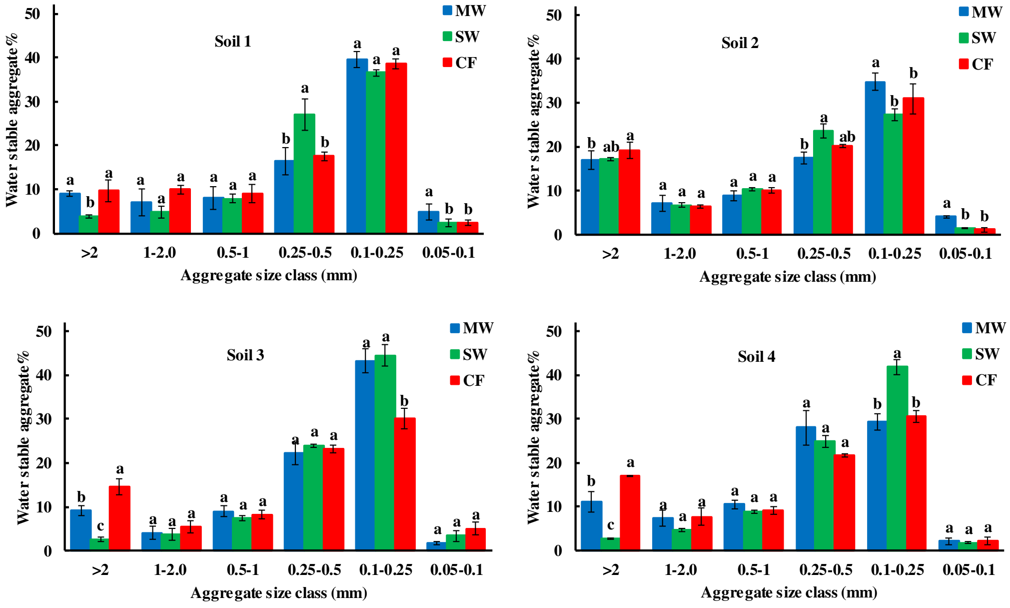
In surface soil (0-7.5 cm), the proportion of coarse macro (CMacA), meso (MesoA) and micro (MicA) aggregates in four soils ranged from 2.5 to 19.1%, 3.3 to 45.8% and 28.7 to 47.8%, respectively. Proportion of CMacA was highest in Soil 2 and lowest in Soil 4; MesoA were highest in Soil 4 and lowest in Soil 1 whereas proportion of MicA was highest in Soil 3 and lowest in Soil 4 (Fig 4.7). Maize-wheat significantly lowered the proportion (by 5.5 to 5.9%) of CMacA in Soil 3 and Soil 4 compared to fallow. However, the cropping sequence did not influence the proportion of CMacA in Soil 1 and Soil 2. Soybean-wheat sequence significantly lowered the proportion of CMacA (by 5.8 to 14.2%) in Soil 1, Soil 3 and Soil 4. Cropping did not influence the proportion of MesoA considerably but it significantly impacted the magnitude of MicA compared to fallow. Maize-wheat system resulted in significantly higher proportion of MicA compared to continuous fallow (by 3.4 to 9.8%) in all soils except Soil 4 where it was at par with continuous fallow. Soybean-wheat improved the proportion of MicA by 10.7 to 12.7% in Soil 3 and Soil 4 compared to continuous fallow (Fig 4.7). The effect of soybean-wheat system on MicA in Soil 1 and Soil 2 was non-significant.

Proportion of CMacA under maize-wheat at 7.5-15 cm soil depth was significantly higher (by 27.4 to 86.3%) than fallow in Soil 1, Soil 2 and Soil 4 (Fig 4.7). In Soil 3 CMacA under maize-wheat was at par with continuous fallow. Soybean-wheat system in Soil 1 to Soil 3, recorded 36.6 to 55.5% lower CMacA than continuous fallow. Conversely, significantly higher proportion of CMacA (by 67.8%) under soybean-wheat system compared to continuous fallow was observed in Soil 4. Proportion of MesoA did not vary considerably between different cropping systems and continuous fallow. Proportion of MicA in maize-wheat was 21.5% higher in Soil 3 while 28.8% lower in Soil 1. In Soil 2 and Soil 4, maize-wheat system did not influence the proportion of MicA compared to continuous fallow. Soybean-wheat sequence resulted in 27.9 to 33.8% lower proportion of MicA in Soil 1 and Soil 4 than fallow. Soybean-wheat system in Soil 3 had 66.9% higher MicA proportion than continuous fallow, but was at par with fallow in Soil 2. Proportion of CMacA, MesoA and MicA in different soils, at 15-30 cm depth ranged from 0.7 to 11, 31.5 to 47.7, 40.0 to 52.2%, respectively. Compared to 0-7.5 and 7.5-15 cm depths, proportion of MacA in 15-30 cm depth was relatively lower and that of MicA was higher. Cropping systems and continuous fallow did not differ considerably with respect to different aggregate sizes in four soils (Fig 4.8).

4.3.2.3 Mean weight diameter

Averaged across land-uses, MWD was lowest in Soil 1 and highest in Soil 2; Soil 3 was at par with Soil 1 but Soil 2 and Soil 4 showed 73 and 21.7% higher MWD than Soil 1 (Table 4.10). In soil with low fertility (Soil 1), soybean-wheat system resulted in significantly lower (by 41%) MWD than continuous fallow, but maize-wheat system did not differ from continuous fallow. In soil with intermediate fertility (Soil 2), cropping systems and fallow did not influence MWD of aggregates significantly. In Soil 3 and Soil 4, both maize-wheat and soybean-wheat had significantly lower MWD (by 23 to 26 and 59 to 62%, respectively) than continuous fallow. With increase in soil depth, MWD of aggregates did not vary considerably at 7.5-15 cm compared to 0-7.5 cm soil, but decreased at 15-30 cm depth ranging between 0.28 and 0.87 mm (Table 4.10). Cropping systems and continuous fallow differed significantly in MWD of aggregates at 7.5-15 cm depth, but did not differ at 15-30 cm depth.

Depth= 0-7.5 cm



Depth= 7.5-15 cm

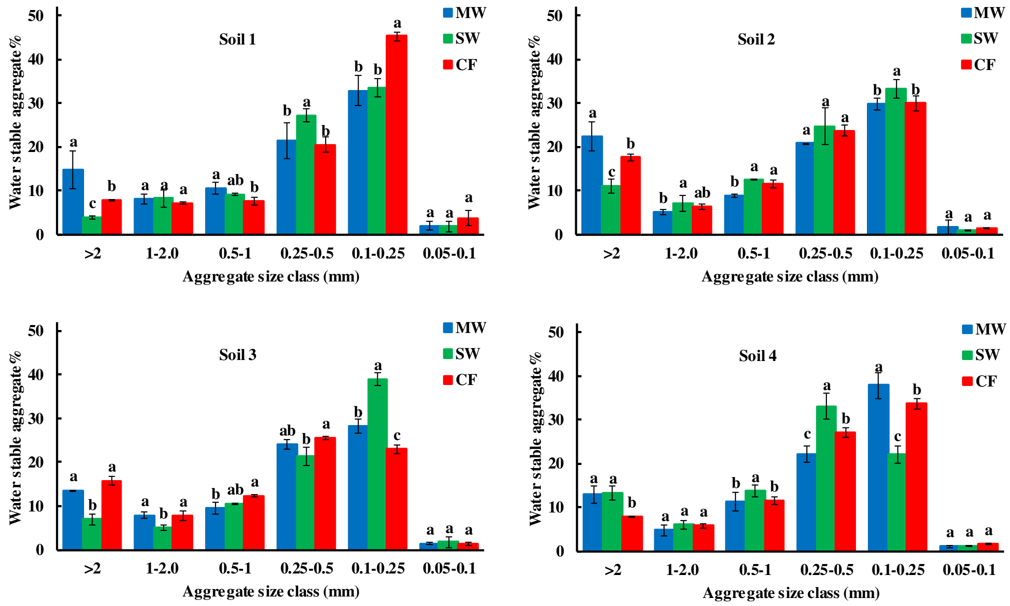


Fig 4.7 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on the proportion of different aggregate sizes in four soils at 0-7.5 and 7.5-15 cm depths. Line bars represent standard deviation. For a given aggregate size, bars labelled with same letters do not differ significantly ($p < 0.05$).

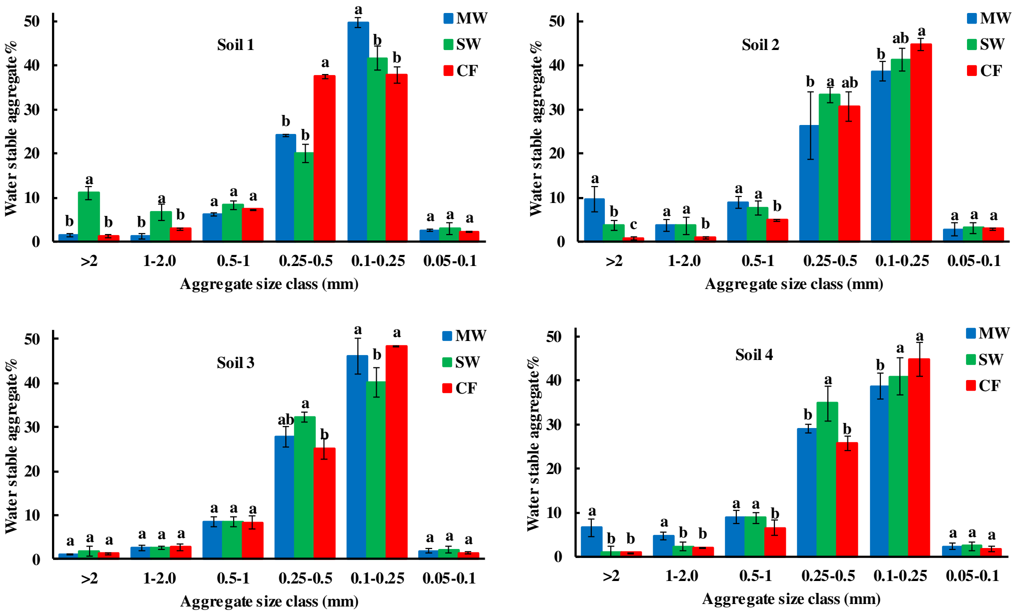


Fig 4.8 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on the proportion of different aggregate sizes in four soils at 15-30 cm depth. Line bars represent standard deviation. For a given aggregate size, bars labelled with same letters do not differ significantly ($p < 0.05$).

Table 4.10 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on mean weight diameter (mm) of aggregates in four soils at different depths

Soil	MW	SW	CF	Mean
			0-7.5 cm	
S 1	0.75	0.49	0.84	0.69^{c}
S 2	1.15	1.17	1.26	1.20^{a}
S 3	0.74	0.41	1.02	0.72^{c}
S 4	0.90	0.44	1.17	0.84^{b}
Mean	0.89^{b}	0.63^{c}	1.07^{a}	
LSD (0.05)	S:0.07	CS:0.06	S*CS (S same): 0.12	S*CS (CS same): 0.11
			7.5-15 cm	
S 1	1.08	0.55	0.72	0.78^{c}
S 2	1.40	0.91	1.20	1.17^{a}
S 3	1.01	0.66	1.14	0.93^{b}
S 4	0.95	1.02	0.73	0.90^{b}
Mean	1.11^{a}	0.78^{c}	0.95^{b}	
LSD (0.05)	S:0.09	CS:0.08	S*CS (S same): 0.17	S*CS (CS same): 0.14
			15-30 cm	
S 1	0.32	0.87	0.37	0.52^{a}
S 2	0.77	0.49	0.28	0.52^{a}
S 3	0.34	0.39	0.35	0.36^{c}
S 4	0.65	0.35	0.30	0.44^{b}
Mean	0.52^{a}	0.53^{a}	0.33^{b}	
LSD (0.05)	S:0.05	CS:0.04	S*CS (S same): 0.10	S*CS (CS same): 0.11

S=Soil CS=Cropping System NS=Not Significant

Mean weight diameter is a direct measure of soil aggregation and soil physical conditions required for plant growth (Singh *et al* 2007). Higher MWD and hence higher soil aggregation leads to lower soil erodibility (Bhattacharyya *et al* 2008). Thus, loss of C and nutrients is also reduced. In surface soils (0-7.5 cm), lower MWD under maize-wheat and soybean-wheat compared to continuous fallow indicates reduced soil aggregation. It suggests that after varied level of C build-up for 16 years in four experimental soils, three years cultivation with only chemical fertilizers resulted in decline in soil aggregation compared to continuous fallow.

4.3.2.4 Aggregate ratio

Except under soybean-wheat in Soil 1 and maize-wheat in Soil 4, aggregate ratio in other soils under the two cropping sequences differed significantly from continuous fallow (Table 4.11). Aggregate ratio in Soil 1, Soil 2 and Soil 3 under maize-wheat was lower by 19 to 33% due to higher proportion of micro-aggregate than continuous fallow. Conversely, in Soil 4 aggregate ratio under maize-wheat was higher by 8% due to higher proportion of macro-aggregate than continuous fallow. Aggregate ratio under soybean-wheat was higher by 14% in Soil 2 due to higher proportion of meso-aggregate, but lower (by 43 to 46%) in Soil 3 and Soil 4 due to lower coarse-macro aggregate and higher micro-aggregate compared to continuous fallow. Aggregate ratio did not change considerably at 7.5-15 cm depth compared

Table 4.11 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on aggregate ratio in four soils at different depths

Soil	MW	SW	CF	Mean
			0-7.5 cm	
S 1	0.91	1.12	1.13	1.06^{c}
S 2	1.30	2.01	1.75	1.69^{a}
S 3	0.99	0.79	1.48	1.09^{c}
S 4	1.82	0.95	1.69	1.49^{b}
Mean	1.26^{b}	1.22^{b}	1.52^{a}	
LSD (0.05)	S:0.12	CS:0.10	S*CS (S same): 0.21	S*CS (CS same): 0.20
			7.5-15 cm	
S 1	1.59	1.38	0.88	1.28^{b}
S 2	1.83	1.63	1.89	1.78^{a}
S 3	1.86	1.08	2.52	1.82^{a}
S 4	1.31	2.84	1.48	1.88^{a}
Mean	1.65^{a}	1.73^{a}	1.70^{a}	
LSD (0.05)	S:0.17	CS: NS	S*CS (S same): 0.31	S*CS (CS same): 0.30
			15-30 cm	
S 1	0.63	1.04	1.22	0.97^{ab}
S 2	1.17	1.09	0.78	1.01^{a}
S 3	0.84	1.08	0.75	0.89^{b}
S 4	1.21	1.09	0.77	1.02^{a}
Mean	0.96^{b}	1.07^{a}	0.88^{b}	
LSD (0.05)	S:0.09	CS:0.08	S*CS (S same): 0.17	S*CS (CS same): 0.20

S=Soil CS=Cropping System NS=Not Significant

to that in surface 0-7.5 cm depth. It ranged from 0.88 to 2.84 at 7.5-15 cm depth. At this depth, cropping and fallow differed considerably in coarse-macro and micro aggregates. In the lower depth (15-30 cm), aggregate ratio reduced considerably ranging between 0.63 and 1.22 (Table 4.11). Cropping systems and continuous fallow did not differ considerably at this depth.

Long-term application of organic amendments in Soil 2, Soil 3 and Soil 4 had resulted in greater total WSA in these soils compared to Soil 1 which did not receive any organic amendment. In an experiment on rice-wheat system, Benbi and Senapati (2010) had reported that application of FYM, rice straw and fertilizer N in different combinations improved total WSA by 22.4 to 26.5% over plots not receiving such treatments. In the present study, cultivation of soils of different initial fertility did not influence total WSA compared to continuous fallow; rather, cultivation significantly influenced the distribution of aggregates in different size classes compared to fallow. Both maize-wheat and soybean-wheat systems resulted in lower proportion of CMacA and higher proportion of MicA leading to lower aggregate ratio depending on soil fertility. Lower proportion of CMacA in cropped soils might be due to the disruption of macro-aggregates with tillage and soil disturbance associated with field preparation and sowing operations. Therefore, cultivation resulted in disruption and structural breakdown of the macro-aggregates to micro-aggregates which also exposed the physically protected soil organic matter inside macro-aggregates. Silva and Ribeiro (1992), Oyedele *et al* (1999) and Franzluebbers *et al* (1999) also concluded that soil mechanical disturbance reduces the structural stability of soil. Moreover, micro-aggregates are stabilized by persistent organic binding substances whereas macro-aggregates are more stabilized by transient organic materials such as plant root and microbial biomass derived polysaccharides and temporary binding agents like fungal hyphae and minute plant roots (Six *et al* 2004). These transient binding agents in macro-aggregates might have facilitated the tillage induced breakdown and decrease in the proportion of CMacA and thereby, increase in MicA under cropping compared to fallow in different soils. Therefore, aggregate ratio was reduced in cropped compared to fallow soils.

4.4 Effect of maize-wheat, soybean-wheat and fallow on chemical pools of C and N

4.4.1 Total organic carbon

At the start of the experiment in 2015, total organic carbon (TOC) concentration in the surface soil (0-7.5 cm) averaged 5.64, 9.04, 9.59 and 12.88 g kg^{-1} in Soil 1, Soil 2, Soil 3 and Soil 4, respectively (Table 4.12). In the sub-surface soil (7.5-15 cm), the TOC concentration was a trifle lower and averaged 4.96, 8.69, 8.15 and 9.66 g kg^{-1} in Soil 1, Soil 2, Soil 3 and Soil 4, respectively (Table 4.12). The differential TOC content of the soils was because of differences in management prior to the start of the current experiment. Soil 1 had never been fertilized with an organic source and it exhibited the lowest TOC concentration.

