संरक्षण कृषि में फसल अवशेषों और पोषक तत्व प्रबंधन विकल्पों से प्रभावित मृदा जैविक कार्बन की स्थिरता

STABILITY OF SOIL ORGANIC CARBON AS AFFECTED BY CROP RESIDUE AND NUTRIENT MANAGEMENT OPTIONS UNDER CONSERVATION AGRICULTURE

अमित कुमार दाश

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Stability of soil organic carbon as affected by crop residue and nutrient management options under conservation agriculture

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This is to certify that the thesis entitled **"Stability of soil organic carbon as affected by crop residue and nutrient management options under conservation agriculture"** submitted to the Faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfilment of the requirements for the degree of **Master of Science** in **Soil Science and Agricultural Chemistry** by **Mr. Amit Kumar Dash, Roll No. 21186** embodies the results of the *bonafide* research work carried out by him under my guidance and supervision. No part of the study reported here has so far been submitted for any other degree or diploma.

It is further certified that the assistance and help received during the course of the investigation has duly acknowledged by him.

Place: New Delhi
Date: 06/07/2020

(Dr. Brahma S. Dwivedi**)**
Chairman
Advisory Committee

Dedicated to
"My family
&
My chairman"

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(Amit Kumar Dash)

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Chapter 1 Introduction

Soil organic carbon (SOC) plays important role in improving soil health, crop productivity and sustainability of the agricultural production systems. The SOC is a chief sink for atmospheric carbon dioxide (CO_2), assuming a greater role in impending climate change scenario. The labile SOC is crucial in the short-term turnover of C, which affects soil functioning and nutrient cycling. On the other hand, the recalcitrant SOC pools are imperative in C sequestration process (Dey *et al*., 2018). Soil C sequestration is a win-win strategy that enhances food production and increases soil quality (Lal, 2004). Carbon may be stored in soils for long period, but it is lost into the atmosphere which is controlled by different factors *viz*., climatic conditions, natural vegetation, soil texture, and drainage. According to The "4‰ initiative" (4 per 1000, 2017), a "4‰" annual growth rate of the soil C stock would make it promising to control the present increase in atmospheric CO_2. Conservation agriculture (CA) helps in build-up soil C stock in agricultural lands which is crucial to improve soil fertility and agricultural production along with achieving the long-term objective of limiting CO_2 increase in the atmosphere. The prevalent agricultural practices involving mono-cropping, intensive tillage and removal or burning of CR accelerate soil erosion, soil degradation and environmental pollution (Montgomery, 2007) and eventually disturb ecosystem functions. The loss of SOC stock varies between 13 and 26% under conventional agriculture in Brazilian semi-arid region (Medeiros *et al.*, 2020).

Conservation agriculture is a crop management system comprised of minimum soil disturbance, maintenance of CR (CR) soil cover, and crop diversification through inclusion of legumes. In the last decade, the CA has been popularized in India, especially in the northwestern parts of Indo Gangetic Plains (IGP). Currently ~ 1.5 Mha of arable area is managed under CA in India (Kassam *et al.*, 2019). Maize-wheat systems consist over 1.8 Mha area in IGP, and is a potential alternative to diversify rice-wheat and other rice-based cropping systems. With introduction of high yielding hybrids of maize, maize-wheat cropping system is the 3rd most important cropping system after rice-wheat and rice-rice having 1.8 Mha area in IGP, and has a high potential for widespread adoption of CA practices (Jat *et al.*, 2019).

Conservation agriculture has a great potential for C sequestration. The cereal CR, if not managed tactfully, can become potential source of CO_2 emission as highlighted in the recent times in IGP, where burning of residue by the farmers resulted in major air pollution causing severe health problems. The CA offers an excellent CR management strategy, wherein CR serves as a precious resource for C sequestration, improvement in soil quality, and better soil aggregation. Nevertheless, CR load needs to be standardised under CA in the IGP for a better SOC stabilization, without compromising the productivity and sustainability of the cropping systems. Retaining CR on the soil surface along with zero-tillage (ZT), results in soil processes that lead to enhanced soil C (Gathala *et al.*, 2014). Management of CR is critical for increasing soil organic matter (SOM) and nutrient supplying capacity, and also for decreasing the ill-effects of CR burning. The surface-placed CR showed a slow decomposition (Yadvinder-Singh *et al.,* 2010). Stable aggregates are indicators of favourable soil structure and are important to stabilization of SOC (Balesdent *et al.*, 2000). Due to continuous intensive tillage, loss of C-rich macro-aggregates occurs with simultaneous gain of C-depleted micro-aggregates (Six *et al.,* 2000). On contrary, occlusion of SOC within soil aggregates by adopting ZT reduces the decomposition rate of SOM (Paustian *et al.,* 2000; Six *et al.,* 2000). Soil structures are the core of soil physical condition, and their formation governs C in long-lived pools. Their internal pore characteristics create the physical environment enabling or disabling connections and thus carbon stabilization or loss (Kravchenko *et al.,* 2015).

The decomposition rate of SOC largely depends on temperature, hence it is interesting to study the influence of raised temperature on SOC associated with various soil aggregate size fractions (Ghosh *et al.*, 2016). On the other hand, this might envisage the stability of aggregate-associated SOC in the current climate change scenario. This also assists estimation of future global SOC stocks. Under CA, lower SOC decay rates were witnessed at higher temperature, compared with conventional tillage practices (CT). In CT the SOC from lower layers showed higher temperature sensitivity compared with that under CA (Parihar *et al*., 2019). Judicious nutrient management strategies affect the quality of SOM, and in turn stability and temperature sensitivity of SOC. The decomposition pattern of labile and recalcitrant SOM is very controversial (Miller *et al*., 1991). The global anticipated soil C stock mostly depends on the temperature sensitivity of the resistant SOC pools (Fang *et al*., 2004). The major uncertainty in projections of CO_2 concentration in the atmosphere is the sensitivity of soil C to warming.

The change in SOM decomposition with temperature is indicated by parameter Q_{10}. The Arrhenius equation shows the variation in relative reaction rates with temperature (Conant *et al*., 2011). The decomposition of soil-derived C is enhanced by addition of readily available C substrate, particularly in soils treated at higher temperature levels (Thiessen *et al.,* 2013). Tropical soils are less sensitive owing to a large store of organic matters in the soils of temperate regions (Zheng *et al.,* 2009). Understanding the effect of raised temperatures on the rates of SOM decomposition under CA is crucial to the knowledge of C dynamics.

The SOM stability and temperature sensitivity of SOC is greatly influenced by the nutrient management practices under CA. Consistent fertilization, particularly integrated nutrient management (INM) upsurges SOC, and increases the stability of aggregates in soils. The SOC and microbial biomass can be improved by site-specific nutrient application (Jha *et al.*, 2014). Soil C status is improved by continuous NPK fertilization along with manure (Gong *et al.,* 2009). Optimum N doses along with CR retention in permanent beds (PB) enhanced SOC build-up (Jat *et al.,* 2019). Permanent residue cover influenced decay rates (Kc) of SOC under PB due to better physical protection. Site-specific N management increased SOC stability, particularly in elevated temperatures (Jat *et al.,* 2019). Due to presence of CR, nutrient scheduling needs to be different from conventional practices, as CR itself acts as a source of nutrients. A significant amount of fertilizers remains on CR and never come in soil contact, if applied through broadcast under ZT. Due to slower decomposition of CR present on the soil surface (Kushwaha *et al*., 2000; Balota *et al*., 2004), rapid leaching of nutrients through the soil profile can be prohibited, which is otherwise more likely when CR is incorporated into the soil. Thus, the type of fertilizers, rate, time and method of application have to be appraised in CA systematically considering nutrient transformation and cycling in CR-retained ZT soil environment.

Only few studies have been conducted on the effect of different CR loads and nutrient application on temperature sensitivity of SOC under CA. Also a little is known about the effect of CR and nutrient management on distribution of SOC within aggregate fractions and stability of aggregates. Hence the present investigation was undertaken with following objectives:

1. To study the effect of nutrient and CR management schedules on dynamics and sequestration of soil organic carbon in maize-wheat-mungbean cropping system under conservation agriculture

2. To study the distribution and temperature sensitivity of soil organic carbon within aggregates as affected by conservation agriculture practises.

Chapter 2 Review of Literature

Relevant literature pertaining to the present investigation is reviewed under following sub-heads:

2.1. Conservation agriculture: Global and Indian scenario

2.2. Soil organic carbon and its stability under CA

2.3. Soil organic carbon as influenced by CR management

2.4. Effect of nutrient management on soil organic carbon under CA

2.5. Temperature sensitivity of soil organic carbon

2.1. Conservation agriculture: Global and Indian scenario

Conservation agriculture (CA) is defined as a crop management practice which includes minimal mechanical disturbance and permanent crop soil cover in combination with crop diversification. It is an important approach for sustainable agriculture (Hobbs, 2007). Besides having a key role in sustainable agriculture, CA acts as sink for CO_2, mitigates pollution, saves fuel and also benefits by way of enhancement in soil quality (Jat *et al.,* 2019). Thus CA has now become a key component of climate-resilient sustainable farming (Govearts *et al.*, 2007).

This concept of CA was first conceived in USA during 1930s, as a consequence of dust bowl. Zero tillage (ZT) was first practised in USA in 1940 and thereafter popularized worldwide. Due to severe dust bowl formation in USSR during 1960s, CA was introduced there during that period. No till system was commercialised in USA during 1965. The current area under CA is ~180 Mha, comprised of 43.2, 32, 22.2, 31 and 19.9 Mha in the countries of USA, Brazil, Australia, Argentina and Canada, respectively. Adoption of CA in India is still in the initial phase, with ~1.5 Mha coverage (Kassam *et al*., 2019). In India CA was started with ZT and mulching, followed by other aspects like crop rotation, cover cropping, and INM. In India, ZT wheat in the rice-wheat system of the Indo-Gangetic plains (IGP) is the most widely adopted CA-based technology. In South Asia, the area under CA is increasing due to lack of labour and rising input prices. In major crops and cropping systems, the conventional agriculture is progressively undergoing a shift from intensive tillage to ZT operations (Bhan and Behera, 2014).

2.2. Soil organic carbon and its stability under CA

For soil quality and environmental sustainability, SOC and aggregate stability are main factors in various agro-ecosystems which are mostly affected by tillage and CR management. Soil aggregates distribution and its' stability can be affected by excessive tillage and other farming practices, and by reduced SOC stocks (Kong *et al*., 2005). Six *et al.* (2000) found that CT had less SOC and aggregate stability. They also stated that CT decreased quantities of macro-aggregates and increased quantities of degraded micro-aggregates. Hassink (1997) reported higher stability of C associated with primary silt and clay sized particles compared to that associated with larger particle size fractions. Lenka and Lal (2013) reported that soil aggregates are more sensitive to management practices and decrease with increase in tillage intensity. According to Fesha *et al.* (2002), CA practices resulted in higher amounts of SOM deposition and formation of water-stable aggregates, compared with CT. Due to larger amount of C- rich macro-aggregates and decreased rate of macro-aggregate degradation under ZT, total SOC increases (Six *et al*., 2000). In ZT systems, increase in SOC leads to increase in aggregation (Paustian *et al.*, 2000; Six *et al.*, 2000). Yuan *et al.* (2003) stated that the mechanism of C sequestration in soils may be due to the protection of SOC inside soil aggregates. The SOC associated with macro-aggregates was less stable than in micro-aggregates (Puget *et al*., 2000). John *et al*. (2005) reported that SOC present in recently formed aggregates was more sensitive to the management. Six *et al.* (2000) stated macro-aggregates are sensitive to soil management practices and labile C is released by their breakdown. A loss of C-rich macro-aggregates results from increasing cultivation intensity, whereas C-depleted micro-aggregates content increases. The proportion of aggregates changed rapidly with a change in tillage and crop rotation (Angers *et al*., 1992). Fungal exudates and binding agents helped improving stability of aggregates (Wright *et al*., 1999).

Retention of CR on soil surface can improve soil aggregation, however the magnitude depends on the quantity and quality of CR (Chivenge *et al*., 2011). The tillage and CR management are the options for increasing SOC stabilization by improving soil aggregation in tropical soils (Choudhury *et al*., 2014). They proved that direct-seeded rice with ZT in wheat (with residue retention) has the maximum potential to secure sustainable yield increase (8.3%) compared with CT. This also led to improvement of soil aggregation (53.8%) and SOC sequestration (33.6%) than the CT with transplanted rice after five years of continuous rice–wheat cropping system.

2.3. Soil organic carbon as influenced by CR management

The SOC is classified into different pools which have varying rates of decomposition *viz.*, the labile and non-labile pool. The non-labile SOC is mainly associated with clay particles and the same is highly site-dependent and strongly correlated with clay content. On the other side, labile pool significantly reacts to the variation in agricultural management practices, and to any continuing degradation or recovering processes (van Antwerpen, 2005). Hence, certain fractions of SOC are more important in maintaining soil quality, and thus more sensitive indicators of the impact of management practices. Quanying *et al.* (2014) stated that due to rapid cycling, the labile pool is more sensitive for assessing changes caused by agricultural practices than the TOC. This labile pool is an important source of energy for soil microorganisms and can indicate how biologically fertile a soil is. For example, of the two soils having same TOC content, but one soil with 50% of its TOC present in the labile pool would be relatively more biologically active than a soil with just 5% of its TOC in labile fractions, with the former having greater potential for nutrient turnover, and better soil structure. Chan *et al.* (2001) stated that knowledge about response of C pools to management can offer valuable information on soil health and function.

Due to rapid turnover of labile pools of SOC, these are very sensitive to changes in agricultural management practices. These pools are quickly mineralized to add CO_2 to the atmosphere and accelerating global warming. But the recalcitrant pool is highly resistant to decomposition by microbes, and remains unaffected by management changes. Lower C contents under intensive tillage under CT was resulted due to oxidation of labile portion of SOM in soil. Melero *et al.* (2009) showed that the contents of labile pool were higher at 0-5 cm depth for CA in the short-term experiment than CT. Labile SOC was more affected by CR management than recalcitrant pools. Thus, effect of CA is more remarkable on the labile pools. Bhattacharyya *et al.* (2012) reported that very labile and labile C pools were significantly improved on account of CA practice compared with conventional practice. Likewise, Dey *et al.* (2016) reported that two years of CA did not exhibit noticeable effect on moderately stable SOC pools in surface or sub-surface soil layer under irrigated rice-wheat system of NW-IGP. But significant effect of ZT, green manuring and brown manuring was documented on very labile SOC (SOC_{VL}) in 0-15 cm soil. Very labile SOC was increased by 35, 25, and 38% respectively under the treatments ZT-ZT, ZT-ZT+ brown manuring (BM) and ZT-ZT+ green manuring (GM) over CT. As SOM in terms of fresh residue was continuously supplied under CA, these plots maintained higher labile SOC pool, which in turn enhanced the SOC lability.) Improvement in labile SOC (SOC_L)

and SOC_{VL} due to CR retention in PB has been reported earlier (Alam *et al.*, 2014; Jat *et al.*, 2019).

Parihar *et al.* (2016) showed that SOC increased by 34.6 to 35.3% at 0–15 cm, and 23.6 to 26.5% at 15–30 cm soil depths with CA (ZT and PB) over CT. They also reported an improvement in improved total SOC as well as SOC_{VL} and SOC_{L} was reported due to CR retention under ZT/PB. Compared with conventional practices, an increase in total SOC by ~20% was reported under ZT with retention of CR (Mohanty *et al.*, 2015). Govaerts *et al.* (2005) found that PB with CR retention improved SOC by 1.4 times in surface layer compared with CT. In 0-5 cm soil layer the SOC content was significantly higher for the ZT treatments with 17.8 g kg^{-1} soil than for the CT treatments with 11.1 g kg^{-1} soil. Green manuring along with ZT showed higher SOC (3.17 g kg^{-1}) compared with CT (2.84 g kg^{-1}) in north-west IGP under rice-wheat cropping (Yaduvanshi and Sharma, 2008). Lal (2004) reported the SOC is below 5 g kg^{-1} in soils of India, compared with 15 to 20 g kg^{-1} in uncultivated virgin soils. This low SOC content is mainly due to continuous ploughing, removal of CR and mining of soil fertility. A ZT system (17-year old) had 8.3% higher cumulative SOC stocks at depths of 0–60 cm compared with CT (Liu *et al*., 2014). Dey *et al.* (2018) showed that adoption of CA in place of CT helped in increasing total SOC (especially SOC_{L} pools). They also found that the benefit was greater with the retention of cereal or cereal+legume residues on soil surface. Appropriate CR management under ZT systems increases soil aggregate stability, reduces soil erosion and helps in soil C sequestration (Madejon *et al*., 2007).

2.4. Effect of nutrient management on soil organic carbon under CA

Nitrogenous fertilizer application enhanced total SOC by virtue of greater biomass production of crops, resulting in retention of higher quantities of fresh organic matter (Manzoni *et al.*, 2010; Cotrufo *et al.*, 2013). Jat *et al.* (2019) reported that 23-40% higher labile SOC and 24-38% higher recalcitrant SOC with N fertilization. Xu and Saiers (2010) showed the total SOC and its' pools increased by long-term fertilization and manuring under CA. Balanced application of nutrients improved shoot and root biomass, which supplied higher rate of CR addition under site-specific nutrient management (SSNM) compared to unfertilized and farmers' fertilizer practice (FFP) plots under ZT.