Soil 4 had been amended with FYM and rice residue for 16 years and thus had the highest TOC concentration. Soil 2 and Soil 3, which had either been receiving FYM or rice residue annually, had intermediate TOC concentrations. Soil 2, Soil 3 and Soil 4 had antecedent TOC concentration higher by 60, 70 and 128% than Soil 1. Increase in TOC concentration and soil fertility with long-term application of organic amendments including FYM and rice straw has been reported earlier (Banger *et al* 2010, Benbi *et al* 1998, Benbi and Senapati 2010, Benbi *et al* 2012b).

Table 4.12 Antecedent TOC concentration (g kg^{-1}) of four soils subjected to maize-wheat (MW) and soybean-wheat (SW) cropping and continuous fallow (CF)

Soil	MW	SW	CF	Mean
			Depth 0-7.5 cm	
S 1	5.86	5.74	5.33	5.64^{c}
S 2	7.37	10.83	8.92	9.04^{b}
S 3	8.50	11.23	9.05	9.59^{b}
S 4	11.89	12.60	14.17	12.88^{a}
Mean	8.41^{c}	10.10^{a}	9.37^{b}	
LSD (0.05)	S:0.80	CS:0.72	S*CS (S same):1.48	S*CS (CS same):1.29
			Depth 7.5-15 cm	
S 1	4.30	5.13	5.46	4.96^{c}
S 2	6.89	9.99	9.19	8.69^{b}
S 3	6.24	9.45	8.77	8.15^{b}
S 4	10.33	9.25	9.40	9.66^{a}
Mean	6.94^{b}	8.45^{a}	8.21^{a}	
LSD (0.05)	S:0.52	CS:0.48	S*CS (S same):1.04	S*CS (CS same):1.08

S=Soil CS=Cropping System NS=Not Significant

After three years of cropping or fallow, average TOC concentration in surface layer (0-7.5 cm) of different soils ranged from 6.31 to 11.13 g kg^{-1} (Table 4.13). Similar to antecedent level, highest TOC concentration was observed in Soil 4 and the lowest in Soil 1. However, differences in TOC concentration between soils were narrowed down. On average, Soil 2, Soil 3 and Soil 4 had 44, 59 and 76% higher TOC concentration than Soil 1. Compared to fallow, cropping significantly influenced TOC concentration though the effect varied with antecedent C level (Fig 4.9). In soils of low (Soil 1) and intermediate fertility (Soil 2 and Soil 3), maize-wheat resulted in significantly lower (by 11.7 to 21.6%) TOC concentration in surface soil compared to fallow (Fig 4.9). On the contrary, soybean-wheat did not influence TOC concentration in Soil 1 and Soil 2 but lowered it in Soil 3 (by 17.3%) compared to fallow. In the high fertility soil (Soil 4), TOC concentration in cropped (maize-wheat and soybean-wheat) and fallow soils did not differ significantly. Therefore, in soils of low to intermediate fertility maize-wheat system was unable to maintain a balance between C loss through decomposition and plant mediated C input similar to that in soybean-wheat and fallow soils resulting in lowering of TOC concentration. In high fertility soil, both the cropping systems could maintain input-output balance similar to fallow soil and thus TOC concentration did not differ.

Table 4.13 Total organic C concentration (g kg^{-1}) in four soils at different depths after 3 years of maize-wheat (MW) and soybean-wheat (SW) cropping and continuous fallow (CF)

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	6.31^d	5.32^c	3.11^b	1.94^a	1.91^a
S2	9.13^c	7.66^b	3.12^b	1.98^a	1.69^a
S3	10.07^b	8.05^b	3.63^a	1.97^a	1.78^a
S4	11.13^a	10.22^a	3.59^a	1.94^a	1.89^a
Land use					
MW	8.64^b	7.36^a	3.19^a	1.86^b	1.87^a
SW	9.05^b	8.02^a	3.55^a	1.89^b	1.70^a
CF	9.78^a	8.06^a	3.35^a	2.12^a	1.88^a
LSD (0.05)					
S	0.64	0.92	0.4	NS	NS
CS	0.50	NS	NS	NS	NS
S*CS (S same)	1.0	1.51	NS	NS	NS
S*CS (CS same)	1.0	1.49	NS	NS	NS

S=Soil CS=Cropping System NS=Not Significant

In all the four soils, TOC concentration gradually decreased with depth and ranged between 1.69 and 1.91 g kg^{-1} in 45-60 cm depth (Table 4.13 and Fig 4.9). The decline in TOC concentration was greater at 15-30 cm soil depth in all soils except Soil 1. In Soil 2 to Soil 4, the TOC concentration in 15-30 cm layer was almost half of that in 7.5-15 cm depth. Choice of a cropping system did not influence TOC concentration in deeper soil layers. The significant effect of cropping systems on TOC concentration in the surface soil was because majority of roots (~ 80%) were in the plough layer and this layer was exposed to most intense agricultural operations.

Soil C stocks in surface (0-7.5 cm) soil, at the start of the experiment averaged 7.29 to 15.76 Mg ha^{-1} in four soils (Table 4.14). After three years of management, soil C stock in surface soil averaged 8.17 to 13.60 Mg ha^{-1} in the four soils (Table 4.15). Cropping

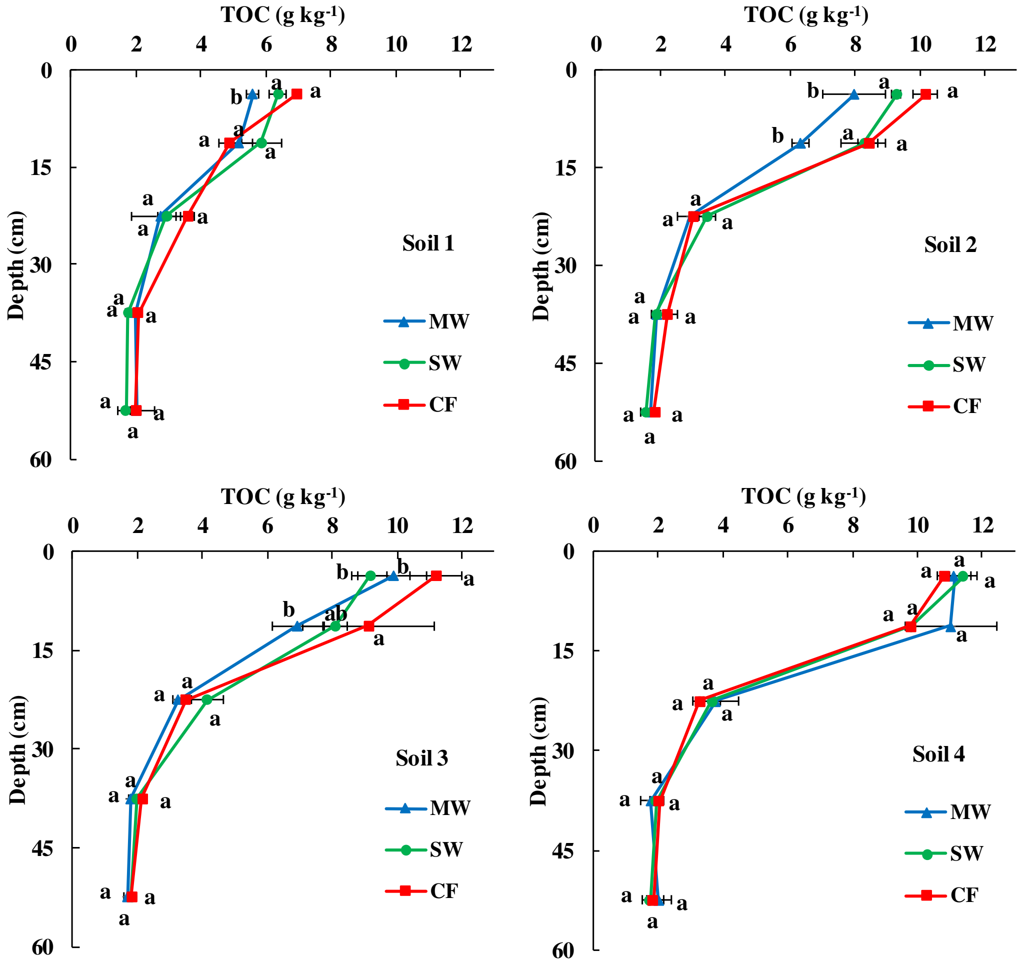


Fig 4.9 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of TOC in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

influenced soil C stocks in the surface soil and the magnitude and direction of change depended on antecedent C level. Soil 1 with low antecedent C level showed build-up of C by 12%, Soil 2 and Soil 3 with intermediate C level did not undergo any significant change in C stocks, whereas Soil 4 with highest antecedent C level experienced significant loss of C stocks by 13.7% (Table 4.17 and Fig 4.10). In sub-surface soil (7.5-15 cm), the antecedent C stocks were lower than the surface layer and averaged 6.71 to 12.28 Mg ha^{-1} in the four soils (Table 4.14). After three years of cropping or continuous fallow, C stocks in the four soils averaged 7.08 to 12.99 Mg ha^{-1} (Table 4.15). In contrast to surface layer, the C stocks in the sub-surface layer exhibited an increase of 5.5 and 5.7% in Soil 1 and Soil 4, respectively and a decline of 11.8% in Soil 2 (Table 4.17 and Fig 4.10). Soil 3 did not experience any considerable change in soil C stock in sub-surface layer.

Table 4.14 Antecedent total organic carbon stocks (Mg ha^{-1}) in surface and sub-surface soils under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) systems

Soil	MW	SW	CF	Mean
			Depth 0-7.5 cm	
S 1	7.52	7.21	7.14	7.29^{c}
S 2	9.36	13.68	11.12	11.39^{b}
S 3	10.89	14.06	11.99	12.31^{b}
S 4	14.34	15.37	17.58	15.76^{a}
Mean	10.53^{b}	12.58^{a}	11.96^{b}	
LSD (0.05)	S:0.94	CS:0.82	S*CS (S same):1.70	S*CS (CS same):1.56
			Depth 7.5-15 cm	
S 1	5.85	6.80	7.47	6.71^{c}
S 2	9.23	13.07	12.90	11.74^{a}
S 3	8.27	12.51	12.03	10.93^{b}
S 4	12.86	12.07	11.92	12.28^{a}
Mean	9.05^{b}	11.11^{a}	11.08^{a}	
LSD (0.05)	S:0.73	CS:0.64	S*CS (S same):1.39	S*CS (CS same):1.60

S=Soil CS=Cropping System NS=Not Significant

Antecedent and current soil C stock in 0-15 cm depth are presented in table 4.16. Comparison of current and antecedent soil C stocks in the plough layer (0-15 cm depth), showed that Soil 1 with lowest fertility accrued C (8.8%) while Soil 4 with highest fertility lost C (5.2%) as a result of cropping and fallowing (Table 4.17 and Fig 4.10). Soils of intermediate fertility did not show a consistent trend, while Soil 2 lost C (5.5%), Soil 3 gained a small amount (2.3%) of C. Most of the studies on maize and soybean based cropping systems involving long-term application of chemical fertilizers have reported increase in TOC stocks (Campbell *et al* 2005, Bhattacharyya *et al* 2007, Mandal *et al* 2007). But the results of the present study suggested that the change in TOC stock in response to cropping was depended on prevailing soil C level. Soil with low antecedent C level exhibited gain in C stocks and that with initially high TOC level lost C during the experimental period. Soil C stocks declined gradually with depth. These ranged from 7.25 to 10.98, 4.59 to 5.81 and 3.99 to 5.28 Mg ha^{-1} at 15-30, 30-45 and 45-60 cm depth, respectively (Table 4.15). Cropping and fallow did not influence C stocks at lower depths. Total soil C stocks (Mg ha^{-1}) in the 60 cm profile in four soils followed the order Soil 4 (45.6) > Soil 3 (43.2) > Soil 2 (39.7) > Soil 1 (33.4). In all the soils, except Soil 4, the C stocks in the 60 cm profile were highest in fallow plots and lowest under maize-wheat sequence. On the contrary, the C stocks in Soil 4 were highest under maize-wheat and lowest in fallow plots (Fig 4.11). In all soils except Soil 4, relatively higher soil bulk density in fallow might have resulted in higher soil C stock compared to cropped soils.

Table 4.15 Effect of 3 years of maize-wheat (MW), soybean-wheat (SW) cropping and continuous fallow (CF) on total organic C stocks (Mg ha^{-1}) in four soils at different depths

Soil	MW	SW	CF	Mean
			Depth 0-7.5 cm	
S 1	7.19	8.00	9.31	8.17^{c}
S 2	10.09	11.71	12.72	11.50^{b}
S 3	12.66	11.46	14.83	12.98^{a}
S 4	13.44	13.93	13.42	13.60^{a}
Mean	10.84^{b}	11.27^{b}	12.57^{a}	
LSD (0.05)	S:0.68	CS:0.5891	S*CS (S same):1.27	S*CS (CS same):1.36
			Depth 7.5-15 cm	
S 1	6.74	7.78	6.71	7.08^{c}
S 2	8.46	10.78	11.79	10.35^{b}
S 3	9.18	10.74	12.48	10.80^{b}
S 4	13.73	12.82	12.43	12.99^{a}
Mean	9.53^{b}	10.53^{a}	10.85^{a}	
LSD (0.05)	S:1.05	CS:0.91	S*CS (S same):1.95	S*CS (CS same):2.00
			Depth 15-30 cm	
S 1	7.25	7.86	9.63	8.25^{b}
S 2	7.80	9.06	8.11	8.33^{b}
S 3	8.68	10.98	9.42	9.69^{a}
S 4	9.85	9.51	8.47	9.28^{ab}
Mean	8.40^{a}	9.35^{a}	8.91^{a}	
LSD (0.05)	S: 1.0.	CS: NS	S*CS (S same): NS	S*CS (CS same): NS
			Depth 30-45 cm	
S 1	5.09	4.59	5.33	5.01^{a}
S 2	5.03	4.93	5.81	5.26^{a}
S 3	4.67	5.13	5.67	5.16^{a}
S 4	4.62	5.17	5.26	5.02^{a}
Mean	4.85^{b}	4.96^{b}	5.52^{a}	
LSD (0.05)	S: NS	CS: 0.46	S*CS (S same): NS	S*CS (CS same): NS
			Depth 45-60 cm	
S 1	5.24	4.42	5.14	4.93^{a}
S 2	4.45	3.99	4.39	4.28^{a}
S 3	4.40	4.72	4.77	4.63^{a}
S 4	5.28	4.45	4.67	4.80^{a}
Mean	4.84^{a}	4.39^{a}	4.74^{a}	
LSD (0.05)	S: NS	CS: NS	S*CS (S same): NS	S*CS (CS same): NS

S=Soil CS=Cropping System NS=Not Significant

Table 4.16 Antecedent and current soil C stocks under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at plough layer (0-15 cm)

Soil	MW	SW	CF	Mean
			Antecedent level	
S 1	13.37	14.01	14.61	14.00^{c}
S 2	18.59	26.75	24.02	23.12^{b}
S 3	19.16	26.56	24.02	23.25^{b}
S 4	27.20	27.44	29.50	28.05^{a}
Mean	19.58^{b}	23.69^{a}	23.04^{a}	
LSD (0.05)	S:1.14	CS:0.98	S*CS (S same):2.14	S*CS (CS same):2.36
			After 3 years	
S 1	13.92	15.79	16.02	15.24^{d}
S 2	18.55	22.49	24.51	21.85^{c}
S 3	21.84	22.20	27.30	23.78^{b}
S 4	27.16	26.75	25.86	26.59^{a}
Mean	20.37^{c}	21.81^{b}	23.42^{a}	
LSD (0.05)	S:1.45	CS:1.25	S*CS (S same):2.63	S*CS (CS same):2.45

S= Soil CS= Cropping system

Table 4.17 Changes in soil C stock (Mg ha^{-1}) at different depths in four soils after 3 years of maize-wheat (MW) and soybean-wheat (SW) cropping and continuous fallow (CF)

Soil	MW	SW	CF	Mean
			Depth 0-7.5 cm	
S 1	-0.33	0.79	2.16	0.88^{a}
S 2	0.73	-1.97	1.60	0.12^{a}
S 3	1.77	-2.60	2.83	0.67^{a}
S 4	-0.91	-1.44	-4.16	-2.17^{b}
Mean	0.32^{a}	-1.30^{b}	0.61^{a}	
LSD (0.05)	S:1.13	CS:0.98	S*CS (S same):2.02	S*CS (CS same):1.77
			Depth 7.5-15 cm	
S 1	0.89	0.98	-0.76	0.37^{ab}
S 2	-0.77	-2.29	-1.11	-1.39^{c}
S 3	0.91	-1.77	0.45	-0.13^{b}
S 4	0.87	0.76	0.51	0.71^{a}
Mean	0.47^{a}	-0.58^{b}	-0.22^{ab}	
LSD (0.05)	S:0.84	CS:0.73	S*CS (S same):1.56	S*CS (CS same):1.58
			Depth 0-15 cm	
S 1	0.55	1.77	1.41	1.24^{a}
S 2	-0.05	-4.26	0.49	-1.27^{b}
S 3	2.69	-4.37	3.29	0.54^{a}
S 4	-0.04	-0.68	-3.64	-1.46^{b}
Mean	0.79^{a}	-1.88^{b}	0.38^{a}	
LSD (0.05)	S:1.31	CS:1.13	S*CS (S same):2.39	S*CS (CS same):2.30