Balanced application of NPK aided in root proliferation, in turn enhancing root biomass and rhizo-deposition C (Pooniya *et al.*, 2015). Aula *et al*. (2016) reported significant enhancement in SOC in response to N application @134 kg N ha^{-1} per year. Under SSNM, synchronous application of nutrients produced higher biomass and annual C incorporations to the soil. The SSNM improved SOC_{VL} and SOC_{L} significantly over unfertilized treatments, but a reverse trend was noticed for less labile SOC (SOC_{LL}) (Parihar *et al.,* 2019). Ghosh *et al.* (2019) found that, after 44 years of intensive cropping, the recommended fertilizer NPK+FYM treated plots had 7.82 g kg^{-1} total SOC in surface soil, which was ~136 and 19% higher compared with unfertilized-control (3.29 g kg^{-1}) and recommended NPK (6.57 g kg^{-1}), respectively. Also, the NPK+FYM plots contained 9.10 g SOC kg^{-1} macro-aggregate-C in surface soil, which was ~121 and 19% higher control (4.12 g kg^{-1}) and NPK (8.61 g kg^{-1}) plots respectively. Likewise, 150% of recommended NPK (6.35 g kg^{-1}) had 13% greater SOC within macro-aggregates compared with that under NPK (5.38 g kg^{-1}) in the surface layer.

2.5. Temperature sensitivity of soil organic carbon

The global mean surface temperatures increased by 0.56-0.92 °C over the last 100 years due to gradual increase in the concentration of atmospheric CO_2 and other heat-trapping gasses (IPCC, 2007). According to researchers global mean surface temperature would rise by about 0.2 °C per decade (IPCC, 2007). Canadell *et al*. (2007) reported that soil CO_2 emission is about eight times greater than the amount of CO_2 from fossil fuel combustion. This leads to study the effect of increasing temperature on SOC decomposition. Several studies suggested temperature as an important factor to regulate SOC stability through variation in the litter quality and quantity (Bird *et al.,* 2002). Hilli *et al.* (2008) observed that stability of SOC was higher with increasing mean annual temperature. The relationship between decomposition and temperature in many soils is usually defined by an exponential or Arrhenius function (Luo, 2007). Generally there are two contrasting views: first, the temperature sensitivity of recalcitrant pool is equal to or even larger than that of labile pool, so expected increase in atmospheric CO_2 concentration accelerate global warming (Hartley and Ineson, 2008); and second, recalcitrant pool is less sensitive or insensitive to temperature change, therefore soil CO_2 emissions will be reduced (Eliasson *et al*., 2005; Bradford *et al*., 2008).

The SOM components have different kinetic properties which often make it difficult to understand the temperature sensitivity of SOC mineralization (Davidson and Janssens, 2006). Arrhenius function indicates that improvement in stability of organic compounds increases temperature sensitivity of decomposition of SOC. The theory suggests that the temperature sensitivity would increase with the recalcitrance of SOC, when mineralization rates of SOC completely depend on activation energy (Li *et al.,* 2015). Further, SOC decomposition is also controlled by management practices and by aggregates size distribution (Jha *et al.,* 2012;

Manna *et al.*, 2013). Global warming due to continuously increasing level of atmospheric CO_2 is a great challenge (IPCC, 2013). Hence, C sequestration received greater consideration in recent past. Kirschbaum (2004) observed that SOC decomposition is governed by temperature and moisture regimes, which may likely be modified with climate change (IPCC, 2013). To study dynamics of SOC, it is important to understand the effect of temperature on the SOM decomposition in different soils as this would support assessment of future global SOC stocks. Temperature sensitivity is indicated by $Q_{10,}$ which theoretically signifies that mineralisation rate of SOC is increased by 10 °C increase in temperature (Fang and Moncrieff, 2001). The Q_{10} will be 1.0, if the rate of the reaction is completely temperature- independent, and Q_{10} will increase with increasing thermal dependency of the reaction. The Q_{10} is used as an indicator of temperature dependency of C decomposition in soil, as the reaction rate changes over a 10 °C temperature rise (Sandeep *et al.,* 2016). Giardina and Ryan (2000) reported less sensitivity or insensitivity of recalcitrant carbon pools to varying temperature, whereas Knorr *et al*. (2005) reported higher Q_{10} of SOC_{NL} compared with SOC_L, whereas reports are there of similar Q_{10} values of both pools (Fang *et al.,* 2005). Dey *et al.* (2018) observed that bio-chemical composition of organic matter is immensely controlled by the amount and type of added CR, affecting chemical stability under elevated temperature. In spite of a large number of studies on mineralization of SOC under varying CR options, the pragmatic studies on C mineralization under elevated temperature are scarce (Yadvinder-Singh *et al.*, 2005). Jat *et al.* (2019) reported that variation in cropping systems, residue quality and management practices under PB did not affect Q_{10} which underlined the significance of minimizing tillage in reducing Q_{10}.

Ghosh *et al.* (2019) reported that the SOC in surface layer of NPK+FYM, NPK and 150% of recommended NPK was 15, 16 and 19% more temperature sensitive compared to unfertilized-control, respectively. Macro-aggregate associated C under 150%NPK was 10% more temperature sensitive than that under unfertilized-control, whereas Q_{10} values of micro-aggregate associated C under 150%NPK and NPK+FYM were 19% and 12% greater than NPK plots. Nevertheless, in surface soils, Q_{10} values of macro-aggregate associated C were significantly higher than those of micro-aggregate associated C. By a sudden temperature increase (from 25 °C to 35 °C), the mean increment in SOC mineralization from bulk soil and macro- and micro-aggregates was 17, 21 and 17% respectively in surface soil layer. Decomposition of soil-derived C increased with the addition of readily available C substrate especially in soils treated at higher temperature levels, whereas the relative stimulation was similar for both temperature regimes (Thiessen *et al.,* 2013). Substrate complexity alone is not accountable for observed temperature sensitivity of SOC and microbial respiration. But this growing temperature sensitivity is due to more complex interactions like stabilization processes, and community structure and amount of active microbial biomass. Both temperature and aggregate size had an interactive significant influence on SOM decomposition rate. The Q_{10} values of SOM decomposition differed significantly among aggregate sizes as follows: macro-aggregate > mineral fraction > bulk soil > micro-aggregate. It was also found that with increasing temperature the differences in Q_{10} values decreased (Wang *et al.,* 2015).

Chapter 3 Materials and Methods

The research work entitled “Stability of soil organic carbon as affected by CR and nutrient management options under conservation agriculture” included determination of SOC pools (both labile and recalcitrant), soil aggregation (separation of macro and micro-aggregates) and aggregate-associated C as affected by CA also, the effect of CA was evaluated on SOC mineralization at two temperatures from bulk soils, macro-aggregates and micro-aggregates. A CA experiment with maize-wheat-mungbean cropping system continuing since 2013 at research farm of ICAR-Indian Agricultural Research Institute (IARI), New Delhi was selected for present investigation. Soil samples were collected from the experiment at harvest of mungbean crop after completion of 6 crop cycles. Detailed description of materials used and methods followed are mentioned hereunder:

3.1. The experimental site

The on-going field experiment on CA-based maize-wheat-mungbean chosen for the study was established during 2013 the at research farm of ICAR-IARI, New Delhi. The experimental site is situated at 28°36$^{/}$-28°39$^{/}$ N latitude, 77°9$^{/}$-77°11$^{/}$ E longitude and at an altitude of 250 m above mean sea level. The area represents Trans-gangetic plain (TGP) transect of the Indo-Gangetic Plain (IGP) region. The average annual temperature at the experimental site is 25.3 °C, maximum temperature being 31°C and minimum temperature 17 °C. May is the hottest month with maximum day temperature reaching to as high as 45 °C, whereas January is the coldest month with minimum temperature dipping as low as 1-2 °C. The TGP is intensively cropped zone with rice-wheat and maize-wheat as predominant cropping systems. Rainfall (mean of 50 years) at the experimental site is 650 mm, about 80% of which is received through south-west monsoon during July to September.

The sandy loam soil of the experimental site is very deep (> 2 m), flat, well-drained and non-saline with a neutral to alkaline reaction. Taxonomically, the soil is classified as Typic Haplustept. The initial properties of the soil are depicted in Table 3.1.

Table 3.1. Initial soil properties of the experimental site

Parameter	Values	Reference
Mechanical composition		Bouyoucos (1962)
Sand (%)	58.2	
Silt (%)	23.8	
Clay (%)	18.0	
Texture	Sandy loam	
pH	8.55	Jackson (1973)
EC (dSm^{-1})	0.55	Jackson (1973)
Bulk density (Mg m^{-3})	1.54	Veihmeyer and Hendrickson (1948)
Walkley-Black C (g kg^{-1})	3.7	Walkley and Black (1934)
CEC [cmol(p^{+}) kg^{-1} soil]	10.5	Jackson (1973)
NH_4^+-N (mg kg^{-1})	10.1	Keeney and Nelson (1982)
NO_3^--N (mg kg^{-1})	8.10	Keeney and Nelson (1982)
0.5 *M* $NaHCO_3$-extractable P (kg ha^{-1})	16.4	Olsen *et al.,* (1954)
Neutral 1 *N* NH_4OAc-extractable K (kg ha^{-1})	165	Hanway and Heidel (1952)

3.2. Details of field experiment

The field experiment with 18 treatments is laid out in a split-plot design with three replications. Main plot is comprised of three levels of CR retention *i.e*, no residue (CR_0), 2 t ha^{-1} CR retention (CR_2), and 4 t ha^{-1} CR retention (CR_4). The main plot is divided into six sub-plots comprising two levels of N (*i.e, e* 100 and 150 kg N ha^{-1}) and three rates of K (i.e., 0, 30 and 60 kg K ha^{-1}) abbreviated as $N_{100}K_0$, $N_{100}K_{30}$, $N_{100}K_{60}$, $N_{150}K_0$, $N_{150}K_{30}$ and $N_{150}K_{60}$. Treatment details are furnished in Table 3.2. Recommended rates of fertilizers as per soil test were 150 kg N, 80 kg P_2O_5, 60 kg K_2O ha^{-1}for both maize and wheat. Maize (cv. PMH-1), wheat (cv. HD-2967) and mungbean (cv Pusa Vishal) were sown in *kharif*, *rabi* and summer seasons, respectively under no-till conditions using Turbo seeder. One-third of recommended N (as per treatment) and entire P and K was applied as basal dressing at time of sowing, using urea, diammonium phosphate and muriate of potash as source of N, P and K, respectively. Remaining N was top-dressed in two equal splits at knee high and silking stage in maize and at crown root initiation and maximum tillering stage in wheat. For weed management prescribed herbicides were applied. Mungbean was raised on residual fertility, and no fertilizers were applied. All crop were raised under assured irrigation. The maize and wheat crops were harvested manually at maturity, at the height already standardized to leave CR as per treatment. After picking the pods of mungbean at maturity, the biomass was retained on the surface by spraying of glyphosate (@10-12 mL L^{-1}).

Table 3.2. Treatment details of CA experiment chosen for the study

S. No.	Treatment Acronym	Treatment Description		
		CR (t ha^{-1})	N rate (kg ha^{-1})	K_2O rate (kg ha^{-1})
1	$CR_0N_{100}K_0$	0	100	0
2	$CR_0N_{100}K_{30}$	0	100	30
3	$CR_0N_{100}K_{60}$	0	100	60
4	$CR_0N_{150}K_0$	0	150	0
5	$CR_0N_{150}K_{30}$	0	150	30
6	$CR_0N_{150}K_{60}$	0	150	60
7	$CR_2N_{100}K_0$	2	100	0
8	$CR_2N_{100}K_{30}$	2	100	30
9	$CR_2N_{100}K_{60}$	2	100	60
10	$CR_2N_{150}K_0$	2	150	0
11	$CR_2N_{150}K_{30}$	2	150	30
12	$CR_2N_{150}K_{60}$	2	150	60
13	$CR_4N_{100}K_0$	4	100	0
14	$CR_4N_{100}K_{30}$	4	100	30
15	$CR_4N_{100}K_{60}$	4	100	60
16	$CR_4N_{150}K_0$	4	150	0
17	$CR_4N_{150}K_{30}$	4	150	30
18	$CR_4N_{150}K_{60}$	4	150	60

3.3. Soil sampling and processing

Soil samples were collected from two depths *i.e.* 0-5 and 5-15 cm from the respective plots at harvest of mungbean crop in the year 2018-19. One part of the sample was air-dried and processed to pass through a 2 mm sieve followed by 0.2 mm sieve for analysis of organic carbon fractions. The second set of undisturbed soil samples was used for separation of aggregates after drying under shade and passing through a 4 mm sieve. The third portion of undisturbed soil sample was used in carbon mineralization study.

3.4. Soil Analysis

3.4.1. Soil pH, electrical conductivity and texture

The pH of soil samples was determined in 1:2.5 soil: water suspension by a digital pH meter using combined electrode. The electrical conductivity (EC) was determined in the supernatant of the same soil: water ratio with the help of a conductivity bridge and expressed as dS m^{-1} at 25 ^{o}C. The sand, silt and clay were determined using a Bouyoucos hydrometer (Bouyoucos, 1962). The textural class of the soils was determined analysed by USDA textural triangle (Brady and Weil, 2002).

3.4.2. Soil organic carbon and its' different pools of varying lability

Total soil organic carbon

Soil samples were finely ground to pass through 0.2 mm sieve and kept in oven for 24 hours at 40 °C prior to determination of total C. Total carbon (TC) was determined by dry combustion method using CHNS Analyzer (EuroVector Instruments, EA 3000, Italy) (Nelson and Sommers, 1982). Total soil inorganic carbon (SIC) was determined through acid-digestion. For this, 5 g soil was treated with excess of standard 0.5 *N* HCl to neutralize all carbonates and the unutilized excess of HCl was back-titrated with 0.25 *N* NaOH (Richards, 1954). The total SOC was calculated by subtracting SIC from TC.

Soil organic carbon pools of varying oxidizability

Different fractions of oxidizable SOC were determined using modified Walkley-Black method, as described by Chan *et al*. (2001). One g of soil sample passed through a 0.2 mm sieve was taken in a 200 mL conical flask for analysis. Three replicates of each sample were taken. 10 mL of 1 *N* $K_2Cr_2O_7$ was added to each flask, followed by addition of 5, 10 and 20 mL of concentrated H_2SO_4 corresponding to 12 *N*, 18 *N* and 24 *N* of H_2SO_4, respectively. The flasks were allowed to stand for 30 minutes. After 30 minutes, about 200 mL of distilled water was added, followed by titrating acid dichromate mixture against 0.5 *N* ferrous ammonium sulphate in the presence of diphenylamine indicator and concentrated H_3PO_4. Total SOC was divided into four fractions in order of decreasing oxidizability (Chan *et al*., 2001):

Very labile SOC (SOC_{VL}): SOC oxidizable with 12 *N* H_2SO_4

Labile SOC (SOC_L): Difference between SOC oxidizable with 18 *N* H_2SO_4 and 12 *N* H_2SO_4

Less labile SOC (SOC_{LL}): Difference between SOC oxidizable with 24 *N* H_2SO_4 and 18 *N* H_2SO_4

Non-labile SOC (SOC_{NL}): Difference between total SOC and that oxidised with 24 *N* H_2SO_4

Carbon management index

The carbon management index (CMI) was calculated using these four SOC fractions (Parihar *et al.*, 2019) using the following formulae

Lability of SOC = $(SOC_{VL} + SOC_{L} + SOC_{LL})/ SOC_{NL}$

Carbon Pool Index (CPI) = Total SOC of sample/ Total SOC of reference

Lability Index of C (LI) = Lability of SOC in sample /Lability of SOC in reference

Carbon management index (CMI) = CPI×LI×100

Replicated soil samples from nearby uncultivated areas were taken and regarded as reference samples. Total SOC and SOC fractions of different lability of the reference samples are given in Table 3.3

Table 3.3. Soil organic carbon (SOC) and its lability in the reference soil sample

Total SOC (g kg^{-1})		Walkley-Black SOC(g kg^{-1})		Non-labile SOC (g kg^{-1})		SOC lability	
0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
6.37	5.74	4.01	3.51	2.36	2.24	1.70	1.56

3.4.3. Soil aggregation and aggregate associated C

Distribution of macro and micro-aggregates

Out of 18 treatment chosen for SOC determination 9 treatments *i.e.*, 3 rates of residue retention (CR_0, CR_2 and CR_4) and three rates of K fertilizations ($N_{150}K_{0,}$ $N_{150}K_{30}$ and $N_{150}K_{60,}$) were used for soil aggregation studies. The larger clods were broken by hands into smaller segments along natural cleavage before air-drying the soil. The clods were passed through 4 mm sieve and retained on 2 mm sieve. Then these clods were placed in a sieve assembly comprised of 2 mm sieve on top followed by 250 µm and 53 µm sieve. This sieve assembly containing soil clods was dipped in water in a Yoder wet sieving apparatus. This was left for 5 minutes to saturate the clods with water and thereafter the apparatus was run for 5-10 minutes. After wet-sieving, aggregates present on each sieve were transferred to a funnel containing a pre-weighed filter paper placed on the volumetric flask. The aggregates present on filter paper were air-dried followed by oven-drying at 40 °C until constant weight and finally weighed. Soil aggregation was calculated, and expressed as percentage. A sub-sample of aggregates was used for total C analysis, whereas another sub-sample was kept for studying mineralization of SOC. Aggregates retained on 250 µm sieve were considered as macro-aggregates (250-2000 µm) and aggregates retained on 53 µm sieve as micro-aggregate (53-250 µm) (Yoder, 1936).

Macro- and micro-aggregate associated C

For determination of C associated with macro- and micro-aggregates, these were ground by mortar and pestle after oven drying at 40 °C for 48 hours and passed through a 0.2 mm sieve. The C was determined using CHNS analyzer (EuroVector Instruments, EA 3000, Italy) (Nelson and Sommers, 1982).