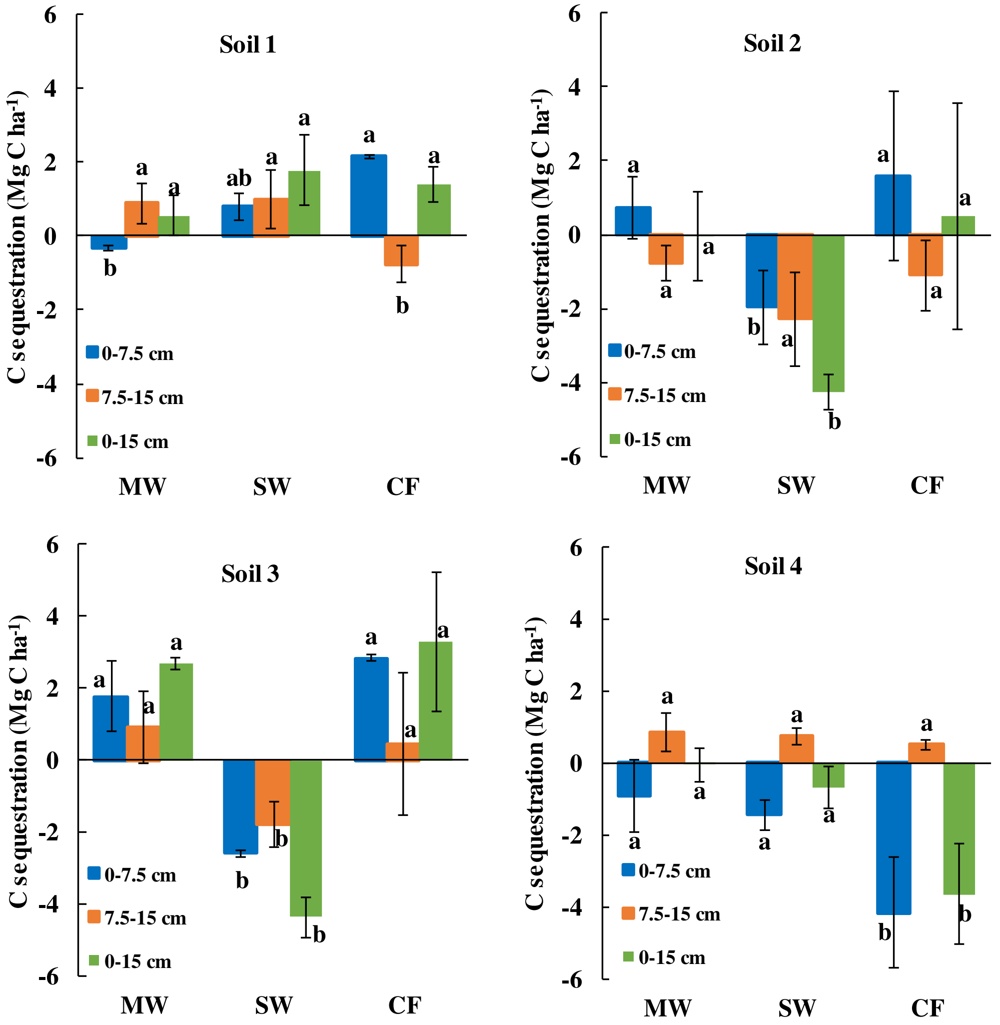


Fig 4.10 Changes in soil C stock (Mg C ha^{-1}) after 3 years of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) in four soils at different depths. Line bars represent standard deviation. For a given depth, bars labelled with same letters do not differ significantly ($p < 0.05$).

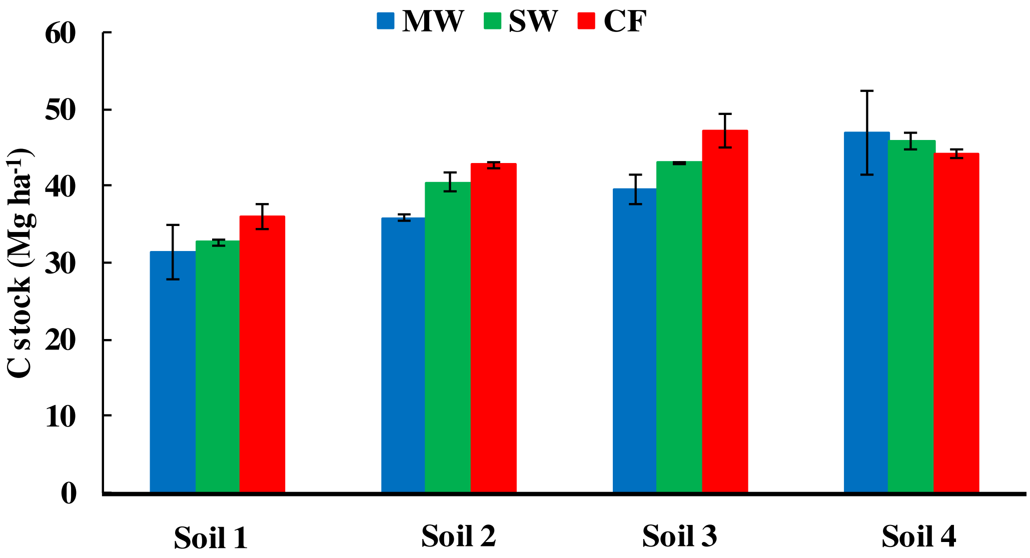


Fig 4.11 Effect of maize-soybean (MW), soybean-wheat (SW) and continuous fallow (CF) on soil C stock in four soils at 0-60 cm depth. Line bars represent standard deviation.

4.4.2 Water soluble carbon

The mean concentration of water soluble C (WSC) in 0-7.5 cm soil ranged from 25.9 mg kg^{-1} to 43.1 mg kg^{-1} in four soils (Table 4.18). On average, Soil 2, Soil 3 and Soil 4 had 66, 29 and 40% higher WSC than Soil 1. The experimental soils also differed in the proportion of WSC to TOC and followed the order Soil 2 (0.48%) > Soil 1 (0.42%) > Soil 3 (0.33%) = Soil 4. Higher WSC in Soil 2 was probably because prior to initiation of the current experiment, it had been amended with FYM, which contains soluble organic matter in the form of water soluble carbohydrates and amino acids (Chantigny *et al* 2002). Gong *et al* (2009) and Singh and Benbi (2018) also reported higher WSC in soils amended with FYM. Cropping with maize-wheat and soybean-wheat resulted in significantly lower WSC compared to fallow (Fig 4.12). The effect depended on the antecedent C level. Water soluble C in Soil 1 and Soil 2 under maize-wheat system did not differ significantly from continuous fallow, but it had 17.7 and 29.5% lower WSC in surface layer than fallow in Soil 3 and Soil 4, respectively. Similarly, soybean-wheat system in Soil 1 and Soil 3 did not differ significantly from continuous fallow, but recorded 29.3 and 40.5% lower WSC in Soil 2 and Soil 4, respectively. Averaged across soils, the proportion of WSC to TOC concentration was significantly higher under maize-wheat (0.42%) and continuous fallow (40%) than soybean-wheat sequence (0.35%). The differences in the magnitude of WSC under maize-wheat and soybean-wheat could be attributed to variation in the quantity and quality of easily metabolizable materials in root exudates of the two cropping system (Xu and Juma, 1993). In soil with high fertility, relatively lower proportion of WSC in cropped soils compared to

Table 4.18 Water soluble carbon concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	25.9^{c}	18.7^{b}	11.8^{b}	13.6^{b}	7.1^{b}
S2	43.1^{a}	26.3^{a}	13.2^{b}	16.7^{a}	14.0^{a}
S3	33.6^{b}	20.6^{b}	16.6^{a}	14.0^{b}	12.2^{a}
S4	36.3^{b}	26.4^{a}	16.6^{a}	13.5^{b}	13.3^{a}
Land use					
MW	34.2^{b}	23.1^{ab}	16.2^{a}	16.2^{a}	12.0^{a}
SW	30.6^{c}	24.1^{a}	14.3^{ab}	13.2^{b}	11.8^{a}
CF	39.4^{a}	21.9^{b}	13.2^{b}	14.1^{b}	11.2^{a}
LSD (0.05)					
S	2.67	2.72	NS	NS	NS
CS	2.93	NS	NS	1.9	NS
S*CS (S same)	6.04	4.17	NS	4.28	4.82
S*CS (CS same)	5.47	4.20	NS	4.65	4.38

S=Soil CS=Cropping System NS=Not Significant

fallow was probably due to the fact that maize-wheat and soybean-wheat systems had relatively higher TOC concentration than fallow.

WSC concentration gradually decreased upto 30 cm depth in all soils, but thereafter, it remained either unchanged or decreased slightly (Table 4.18 and Fig 4.12). Decrease in WSC with depth had also been reported earlier by Benbi *et al* (2015) and Singh and Benbi (2018). Below the 0-7.5 cm depth, cropping systems differed in WSC concentration only in soils with low and intermediate fertility. In soil with high fertility (Soil 4), cropping systems did not differ in WSC concentration at lower depths. Depth distribution of the proportion of WSC to TOC presented a dissimilar trend. In Soil 1 and Soil 2, with increase in depth, proportion of WSC did not vary up to 30 cm depth, but thereafter it showed a gradual increase at 30-45 cm depth followed by slight or constant decrease. The decayed soluble organic matter may have percolated to lower layers over time leading to increased proportion of WSC to TOC.

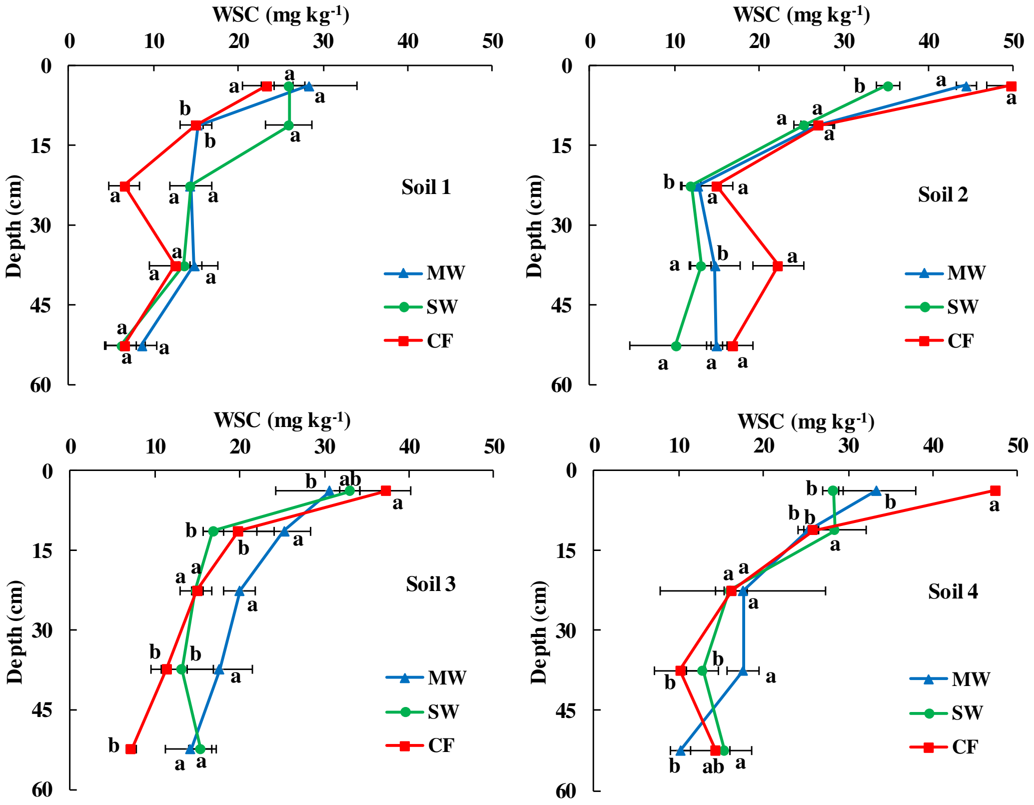


Fig 4.12 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of water soluble carbon in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

4.4.3 Hot water soluble carbon

The mean concentration of hot water soluble C (HWSC) in surface soil (0-7.5 cm) ranged from 296 mg kg^{-1} (Soil 3) to 406 mg kg^{-1} (Soil 4) (Table 4.19). HWSC comprised 2.9 to 5% of TOC in different soils which followed the order Soil 1 (5%) > Soil 2 (4.2%) > Soil 4 (3.6%) > Soil 3 (2.9%). Substrate quality is one of the prime factors effecting decomposition of organic matter in soil (Nieder *et al* 2003). Benbi and Khosa (2014) have shown that decomposition of FYM was faster compared to rice straw over same period of time because the former had relatively lower C:N and Lignin:N ratio (37.4 and 15.6, respectively) compared to the later (75.2 and 34, respectively). In the present study, the highest proportion of HWSC to TOC in Soil 1 may be due to the fact that it had not been amended with any organic material for long-term and thus, the prevailing organic matter in it, in the meantime, have undergone the greatest decomposition as compared to other soils. Soil 2, Soil 3 and Soil 4 had received FYM, rice straw and their combined application, respectively, for 16 years; as organic material in FYM decomposes faster than rice straw, their decomposition in soils might have followed the order Soil 2 > Soil 4 > Soil 3. Hence, the proportion of HWSC to

TOC in soils also followed the similar order.

Table 4.19 Hot water soluble carbon concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depth

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	320^{b}	213^{d}	138^{a}	65^{a}	25^{b}
S2	386^{a}	345^{b}	125^{b}	45^{b}	33^{ab}
S3	296^{b}	268^{c}	120^{b}	55^{b}	26^{b}
S4	406^{a}	366^{a}	130^{ab}	56^{ab}	41^{a}
Land use					
MW	320^{b}	292^{b}	135^{a}	60^{a}	26^{a}
SW	342^{b}	290^{b}	130^{a}	42^{b}	32^{a}
CF	395^{a}	312^{a}	120^{b}	63^{a}	36^{a}
LSD (0.05)					
S	37	16	NS	NS	NS
CS	26	18	9	10	NS
S*CS (S same)	56	38	20	NS	NS
S*CS (CS same)	57	34	20	NS	NS

S=Soil CS=Cropping System NS=Not Significant

Hot water soluble C concentration was lower by 18.1 to 25% under maize-wheat compared to continuous fallow in all soils except Soil 3 where it did not differ from continuous fallow. Likewise, soybean-wheat also resulted in significantly lower HWSC concentration (18.1 to 20.8%) compared to continuous fallow in all soils except Soil 1 where it did not differ from continuous fallow. However, HWSC comprised 3.9 to 4.1% of TOC in the three land-uses. These values of HWSC are consistent with those reported by Leinweber *et al* (1995) and Benbi *et al* (2015), but were higher compared to that reported by Gregorich *et al* (2003) and Bu *et al* (2010). The amount extracted by hot water depends on temperature of water. Higher quantity of HWSC in this study may be attributed to higher extraction temperature (boiling) compared to that (80 ^{o}C) of aforesaid studies (Gregorich *et al* 2003 and Bu *et al* 2010). Legume based cropping systems contain relatively higher amount of WSC in the soil (Mazzarino *et al* 1993, Campbell *et al* 1999), possibly because legumes exude soluble molecules more for biological N_2 fixation in the rhizosphere. However, in the present study, such effect of higher HWSC in soybean-wheat system than in maize wheat was recorded only in soil with low fertility (Soil 1).

With increase in soil depth, HWSC concentration showed a decreasing trend and dropped to 25 to 41 mg kg^{-1} in 45-60 cm soil depth (Table 4.19). Irrespective of the land-use, the decrease was greater at 15-30 cm depth in all soils (Fig 4.13). In the deeper soil layers, the effect of different land-uses on HWSC was not discernible. Depth distribution of proportion of HWSC to TOC also followed a similar trend. Decrease in HWSC with increasing depth was possibly due to decrease in TOC concentration.

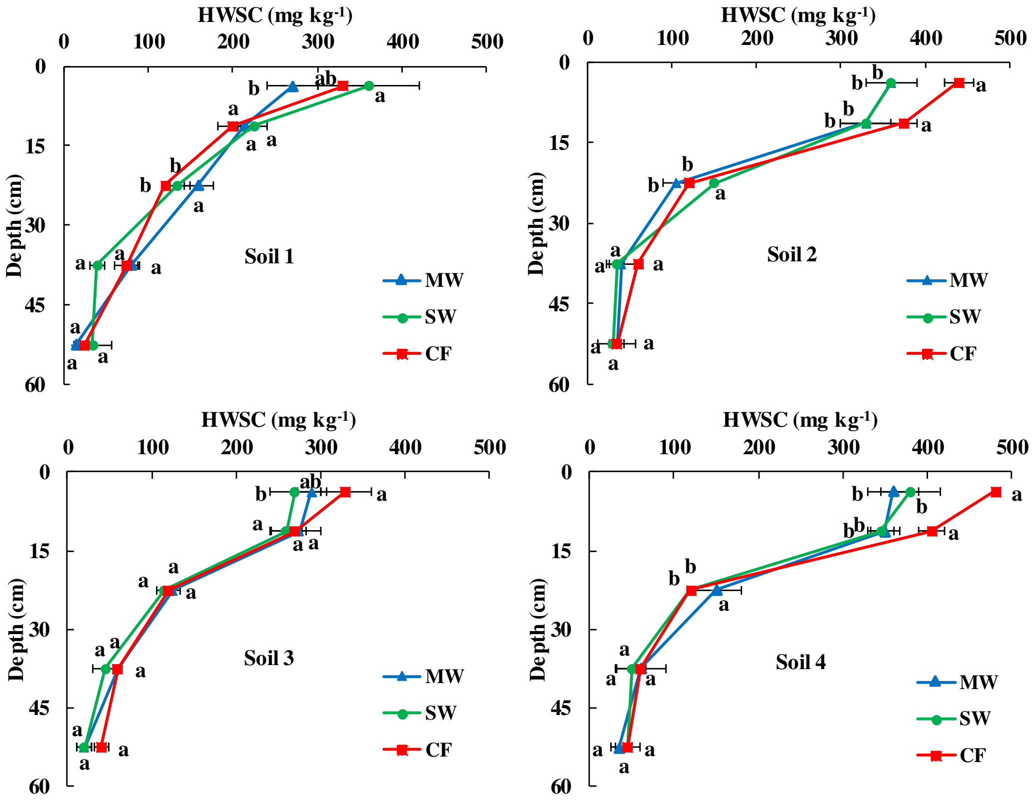


Fig 4.13 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of hot water soluble carbon in four soils of different fertility. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

4.4.4 $KMnO_4$ oxidizable carbon

The average concentration of $KMnO_4$ oxidizable C in surface soil (0-7.5 cm) ranged from 830 to 1553 mg kg^{-1}, lowest being in Soil 1 and the highest in Soil 4 (Table 4.20). On average, Soil 2, Soil 3 and Soil 4 had 70, 19 and 87% higher $KMnO_4$-C, respectively compared to Soil 1. The soils also differed significantly with respect to proportion of $KMnO_4$-C to TOC. Averaged across cropping systems, the proportion of KMnO4-C to TOC in different soils followed the order Soil 2 (15.5%) > Soil 4 (14.0%) > Soil 1 (13.1%) > Soil 3 (9.8%). The differential amount of $KMnO_4$-C in various soils could be explained on the basis of their long-term management with organic and inorganic fertilizers. Soil 2 that exhibited the greatest proportion of $KMnO_4$-C has been amended with FYM prior to the start of this experiment. Long-term application of organic manure has been reported to increase $KMnO_4$-C in soil (Blair *et al* 2006, Yang *et al* 2012, Benbi *et al* 2015). Lower proportion of $KMnO_4$-C in soils amended with rice straw (Soil 3 and Soil 4) suggests relative recalcitrance of added C.

Except under soybean-wheat in Soil 1, cropping significantly lowered $KMnO_4$-C compared to continuous fallow in all the four soils (Table 4.20 and Fig 4.14). The decline was more pronounced under maize-wheat than soybean-wheat sequence, being 21.3 to 29.2% under the former and 16.5 to 18.8% under the latter sequence in different soils. The proportion of $KMnO_4$-C to TOC followed the order continuous fallow (14.1%) > soybean-wheat (12.9%) > maize-wheat (12.2%). Carbon management index (CMI) under maize-wheat, soybean-wheat and continuous fallow ranged between 36.1 to 68.4, 46.2 to 78.0 and 58.3 to 86.6%, respectively (Table 4.21). While in all the four soils, maize-wheat exhibited the lowest CMI and continuous fallow the highest, their magnitudes and differences depended on the antecedent C level. $KMnO_4$-oxidizable C has been used as a measure of labile C under a variety of soils and land uses (Blair *et al* 1995, 2006). Carbon management index, integrating TOC with $KMnO_4$ oxidizable C, is a sensitive indicator of short-term and medium term soil management impacts on change in soil organic C (Whitbread *et al* 1998). It acts as an indicator of soil C rehabilitation with greater values indicating soil C rehabilitation and smaller values indicating C loss (Blair *et al* 1995). In the present study, irrespective of

Table 4.20 $KMnO_4$ oxidizable carbon concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	830^d	752^d	598^b	194^b	183^b
S2	1415^b	1087^b	925^a	222^a	205^a
S3	993^c	845^c	252^d	197^b	182^b
S4	1553^a	1248^a	338^c	200^b	163^c
Land use					
MW	1039^c	922^c	487^b	205^b	182^b
SW	1171^b	1046^a	523^b	186^c	170^c
CF	1383^a	981^b	575^a	217^a	198^a
LSD (0.05)					
S	30	53	43	18	17
CS	18	32	43	10	10
S*CS (S same)	38	69	90	23	21
S*CS (CS same)	42	74	83	25	23

S=Soil CS=Cropping System NS=Not Significant

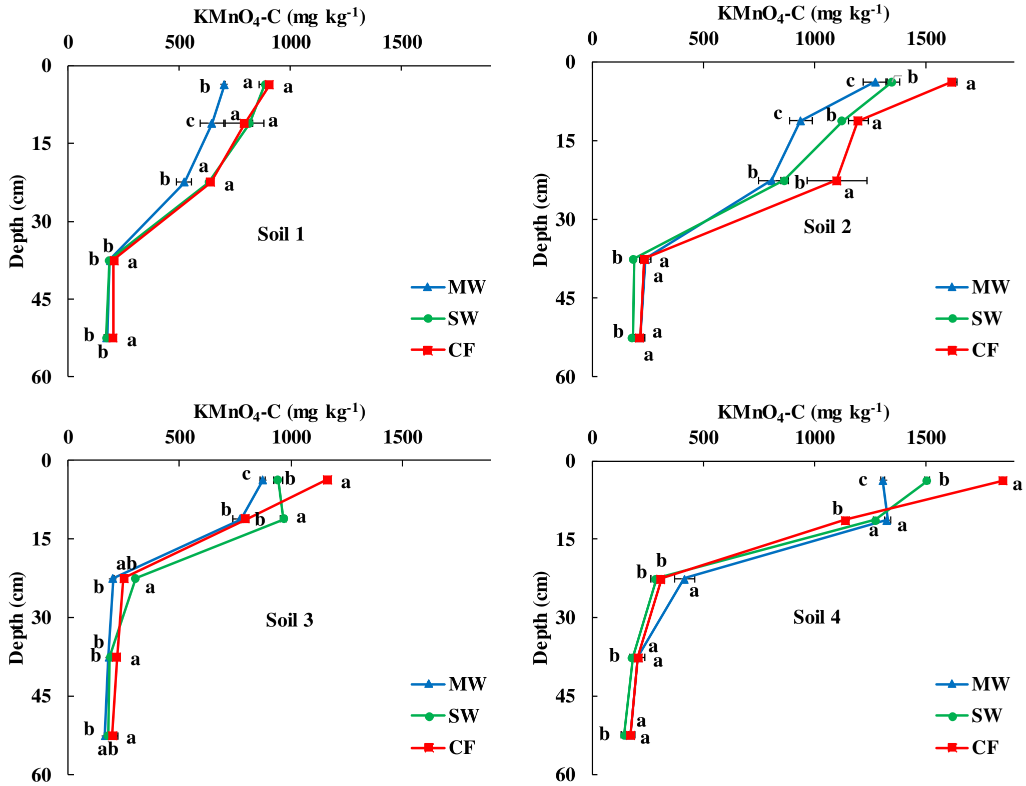


Fig 4.14 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of $KMnO_4$ oxidizable carbon in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

antecedent C level, the lowest CMI in maize-wheat and relatively lower CMI in soybean-wheat system compared to continuous fallow suggests that cropping resulted in degradation of soil organic C. In soil with lowest antecedent C level, cropped and fallow plots behaved in a similar manner with respect to C loss. Relatively higher CMI of soybean-wheat than maize-wheat sequence suggests that the former had higher C rehabilitation rate than the later.

With increase in soil depth, $KMnO_4$-C gradually decreased and on average ranged from 182 to 205 mg kg^{-1} at 45-60 cm soil depth (Fig 4.14). However, $KMnO_4$-C concentration showed a greater decrease at 15-30 cm depth in Soil 3 and Soil 4 and at 30-45 cm depth in Soil 2. Below 0-7.5 cm, cropping systems did not differ significantly in $KMnO_4$-C concentration. Proportion of $KMnO_4$ C to TOC was almost constant at all the depths in Soil 1 and Soil 2. Similarly, in Soil 3 and Soil 4, similar proportion of $KMnO_4$-C was observed at all depths except 15-30 cm where it was relatively higher (17.8 to 36.6%). The $KMnO_4$-C in soils under cropping as well as fallow did not differ significantly below 7.5 cm soil depth. Conteh *et al* (1997) also reported decrease in labile C with increasing soil depth.

Table 4.21 Carbon management index (CMI) of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) in four soils at different depths

Soil	MW	SW	CF	Mean
Depth 0-7.5 cm				
S 1	36.1^{b}	46.2^{a}	46.7^{a}	43.0
S 2	68.4^{b}	71.1^{b}	86.6^{a}	75.4
S 3	43.6^{c}	47.3^{b}	58.3^{a}	49.7
S 4	66.6^{b}	78.0^{a}	-	72.3
Mean	53.7^{b}	60.6^{a}	63.9^{a}	
$\text{LSD}_{\text{land-uses}}$ (0.05)	S 1:1.89	S 2:1.95	S 3:5.9	S 4:1.8
Depth 7.5-15 cm				
S 1	57.5^{b}	73.5^{a}	73.3^{a}	68.1
S 2	84.4^{c}	101.2^{b}	108.2^{a}	97.9
S 3	67.8^{b}	85.1^{a}	67.7^{b}	73.5
S 4	117.3^{a}	113.6^{a}	-	115.5
Mean	81.8	93.3	83.1	
$\text{LSD}_{\text{land-uses}}$ (0.05)	S 1:5.5	S 2:4.9	S 3:6.1	S 4:13.6
Depth 15-30 cm				
S 1	193.7^{b}	235.2^{a}	227.2^{a}	218.7
S 2	331.7^{b}	337.8^{b}	506.5^{a}	392.0
S 3	63.3^{c}	95.8^{a}	78.3^{b}	79.1
S 4	136.2^{a}	91.8^{b}	-	114.0
Mean	181.2	190.1	270.7	
$\text{LSD}_{\text{land-uses}}$ (0.05)	S 1:3.0	S 2:26.0	S 3:142.2	S 4:33.4
Depth 30-45 cm				
S 1	89.9^{b}	90.2^{b}	98.5^{a}	92.9
S 2	120.0^{a}	90.3^{b}	113.8^{a}	108.1
S 3	87.6^{b}	90.0^{b}	105.5^{a}	94.4
S 4	102.9^{a}	86.4^{a}	-	94.6
Mean	100.1	89.2	106.0	
$\text{LSD}_{\text{land-uses}}$ (0.05)	S 1:10.3	S 2:27.3	S 3:20.7	S 4:6.9
Depth 45-60 cm				
S 1	100.8^{b}	99.5^{b}	118.1^{a}	106.2
S 2	130.0^{a}	109.6^{b}	128.2^{ab}	122.6
S 3	97.1^{b}	104.6^{ab}	118.6^{a}	106.8
S 4	98.1^{a}	83.3^{a}	-	90.7
Mean	106.5	99.2	121.6	
$\text{LSD}_{\text{land-uses}}$ (0.05)	S 1:18.5	S 2:18.0	S 3:18.7	S 4:8.6

4.4.5 Organic carbon fractions of different oxidizability

The proportion of very labile (C_{VL}), labile (C_L), less labile (C_{LL}) and recalcitrant (C_R) C pools to TOC in different soils (0-7.5 cm depth) ranged from 27.3 to 51.6%, 13.3 to 20.0%, 3.2 to 18.0%, and 14.8 to 51.3%, respectively (Fig 4.15). Averaged across cropping systems, the proportion of C_{VL} in Soil 1 was statistically at par with Soil 2 and Soil 4. However, Soil 3 showed significantly lower (by 14.7%) proportion of C_{VL} pool compared to Soil 1. None of the soils differed in the proportion of C_L and C_{LL} pool to TOC under continuous fallow. The proportion of C_R was lower by 7.4 and 5.3% in Soil 2 and Soil 4, respectively, but was higher by 12.6% in Soil 3 compared to Soil 1.

Majority of the differences in the proportion of organic C pools of different oxidizability, when compared with the fallow, were found in the very labile (C_{VL}) and resistant (C_R) pool. Very labile pool and C_R pools constitued 27.3 to 48.3% and 21.7 to 51.3% of TOC, respectively. In soil with low fertility, maize-wheat sequence showed significantly higher (48.2%) C_{VL} pool but all other pools were almost similar in magnitude to continuous fallow (Fig 4.15). However, soils under soybean-wheat did not differ significantly from continuous fallow in either of the pools in soil of low antecedent C level. Cropping systems and continuous fallow did not differ significantly with respect to lability index (LI) in Soil 1 (Table 4.22). In medium fertility soil (Soil 2), maize-wheat did not differ from continuous fallow in C_{VL} pool but showed significantly higher (30.3%) C_R pool compared to continuous fallow. In this soil (Soil 2), soybean-wheat showed significantly lower proportion (43.7%) of C_{VL} pool, but higher proportion (28.2%) of C_R pool compared to fallow. Both cropping systems exhibited significantly lower (1.8) LI than continuous fallow. In Soil 3, only maize-wheat system showed significantly lower proportion (27.4%) of C_{VL} pool and lower LI (1.2) compared to continuous fallow. Proportion of C_{VL} pool in soybean-wheat system, that of C_R pool and LI in both cropping systems were statistically at par with continuous fallow. In Soil 4, maize-wheat system showed significantly lower proportion (34.6%) of C_{VL} pool but soybean-wheat system was at par with continuous fallow. Proportion of C_R pool was significantly higher (31.7 to 39.8%) and LI was significantly lower (1.45 to 1.8) in both cropping systems compared to continuous fallow (1.2). The results of the present study showed that most of the organic C was in C_{VL} and C_R pool in contrast to the findings of Chan *et al* (2001) who reported higher proportion (65%) of organic C in only C_{VL} and C_L pools. This could be because their study was conducted with pasture where plant C input is different from maize-wheat and soybean-wheat system. Moreover, in the present experiment long-term application of organic amendments to rice-wheat system resulted in greater stabilization of organic C in C_R pool with time (Benbi *et al* 2015). Ding *et al* (2012) also reported that large amounts of C input through manure were gradually stabilized in soil with a great proportion of recalcitrant C. In soils with intermediate (Soil 2) and high antecedent C level (Soil 4),

Table 4.22 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on lability index in four soils at different depths

Soil	MW	SW	CF	Mean
		Depth 0-7.5cm		
S 1	1.79	1.71	1.65	1.72^{b}
S 2	1.80	1.81	1.98	1.86^{a}
S 3	1.19	1.39	1.37	1.31^{c}
S 4	1.45	1.81	1.99	1.75^{b}
Mean	1.56^{b}	1.68^{a}	1.75^{a}	
LSD (0.05)	S:0.08	CS:0.07	S*CS (S same): 0.15	S*CS (CS same): 0.15
		Depth 7.5-15 cm		
S 1	1.20	1.34	1.38	1.30^{b}
S 2	1.17	1.53	1.11	1.27^{ab}
S 3	1.49	1.50	1.28	1.42^{a}
S 4	1.07	1.54	1.36	1.32^{ab}
Mean	1.23^{b}	1.48^{a}	1.28^{b}	
LSD (0.05)	S:0.14	CS:0.12	S*CS (S same): 0.26	S*CS (CS same): 0.23
		Depth 15-30 cm		
S 1	1.20	1.21	1.14	1.18^{b}
S 2	1.41	1.29	1.46	1.39^{a}
S 3	1.19	1.13	1.34	1.22^{b}
S 4	1.34	1.28	1.62	1.41^{a}
Mean	1.28^{ab}	1.23^{b}	1.39^{a}	
LSD (0.05)	S:0.13	CS:0.11	S*CS (S same): NS	S*CS (CS same): NS
		Depth 30-45 cm		
S 1	1.13	1.25	1.14	1.17^{a}
S 2	1.31	1.25	1.15	1.24^{a}
S 3	1.20	1.17	1.11	1.16^{a}
S 4	1.28	1.14	1.19	1.21^{a}
Mean	1.23^{a}	1.20^{ab}	1.15^{b}	
LSD (0.05)	S:0.09	CS:0.08	S*CS (S same): NS	S*CS (CS same): NS
		Depth 45-60 cm		
S 1	1.04	1.11	1.21	1.12^{ab}
S 2	1.33	1.32	1.14	1.26^{a}
S 3	1.13	1.24	1.13	1.17^{ab}
S 4	1.12	1.11	1.01	1.08^{b}
Mean	1.15^{a}	1.20^{a}	1.12^{a}	
LSD (0.05)	S:0.15	CS: NS	S*CS (S same): NS	S*CS (CS same): NS

S=Soil CS=Cropping System NS=Not Significant

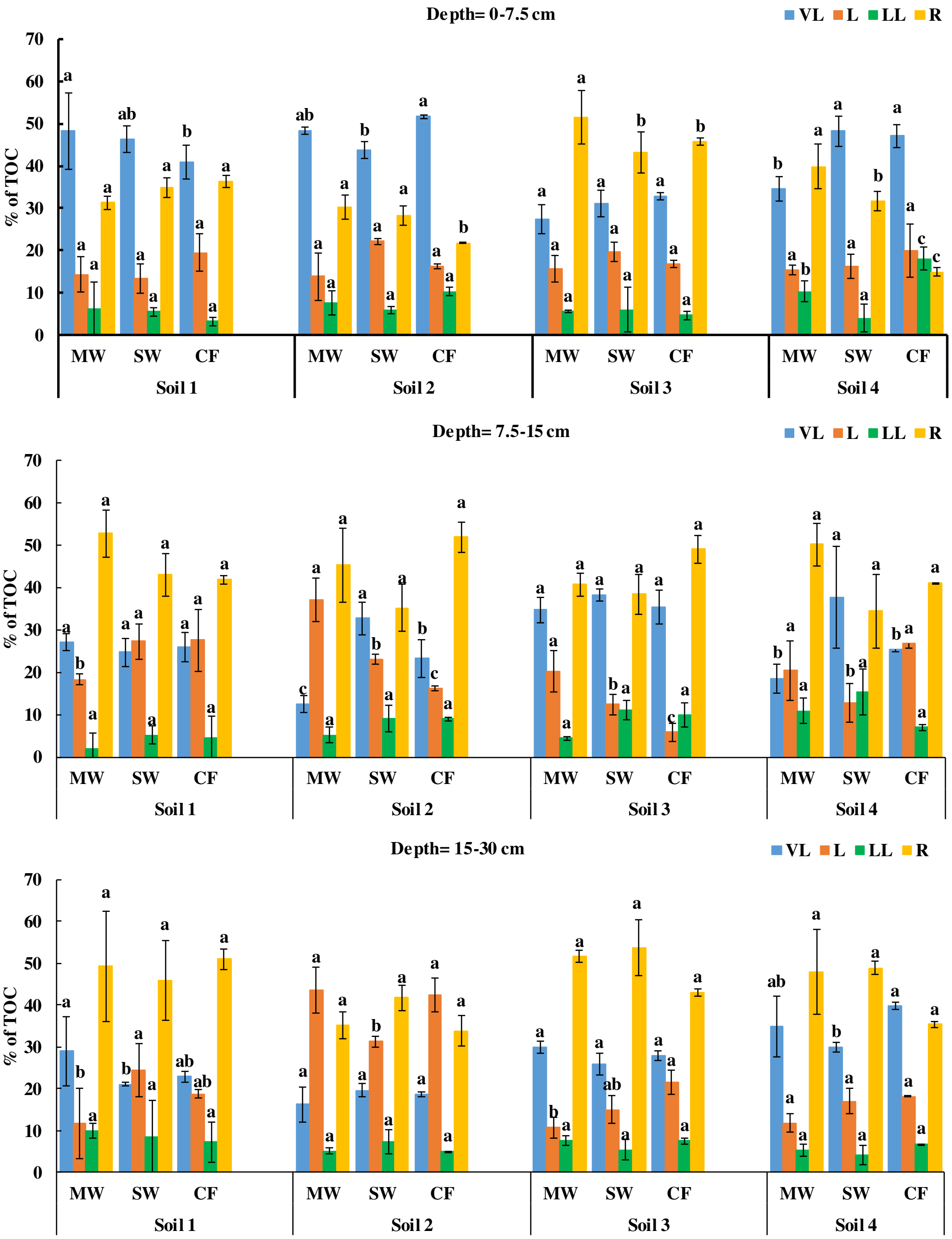


Fig 4.15 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on the proportion of very labile (VL), labile (L), less labile (LL) and recalcitrant fractions (R) to total organic carbon in four soils at 0-7.5, 7.5-15 and 15-30 cm depths. Line bars represent standard deviation. For a given pool of organic C, bars labelled with same letters within a soil do not differ significantly ($p < 0.05$).