3.4.5. Soil organic carbon mineralization

For carbon mineralization studies, sub-samples of bulk soils, macro-aggregates and micro-aggregates from same 9 treatments were placed at two temperatures (20 °C and 30 °C) in laboratory incubators for 64 days. For this, 25 g of undisturbed moist soil or respective aggregate fraction (dry weight basis) from each treatment in three replicates was weighed in individual 500 mL conical flasks. Empty conical flasks with alkali trap (vial containing 5 mL of 0.25 *N* NaOH) were kept as blanks in respective studies. In each sample, water was maintained at field capacity (-33 kPa) with alkali trap (vial containing 5 mL of 0.25 *N* NaOH) and the flasks were air tightened. Firstly, the soil samples were pre-incubated for one to two weeks at 25 °C that helped to discard "pulsing effect". The CO_2 was trapped in 5 mL 0.25 *N* NaOH. The rate of CO_2 production of the soil samples was measured at 2, 4, 8, 16, 32 and 64 days of the incubation. But for samples incubated for 32 and 64 days, 5 mL of 0.5 *N* NaOH was used. The amounts of CO_2 trapped were determined by back titration of the excess 0.25 *N* NaOH with 0.1 *M* HCl. Before that saturated $BaCl_2$ (so as to convert Na_2CO_3 to $BaCO_3$) was added followed by phenolphthalein indicator. At each sampling date, compressed air was flushed into the flasks to facilitate O_2 supply after removal of NaOH. The C mineralization was calculated through following formula:

$$\text{C mineralized (mg 100g}^{-1}\text{ soil)} = \{(B-A) \times N \times 6 \times 100\}/ W$$

Where B and A are the volume (ml) of HCl consumed for titrating 10 ml 0.5 *M* NaOH in control (flask without soil) and soil, *N* is the normality of HCl and 6 is the equivalent weight of C. Cumulative C mineralization (Ct) was computed by summing up the C mineralization at different days of observation.

An exponential model (Stanford and Smith, 1972) was used to determine C loss with time:

$$Ct = Co\ (1-e^{-Kct})$$

Where Co represents the potentially mineralizable SOC, Ct represents the cumulative C mineralized at time t, and Kc represents decay rate SOC mineralization.

The temperature sensitivity of soil respiration is expressed as the van’t Hoff’s temperature coefficient Q_{10}, which describes the factor by which the rate increases with a 10°C rise in temperature, and was calculated using the following formula (Janssens and Pilegaard, 2003):

$$Q_{10} = (\text{Rate of C mineralization at 30 }^{o}\text{C/Rate of C mineralization at 20 }^{o}\text{C})^{(10/T_2\text{-}T_1)}$$

Where, T_2 and T_1 are 30 °C and 20 °C respectively. Here rate of mineralization means, the Kc value obtained from Stanford and Smith equation at respective temperatures.

3.5. Statistical analysis

The recorded data for different soil parameters were analyzed using analysis of variance (ANOVA) (Gomez and Gomez, 1984) for split-plot design (SAS Institute, Cary, NC). The least significant difference (LSD) test was used to indicate the treatments effects at 5% level of significance ($p=0.05$).

4.1. Effect of CR and nutrient management options on total SOC and its' pools of varying oxidizability

4.1.1. Total soil organic carbon

Total SOC was higher in 0-5 cm layer compared with that in 5-15 cm layer, irrespective of treatments (Table 4.1). Treatment CR_4 had the highest total SOC, followed by CR_2 and CR_0 in all soil depths. In 0-5 cm soil layer, total SOC was almost double and 67.5% higher in CR_4 and CR_2, respectively compared with that under CR_0. Treatments with 150 kg ha^{-1} N application ($N_{150}K_0$, $N_{150}K_{30}$ and $N_{150}K_{60}$) registered significantly higher total SOC compared with treatments receiving 100 kg ha^{-1} N application, irrespective of K rates, in both 0-5 and 5-15 cm soil depths. Treatment $N_{150}K_{60}$ had the highest total SOC content in 0-5 cm (11.6 g kg^{-1}) and 5-15 cm (8.80 g kg^{-1}) (Table 4.1). Treatment $N_{100}K_{60}$ had 7.86% higher total SOC compared with $N_{100}K_0$, whereas $N_{150}K_{60}$ had 6.79% higher total SOC than $N_{150}K_0$, in 0-5 cm soil layer. On the other hand, different rates of K application at similar N doses did not have significant effect on total SOC in 5-15 cm layer. Treatments $N_{150}K_0$, $N_{150}K_{30}$ and $N_{150}K_{60}$ had 13.3, 14.9 and 15.4% higher total SOC compared with $N_{100}K_0$, $N_{100}K_{30}$ and $N_{100}K_{60}$ treatments, respectively in 5-15 cm soil depth. No interaction effect between CR and nutrient management was observed.

4.1.2. Walkley-Black carbon

Averaged across nutrient management options, treatment with retention of 4 t CR ha^{-1}(CR_4) had highest amount of Walkley-Black C i.e. WBC (10.8 g kg^{-1}) followed by CR_2 (8.95 g kg^{-1}) and CR_0 treatment (5.10 g kg^{-1}) in 0-5 cm soil depth (Table 4.1). Similarly in 5-15 cm soil depth, the values of WBC were 8.13, 6.48 and 3.74 g kg^{-1} under CR_4, CR_2 and CR_0 treatment, respectively. Among nutrient management options, WBC was significantly higher with increase in N rates irrespective of K rates in both 0-5 and 5-15 cm soil layers. The fertilizer K rates at similar N application rates did not register significant changes in WBC in either soil depths. For WBC interaction effect between CR and nutrient management options was not significant.

Table 4.1. Effect of crop residue retention and nutrient management options on total soil organic carbon (g kg^{-1}) and its' pools (g kg^{-1}) of varying lability after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Treatments	Very labile C		Labile C		Less labile C		Non labile C		Walkley-Black C		Total organic C	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
Crop residue load												
CR$_0$	1.92	1.69	1.50	0.58	1.69	1.47	1.54	1.36	5.10	3.74	6.65	5.11
CR$_2$	2.81	2.63	2.93	1.04	3.22	2.82	2.18	1.96	8.95	6.48	11.14	8.44
CR$_4$	3.39	3.18	3.59	1.40	3.78	3.55	2.54	2.35	10.76	8.13	13.30	10.48
Mean	2.70	2.50	2.67	1.00	2.89	2.61	2.08	1.89	8.27	6.11	10.36	8.01
LSD (p =0.05)	0.22	0.13	0.31	0.10	0.19	0.15	0.16	0.26	0.67	0.32	0.83	0.43
Nutrient management options												
N$_{100}$K$_0$	2.48	2.35	2.24	0.86	2.53	2.38	1.92	1.67	7.24	5.60	9.16	7.27
N$_{100}$K$_{30}$	2.53	2.41	2.40	0.90	2.67	2.40	1.96	1.78	7.60	5.72	9.56	7.50
N$_{100}$K$_{60}$	2.59	2.39	2.53	0.94	2.75	2.47	2.01	1.82	7.87	5.81	9.88	7.62
N$_{150}$K$_0$	2.75	2.54	2.85	1.06	3.04	2.69	2.15	1.96	8.64	6.29	10.79	8.24
N$_{150}$K$_{30}$	2.88	2.63	2.96	1.12	3.14	2.82	2.21	2.03	8.98	6.59	11.19	8.62
N$_{150}$K$_{60}$	3.00	2.67	3.06	1.15	3.24	2.91	2.28	2.09	9.30	6.70	11.58	8.80
Mean	2.70	2.50	2.67	1.00	2.89	2.61	2.08	1.89	8.27	6.11	10.35	8.00
LSD (p = 0.05)	0.22	0.23	0.25	0.08	0.23	0.26	0.17	0.17	0.32	0.39	0.54	0.42

4.1.3. Very labile SOC

CR addition had significant effect on very labile pool (SOC_{VL}) in both soil layers. The CR_4 treatment had significantly higher SOC_{VL} (3.39 g kg^{-1}) than CR_0 or CR_2. Similarly CR_2 had significantly higher SOC_{VL} (2.81 g kg^{-1}) compared with CR_0 (1.92 g kg^{-1}) in 0-5 cm soil depth (Table 4.1). In 5-15 cm soil depth, CR_4 treatment had 76.6% and 20.6% higher SOC_{VL} compared with CR_0 respectively. Treatment with 150 kg ha^{-1} N had significantly higher SOC_{VL} compared with 100 kg ha^{-1} N in both 0-5 and 5-15 cm soil depth. But there was no significant increase in SOC_{VL} due to graded rates of K in both soil depths. The highest SOC_{VL} (2.67 g kg^{-1}) was recorded under $N_{150}K_{60}$ and the lowest in $N_{100}K_0$ (2.35 g kg^{-1}) in 0-5 cm soil depth (Table 4.1). No interaction between CR retention and nutrient management options was recorded.

4.1.4. Labile SOC

Different CR loads showed similar distribution of SOC in labile pool (SOC_L) as that of SOC_{VL} in both soil depths. Treatment CR_4 had highest SOC_L (3.59 and 1.40 g kg^{-1}) in 0-5 and 5-15 cm soil layer, respectively. The CR_2 registered 95.5% and 79.3% higher SOC_L compared with CR_0 in 0-5 and 5-15 cm soil layers, respectively (Table 4.1). At a given K rate 150 kg N ha^{-1} had significantly higher SOC_L in both 0-5 and 5-15 cm soil depths compared with 100 kg N ha^{-1}. Different K rates did not affect SOC_L content. The $N_{100}K_{60}$ had 20.9 and 22.3% lower SOC_L compared with that under $N_{150}K_{60}$ in 0-5 and 5-15 cm soil depths, respectively. No interaction between CR retention and nutrient management was observed.

4.1.5. Less labile SOC

Treatment CR_4 had highest amount of SOC_{LL} (3.78 and 3.55 g kg^{-1}), followed by CR_2 (3.22 and 2.82 g kg^{-1}) and CR_0 (1.69 and 1.47 g kg^{-1}) in 0-5 and 5-15 cm soil depths, respectively (Table 4.1). The SOC_{LL} was 17.4% less in CR_2 compared with CR_4 treatment in 0-5 cm depth. Similarly, SOC_{LL} was decreased by 25.8% in CR_0 as compared to CR_2 treatment in 0-5 cm soil depth. Similar trend was followed in 5-15 cm soil depth. The N_{150} treatment had significantly higher SOC_{LL} compared with N_{100} in both 0-5 and 5-15 cm soil depth. The $N_{150}K_{60}$ had highest amount of SOC_{LL} in 0-5 cm (2.28 g kg^{-1}) and 5-15 cm depth (2.09 g kg^{-1}) (Table 4.1). Treatment $N_{150}K_{60}$ had 22.2, 21.2 and 17.8% higher SOC_{LL} to that under $N_{100}K_{60}$, $N_{100}K_{30}$ and $N_{100}K_0$ in 0-5 cm soil depth. Similar results were obtained in 5-15 cm soil depth. For SOC_{LL}, no interaction between CR and nutrient management was observed.

4.1.6. Non-labile SOC

Alike the other pools of SOC, CR_4 had significantly higher amount of SOC_{NL} (2.54 g kg^{-1}) compared with CR_2 (2.18 g kg^{-1}) and CR_0 (1.54 g kg^{-1}) treatments in 0-5 cm soil depth (Table 4.1). In 5-15 cm soil depth, CR_4 treatment had 72.7 and 20.5% higher SOC_{NL} compared with CR_0 and CR_2 treatments, respectively. The SOC_{NL} was significantly increased with an increase in N rate. Treatment $N_{150}K_{60}$ had 2.28 g kg^{-1} and 2.09 g kg^{-1} SOC_{NL} in 0-5 and 5-15 cm soil depths, respectively which was highest among all nutrient rates (Table 4.1). No interaction was recorded between CR and nutrient management options.

4.2. Effect of different CR and nutrient management options on soil aggregation and aggregate associated carbon

4.2.1. Macro-aggregates

CR retention under CA had significant impact on macro-aggregate percentage. Retention of 4 t ha^{-1} residue of both crops (CR_4) had 25.5 and 9.13% higher macro-aggregates compared of CR_0 and CR_2, respectively in 0-5 cm soil depth (Table 4.2). Similarly, in 5-15 cm soil depth CR_4 treatment had 20.4 and 11.3% higher macro-aggregates compared with CR_0 and CR_2 treatment, respectively. There was also significant improvement in macro-aggregates in CR_2 over CR_0 in 0-5 cm soil depth *i.e.*, CR_2 treatment had 15% more macro-aggregates than CR_0. Different K fertilization rates did not affect macro-aggregate percentage. There was no interaction between CR and nutrient management options was not significant.

4.2.2. Micro-aggregates

The effect of CR management on micro-aggregates percentage was reverse of that on macro-aggregate percentage. Highest amount of micro-aggregates (%) were recoeded in CR_0 in 0-5 cm (37.9%) and 5-15 cm (34.4%) soil depths, which were significantly greater than CR_2 and CR_4 (Table 4.2). The treatments CR_2 and CR_4 registered similar amount of micro-aggregates (%) in both soil depths. However, micro-aggregate percentage did not vary significantly as a result of variation in nutrient management options. In micro-aggregates distribution, no interaction between CR and nutrient management options was not apparent.

Table 4.2. Effect of crop residue retention and K fertilizations on aggregate percentage and aggregate associated C (g kg^{-1} soil) after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Treatments	MA (%)		MI (%)		MA-TC (g kg^{-1} soil)		MI-TC (g kg^{-1} soil)	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
Crop residue loads								
CR_0	51.21	54.03	37.86	34.37	9.41	8.39	5.37	4.29
CR_2	58.91	58.44	30.32	28.47	12.06	9.38	6.44	5.28
CR_4	64.29	65.05	28.02	25.99	13.94	11.58	7.49	6.59
Mean	58.13	59.17	32.06	29.58	11.80	9.78	6.43	5.38
LSD (p = 0.05)	5.27	6.21	5.04	4.41	1.79	1.37	0.91	0.86
Fertilizer K rates								
$N_{150}K_0$	57.20	58.43	32.14	29.98	11.52	9.68	6.36	5.36
$N_{150}K_{30}$	59.49	59.55	32.70	29.14	12.01	9.80	6.37	5.37
$N_{150}K_{60}$	57.72	59.54	31.36	29.70	11.88	9.87	6.58	5.43
Mean	58.13	59.17	32.06	29.60	11.80	9.78	6.43	5.38
LSD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

MA: Macro-aggregates; MA-TC: Macro-aggregate-associated carbon; MI: Micro-aggregates; MI-TC: Micro-aggregate-associated carbon

4.2.3. Macro-aggregate associated carbon

CR retention on soil surface had a significant effect on macro-aggregate associated C in both soil depths. Maximum amount of macro-aggregate associated C was recorded in CR_4 (13.9 g kg^{-1}) followed by CR_2 treatment (12 g kg^{-1}) and CR_0 treatment (9.4 g kg^{-1}) in 0-5 cm soil depth (Table 4.2). In 5-15 cm soil depth CR_4 treatment had 38 and 23.4% higher macro-aggregate associated C than that under CR_0 and CR_2 treatments, respectively. Treatments CR_0 and CR_2 had similar macro-aggregate associated C in 5-15 cm soil depth. Nutrient management options did not show any significant effect on this soil parameter. In macro-aggregates associated C no interaction effect was observed between CR and nutrient management.

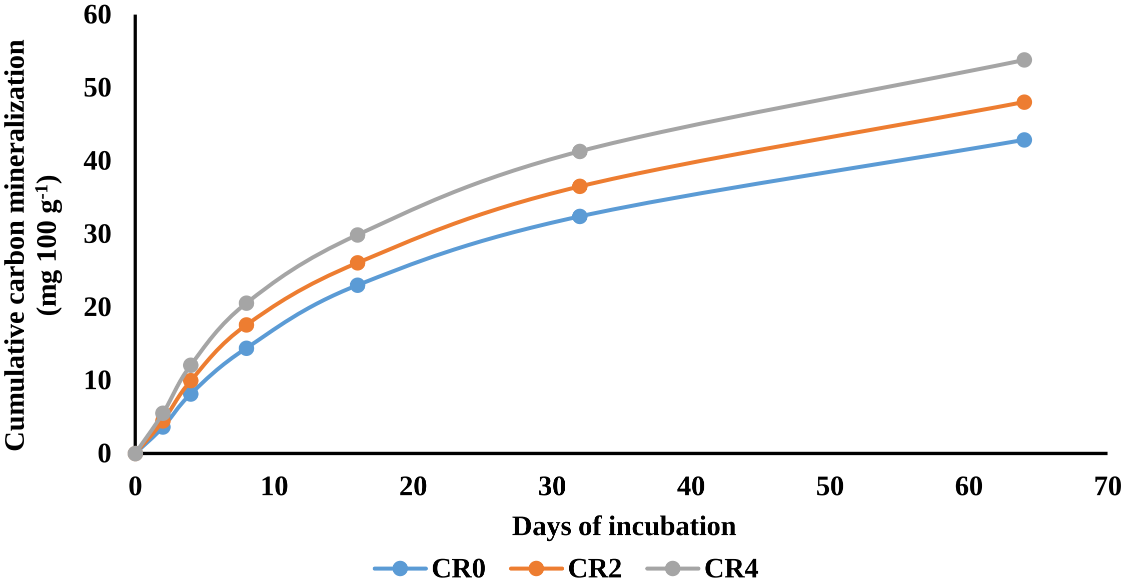
4.2.4. Micro-aggregate associated carbon

The CR_4 treatment had 16.3 and 39.4% higher micro-aggregate associated C compared with CR_2 and CR_0 treatments in 0-5 cm soil depth (Table 4.2). In 5-15 cm soil, increasing load of CR significantly increased micro-aggregate associated C, which was being highest in CR_4 (6.59 g kg^{-1}) followed by CR_2 (5.28 g kg^{-1}) and CR_0 (4.29 g kg^{-1}) (Table 4.2). Among nutrient management options, no significant difference was noticed for micro-aggregate associated C in both soil depths. For micro-aggregates associated C, interaction between CR and K fertilization was absent.

4.3. Effect of CR and nutrient management options on cumulative mineralization of SOC

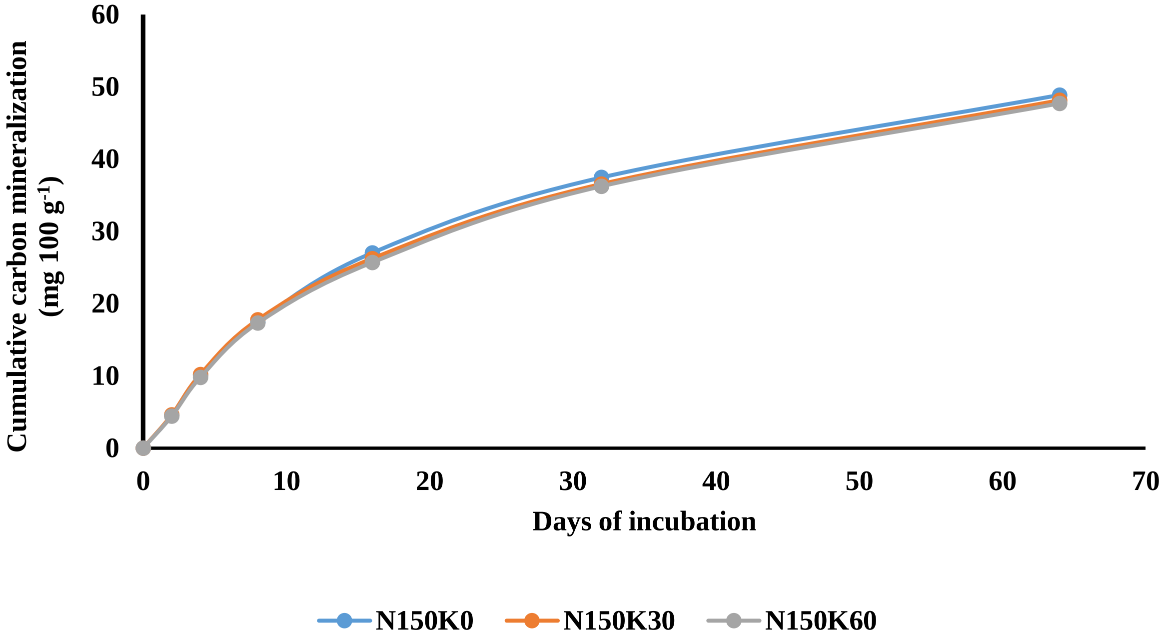
4.3.1. Bulk soil

In the soil representing 0-5 cm soil depth incubated at 20 °C, CR_4 had 53 and 24% cumulative C mineralization (Ct) as compared to CR_0 and CR_2 on day 2 (Figure 4.1). On day 4, CR_4 had 48.4 and 21.4% higher Ct as compared to CR_0 and CR_2 in 0-5 cm soil depth at 20 °C. On day 8, highest Ct was observed under CR_4 treatment (20.6 mg 100 g^{-1} soil), followed by CR_2 treatment (17.6 mg 100 g^{-1} soil) and CR_0 (17.6 mg 100 g^{-1} soil) in 0-5 cm soil depth (Figure 4.1). On day 16, there was no significant difference in Ct between CR_0 and CR_2, although CR_4 had 30 and 14.6% higher Ct than that in CR_0 and CR_2. On day 64 CR_4 had highest Ct (53.8 mg 100 g^{-1} soil) followed by CR_2 (48 mg 100 g^{-1} soil) and CR_0 (42.9 mg 100 g^{-1}soil) (Table 4.3). Among nutrient management options *i.e.*, K rates no significant difference was noticed in Ct irrespective of days of incubation.



LSD (p = 0.05): Day 2: 0.63 Day 4: 0.95 Day 8: 0.94

Day 16: 3.21 Day 32: 3.29 Day 64: 2.98



LSD (p = 0.05): NS for all days of observation

Fig 4.1. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 20 °C in bulk soil from 0-5 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Table 4.3. Effect of crop residue retention and K fertilizations on cumulative soil organic carbon mineralization after 64 days of incubation after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Treatments	Ct (mg 100g^{-1})											
	BS				MA				MI			
	20 °C		30 °C		20 °C		30 °C		20 °C		30 °C	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
Crop residue loads												
CR_0	42.88	38.96	51.07	44.83	48.36	42.46	57.05	42.46	48.36	29.66	44.42	38.82
CR_2	48.05	43.93	57.19	51.23	54.30	48.52	63.03	48.52	54.30	36.08	50.01	45.46
CR_4	53.79	48.18	63.22	57.27	60.29	53.93	68.21	53.93	61.85	42.05	56.13	50.9
Mean	48.24	43.69	57.16	51.11	54.31	48.30	62.76	48.30	54.83	35.93	50.18	45.06
LSD ($p = 0.05$)	2.98	3.46	3.17	2.27	3.36	5.04	6.15	5.04	5.12	4.90	4.98	4.89
Fertilizer K rates												
$N_{150}K_0$	48.87	42.14	57.16	51.14	54.02	48.04	63.26	48.04	54.68	35.91	50.13	45.05
$N_{150}K_{30}$	48.14	43.27	57.30	51.40	54.25	48.20	62.91	48.20	55.14	36.05	50.19	45.41
$N_{150}K_{60}$	47.71	45.66	57.02	50.80	54.69	48.67	62.11	48.67	54.69	35.83	50.24	44.79
Mean	48.24	43.69	57.16	52.11	54.32	48.3	62.76	48.3	54.83	35.93	50.18	45.08
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

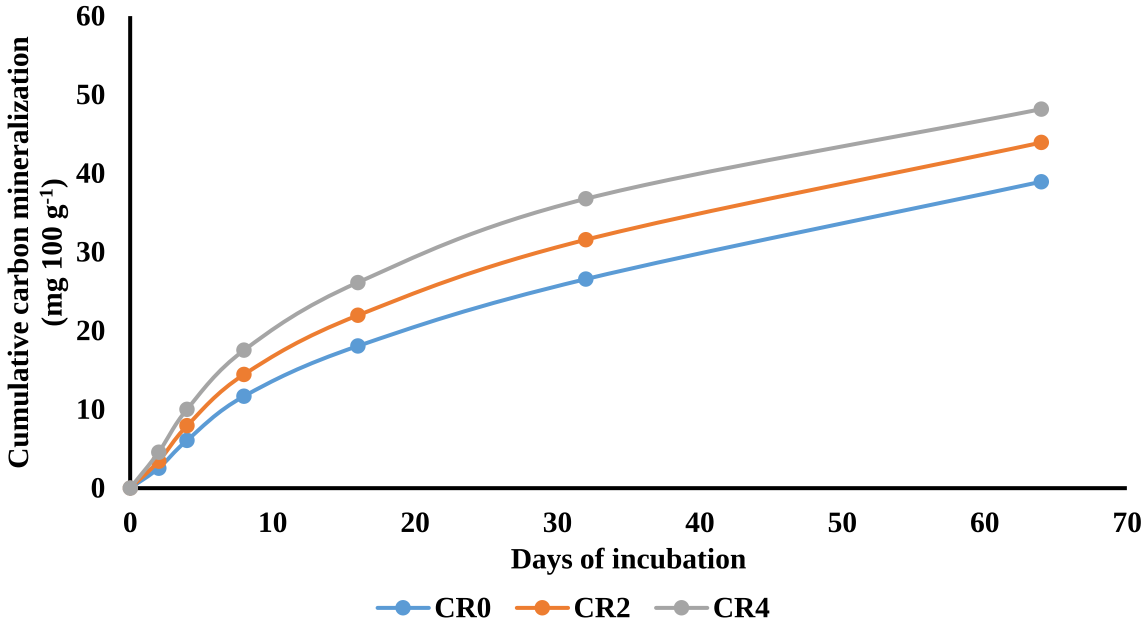
BS: Bulk soil; MA: Macro-aggregates; MI: Micro-aggregates

Soils from 5-15 cm depth registered lower values of Ct than 0-5 cm depth. In 5-15 cm soil depth at 20 °C, similar trend of Ct was recorded with different CR loads. On day 2, the CR_4 treatment had 80 and 33.2% higher rate of CO_2 evolution as compared to CR_0 and CR_2 treatments (Figure 4.2). On day 4, CR_4 had 64.8 and 26.4% higher values of Ct as compared with CR_0 and CR_2 in 5-15 cm soil depth at 20 °C. On day 8, highest values of Ct were recorded in CR_4 (17.5 mg 100 g^{-1} soil), followed by CR_2 (14.5 mg 100 g^{-1} soil) and CR_0 (11.69 mg 100 g^{-1} soil) in 5-15 cm soil depth. On the day 16 and 32, the CR_4 treatment registered highest values of Ct, followed by CR_2 and CR_0 (Figure 4.2). On 64th day CR_4 treatment had highest Ct (48.2 mg 100 g^{-1} soil) followed by CR_2 (43.9 mg 100 g^{-1} soil) and CR_0 (38.96 mg 100g^{-1}soil). No significant difference on Ct was noticed due to different K management options *i.e.* $N_{150}K_0$, $N_{150}K_{30}$, and $N_{150}K_{60}$.

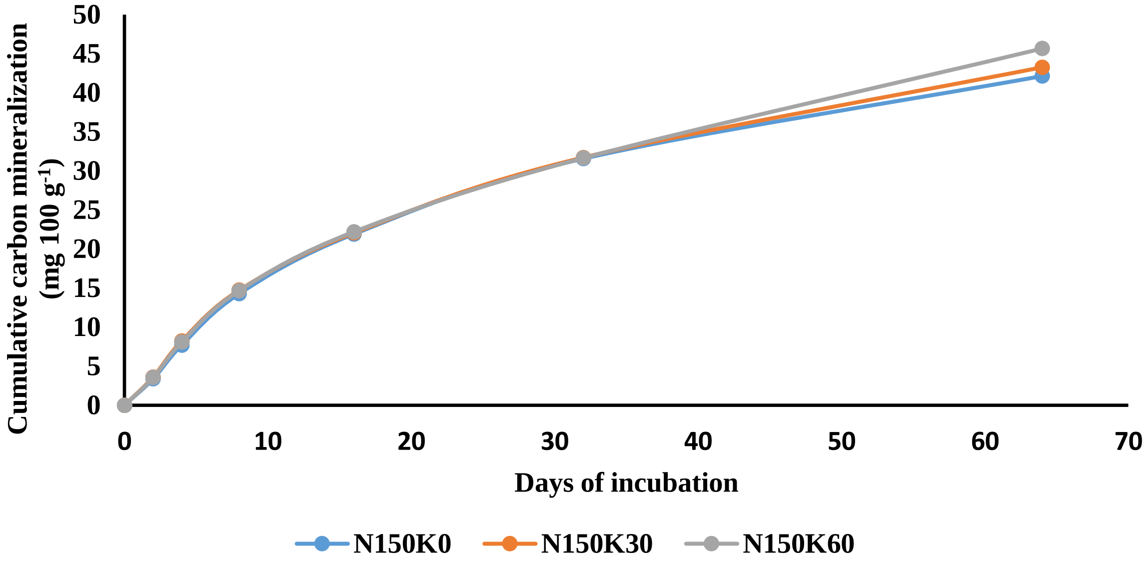
The Ct at 30 °C was higher than that recorded at 20 °C, irrespective of days of incubation and soil depths. On day 2, maximum Ct was observed in CR_4 (6.5 mg 100 g^{-1} soil), followed by CR_2 (5.66 mg 100 g^{-1} soil) and CR_0 (4.53 mg 100 g^{-1} soil) in 0-5 cm soil depth (Figure 4.3). On day 4 CR_4 treatment had 39% and 15.5% higher values of Ct compared with CR_0 and CR_2 in 0-5 cm soil depth. On day 8, CR_4 and CR_2 registered 32.7% and 16.7% higher Ct than CR_0 treatment, respectively in soil from 0-5 cm depth. On day 16, the CR_4 treatment registered highest Ct (36.2 mg C 100 g^{-1} soil), followed by CR_2 (32.2 mg C 100 g^{-1} soil) and CR_0 (28.1 mg 100 g^{-1} soil) in soil from 0-5 cm depth (Figure 4.3). On 64th day also, Ct under CR_4 treatment was markedly higher than CR_0. The Ct remained unaffected due to K fertilization (Table 4.3). Observations in soil from 5-15 cm revealed highest Ct values in CR_4, followed by CR_2 and CR_0 throughout incubation period (Figure 4.4). On day 64, CR_4 had 27.7% and 11.7% higher Ct compared with CR_0 and CR_2 respectively (Table 4.3). Effect of nutrient management options *i.e.,* fertilizer K rates was not significant across incubation period. Interaction effect between CR and nutrient management was absent irrespective of temperature and depth of soil.

4.3.2. Macro-aggregates

Among different size fractions, highest Ct values were obtained in macro-aggregates, followed by bulk soil and micro-aggregates, irrespective of temperature of incubation or depth of soil. On day 2, at 20 °C the CR_4 treatment had 41.5 and 15.4% higher value of Ct compared with CR_0 and CR_2 from 0-5 cm soil depth (Figure 4.5). On day 4, the CR_4 treatment had 34.9 and 11.5% higher Ct compared with CR_0 and CR_2 in 0-5 cm soil depth. Similarly maximum Ct on day 8, 16, 32 and 64 were registered under CR_4, followed by CR_2 and CR_0 (Figure 4.5). Fertilizer K rates, however, failed to alter the Ct values, irrespective of days of incubation.

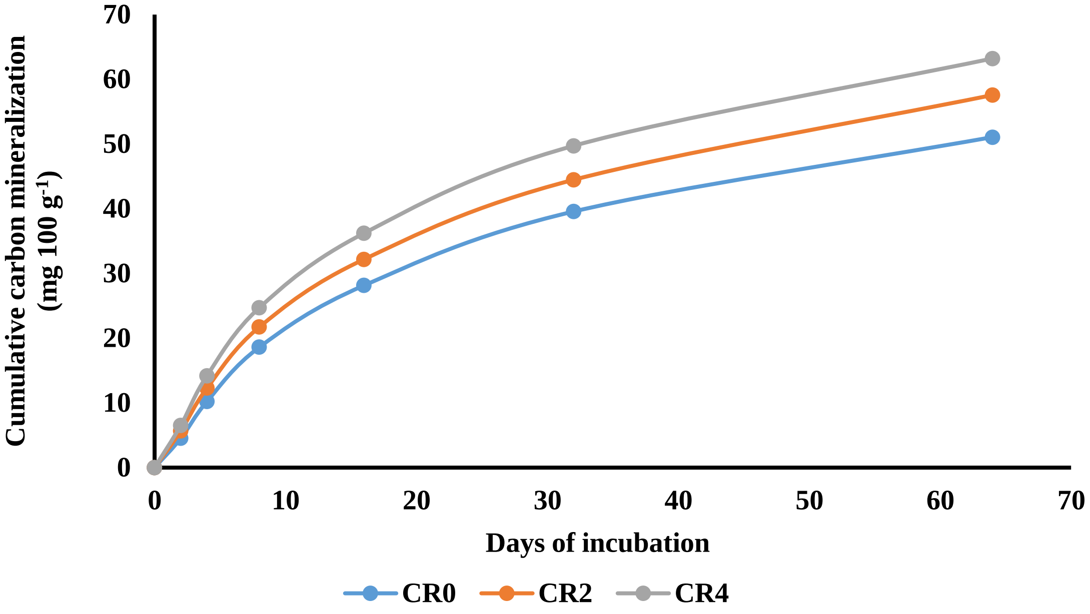


LSD (p = 0.05): Day 2: 0.20 Day 4: 0.36 Day 8: 0.89
Day 16: 1.40 Day 32: 1.31 Day 64: 3.46

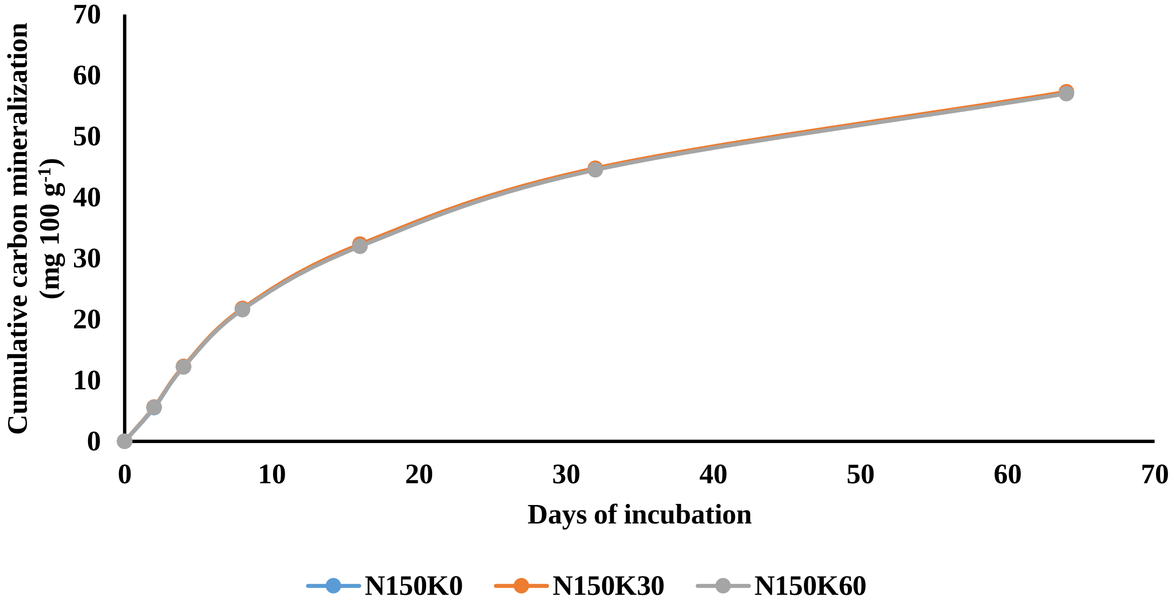


LSD (p = 0.05): NS for all days of observation

Fig 4.2. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 20 °C in bulk soil from 5-15 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