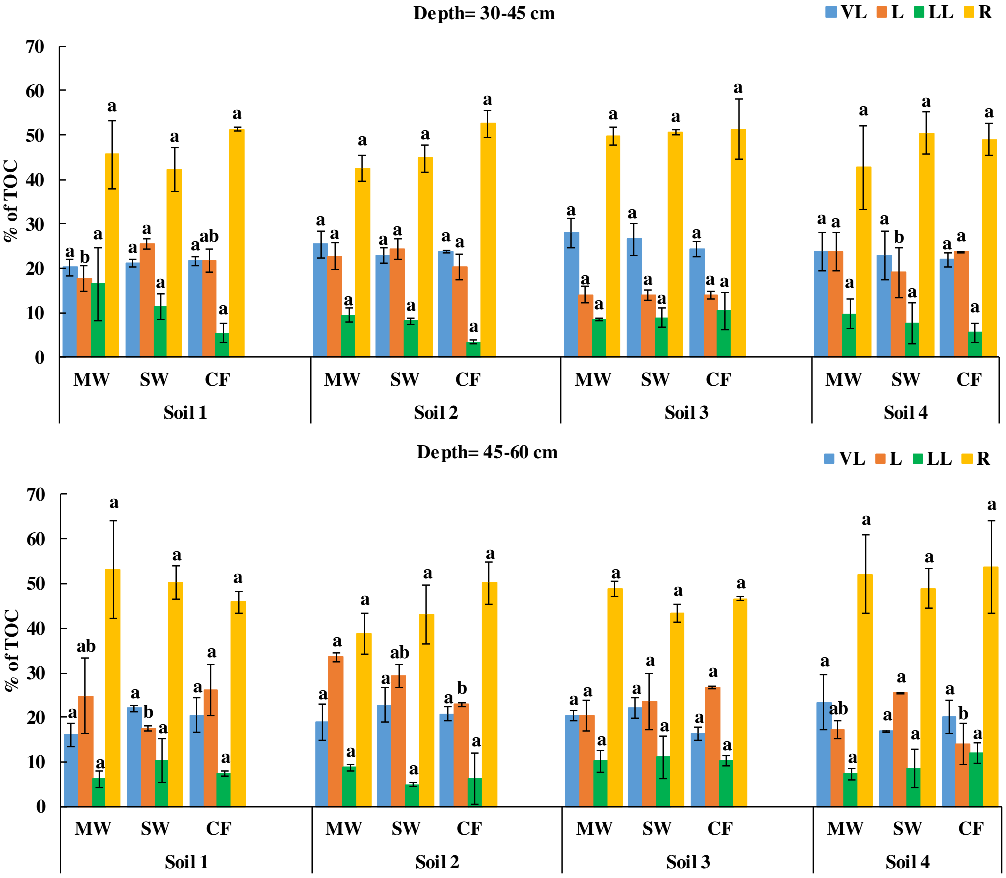


Fig 4.16 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on the proportion of very labile (VL), labile (L), less labile (LL) and recalcitrant fractions (R) to total organic carbon in four soils at 30-45 and 45-60 cm depths. Line bars represent standard deviation. For a given pool of organic C, bars labelled with same letters within a soil do not differ significantly ($p < 0.05$).

lower oxidizable pool of very labile C, lower LI and higher recalcitrant pool under the two cropping sequences suggests that organic C in these land-uses had higher C stabilization compared to continuous fallow.

The C_{VL} pool declined with soil depth in all the soils expect Soil 3. The proportion of C_L and C_{LL} pools did not vary with depth. However, the proportion of C_R pool slightly increased with depth in all soils except Soil 3. At 45-60 cm soil depth, the proportion of C_{VL}, C_L, C_{LL} and C_R pools ranged from 16.0 to 23.3, 14.0 to 33.5, 4.8 to 12.0 and 38.7 to 53.7, respectively. Effect of cropping and fallow on proportion of different organic C fractions at various sub-surface depths is shown in Fig 4.15 and 4.16. Several studies have documented decreasing level of easily decomposable C_{VL} pool with soil depth probably because of lower supply of organic residues at lower depths (Andrade *et al* 2005, Rangel *et al* 2008 and Barreto *et al* 2011).

4.4.6 Aggregate associated C

Irrespective of soil, macro-aggregates had higher C concentration than micro-aggregates. In surface soil, carbon concentrations in CMacA, MesoA and MicA in different soils ranged from 8.4 to 15.0, 6.1 to 20.1 and 5.5 to 8.3 g kg^{-1} aggregate, respectively (Table 4.23). Average C concentration in macro-aggregates was higher than in micro-aggregates by 51, 80, 74 and 86% in Soil 1, Soil 2, Soil 3 and Soil 4, respectively. Aggregate associated C in different sized aggregates in surface soil was highest in Soil 4 and the lowest in Soil 1. Cropping systems and continuous fallow did not significantly influence C concentrations of aggregates in different soils. Aggregate associated C in CMacA, MesoA and MicA at 7.5-15 cm depth was almost similar to that at 0-7.5 cm depth, but it decreased at 15-30 cm and ranged from 6.1 to 18.8, 2.3 to 13.4 and 3.0 to 4.2 g kg^{-1} aggregate, respectively (Table 4.24 and 4.25). While in 7.5-15 cm soil layer, cropping systems and continuous fallow differed significantly in aggregate associated C in different sized aggregates, but there was no significant difference at 15-30 cm depth.

In surface soil, the highest carbon preservation capacity (CPC) of CMacA was observed in Soil 4 (2.56 g kg^{-1} soil) and the lowest in Soil 3 (0.34 g kg^{-1} soil) (Fig 4.17). Among meso-aggregates, the highest CPC was observed in 0.25-0.5 mm fraction in Soil 3 (3.25 g kg^{-1} soil), but lowest in 1.0-2.0 mm fraction in Soil 1 (0.45 g kg^{-1} soil). Soil 3 and Soil 4 resulted in the highest (3.98 g kg^{-1} soil) and the lowest (1.85 g kg^{-1} soil) CPC of MicA, respectively. However, averaged across cropping systems and fallow, CPC of all aggregate size fractions was highest in Soil 4 and lowest in Soil 1 except for 1.0-2.0 mm fraction (MesoA) and for MicA. Cropping systems differed significantly with respect to the CPC of CMacA compared continuous fallow. Depending upon antecedent C level, maize-wheat and soybean-wheat systems recorded 24 to 45% and 22 to 84% lower CPC of CMacA compared to that in continuous fallow. However, Cropping did not influence CPC of MesoA and MicA

Table 4.23 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on different sized aggregate associated C (g kg^{-1} aggregate) in four soils at 0-7.5 cm depth

Soil	MW	SW	CF	Mean
>2 mm				
S 1	8.4	9.4	10.8	9.5^{c}
S 2	9.5	10.0	11.6	10.4^{c}
S 3	11.9	13.3	13.4	12.9^{b}
S 4	12.5	14.2	15.0	13.9^{a}
Mean	10.6^{c}	11.7^{b}	12.7^{a}	
LSD (0.05)	S:0.9	CS:0.8	S*CS (S same): NS	S*CS (CS same): NS
1.0-2.0 mm				
S 1	8.9	9.3	9.7	9.3^{d}
S 2	10.5	11.1	15.2	12.3^{c}
S 3	12.2	13.4	16.3	14.0^{b}
S 4	13.9	15.7	16.8	15.5^{a}
Mean	11.4^{c}	12.4^{b}	14.5^{a}	
LSD (0.05)	S:1.4	CS:0.7	S*CS (S same): 1.5	S*CS (CS same): 1.8
0.5-1.0 mm				
S 1	8.2	10.6	10.9	9.9^{d}
S 2	11.2	12.8	16.8	13.6^{c}
S 3	14.6	15.6	16.6	15.6^{b}
S 4	17.6	17.9	20.1	18.6^{a}
Mean	12.9^{c}	14.2^{b}	16.15^{a}	
LSD (0.05)	S:1.0	CS:1.0	S*CS (S same): NS	S*CS (CS same): NS
0.25-0.5 mm				
S 1	6.1	7.0	6.4	6.5^{c}
S 2	7.6	9.0	9.9	8.8^{b}
S 3	8.1	13.5	12.8	11.5^{a}
S 4	9.0	11.3	12.2	10.8^{a}
Mean	7.7^{b}	10.2^{a}	10.3^{a}	
LSD (0.05)	S:0.9	CS:1.0	S*CS (S same): NS	S*CS (CS same): NS
<0.25 mm				
S 1	5.6	5.6	5.5	5.6^{b}
S 2	5.0	6.4	7.4	6.2^{b}
S 3	6.6	8.3	8.3	7.7^{a}
S 4	8.2	7.5	7.9	7.9^{a}
Mean	6.3^{b}	6.99^{ab}	7.3a	
LSD (0.05)	S:1.0	CS:0.7	S*CS (S same): NS	S*CS (CS same): NS

S=Soil CS=Cropping System NS=Not Significant

Table 4.24 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on different sized aggregate associated C (g kg^{-1} aggregate) in four soils at 7.5-15 cm depth

Soil	MW	SW	CF	Mean
		>2 mm		
S 1	9.8	10.2	8.7	9.6^{c}
S 2	8.6	9.8	11.1	9.8^{c}
S 3	9.1	11.8	13.0	11.3^{b}
S 4	11.0	12.1	15.9	13.0^{a}
Mean	9.6^{b}	11.0^{a}	12.2^{a}	
LSD (0.05)	S:1.3	CS:1.2	S*CS (S same): 2.5	S*CS (CS same): 2.3
		1.0-2.0 mm		
S 1	9.3	9.3	10.3	9.6^{c}
S 2	10.4	11.5	11.9	11.3^{b}
S 3	11.0	14.6	11.2	12.3^{b}
S 4	14.7	13.2	16.4	14.8^{a}
Mean	11.4^{a}	12.2^{a}	12.52^{a}	
LSD (0.05)	S:1.9	CS: NS	S*CS (S same): 2.8	S*CS (CS same): 2.9
		0.5-1.0 mm		
S 1	9.0	9.4	9.3	9.2^{d}
S 2	9.9	12.1	11.3	11.1^{c}
S 3	11.3	15.7	12.4	13.1^{b}
S 4	16.8	13.7	18.6	16.4^{a}
Mean	11.8^{a}	12.7^{a}	12.9^{a}	
LSD (0.05)	S:1.5	CS: NS	S*CS (S same): 2.5	S*CS (CS same): 2.5
		0.25-0.5 mm		
S 1	5.6	5.5	5.3	5.5^{c}
S 2	7.6	7.1	7.7	7.4^{b}
S 3	7.9	9.3	8.0	8.4^{b}
S 4	10.9	9.1	10.3	10.1^{a}
Mean	8.0^{a}	7.7^{a}	7.8^{a}	
LSD (0.05)	S:0.9	CS: NS	S*CS (S same): NS	S*CS (CS same): NS
		<0.25 mm		
S 1	5.9	5.0	5.1	5.3^{b}
S 2	4.9	6.5	4.9	5.4^{b}
S 3	6.7	6.9	6.4	6.7^{a}
S 4	7.7	6.8	6.5	7.0^{a}
Mean	6.3^{a}	6.3^{a}	5.7^{a}	
LSD (0.05)	S:0.6	CS: NS	S*CS (S same): NS	S*CS (CS same): NS

S=Soil CS=Cropping System NS=Not Significant

Table 4.25 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on different sized aggregate associated C (g kg^{-1} aggregate) in four soils at 15-30 cm depth

Soil	MW	SW	CF	Mean
>2 mm				
S 1	7.5	6.8	10.4	8.3^{b}
S 2	6.1	6.9	18.8	10.6^{a}
S 3	12.6	8.9	13.2	11.6^{a}
S 4	7.7	9.4	10.6	9.2^{b}
Mean	8.5^{b}	8.0^{b}	13.3^{a}	
LSD (0.05)	S:1.2	CS:1.1	S*CS (S same): 2.3	S*CS (CS same): 2.2
1.0-2.0 mm				
S 1	8.0	8.9	8.4	8.4^{c}
S 2	7.1	8.3	13.4	9.6^{b}
S 3	10.6	10.2	11.3	10.7^{a}
S 4	8.5	9.3	10.3	9.4^{bc}
Mean	8.5^{b}	9.2^{b}	10.8^{a}	
LSD (0.05)	S:0.8	CS:0.8	S*CS (S same): 1.8	S*CS (CS same): 1.6
0.5-1.0 mm				
S 1	5.1	7.7	6.8	6.5^{d}
S 2	6.4	7.6	8.9	7.6^{c}
S 3	7.9	7.4	10.1	8.5^{b}
S 4	8.8	8.5	10.2	9.2^{a}
Mean	7.1^{c}	7.8^{b}	9.0^{a}	
LSD (0.05)	S:0.8	CS:0.5	S*CS (S same): 1.1	S*CS (CS same): 1.2
0.25-0.5 mm				
S 1	2.3	3.9	3.2	3.2^{c}
S 2	3.7	4.5	5.3	4.5^{b}
S 3	4.8	6.0	5.3	5.4^{a}
S 4	4.9	4.2	4.4	4.5^{b}
Mean	3.9^{b}	4.7^{a}	4.5^{a}	
LSD (0.05)	S:0.4	CS:0.3	S*CS (S same): 0.7	S*CS (CS same): 0.7
<0.25 mm				
S 1	3.1	3.0	3.7	3.3^{b}
S 2	3.4	2.9	3.8	3.4^{b}
S 3	3.6	4.1	4.2	3.9^{a}
S 4	4.0	4.1	4.3	4.1^{a}
Mean	3.5^{b}	3.5^{b}	4.0^{a}	
LSD (0.05)	S:0.4	CS:0.2	S*CS (S same): 0.3	S*CS (CS same): 0.5

S=Soil CS=Cropping System NS=Not Significant

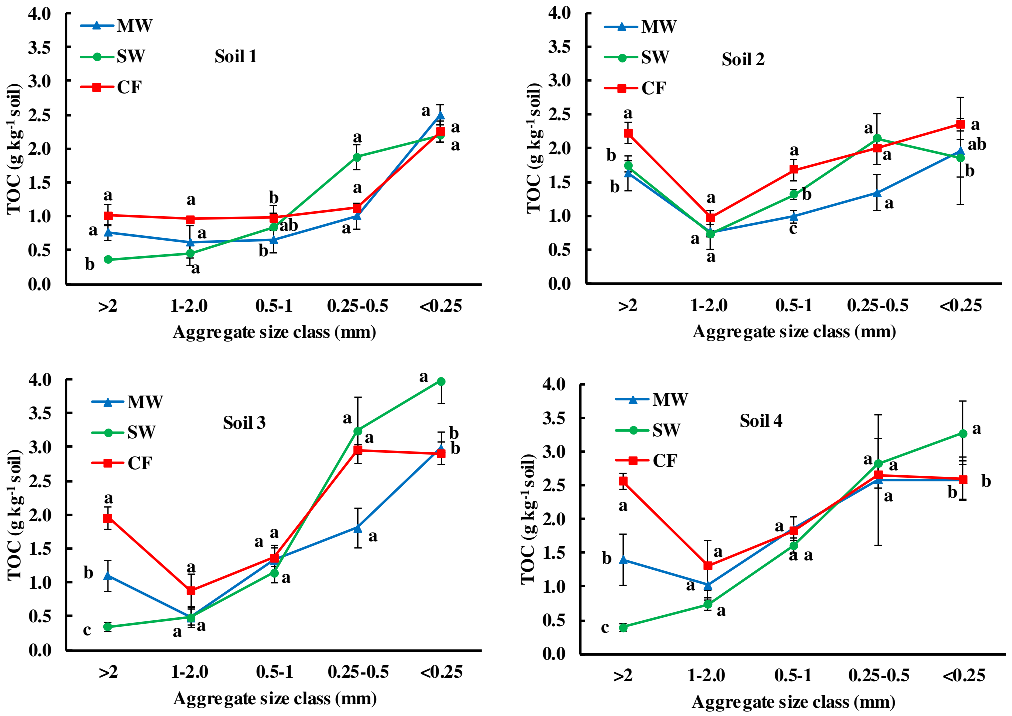
considerably compared to continuous fallow. With increase in soil depth, CPC of all aggregate size fractions at 7.5-15 cm depth was almost similar to that at 0-7.5 cm depth (Fig 4.17), but it decreased considerably at 15-30 cm depth (Fig 4.18).