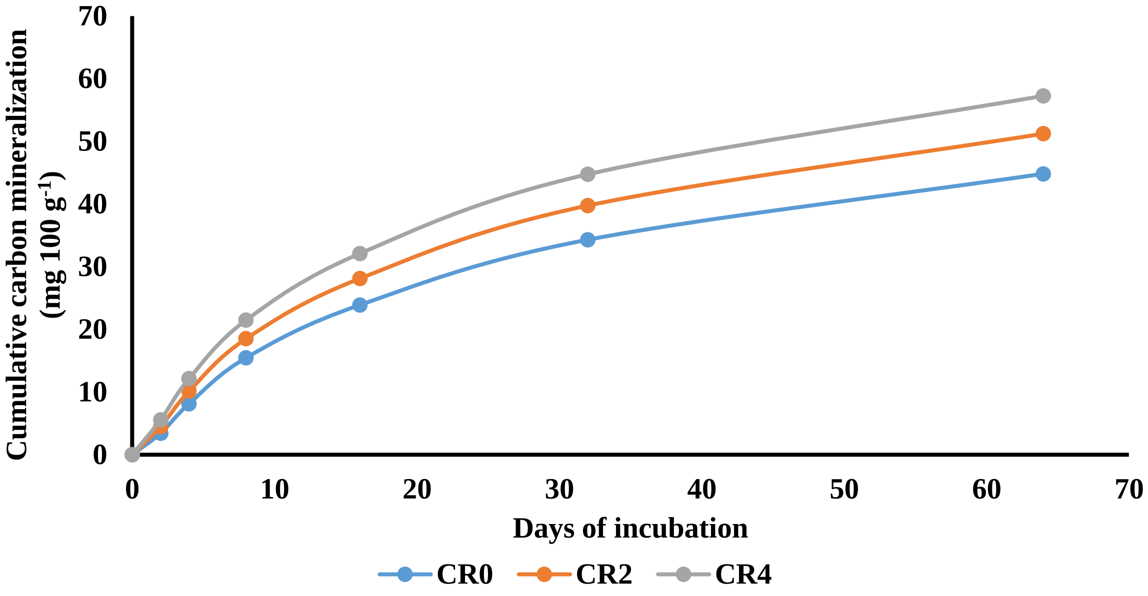


LSD (p = 0.05): Day 2: 0.51 Day 4: 0.60 Day 8: 0.79
Day 16: 0.86 Day 32: 1.10 Day 64: 3.17

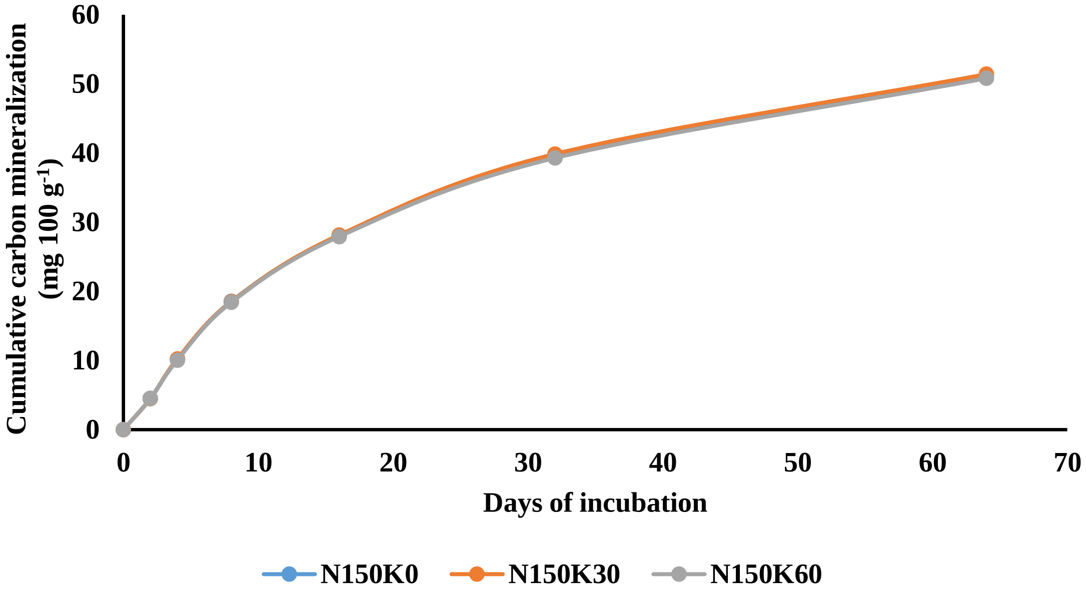


LSD (p = 0.05): NS for all days of observation

Fig 4.3. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 30 °C in bulk soil from 0-5 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

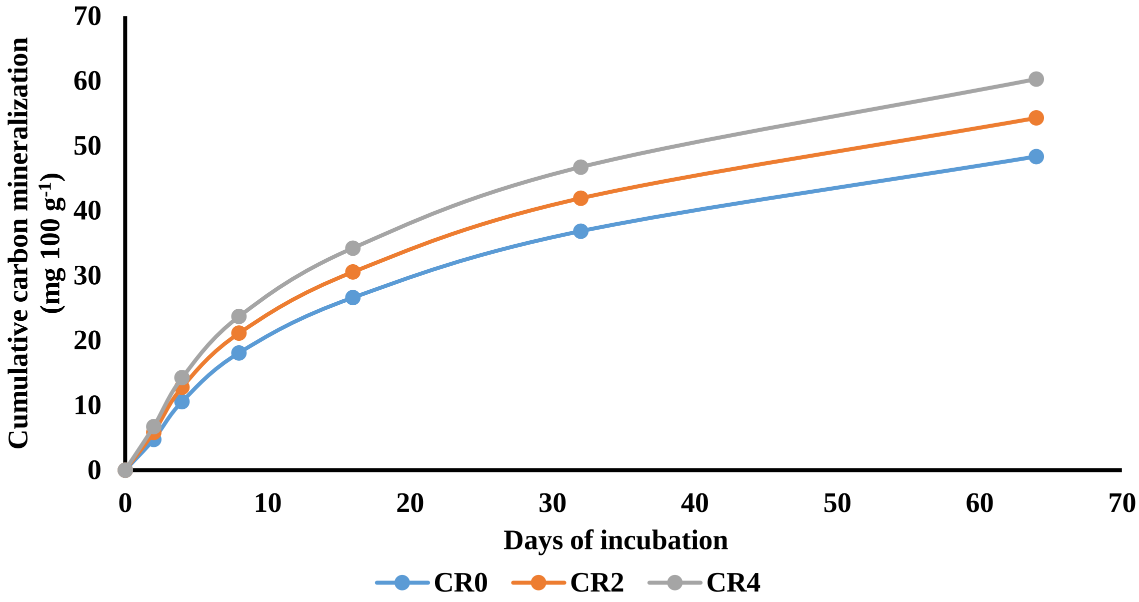


LSD (p = 0.05): Day 2: 0.31 Day 4: 0.37 Day 8: 0.33
Day 16: 0.42 Day 32: 0.60 Day 64: 2.27

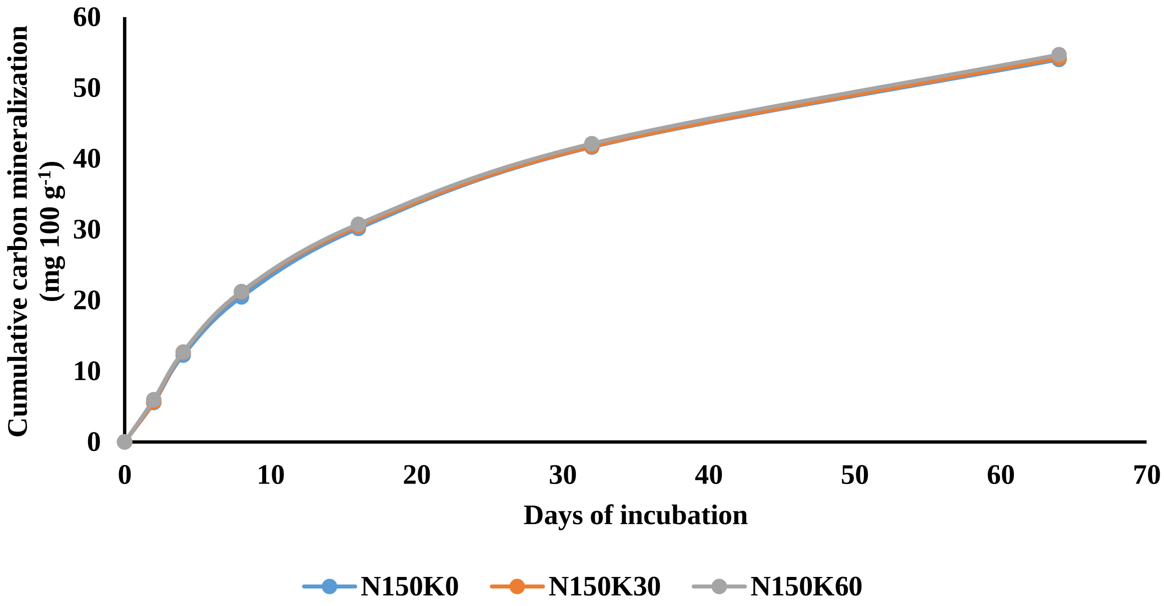


LSD (p = 0.05): NS for all days of observation

Fig 4.4. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 30 °C in bulk soil from 5-15 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture



LSD (p = 0.05) Day 2: 0.60 Day 4: 0.32 Day 8: 0.70
Day 16: 0.47 Day 32: 0.22 Day 64: 3.36



LSD (p = 0.05): NS for all days of observation

Fig 4.5. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 20 °C in macro-aggregates from 0-5 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

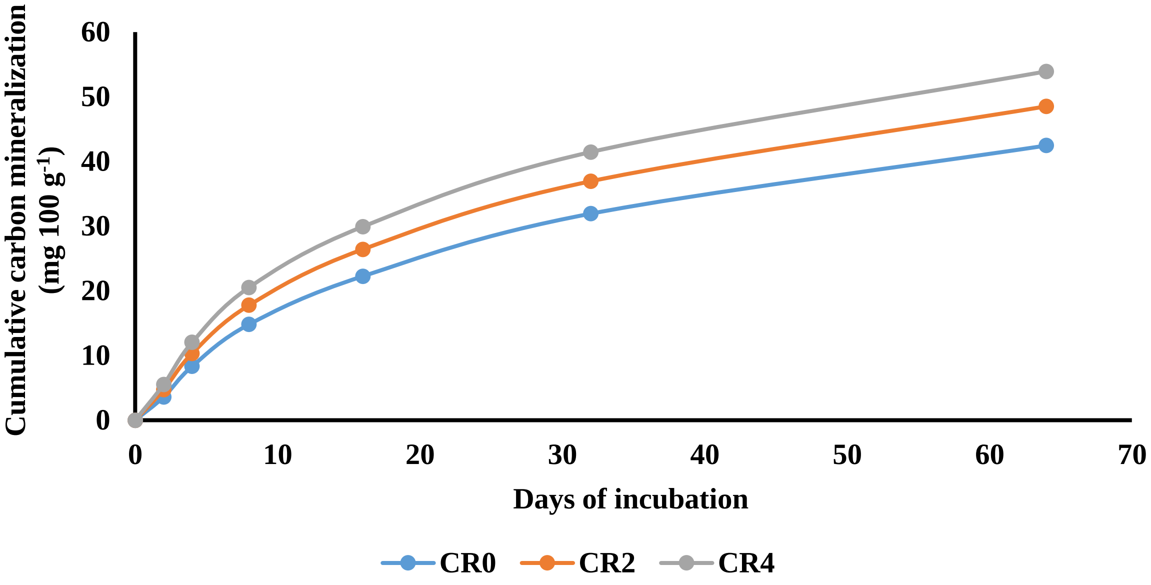
The Ct was lower in 5-15 cm compared with top 0-5 cm layer. During entire incubation period, the CR_4 registered highest Ct, followed by CR_2 and CR_0. On day 2, CR_4 treatment had 53.7 and 17.2% higher Ct as compared to CR_0 and CR_2, respectively. On day 16, CR_4, CR_2 and CR_0 had 29.9, 26.4 and 22.2 mg Ct 100 g^{-1} soil, respectively (Figure 4.6). On other days, CR_4 was superior to other CR options. No significant difference was observed due to K rates *i.e.*, $N_{150}K_0$, $N_{150}K_{30}$, $N_{150}K_{60}$.

The Ct values were higher at 30 °C compared 20 °C temperature regime at all sampling intervals. On day 2, maximum Ct was observed in CR_4 treatment (7.66 mg 100 g^{-1} soil), followed by CR_2 (6.57 mg 100 g^{-1} soil) and lowest in CR_0 (5.5 mg 100 g^{-1} soil) in 0-5 cm soil depth (Figure 4.7). On day 4, the CR_4 treatment had 34.5 and 14.5% higher Ct compared to CR_0 and CR_2 treatment in 0-5 cm soil depth (Table 4.3). On the other days also, similar trends were noticed due to graded CR loads. On day 64, the CR_4 treatment had 19.5 and 8.2% higher Ct as compared to CR_0 and CR_2 treatment respectively (Table 4.3). With fertilizer K rates, differences in Ct were non-significant.

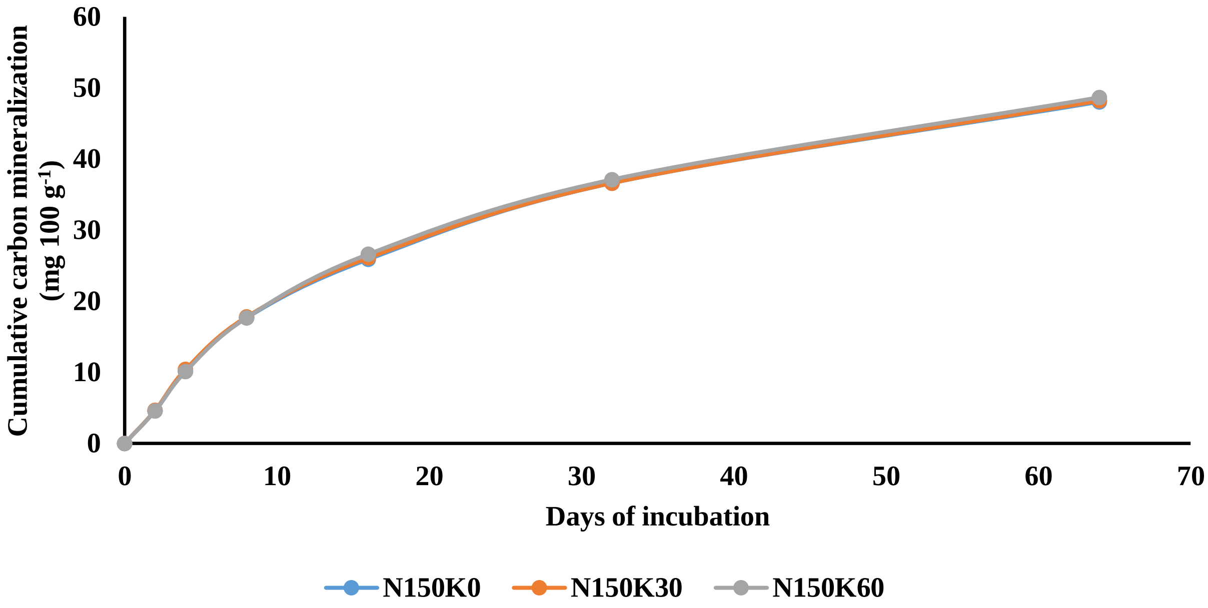
In 5-15 cm soil depth, Ct was lower than 0-5 cm soil depth at 30 °C. On day 2, maximum CO_2 evolution was observed in CR_4 treatment (5.52 mg 100 g^{-1} soil), followed by CR_2 (4.7 mg 100 g^{-1} soil) and CR_0 treatment (3.59 mg 100 g^{-1} soil) in 5-15 cm soil depth (Figure 4.8). Cumulative C mineralization showed an increasing trend with days of incubation, and on day 64, CR_4 treatment had highest Ct (53.9 mg 100 g^{-1} soil), followed by CR_2 (58.5 mg 100 g^{-1} soil) and CR_0 (42.4 mg 100 g^{-1}soil) (Table 4.3). Among nutrient management options difference in rate of CO_2 evolution were non-significant due to K fertilization. For macro-aggregates interaction between CR and nutrient management was not significant at either temperature or depth of soil.

4.3.3. Micro-aggregates

Cumulative mineralization of native SOC from micro-aggregates on day 2 at 20 °C was similar with macro-aggregates in 0-5 cm soil depth. On day 8, the Ct in CR_4 treatment was 24 mg 100 g^{-1} soil, followed by CR_2 treatment (21.6 mg 100 g^{-1} soil) and CR_0 (18.6 mg 100 g^{-1} soil) in 0-5 cm soil depth at 20 °C (Figure 4.9). On day 16, the CR_4 treatment had 26.69 and 9.7% higher Ct compared with CR_0 and CR_2 treatment respectively. On day 64 CR_0, CR_2, and CR_4 treatment had 48.4, 54.3 and 61.8 mg Ct 100 g^{-1} soil, respectively. With K supply no significant difference was recorded in Ct across sampling intervals.

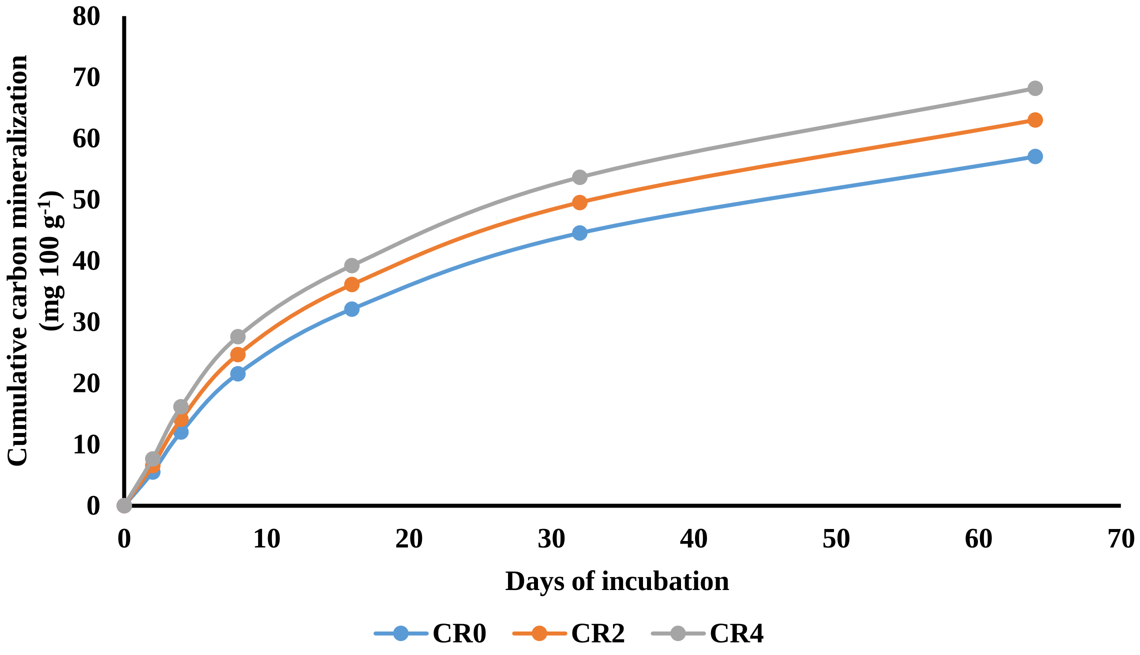


LSD (p = 0.05)   Day 2: 0.42   Day 4: 0.74   Day 8: 0.94
Day 16: 1.16   Day 32: 1.09   Day 64: 5.04

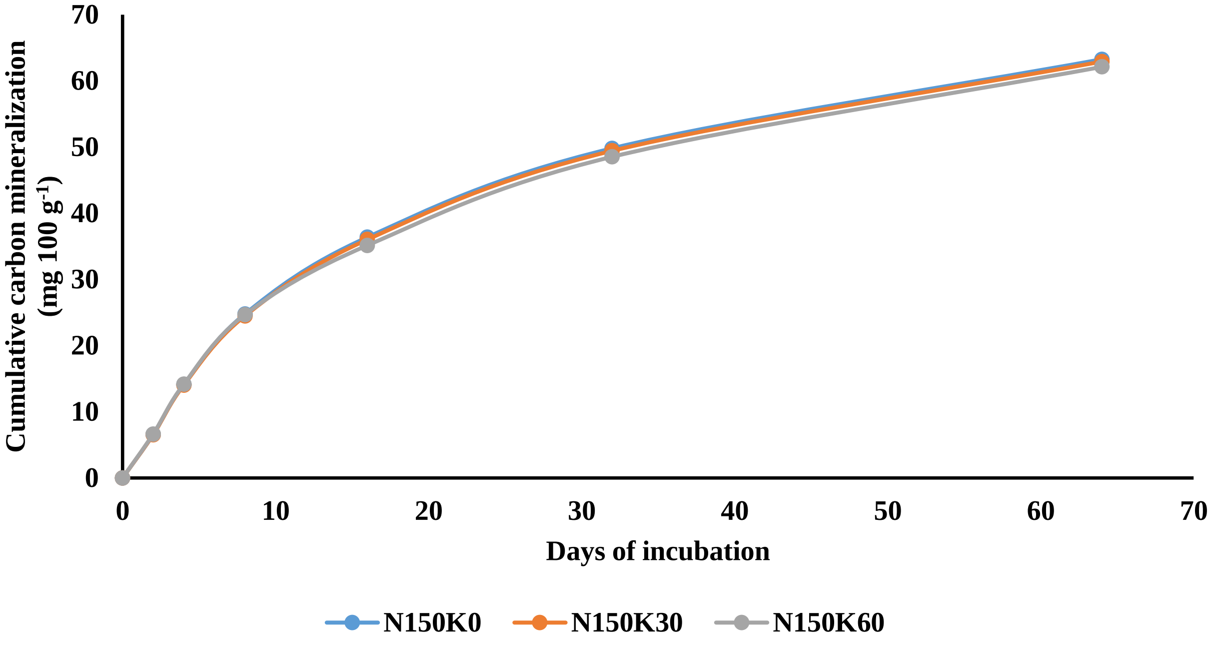


LSD (p = 0.05): NS for all days of observation

Fig 4.6. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 20 °C in macro-aggregates from 5-15 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

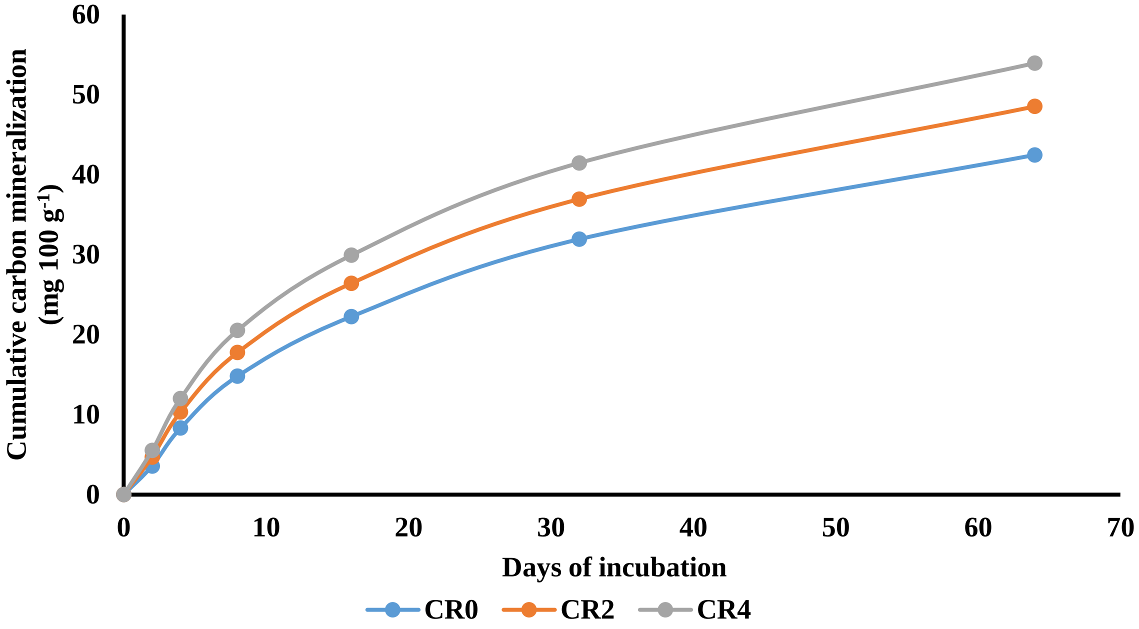


LSD (p = 0.05) Day 2: 0.28 Day 4: 0.29 Day 8: 0.45
Day 16: 2.76 Day 32: 2.84 Day 64: 6.15

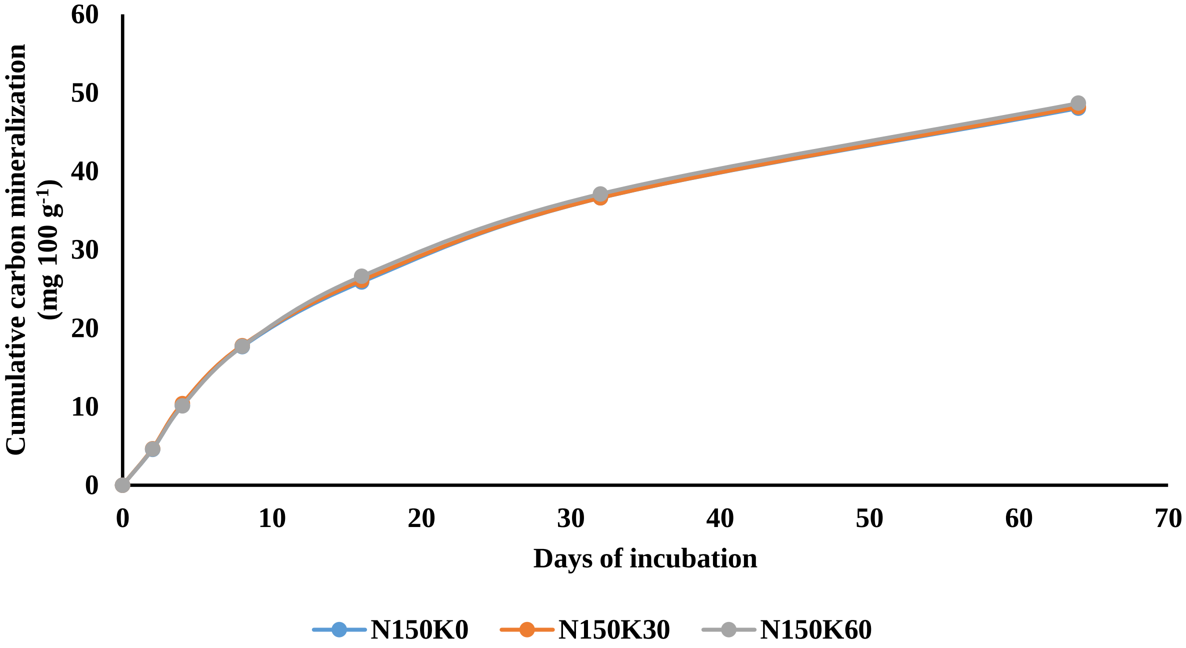


LSD (p = 0.05): NS for all days of observation

Fig 4.7. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 30 °C in macro-aggregates from 0-5 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

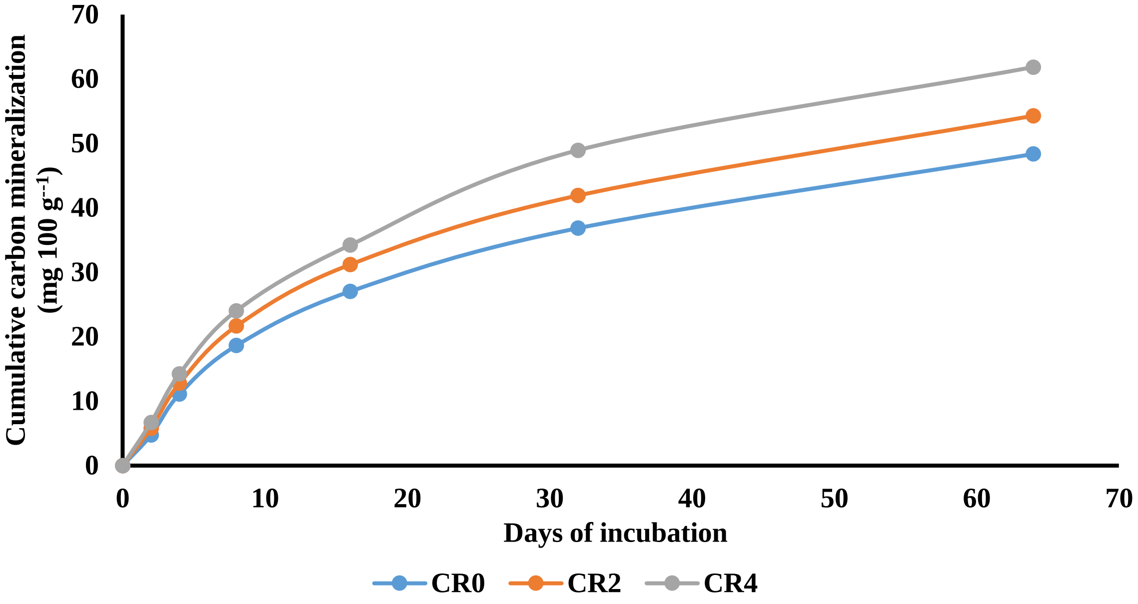


LSD (p = 0.05) Day 2: 0.42 Day 4: 0.74 Day 8: 0.94
Day 16: 1.16 Day 32: 1.09 Day 64: 5.04

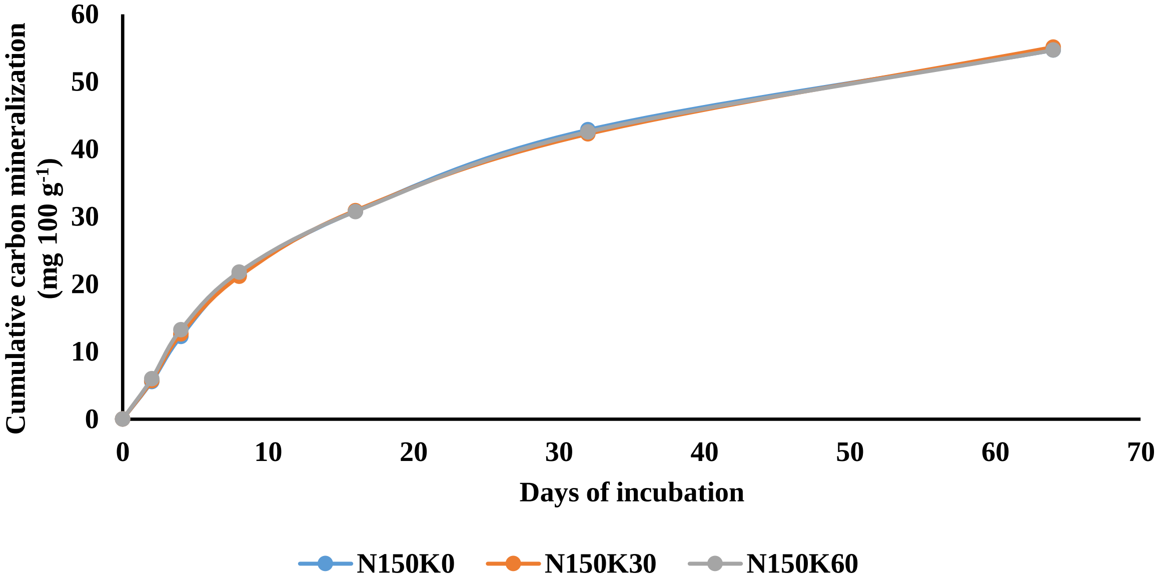


LSD (p = 0.05): NS for all days of observation

Fig 4.8. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 30 °C in macro-aggregates from 5-15 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture



LSD (p = 0.05) Day 2: 0.60 Day 4: 1.54 Day 8: 2.28
Day 16: 2.16 Day 32: 1.32 Day 64: 5.12



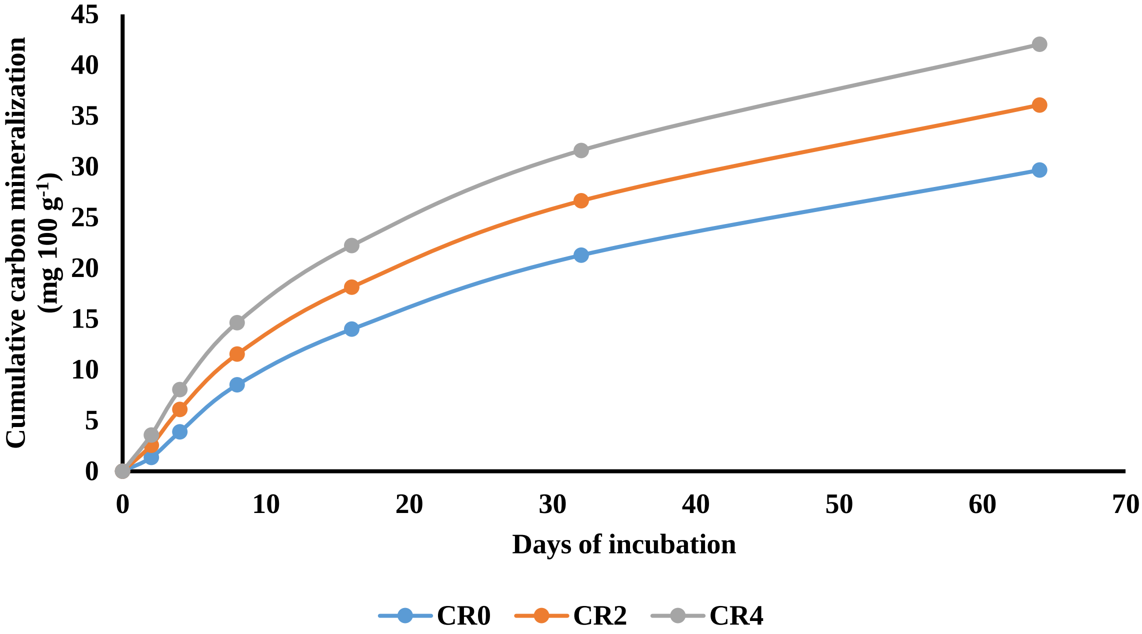
LSD (p = 0.05): NS for all days of observation

Fig 4.9. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 20 °C in micro-aggregates from 0-5 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