Long-term application of FYM and rice straw, alone or in combination, in Soil 2, Soil 3 and Soil 4 resulted in increased C accumulation in all aggregate size fractions, the effect being more pronounced on macro-aggregates than on micro-aggregates. Aggregate associated C primarily depends on the amount of intra aggregate particulate organic matter (iPOM) in soil. Due to physical protection, iPOM in macro-aggregates are subjected to slower decomposition and thus, it stays more in macro-aggregate than in micro-aggregates. More recalcitrant nature of partially decomposed iPOM slows down the decomposition rate leading to higher C density in macro-aggregates (Elliot 1986). Long-term addition of FYM and rice straw containing easily available C substrates increased the microbial activity of soils which resulted in higher incorporation of iPOM in the macro-aggregates (Haynes 1993). Aoyama *et al* (1999) reported added organic matter first enters the soil in particulate form and during decomposition; it gradually stabilizes the soil macro-aggregates. In the present study, Soil 4 received combined application of FYM and rice straw and thus higher C input which resulted in greater macro-aggregate associated C compared to other soils. Several other studies have also reported higher macro-aggregate associated C than in micro-aggregates (Saroa and Lal 2003, Mikha and Rice 2004). In the present study, organic amendments were applied to surface soil; therefore, the decomposition products did not move to the lower depths resulting in poor C stabilization in aggregates at 15-30 cm depth. In surface 7.5 cm soil, CPC of MicA was observed to be higher in most cases than other aggregate fractions even when these had relatively lower C concentration than macro-aggregates. The reason is that the proportion of micro-aggregates was higher than macro-aggregates to such an extent that C concentration within those aggregates did not contribute considerably towards their CPC.

4.4.7 Total nitrogen

Average Total N in surface soil (0-7.5 cm) ranged from 495 to 1135 mg kg^{-1} (Table 4.26). Soil 4 had the highest and Soil 1 the lowest total N concentration. Soil 2, Soil 3 and Soil 4 had 67, 82 and 129% higher total N concentration than Soil 1. Maize-wheat sequence significantly lowered total N concentration (by 23 and 15%, respectively) in Soil 1 and Soil 2 compared to continuous fallow (Fig 4.19). However, soybean-wheat system significantly improved total N (by 11%) in Soil 4 over continuous fallow. Maize-wheat system in Soil 3 and Soil 4 and soybean-wheat system in Soil 1, Soil 2 and Soil 3 were at par with continuous fallow in total N concentration. In soil with low (Soil 1) and intermediate fertility (Soil 2), lower total N in cropped soils compared to fallow soils might be attributed to the significantly lower total organic C concentration in these cropped soils compared to fallow. Maize-wheat system in Soil 1 and Soil 2 had higher nitrification potential compared to other soils and there

Depth= 0-7.5 cm



Depth= 7.5-15 cm

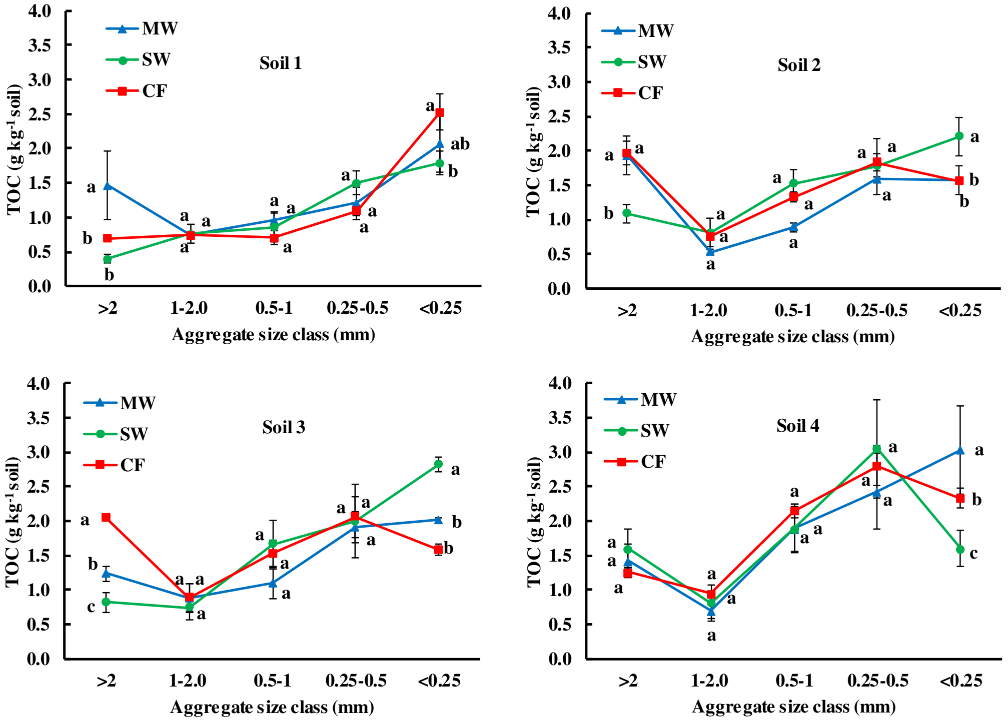


Fig 4.17 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on C preservation capacity of different aggregate size in four soils at 0-7.5 and 7.5-15 cm depths. Line bars represent standard deviation. For a given aggregate size, values labelled with different alphabets differ significantly ($p < 0.05$).

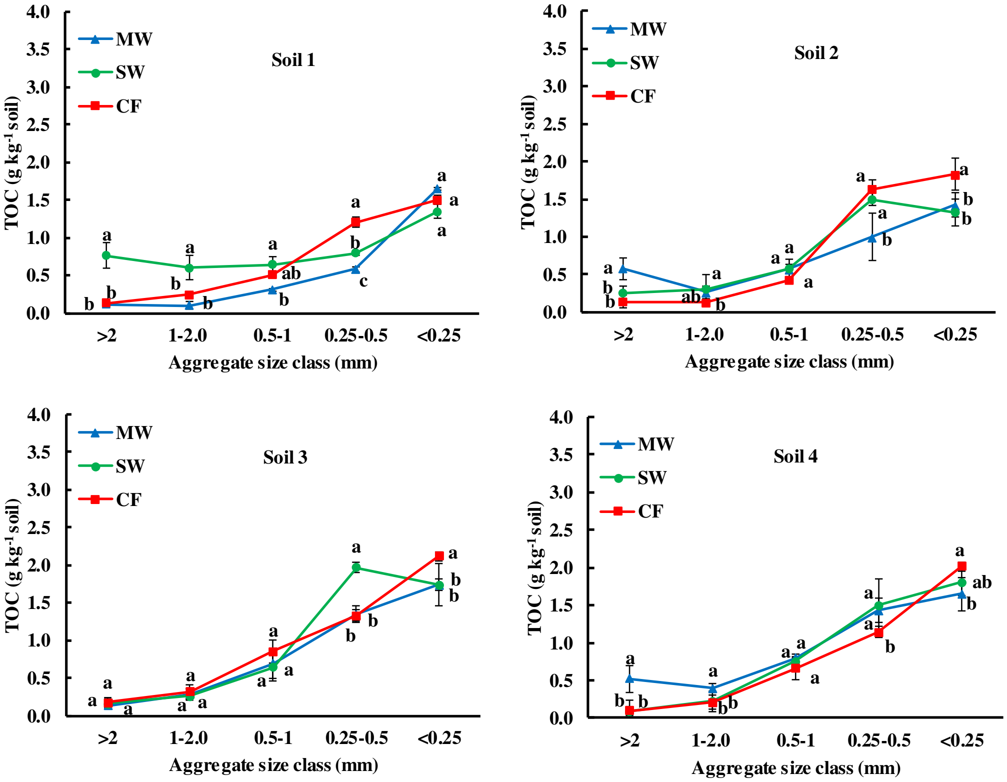


Fig 4.18 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on C preservation capacity of different aggregate size in four soils at 15-30 cm depth. Line bars represent standard deviation. For a given aggregate size, values labelled with different alphabets differ significantly ($p < 0.05$).

Table 4.26 Total N concentration (mg kg^{-1}) in four soils and under maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths

Soil	Depth (cm)				
	0-7.5	7.5-15	15-30	30-45	45-60
S1	495^{d}	708^{c}	165^{d}	296^{a}	295^{b}
S2	828^{c}	778^{b}	352^{c}	325^{a}	340^{a}
S3	901^{b}	811^{b}	493^{a}	337^{a}	281^{b}
S4	1135^{a}	1073^{a}	443^{b}	315^{a}	335^{a}
Land use					
MW	800^{b}	774^{b}	353^{b}	299^{b}	329^{a}
SW	863^{a}	870^{a}	355^{b}	320^{ab}	300^{b}
CF	856^{a}	885^{a}	383^{a}	336^{a}	310^{ab}
LSD (0.05)					
S	50	54	43	NS	42
CS	43	37	19	NS	23
S*CS (S same)	95	80	42	78	50
S*CS (CS same)	107	82	53	82	57

S=Soil CS=Cropping System NS=Not Significant

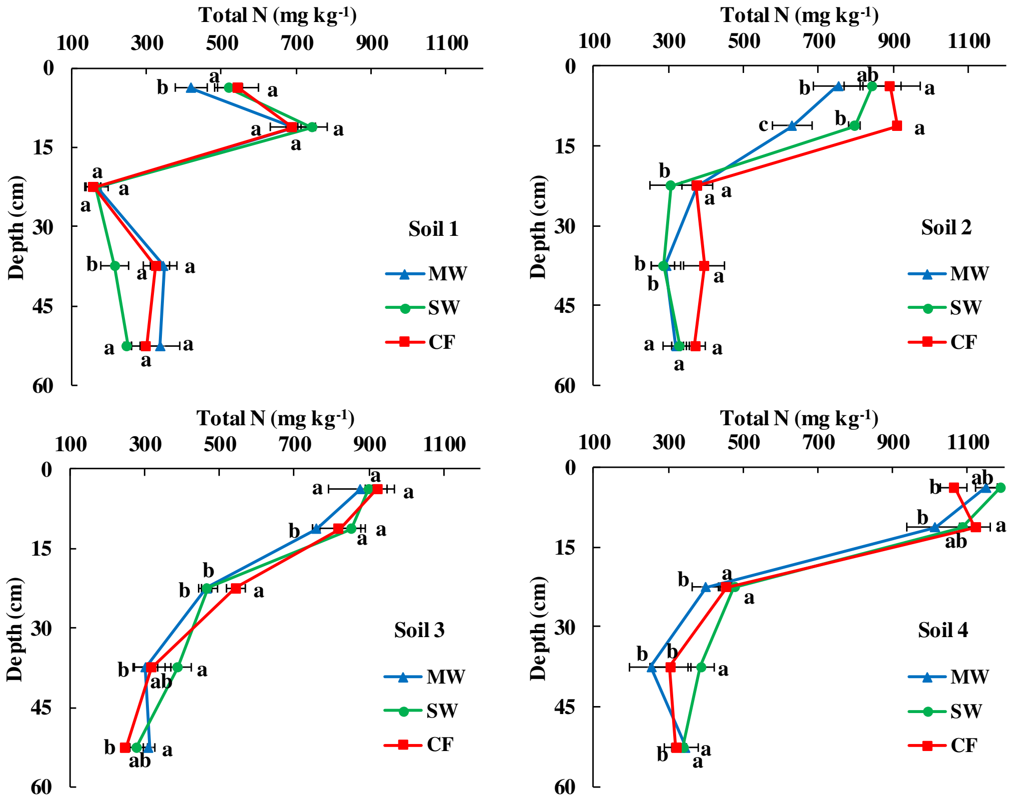


Fig 4.19 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on depth distribution of total N in four soils. Line bars represent standard deviation. Values labelled with same letters at a given depth do not differ significantly ($p < 0.05$).

could be higher leaching of NO_3^--N. These factors might have contributed to lower total N concentration under maize-wheat compared to fallow in Soil 1 and Soil 2.

With increase in soil depth, the concentration of total N decreased upto 15-30 cm depth in Soil 2 to Soil 4 (Table 4.26 and Fig 4.19). In Soil 1, total N concentration increased at 7.5 cm depth followed by decrease at 15-30 cm depth. In the deeper soil layers below 30 cm, the total N concentration stayed almost constant or decreased gradually. In deeper soil layers, the effect of cropping and continuous fallow on total N concentration was not discernible. Similar result under continuous maize cultivation in loam and sandy loam soils were also reported by Lou *et al* (2012).

4.5 Effect of maize-wheat, soybean-wheat and fallow on biological pools of C and N

4.5.1 Mineralizable carbon

Cumulative C mineralization after 64 days of incubation of surface soil ranged from 232.3 to 513.4 mg C kg^{-1} in four soils drawn from different land-uses in the field (Table 4.27). Averaged across land-uses, the cumulative C mineralization in the four soils did not differ significantly. Cropping significantly influenced cumulative C mineralization in Soil 1 and Soil 2 compared to fallow. In both the soils, C mineralization was significantly lower under maize-wheat and soybean-wheat systems compared to continuous fallow by 34 to 44% and 31 to 54%, respectively (Fig 4.20). On the contrary, cropped and fallow soils did not differ significantly in C mineralization in Soil 3 and Soil 4. Cumulative amount of C mineralized in the sub-surface (7.5-15 cm) soil was lesser than in the surface soil (Fig 4.20). Four soils and cropping systems did not differ significantly in cumulative C mineralization at this depth. In the soils collected from 0-7.5 and 7.5-15 cm soil depths, the time course of C mineralization exhibited two phases: an initial flush for 3 to 5 days followed by a progressively decreasing rate of C mineralization for rest of the incubation period (Fig 4.21). Mineralization of easily decomposable organic C substrates resulted in the initial flush. Soil disturbance caused by sieving, drying and rewetting of soil samples prior to incubation caused increased solubility of humic substances, microbial death, release of aggregate protected organic C by aggregate disruption and thus accelerated organic matter decomposition showing the initial flush (Benbi and Richter 2002). Afterwards, relatively recalcitrant fractions started to mineralized showing progressively decreasing rate of mineralization (Rochette *et al* 2006). In low to intermediate fertility soils (Soil 1 and Soil 2), cultivation involving preparatory tillage and other cultural practices probably facilitated rapid oxidation and decomposition of the plant mediated organic residues in cropped soils compared to soils under continuous fallow. Much of organic matter in cropped soils might have already mineralized, whereas existing organic matter in continuous fallow had not experienced such oxidizing conditions and thus, exhibited comparatively higher C mineralization when subjected to favorable moisture and temperature conditions during incubation. No differene in C mineralization between cropping and fallow

Table 4.27 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on cumulative C mineralization after 64 days of incubation (mg C kg^{-1} soil) in four soils at 0-7.5 and 7.5-15 cm depths

Soil	MW	SW	CF	Mean
		Depth 0-7.5 cm		
S 1	297	311	449	352^{a}
S 2	289	232	513	345^{a}
S 3	345	323	372	346^{a}
S 4	355	354	415	375^{a}
Mean	321^{b}	305^{b}	437^{a}	
LSD (0.05)	S: NS	CS:34	S*CS (S same): 74	S*CS (CS same): 69
		Depth 7.5-15 cm		
S 1	202	212	284	233^{a}
S 2	174	196	209	193^{ab}
S 3	166	194	186	182^{b}
S 4	244	213	225	228^{ab}
Mean	196^{a}	204^{a}	226^{a}	
LSD (0.05)	S:36	CS: NS	S*CS (S same): NS	S*CS (CS same): NS

S=Soil CS=Cropping System NS=Not Significant

in high C soil might be attributed to shorter incubation time. In soils with high C, short-term incubation might not be sufficient to observe the differences in mineralizable C among different land-uses.

Soil 1 collected from maize-wheat plots and Soil 2 collected from both the cropped plots had significantly lower basal soil respiration (BSR) rate (by 23 to 48% and 13 to 43%, respectively) compared to fallow soils (Table 4.28). However, land-use did not influence BSR of Soil 3 and Soil 4. The soils representing 7.5-15 cm layer did not differ significantly with respect to BSR rate. Basal soil respiration is an indicator of overall microbial activity in soil (Saviozzi *et al* 2001). In soils with low (Soil 1) and intermediate fertility (Soil 2) continuous fallow probably fostered higher microbial activity than maize-wheat and soybean-wheat systems, which resulted in higher BSR. However, the differences in BSR rates may be relatively small in field conditions than the experimental values since the laboratory incubation conditions are more favorable than the ones existing in the field.