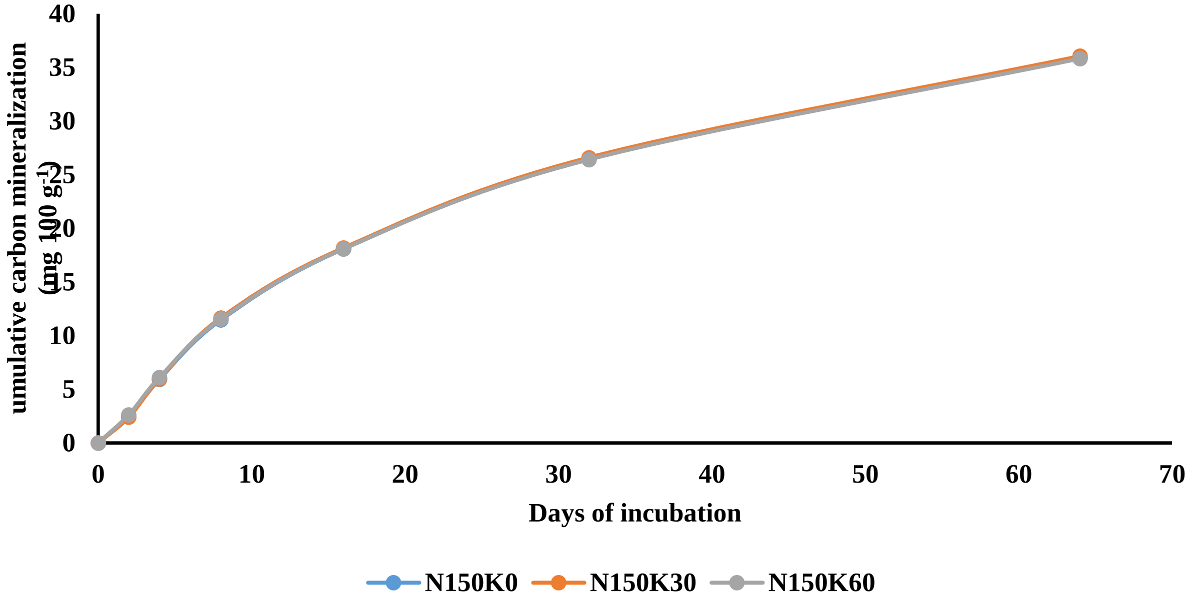
Micro-aggregates at 5-15 cm soil depth had lower Ct than upper 0-5 cm soil depth. In 5-15 cm soil depth at 20 °C, the trend for Ct under CR treatments was similar to that observed at 0-5 cm soil depth. On day 2, the CR_4 treatment had 163 and 39.2% higher Ct as compared to CR_0 and CR_2 treatment respectively (Figure 4.10). On day 4, the CR_4 treatment had 107% and 32.1% Ct as compared to CR_0 and CR_2 treatment respectively. On day 8 highest Ct was found in CR_4 treatment (14.6 mg 100 g^{-1} soil), followed by CR_2 (11.5 mg 100 g^{-1} soil) and CR_0 treatment (8.51 mg 100g^{-1} soil) (Table 4.10). On 64th day, similar trend was followed as previous days of incubation as CR_0, CR_2, and CR_4 treatments had 29.7, 36 and 42 mg 100 g^{-1} soil Ct respectively (Table 4.3 and Figure 4.11). No significant difference was observed in the cumulative SOC mineralization due to K rates applied in conjugation with 150 kg N ha^{-1}.

At 30 °C on day 2, maximum Ct was observed in CR_4 treatment (5.6 mg 100 g^{-1} soil), followed by CR_2 (4.48 mg 100 g^{-1} soil) and lowest in CR_0 (3.68 mg 100 g^{-1} soil) in soil from 0-5 cm depth (Figure 4.11). On day 4, the CR_4 showed 51.7 and 24.8% higher Ct as compared to CR_0 and CR_2 treatment, respectively. Subsequent days also, the cumulative C mineralization was invariably greater in CR_4 compared with CR_0 and CR_2. Finally on day 64, CR_4 treatment showed 26.3 and 12.2% higher Ct as compared to CR_0 and CR_2 treatments respectively. With nutrient management options (K rates) the differences in Ct were non-significant (Table 4.3).

In 5-15 cm soil depth, the Ct at 30 °C was lower than 0-5 cm soil depth. On day 2, maximum CO_2 evolution was observed in CR_4 treatment (4.5 mg 100 g^{-1} soil), followed by CR_2 (3.32 mg 100g^{-1} soil) and lowest in CR_0 treatment (2.41 mg 100g^{-1} soil) in 5-15 cm soil depth (Figure 4.12). The differences in Ct owing to varying CR retention rates were significant ($p < 0.05$) at all other days, and the Ct values were invariably greater with 4 t ha^{-1} CR retention. Finally on 64th day, the CR_4 treatment showed highest Ct (50.9 mg 100 g^{-1} soil), followed by CR_2 (45.4 mg 100 g^{-1} soil) and CR_0 (38.8 mg 100 g^{-1}soil) (Table 4.3 and Figure 4.12). The Ct remained unaffected due to K fertilization at different days of observation in micro-aggregates from 5-15 cm soil depth at 30 °C temperature regime. Also, the interaction between CR and fertilizer K rates was not significant at either temperature regimes or soil depth.

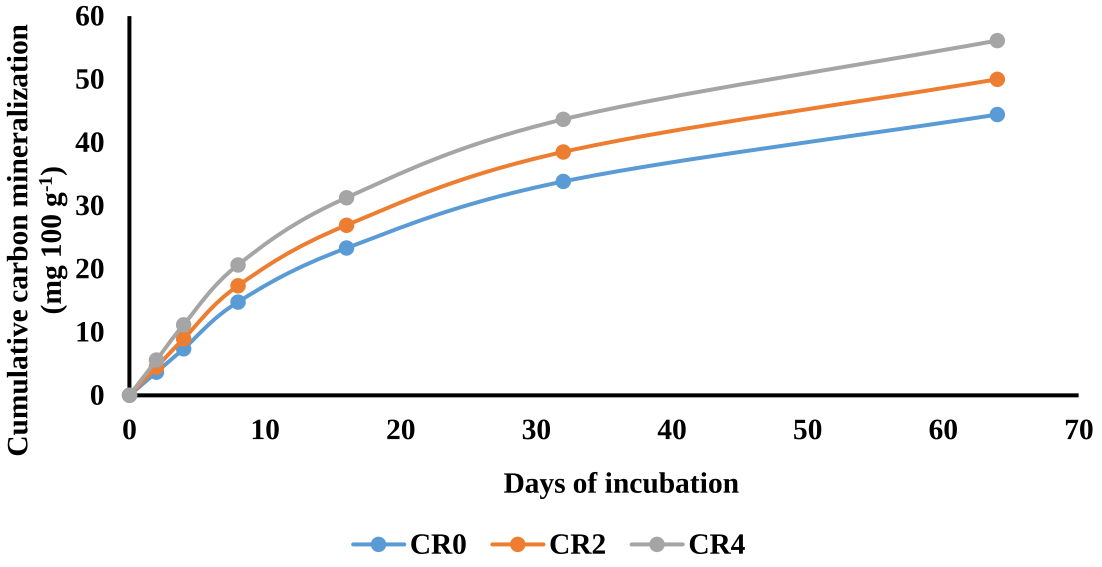


LSD (p = 0.05) Day 2: 0.34 Day 4: 0.29 Day 8: 0.73
Day 16: 0.87 Day 32: 0.77 Day 64: 4.90

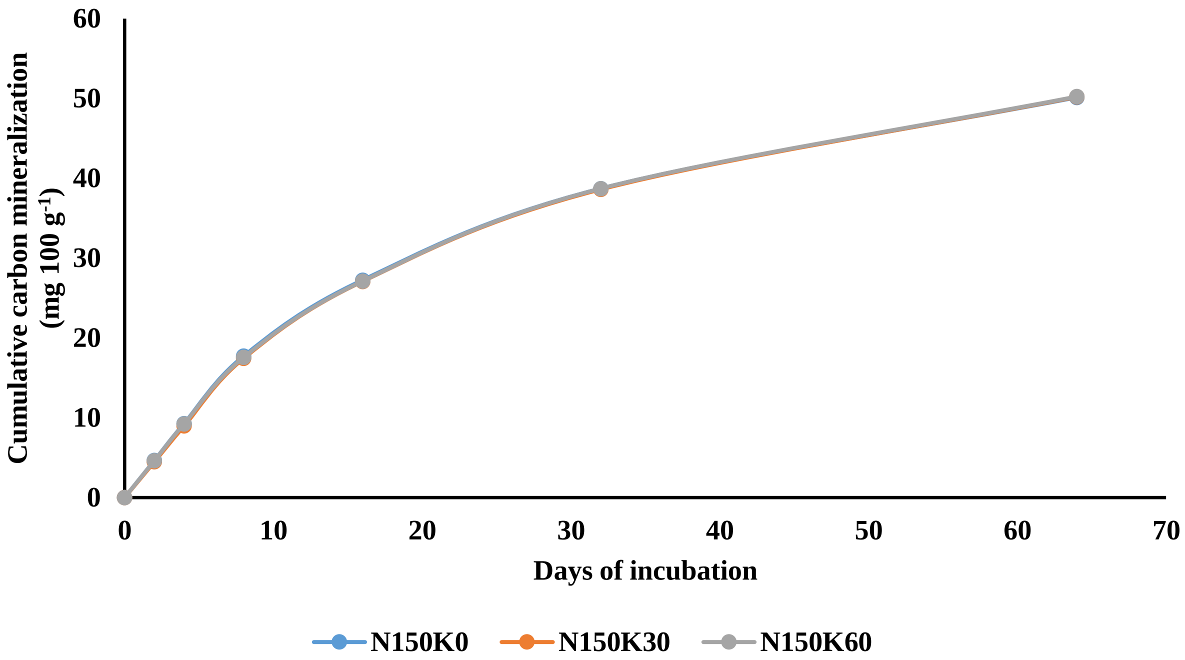


LSD (p = 0.05): NS for all days of observation

Fig 4.10. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 20 °C in micro-aggregates from 5-15 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

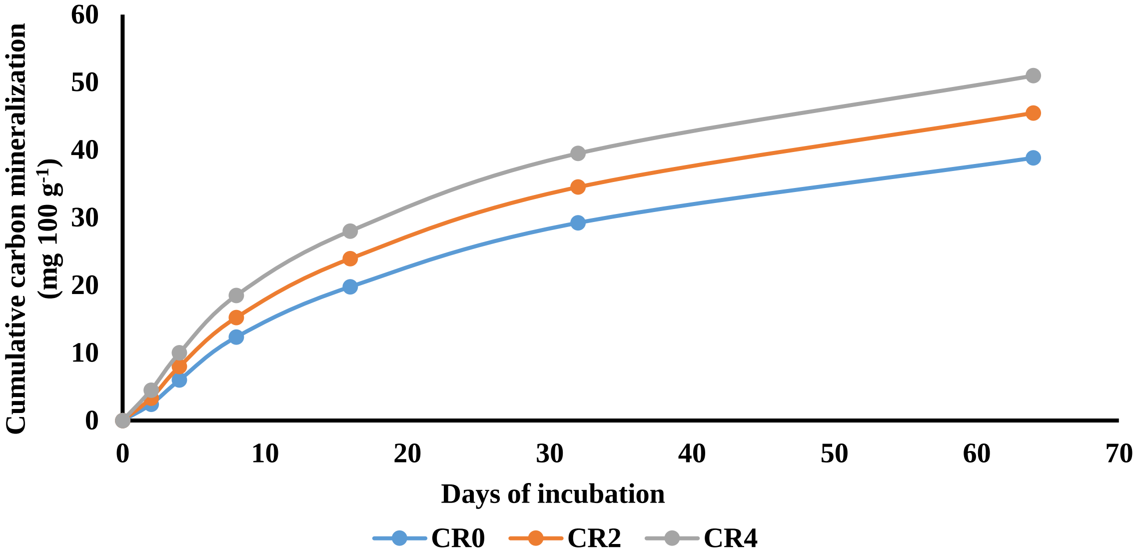


LSD (p = 0.05) Day 2: 0.49 Day 4: 0.97 Day 8: 1.20
Day 16: 1.04 Day 32: 0.97 Day 64: 4.98

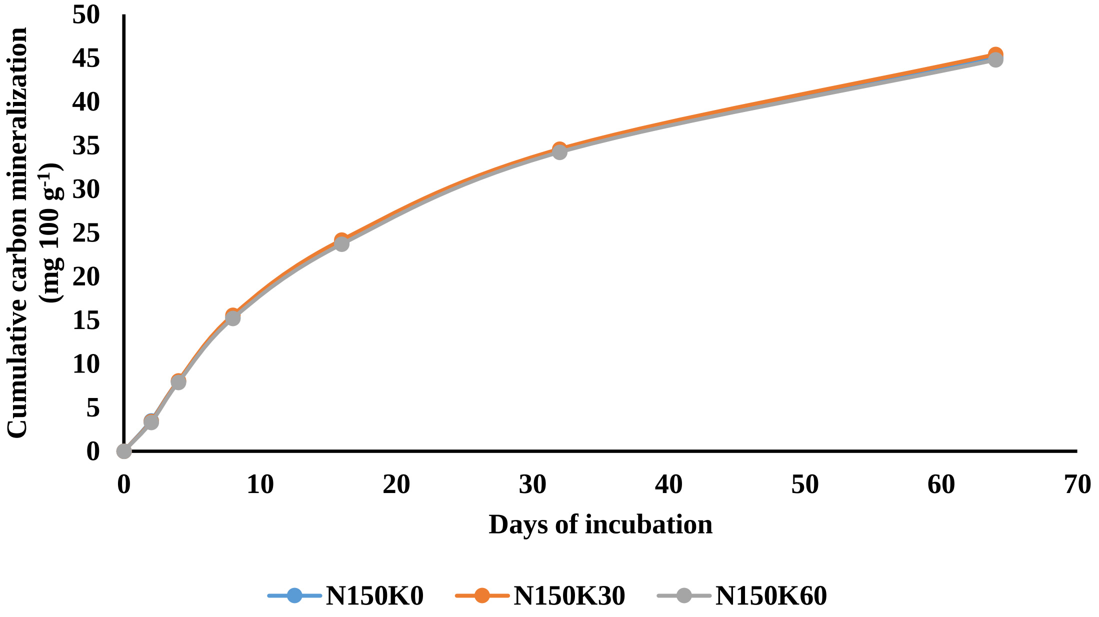


LSD (p = 0.05): NS for all days of observation

Fig 4.11. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 30 °C in micro-aggregates from 0-5 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture



LSD (p = 0.05)	Day 2: 0.23	Day 4: 0.40	Day 8: 0.45
Day 16: 0.50	Day 32: 0.71	Day 64: 4.89



LSD (p = 0.05): NS for all days of observation

Fig 4.12. Effect of crop residue retention and K fertilization on cumulative carbon mineralization (Ct) at 30 °C in micro-aggregates from 5-15 cm depth after 6 years of maize-wheat-mungbean cropping under conservation agriculture

4.4. Effect of CR retention and K fertilization options on proportion of total soil organic carbon mineralized after 64 days of incubation

4.4.1. Bulk soil

The CR_0 treatment *i.e.,* no residue retention showed significantly higher percentage total SOC mineralized compared with CR_4 and CR_2, irrespective of soil depth at both 20 °C and 30 °C temperature regimes, although the values were higher at 30 °C (Table 4.4). At 20 °C, 5.84% of total SOC in CR_0 was mineralized in 64 days, which were significantly higher than that under CR_2 and CR_4, in 0-5 cm layer. Similarly in 5-15 cm soil layer, the CR_4 treatment registered the lowest values of per cent SOC mineralized 4.3%) out of total SOC, compared with CR_2 (4.9%) and CR_0 (6.9%) (Table 4.4). At 30 °C, CR_0 had 6.9% % and 7.9% of total SOC mineralized in 0-5 and 5-15 cm soil depths, respectively. Treatments CR_4 and CR_2 registered similar percentage of total SOC mineralized at 20 °C and 30 °C in 0-5 cm and 5-15 cm soil depth. Fertilizer K rates had no significant effect on percent SOC mineralized at either soil depth or temperature regime. For bulk soil interaction effect between CR and nutrient management was not significant irrespective of temperature and depth of soil.

4.4.2. Macro-aggregates

In 0-5 cm soil depth significant difference in per cent total SOC mineralized was observed between CR_0 and CR_4 treatment *i.e.,* CR_0 treatment exhibited 5.21% and CR_4 had 4.38% mineralization of total SOC at 20 °C (Table 4.4). No significant difference in per cent SOC mineralization was observed between CR loads when soils representing 5-15 cm layer depth at 20 °C. At 30 °C, however, highest total SOC mineralization was noticed in CR_0 (6.11%), followed by CR_2 (5.3%) and CR_4 treatment (4.9%) in 0-5 cm soil depth. Difference in % total SOC mineralized at either soil depth or temperature regime were statistically not significant due to nutrient management (K). For macro-aggregates interaction effect between CR and nutrient management was not significant irrespective of temperature and depth of soil.

4.4.3. Micro-aggregates

Percentage of total SOC mineralized from treatments CR_0, CR_2 and CR_4 were not significantly different in 0-5 cm soil layer at both the temperature regimes. At 30 °C , soils from 5-15 cm depth under CR_0 treatment had significantly higher per cent total SOC mineralized (9.2%) compared with CR_4 treatment (7.8%) (Table 4.4). Different K management options did not significantly affect this soil parameter. For micro-aggregates interaction effect between CR and nutrient management was not significant irrespective of temperature and depth of soil.