Table 4.28 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on basal soil respiration rate (mg C kg^{-1} soil day^{-1}) after 64 days of incubation in four soils at 0-7.5 and 7.5-15 cm depths

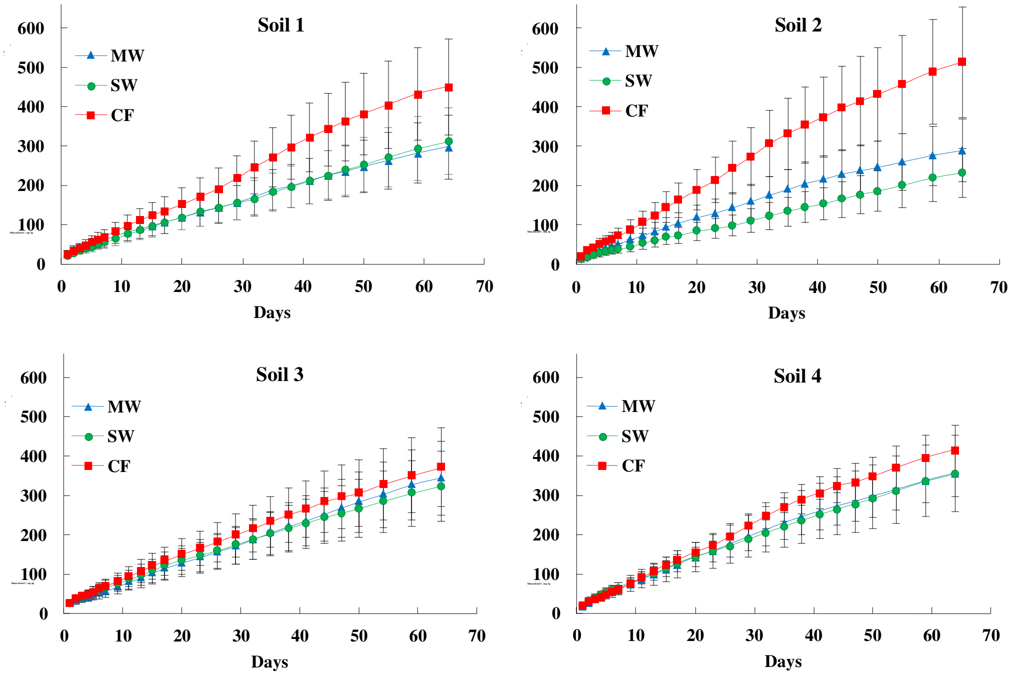
Soil	MW	SW	CF	Mean
		Depth 0-7.5 cm		
S 1	3.56	4.00	4.62	4.06^{a}
S 2	2.96	3.24	5.64	3.95^{a}
S 3	4.28	3.92	4.32	4.17^{a}
S 4	4.20	4.32	4.56	4.36^{a}
Mean	3.75^{b}	3.87^{b}	4.78^{a}	
LSD (0.05)	S: NS	CS:0.5	S*CS (S same): 1.06	S*CS (CS same): 1.25
		Depth 7.5-15 cm		
S 1	2.32	2.93	3.26	2.84^{a}
S 2	2.33	2.71	3.48	2.84^{a}
S 3	2.00	2.48	2.46	2.31^{a}
S 4	3.01	2.81	3.18	3.00^{a}
Mean	2.41^{a}	2.73^{a}	3.09^{a}	
LSD (0.05)	S: NS	CS: NS	S*CS (S same): NS	S*CS (CS same): NS

S=Soil CS=Cropping System NS=Not Significant

4.5.2 Mineralizable nitrogen

Cumulative N mineralized after 56 days of incubation of surface soils ranged from 78.4 to 93.8 mg N kg^{-1} (Table 4.29). Averaged across cropping systems, cumulative N mineralization in all the experimental soils was almost similar. In Soil 1 and Soil 2, land-use did not influence cumulative N mineralization significantly. In Soil 3 and Soil 4, maize-wheat soils showed significantly higher (by 8.5 to 9.8%) N mineralization than fallow soils. Soil 3 from soybean-wheat was at par with fallow, but Soil 4 from soybean-wheat showed significantly lower (by 8.1%) N mineralization. Cumulative amount of N mineralized in sub-surface soils was relatively low compared to surface soil and ranged between 66.2 and 93.8 mg N kg^{-1} (Table 4.29). Soils and cropping systems differed significantly in cumulative N mineralization at this depth. Temporal trends of cumulative N mineralization in four soils at 0-7.5 and 7.5-15 cm depths are presented in Fig 4.22. Maize-wheat under intermediate to high fertility (Soil 3 and Soil 4) might have accumulated higher amount of residues comprising active fractions of organic N and thus showed significantly higher cumulative N mineralization compared to continuous fallow system over time.

Depth= 0-7.5 cm



Depth=7.5-15 cm

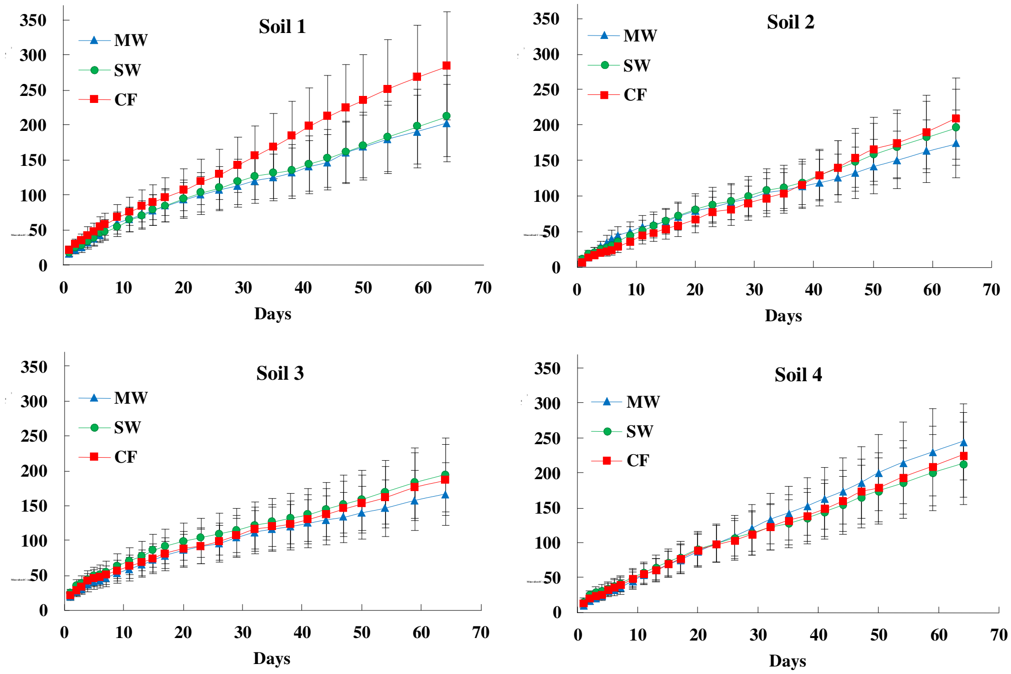
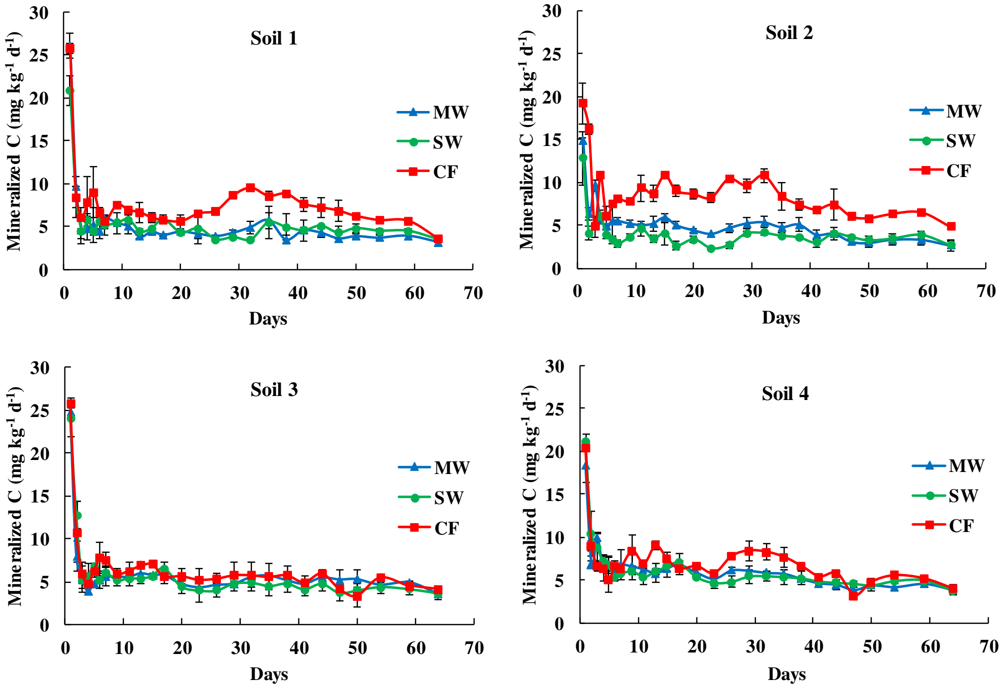


Fig 4.20 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on cumulative C mineralization after 64 days of incubation in four soils at 0-7.5 and 7.5-15 cm depths. Line bars represent standard error.

Depth= 0-7.5 cm



Depth= 7.5-15 cm

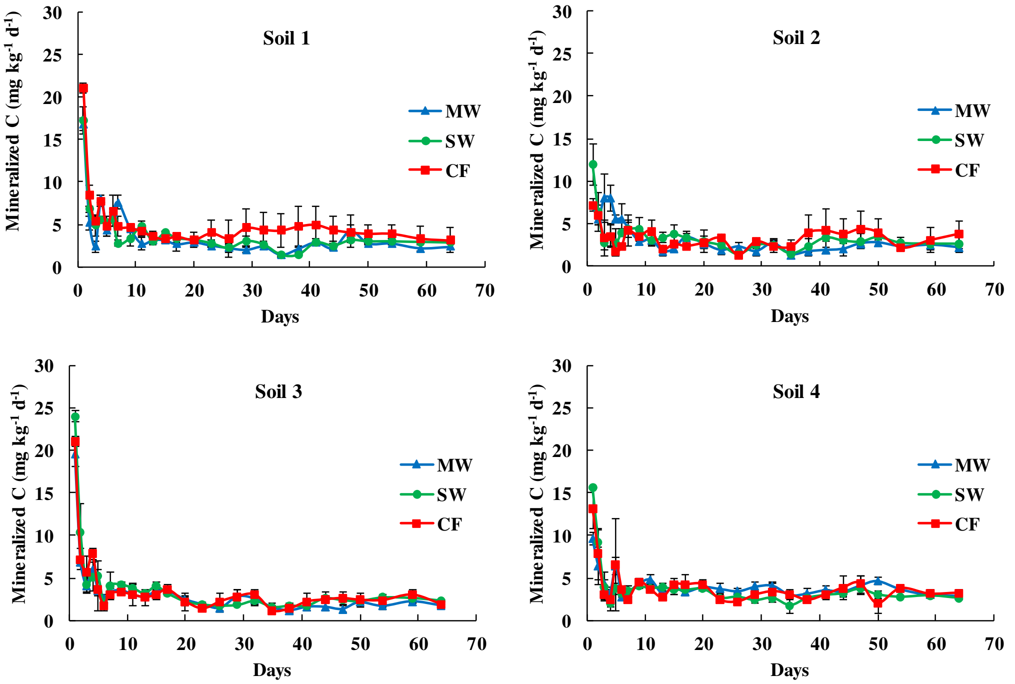


Fig 4.21 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on rate of C mineralization during 64 days of incubation in four soils at 0-7.5 and 7.5-15 cm depths. Line bars represent standard error.

Table 4.29 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on cumulative N mineralization (mg N kg^{-1}) in four soils at different depths

Soil	MW	SW	CF	Mean
		Depth 0-7.5 cm		
S 1	91.0	87.7	90.3	89.6^{ab}
S 2	91.4	93.3	89.6	91.5^{a}
S 3	91.9	84.4	84.7	87.0^{bc}
S 4	93.8	78.4	85.4	85.8^{c}
Mean	92.0^{a}	85.9^{b}	87.5^{b}	
LSD (0.05)	S:3.3	CS:2.8	S*CS (S same): 6.5	S*CS (CS same): 11.3
		Depth 7.5-15 cm		
S 1	73.2	79.3	84.7	79.1^{b}
S 2	79.8	87.2	93.8	86.9^{a}
S 3	76.5	66.2	71.4	71.4^{c}
S 4	76.5	66.7	81.9	75.0^{c}
Mean	76.5^{b}	74.9^{b}	82.9^{a}	
LSD (0.05)	S:3.8	CS:3.2	S*CS (S same): 7.2	S*CS (CS same): 9.1

S=Soil CS=Cropping System NS=Not Significant

The time course of N mineralization in soils from the cropped and fallow plots revealed that rate of N mineralization was higher in first two weeks irrespective of soil depth and soil fertility. During the first two weeks, cumulative N mineralization ranged from 51.8 to 77.0 and 29.4 to 66.5 mg kg^{-1} at 0-7.5 and 7.5-15 cm depths, respectively. Thereafter, N mineralization exhibited a relatively slower rate with increase in incubation time. The faster N mineralization during initial period may be attributed to rapid growth of microbial population due to higher availability of easily metabolizing C and organic N and thus, higher microbial activity. With progress in time, recalcitrant organic N fractions started contributing to N mineralization which exhibit relatively slower N mineralization. Values of cumulative N mineralization in the present study were slightly higher than reported by Haer and Benbi (2003) (8.2 to 75.6 mg N kg^{-1}). Higher values of cumulative N mineralization in this study might be attributed to higher level of soil organic C (6.31 to 11.13%) compared to their experimental soils (< 1%). Bhat *et al* (2018) have reported trend of N mineralization in soils receiving different organic and inorganic amendments similar to the present study. Vimlesh and Giri (2011) have also reported increased rate of N mineralization during initial weeks which progressively decreased with incubation time.

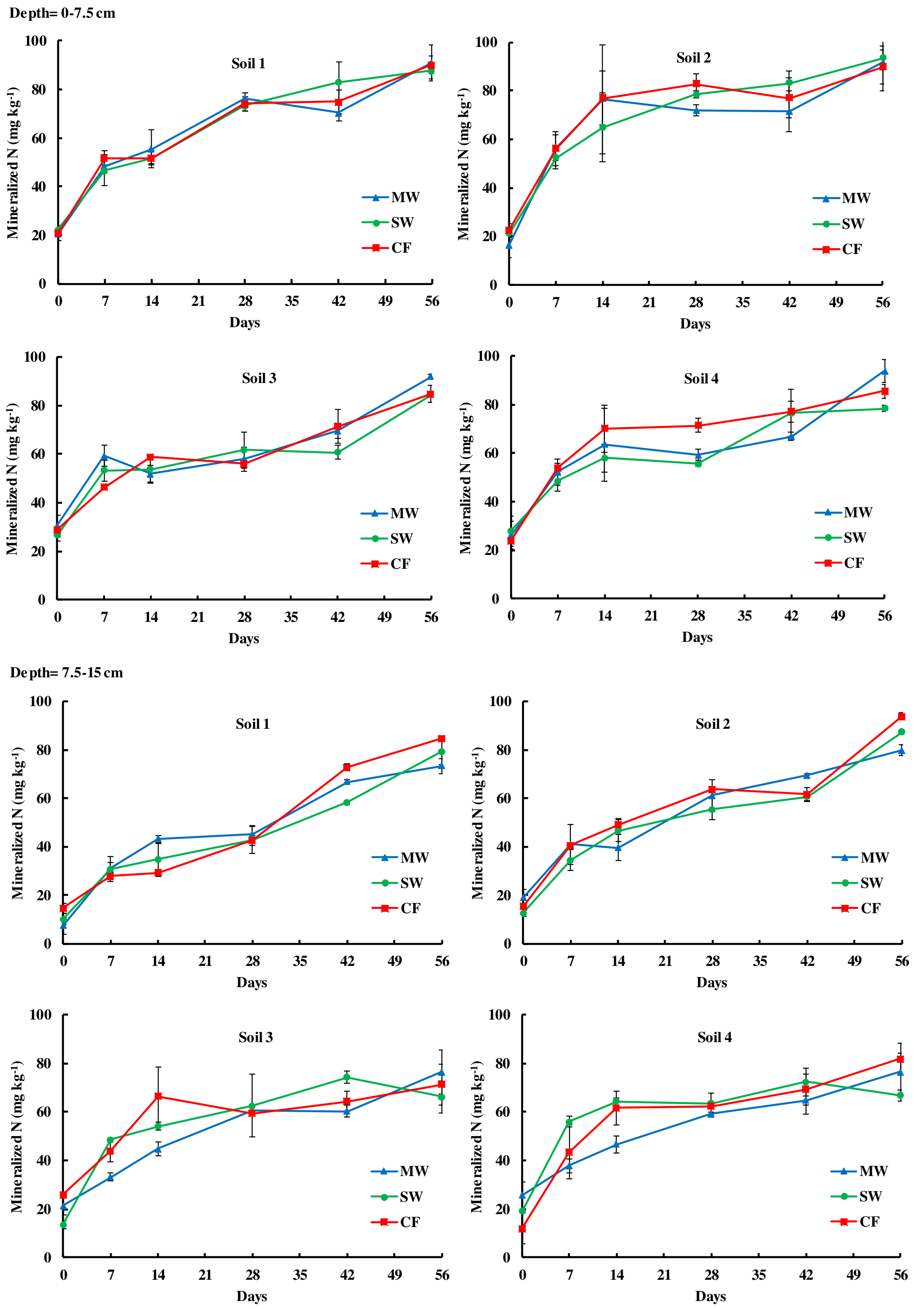


Fig 4.22 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on cumulative N mineralization (mg N kg^{-1} soil) after 56 days of incubation in four soils at 0-7.5 and 7.5-15 cm depths. Line bars represent standard deviation.

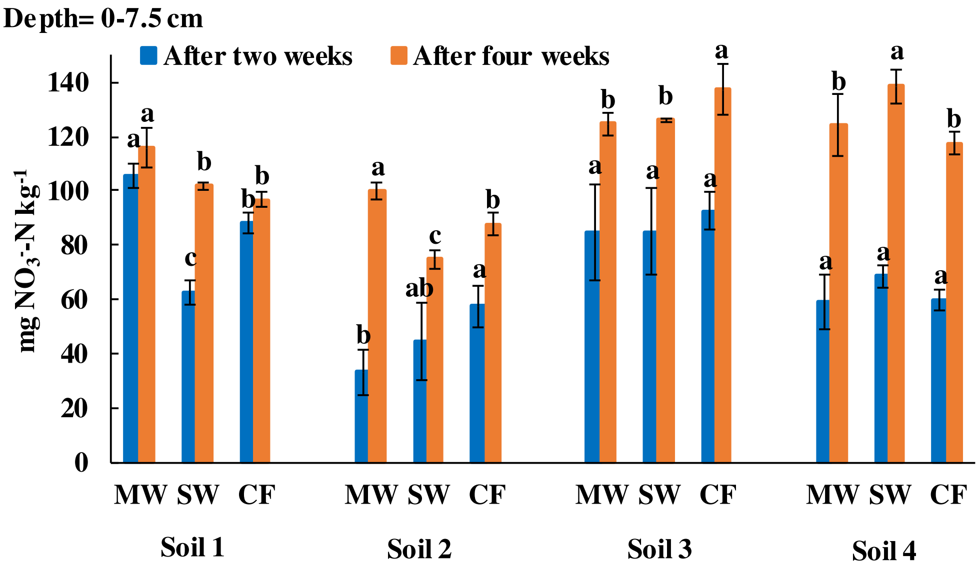
4.5.3 Nitrification potential

Mean nitrification potential after 28 days of incubation of surface soils ranged from 87.4 mg NO_3^-N kg^{-1} (Soil 2) to 129.2 mg NO_3^-N kg^{-1} (Soil 3) (Table 4.30). On average, Soil 2 had 16.4% lower nitrification potential compared to Soil 1 whereas Soil 3 and Soil 4 had 21 to 23% higher nitrification potential than Soil 1. Cropping systems significantly influenced nitrification potential of soils. Soil 1 and Soil 2 under maize-wheat system had significantly higher (by 13 to 19%) nitrification potential compared to fallow. Conversely, Soil 3 under maize-wheat had significantly lower (by 9%) nitrification potential than fallow. No statistically significant difference in nitrification potential of Soil 4 was observed between maize-wheat and fallow. In low fertility soil (Soil 1), soybean-wheat system did not differ from fallow but in soils with intermediate fertility (Soil 2 and Soil 3), nitrification potential under soybean-wheat was significantly lower (by 14 and 8%, respectively) than fallow. On the contrary, in high fertility soil (Soil 4), soybean-wheat resulted in significantly higher (by 17.8%) nitrification potential than fallow. Amount of N nitrified in cropped and fallow soils was higher after 28 days of incubation compared to 14 days of incubation (Fig 4.23). On average, the amount of NH_4^+-N nitrified after 28 days of incubation was 22, 93, 48 and 102% higher in Soil 1, Soil 2, Soil 3, Soil 4, respectively, compared to that after 14 days of incubation. Tabatabai *et al* (1992) also reported significant influence of cropping systems and

Table 4.30 Nitrification potential (mg NO_3^--N kg^{-1}) of four soils and maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) at different depths after 4 weeks of incubation

Soil	Depth (cm)	
	0-7.5	7.5-15
S1	104.6^b	111.9^a
S2	87.4^c	81.2^c
S3	129.2^a	97.3^b
S4	126.7^a	114.6^a
Land use		
MW	116.0^a	97.8^b
SW	110.2^b	105.5^a
CF	109.7^b	100.4^b
LSD (0.05)		
S	5.0	5.86
CS	4.3	5.07
S*CS (S same)	9.5	11.3
S*CS (CS same)	11.4	16.2

S=Soil CS=Cropping System NS=Not Significant


Depth= 0-7.5 cm

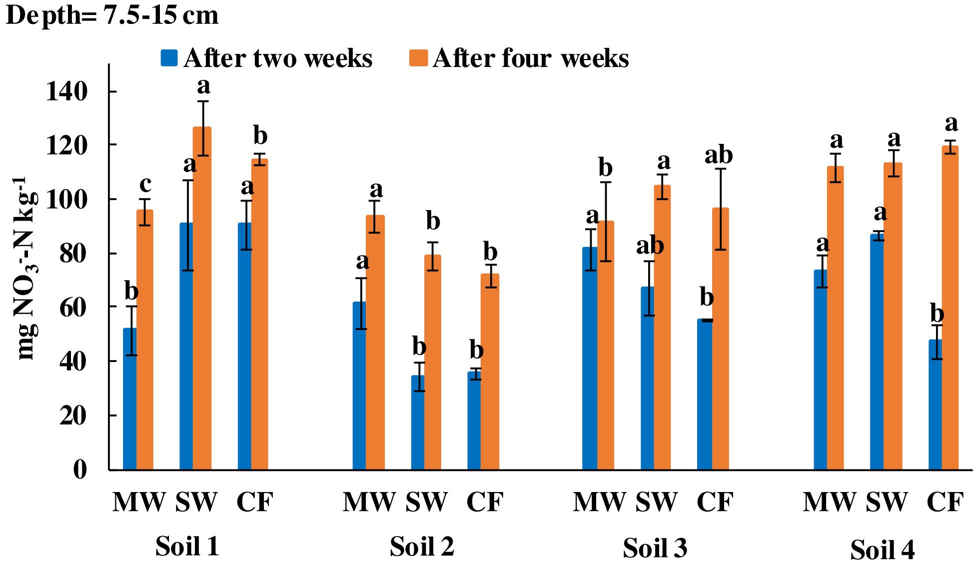

Depth= 7.5-15 cm

Fig 4.23 Effect of maize-wheat (MW), soybean-wheat (SW) and continuous fallow (CF) on nitrification potential (mg NO_3^--N kg^{-1}) in four soils at 0-7.5 and 7.5-15 cm depths after two and four weeks of incubation. Line bars represent standard deviation. For a given incubation time, bars labelled with same alphabets within a soil do not differ significantly ($p < 0.05$).

N fertilizer on nitrification potential of soils. Their findings showed that plots receiving NH_4^+ containing or forming fertilizer exhibited significantly higher nitrification potential over the unfertilized plots. Similarly, in the present study, maize-wheat system receiving larger amount of NH_4^+ forming fertilizer (urea) showed significantly higher nitrification in Soil 1 and Soil 2 compared to fallow. Greater nitrification in soils receiving higher NH_4^+-N was due to addition of direct source of NH_4^+-N that increased the microbial population responsible for nitrification and/or enhanced the efficiency of nitrifiers by inducing the enzymes responsible for converting NH_4^+ to NO_3^- (Tabatabai 1992). Higher nitrification in Soil 1 and Soil 2 indicates greater potential for NO_3^- leaching. Soybean based systems also have higher NH_4^+-N in soil due to biological N_2 fixation; however, being easily available to plants it does not influence the nitrification potential. Therefore, soybean-wheat system showed significantly lower nitrification potential compared to continuous fallow. Significant increase in the amount of NO_3^--N with incubation time from 14 to 28 days suggests that notable amount of added NH_4^+-N in soils was still to be nitrified at the end of 14 days and the rate depended on soil fertility.

Except Soil 1, all experimental soils exhibited relatively lower nitrification potential at 7.5-15 cm depth than surface soil (0-7.5 cm). In soil with low fertility (Soil 1), nitrification potential of sub-surface soil was similar to surface soil. On average, maize-wheat did not influence nitrification potential compared to continuous fallow, however, soybean-wheat significantly lowered nitrification potential of soil.

CHAPTER V

SUMMARY

The present study was conducted to assess the effect of maize-wheat, soybean-wheat and continuous fallow on carbon (C) and nitrogen (N) dynamics in four soils of different antecedent C level. The specific objectives of the study were to study the effect of cropping system on organic matter and N dynamics, aggregation and C and N turnover in soils of different antecedent C level. Field experiments involving maize-wheat, soybean-wheat and continuous fallow had been in progress since kharif 2015 on four soils at research farm of Department of Soil Science, Punjab Agricultural University, Ludhiana. The experimental soils were sandy loam (60% sand and 17% clay) in texture and classified as Typic Ustorthents. Prior to the initiation of the present experiment, long-term applications of farmyard manure (FYM) and rice straw, alone or in combination, in three soils and no application of any organic amendment in one soil, resulted in four soils of different antecedent C level. Soil 1 received no organic amendment; whereas Soil 2, Soil 3 and Soil 4 received FYM, rice straw and FYM plus rice straw, respectively for a period of 16 years. These treatments were discontinued at the start of the present experiment in 2015 and in each soil three land-uses involving two cropping sequences viz. maize-wheat and soybean-wheat and a continuous fallow were introduced as treatments. Recommended rates of fertilizer NPK were applied to each crop.

Soil samples were collected in May, 2018 at wheat harvest from each treatment (cropped and fallow) at 0-7.5, 7.5-15, 15-30, 30-45 and 45-60 cm depth. The samples were analyzed for selected physical and chemical properties and C and N pools in soils using standard methods. Root and shoot biomass of maize, soybean and wheat were recorded at their respective maximum vegetative growth stages. Root samples were collected from 0-15, 15-30 and 30-45 cm depths. Root and shoot samples of all the crops were analyzed for total C using CHN analyzer. In order to compute changes in soil C stocks, archived soil samples collected in May, 2015 were analyzed for total organic C (TOC).

All the four soils were neutral to alkaline in reaction (pH 6.8 to 8.0) and non-saline (EC = 0.30 to 0.45 dS m^{-1}). While the four soils differed significantly in mineral N in the surface layer (0-7.5 cm), cropping systems and continuous fallow did not influence mineral N significantly. Soil 2 had the highest and Soil 3 the lowest mineral N concentration. Mineral N concentration decreased with soil depth. In line with TOC, the highest concentrations of available P and K were observed in Soil 4 and the lowest in Soil 1. Cropped Soil 2 differed significantly from fallow in available P concentration and had 20% lower concentration. Available K concentration in cropped soils was 12 to 61% lower compared to fallow soils. Concentration of both available P and K decreased gradually with soil depth. Similar to available P and K, the total N at surface soil (0-7.5 cm) in four soils was highest in Soil 4 and lowest in Soil 1. Average total N concentration in the surface soil ranged from 495 to 1135 mg kg^{-1} in the four soils. In Soil 1 and Soil 2, maize-wheat system lowered total N by 15 to 23% compared to continuous fallow. Concentration of total N decreased gradually with soil depth. Therefore, the four soils differed not only in antecedent C level but also in available nutrient status and overall soil fertility. Soil bulk density in surface soils varied within 1.61 to 1.71 Mg m^{-3}, which increased at lower depths. Cropping and continuous fallow did not influence total water stable aggregates in four soils, however, distribution of aggregates into different size classes was impacted. Under maize-wheat sequence, Soil 3 and Soil 4 had significantly lower proportion (by 5.5 to 5.9%) of coarse macro-aggregates (CMacA, >2 mm size) compared to continuous fallow. Soybean-wheat system resulted in a similar decline (by 5.8 to 14.2%) in all the four soils. Maize-wheat system had significantly higher (by 3.4 to 9.8%) amount of micro-aggregates (MicA, < 0.25 mm size) compared to fallow in all soils except Soil 4. However, under soybean-wheat system higher proportion of MicA compared to continuous fallow (by 10.7 to 12.7%) was observed only in Soil 3 and Soil 4. Compared to 0-7.5 cm soil depth, amount of total water stable aggregates and their distribution among various size classes under different land-uses did not exhibit a noticeable change at 7.5-15 cm depth. Macro-aggregates in all soils had higher C concentration compared to micro-aggregates. In surface soil, C concentrations in CMacA, meso-aggregate (MesoA, 2-0.25 mm size) (average) and MicA were highest in Soil 4 and lowest in Soil 1. Carbon concentrations in CMacA, MesoA and MicA in different soils ranged from 8.4 to 15.0, 6.1 to 20.1 and 5.5 to 8.3 g kg^{-1} aggregate, respectively. The cropping systems and continuous fallow did not affect aggregate associated C concentrations in different soils. Depending upon antecedent soil C level, maize-wheat and soybean-wheat systems had 24 to 45% and 22 to 84% lower carbon preservation capacity (CPC) of CMacA compared to that in continuous fallow. Carbon preservation capacity of MesoA and MicA did not differ considerably in cropped soils compared to fallow. Carbon preservation capacity of aggregate of different sizes at 7.5-15 cm depth was similar to 0-7.5 cm depth, but decreased considerably at 15-30 cm depth.

Antecedent C level in four soils followed the order Soil 4 > Soil 3 > Soil 2 > Soil 1 both in surface (0-7.5 cm) and sub-surface (7.5-15 cm) soils. After three years of cropping and continuous fallow, the TOC level in four soils followed an order similar to antecedent status but the magnitude of differences among soils was narrowed down. In soils with low and intermediate antecedent C level, maize-wheat system resulted in 11.7 to 21.6% decline in TOC compared to continuous fallow. Comparison of soil C stock in the plough layer (0-15 cm) revealed that Soil 1 with lowest antecedent C level accrued C (8.8%) while Soil 4 with highest antecedent C level lost C (5.2%) as a result of cropping. Both TOC and soil C stocks decreased gradually with soil depth. Total soil C stocks (Mg ha^{-1}) in 60 cm profile followed the order Soil 4 (45.6) > Soil 3 (43.2) > Soil 2 (39.7) > Soil 1 (33.4). The proportion of water soluble C (WSC) to TOC in four soils (0-7.5 cm) followed the order Soil 2 (0.48%) > Soil 1 (0.42%) > Soil 3 (0.33%) = Soil 4. Water soluble C under maize-wheat system was 17.7 and 29.5% lower compared to continuous fallow in Soil 3 and Soil 4, respectively, whereas soybean-wheat system recorded 29.3 and 40.5% lower WSC compared to fallow in Soil 2 and Soil 4, respectively. Concentration of WSC decreased with soil depth and did not follow a consistent trend. Hot water soluble C (HWSC) comprised 2.9 to 5% of TOC in different soils. Hot water soluble C concentration was lower by 18.1 to 25% under maize-wheat compared to fallow in all soils except Soil 3. Soybean-wheat system had significantly lower (by 18.1 to 20.8%) HWSC compared to continuous fallow in all soils except Soil 1. Hot water soluble C concentration decreased with soil depth. Proportion of permanganate oxidizable C ($KMnO_4$-C) to TOC in different soils followed the order Soil 2 (15.5%) > Soil 4 (14.0%) > Soil 1 (13.1%) > Soil 3 (9.8%). Both maize-wheat and soybean-wheat systems had lower concentration of $KMnO_4$-C in all soils compared to continuous fallow. Maize-wheat system exhibited a greater decrease (21.3 to 29.2%) in $KMnO_4$-C than soybean-wheat (16.5 to 18.8%). $KMnO_4$-C concentration decreased gradually with soil depth. Characterization of TOC in terms of ease of oxidation or lability with three solutions of $K_2Cr_2O_7$:H_2SO_4 ratio 1:0.5, 1:1 and 1:2 showed that majority of differences in organic C pools were in very labile (C_{VL}) and recalcitrant (C_R) pools. Very labile pool and C_R pools constitued 27.3 to 48.3% and 21.7 to 51.3% of TOC, respectively. In soil with low antecedent C, maize-wheat system had significantly higher (48.2%) C_{VL} pool compared to continuous fallow. In soil with intermediate C level (Soil 2), the maize-wheat system exhibited significantly higher recalcitrant (C_R) pool (30.3%) compared to continuous fallow. In this soil (Soil 2), soybean-wheat resulted in significantly lower proportion (43.7%) of C_{VL} pool, but higher proportion (28.2%) of C_R pool compared to continuous fallow. In Soil 3 and Soil 4, maize-wheat system had significantly lower proportion (by 27.4 to 34.6%) of C_{VL} pool compared to continuous fallow. In Soil 4, both the cropping systems had significantly higher proportion of C_R pool (31.7 to 39.8%) compared to continuous fallow. With increase in soil depth, proportion of C_{VL} pool decreased, that of labile (C_L) and less labile (C_{LL}) pools remained unchanged, but that of C_R pool increased slightly.

Cumulative C mineralization after 64 days of incubation of surface soils ranged from 232 to 513 mg C kg^{-1}. Soil 1 and Soil 2 drawn from cropped plots showed 31 to 54% lower cumulative C mineralization compared to that from fallow plots. Cumulative N mineralization after 56 days of incubation of surface soils ranged from 78 to 94 mg N kg^{-1}. Maize-wheat system in Soil 3 and Soil 4, exhibited significantly higher (by 8.5 to 9.8%) cumulative N mineralization than continuous fallow. Soybean-wheat system exhibited significantly lower (by 8.1%) cumulative N mineralization only in Soil 4. Nitrification potential after 28 days of incubation of surface soils ranged from 87.4 to 129.2 mg NO_3^-N kg^{-1}. Compared to continuous fallow, nitrification potential under maize-wheat system was higher in Soil 1 and Soil 2 (13 to 19%) but lower in Soil 3 (by 9%), whereas it was similar to continuous fallow in Soil 4. Soybean-wheat system influenced the nitrification potential in soils with intermediate and high antecedent C level. In soils with intermediate C status, the nitrification potential was significantly lower (by 8 to 14%), but in high C soil, it was significantly greater (by 17.8%) compared to continuous fallow.

The results of the study showed that, cropping systems and continuous fallow differentially impacted soil C and N pools and the effects varied with the antecedent soil C level. After three years of management, continuous fallow maintained a higher level of TOC than maize-wheat and soybean-wheat sequences in all the soils; however, the three land-uses resulted in 0.55 to 1.41 Mg ha^{-1} C sequestration in surface 0-15 cm soil with low antecedent C level but 0.04 to 3.64 Mg ha^{-1} C loss in soil with high fertility. Cultivation reduced water extractable pools of soil organic C (WSC and HWSC) and the antecedent soil C modulated the extent of decline. Cultivation resulted in disruption of soil aggregates leading to preponderance of micro-aggregates than macro-aggregates compared to fallow. However, the carbon preservation capacity of aggregates was similar under different land-uses. Fallow soils showed greater C mineralization potential than cropped soils when the soil fertility was low to moderate. Compared to soybean-wheat and continuous fallow, maize-wheat system exhibited higher N mineralization in soil with moderate to high fertility and higher nitrification potential in soil with low to moderate fertility. The results suggested that prior to selecting a cropping system, the prevailing organic C status of the soil must be considered; it was the antecedent C level which decided the magnitude and direction of changes in C and N dynamics within a given management practice. However, further research on long-term effects of legume and non-legume based cropping systems on soil C and N dynamics is required. Apart from the antecedent soil C level, the quality of the prevailing soil organic C may also influence the C and N dynamics. The study also provided a scope for further research on how both quantity and composition of soil organic matter influenced the changes in C and N dynamics under different land-uses.

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