Table 4.4. Effect of crop residue retention and K fertilizations options on proportion of total soil organic carbon mineralized after 64 days after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Treatments	Percentage of total SOC mineralized											
	BS				MA				MI			
	20 °C		30 °C		20 °C		30 °C		20 °C		30 °C	
Crop residue loads	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
CR$_0$	5.84	6.93	6.94	7.94	5.21	5.16	6.11	5.17	9.20	7.02	8.43	9.19
CR$_2$	4.04	4.93	4.80	5.76	4.57	5.21	5.29	5.21	8.50	6.94	7.83	8.74
CR$_4$	3.81	4.36	4.47	5.18	4.38	4.68	4.97	4.68	8.41	6.48	7.60	7.85
Mean	4.56	5.40	5.40	6.29	4.72	5.02	5.45	5.02	8.70	6.81	7.95	8.60
LSD ($p = 0.05$)	0.85	1.13	0.72	0.82	0.81	NS	0.80	NS	NS	NS	NS	1.17
Fertilizer K rates												
N$_{150}$K$_0$	4.84	5.38	5.62	6.56	4.82	5.01	5.63	5.02	8.72	6.92	7.99	8.72
N$_{150}$K$_{30}$	4.54	5.38	5.43	6.29	4.62	5.00	5.35	5.00	8.78	6.86	7.99	8.69
N$_{150}$K$_{60}$	4.30	5.46	5.16	6.03	4.71	5.05	5.38	5.05	8.60	6.66	7.88	8.38
Mean	4.56	5.40	5.40	6.29	4.72	5.02	0.86	5.02	8.70	6.81	7.95	8.60
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

BS: Bulk soil; MA: Macro-aggregates; MI: Micro-aggregates

4.5. Effect of CR and K fertilization on decay rate of SOC mineralization

4.5.1. Bulk soil

At both temperature regimes, CR_0 had significantly higher Kc ($\times 10^{-3}$) values compared to CR_4 and CR_2 treatment irrespective of soil depth (Table 4.5). On the other hand Kc values were higher at 30 °C compared with those at 20 °C. The CR_0 treatment at 20 °C showed 51.7 and 44.2% greater Kc compared with that in case CR_4 and CR_2 in 0-5 cm soil depth, respectively. In 5-15 cm soil depth, CR_4 (0.50 day^{-1}) registered lowest Kc, followed by CR_2 (0.76 day^{-1}) and CR_0 (1.09 day^{-1}) (Table 4.5). At 30 °C CR_0 treatment exhibited 65% higher Kc than CR_4 in 0-5 and 5-15 cm soil depths. Again, CR_0 treatment had 56.1% and 37.8% greater Kc compared with CR_2 treatment in 0-5 and 5-15 cm soil depths, respectively at 30 °C. The treatments CR_4 and CR_2 registered similar Kc at 20 °C and 30 °C in 0-5 cm soil depth. But in 5-15 cm soil depth CR_2 and CR_0 showed 22% and 23.5% higher Kc values compared to CR_4 treatment 20 °C. Nutrient management (K) options had no significant difference on decay rate in either soil depths. For bulk soil interaction effect between CR and nutrient management was not significant irrespective of temperature and depth of soil for Kc.

4.5.2. Macro-aggregates

Treatment CR_4 registered 22.3 and 17.6% lower Kc value in macro-aggregates at 20 °C compared with CR_0 treatment in 0-5 and 5-15 cm soil depths, respectively (Table 4.5). On the contrary, no significant difference was observed between CR_0 and $CR_{2,}$ and also between $CR_{2.}$ Irrespective of soil depth, higher Kc values were registered in macro-aggregates at 30 °C compared with 20 °C. The CR_0 had 43.2% and 32.5% greater Kc value at 30 °C as compared to CR_4 and CR_2 treatment in 0-5 cm soil depth respectively. In 5-15 cm soil depth no statistical difference was found between different CR loads at 30 °C. Fertilizer K management options did not affect Kc values at either temperature regime and soil depth. For macro-aggregates interaction effect between CR and nutrient management was not significant irrespective of temperature and depth of soil for Kc.

4.5.3. Micro-aggregates

Micro-aggregates showed higher value of Kc as compared to bulk soil and macro-aggregates, irrespective of temperature and soil depth. At 20 °C, there was no significant difference in Kc value among the CR treatments in 0-5 cm soil depth (Table 4.5). But in 5-15 cm soil depth, CR_4 treatment had 17.5% lower Kc than CR_0 treatment. At 30 °C similar trend was observed in 0-5 cm. In 5-15 cm soil depth, the CR_4 treatment had 18.5 and 13.3% lower Kc compared with CR_0 and CR_2. The Kc values tended to be greater at $N_{150}K_0$ compared with $N_{150}K_{60}$, although the differences were not significant. For micro-aggregates interaction effect between CR and nutrient management was not significant irrespective of temperature and depth of soil for Kc.

4.6. Effect of CR retention and K fertilization on temperature sensitivity of SOC mineralization

4.6.1. Bulk soil

The Q_{10} values decreased with an increase in CR load, although the differences were not significant at either soil depths (Table 4.6). The lower depth (5-15 cm) had higher Q_{10} value compared with that in upper soil layer (0-5 cm). Different nutrient management (K rates) options did not affect temperature sensitivity of SOC mineralization at either sampling depths. For $Q_{10,}$ there was no significant interaction between CR retention rates and K fertilization at both soil depths.

4.6.1. Macro-aggregates

The Q_{10} of SOC mineralization was significantly higher under CR_0 compared with CR_4, in 0-5 cm soil depth i.e. 10.7% higher in CR_0 than CR_4 treatment (Table 4.6). In 5-15 cm soil depth different CR loads or K doses did not affect the Q_{10} values significantly. For $Q_{10,}$ there was no significant effect interaction between CR loads and K fertilization rates was noticed with respect to Q_{10} at either soil depth.

4.6.2. Micro-aggregates

In general, micro-aggregates had higher Q_{10} value of SOC mineralization as compared to bulk soil and macro-aggregates at both soil depths. However, CR and nutrient (K) application did not affect Q_{10} value at both 0-5 and 5-15 cm soil depth. Although not statistically significant, Q_{10} value showed decreasing trend with the incremental residue loads at both soil depths. Alike bulk soil and macro-aggregates, the interaction between CR and fertilizer K rates was not significant on Q_{10} at both soil depths.

Table 4.5. Effect of crop residue retention and K fertilizations on decay rate ($Kc \times 10^{-3}$) of carbon mineralisation after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Treatments	$Kc \times 10^{-3}$ (day^{-1})											
	BS				MA				MI			
	20 °C		30 °C		20 °C		30 °C		20 °C		30 °C	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
Crop residue loads												
CR_0	0.88	1.09	1.14	1.31	0.85	0.85	1.06	0.97	1.07	1.20	1.37	1.51
CR_2	0.61	0.76	0.73	0.95	0.69	0.80	0.80	0.91	1.00	1.11	1.31	1.42
CR_4	0.58	0.50	0.69	0.79	0.66	0.70	0.74	0.84	0.99	0.99	1.19	1.23
Mean	0.69	0.78	0.85	1.01	0.73	0.78	0.86	0.90	1.02	1.11	1.29	1.38
LSD ($p = 0.05$)	0.12	0.19	0.17	0.22	0.15	0.12	0.20	NS	NS	0.15	NS	0.16
Fertilizer K rates												
$N_{150}K_0$	0.72	0.84	0.86	1.08	0.73	0.78	0.86	0.92	1.03	1.14	1.33	1.42
$N_{150}K_{30}$	0.69	0.83	0.84	1.04	0.75	0.78	0.92	0.88	1.03	1.10	1.26	1.40
$N_{150}K_{60}$	0.67	0.68	0.86	0.94	0.73	0.79	0.82	0.92	1.01	1.05	1.27	1.34
Mean	0.69	0.78	0.85	1.02	0.73	0.78	0.86	0.90	1.02	1.09	1.28	1.38
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

BS: Bulk soil; MA: Macro-aggregates; MI: Micro-aggregates

Table 4.6. Effect of crop residue retention and K fertilizations on temperature sensitivity (Q10) of carbon mineralisation after 6 years of maize-wheat-mungbean cropping under conservation agriculture

Treatments	Q_{10}					
	BS		MA		MI	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
Crop residue loads						
CR_0	1.31	1.34	1.24	1.21	1.39	1.39
CR_2	1.19	1.25	1.16	1.14	1.28	1.28
CR_4	1.16	1.18	1.12	1.20	1.20	1.21
Mean	1.22	1.25	1.17	1.18	1.29	1.29
LSD ($p = 0.05$)	NS	NS	0.09	NS	NS	NS
Fertilizer K rates						
$N_{150}K_0$	1.21	1.29	1.18	1.21	1.38	1.34
$N_{150}K_{30}$	1.19	1.37	1.22	1.16	1.22	1.27
$N_{150}K_{60}$	1.26	1.10	1.13	1.19	1.28	1.27
Mean	1.22	1.25	1.17	1.18	1.29	1.29
LSD ($p = 0.05$)	NS	NS	NS	NS	NS	NS

BS: Bulk soil; MA: Macro-aggregates; MI: Micro-aggregates

Chapter 5 Discussion

5.1. Effect of CR retention on soil organic carbon dynamics

5.1.1. Soil aggregation and aggregate associated C

CR retention at 4 t ha^{-1} under CR_4 provided continuous supply of fresh organic matter for build-up of water-stable soil aggregates (Fesha *et al.,* 2002) (Table 4.2). The fresh CR released polysaccharides and organic acids during their decomposition, which helped in binding of soil particles and prevented disintegration. Under continuous ZT environment, retention of CRs contributed significantly to soil aggregate build-up (Verhulst *et al*., 2010). Differential influence of plant roots and their rhizosphere on soil aggregation could be another possible reason for such results. Plant roots enhance soil aggregation through release of a variety of compounds such as polygalacturonic acid that have a cementing effect on soil particles and stabilize aggregates by increasing bond strength (Czarnes *et al*., 2000). In addition, inclusion of legume (mungbean) might have also contributed in increased soil aggregation microbial biomass and water-stable aggregates. Soil macro-aggregates are formed around fresh CR, which then becomes coarse intra-aggregate particulate organic matter (iPOM) (Six *et al*., 2000). The CR retention enhances microbial activity through providing of C-rich substrates, which promotes secretion of intermediary reaction products that are the main contributor towards binding of residue and soil particles into macro-aggregates (Six *et al*., 1999).

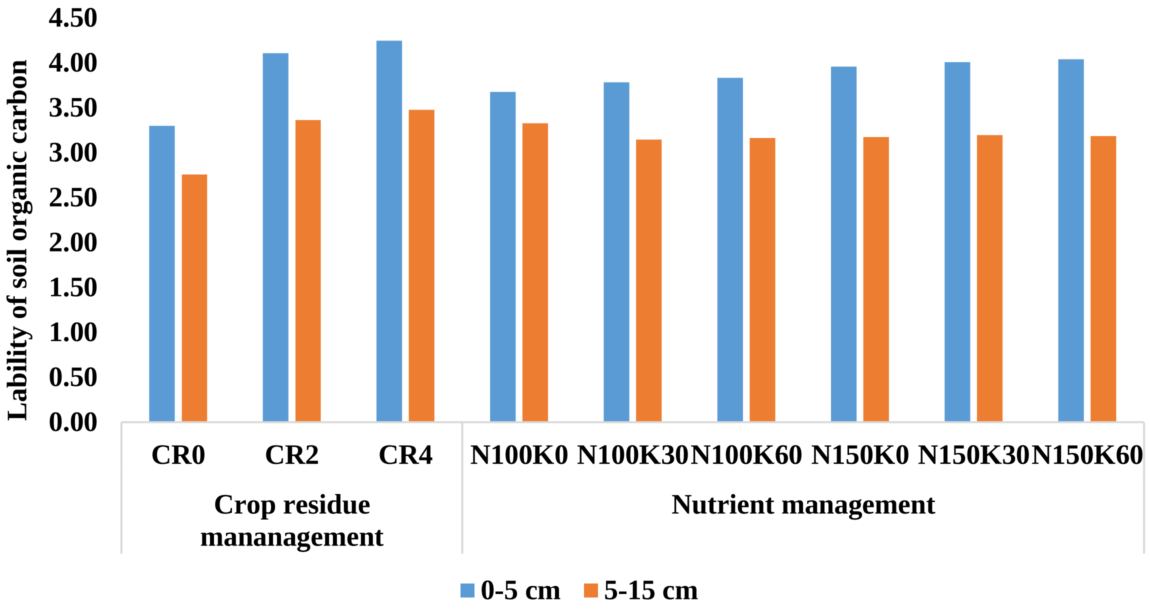
The micro-aggregates present in soil combine with the fresh organic matter to form macro-aggregates thus lowering the percentage of micro-aggregates as observed in CR retained plots in the present case (Table 4.2). Highest amount of micro-aggregates (%) was found in CR_0 in 0-5 cm (37.9%) and 5-15 cm (34.4%) soil depth, which was significantly greater than CR_2 and CR_4 (Table 4.2). In ZT plots, the released products of organic matter degradation prove nucleation sites for microbial activity (Cheshire, 1979; Puget *et al.*, 1995; Jastrow, 1996). Under zero-till conditions, minimum mechanical disturbance hindered the process of aggregate breakdown and formation of new micro-aggregates. Furthermore, CRs protects the soil from eroding impact of rainfall (Dikgwatlhe *et al.,* 2014; Ghosh *et al.,* 2019), in turn promoting stabilization of soil aggregates. Therefore, the treatment CR_4 promoted build-up of macro-aggregates accompanied by a lower micro-aggregate percentage. On the other hand, omission of CR load hindered macro-aggregate formation in CR_0, and further the macro-aggregates present there were more prone to loss due to environmental factors compared with CR_2 or CR_4.

The macro-aggregates are inherently C-rich compared with micro-aggregates which are produced after C loss due to mechanical disturbance and breaking of macro-aggregates (Six *et al.,* 2000). In the present study, incremental CR load significantly increased macro-aggregate and micro-aggregate associated C (Table 4.2). These findings corroborated with previous reports (Mathew *et al.,* 2012; Zhu *et al*., 2014). The SOC associated with 'micro-aggregates within macro-aggregates' is physically protected against microbial degradation and other environmental forces. These C pools had a very slow turnover rate under ZT conditions, and thus get accumulated under higher levels of CR retention (Balesdent *et al*., 2000; Six *et al.,* 2000).

5.1.2. Soil organic carbon and its' pools of varying lability

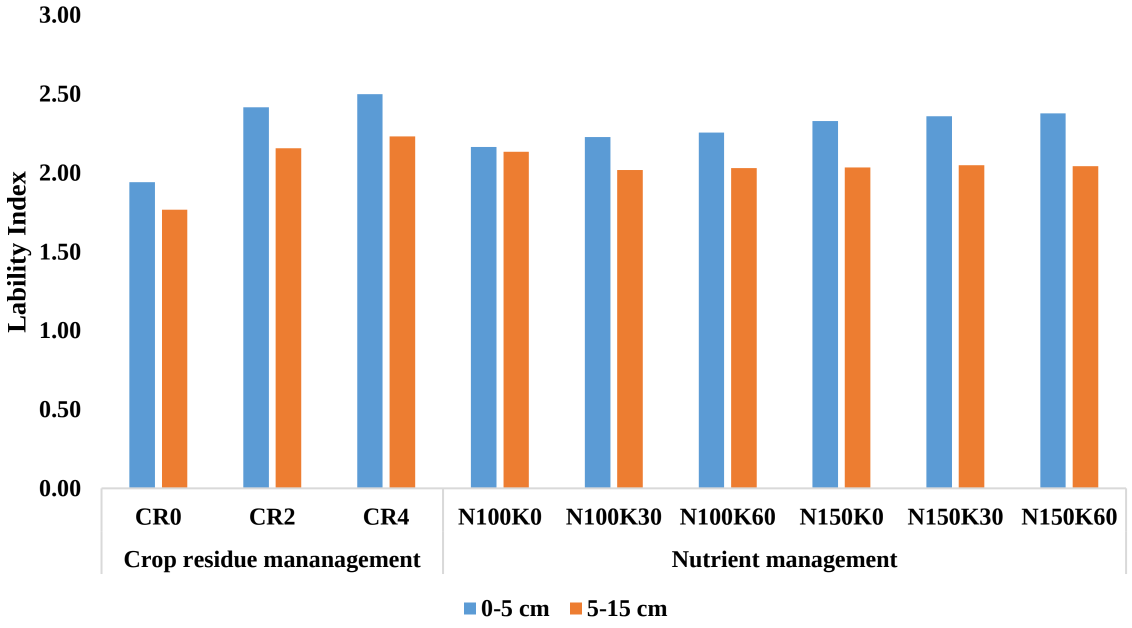
Crop residue retained under CR_4 and CR_2 played an important role in SOC build-up (Table 4.1) (Chivenge *et al*., 2007). Least mechanical disturbance under CA ensured maximum build-up of SOC due to greater physical protection and continuous supply of fresh organic matter in CR_4 followed by CR_2. Surface CR retention and non-inversion of soil promoted significantly higher SOC build-up in surface 0-5 cm layer compared with lower depths (Alam *et al*., 2014). Maintenance of a low temperature regime and increased water retention slows down the decomposition of SOM under CA plots having higher amount of CR than those with no residue addition (Amini and Asoodar, 2015). The CR retained on soil surface provided steady SOM source due to slower decomposition (Dikgwatlhe *et al.,* 2014), leading to abundance of C-rich macro-aggregates under CR retention.

The amount of CR retained under CR_4 and CR_2 often exceeded the capability of microbes for humification and breakdown into CO_2 with possible upsurge in labile SOC (Table 4.1). The products released by decomposition and root exudation processes enhance the aggregation of clay and silt particles and formation of temporary binding agents (*i.e.,* fungal hyphae) which ultimately increased macro-aggregation. Higher build-up of SOC_{VL}, SOC_{L} and SOC_{LL} (Table 4.1) in these plots ultimately registered higher lability and LI under CR_4 followed by CR_2 in both 0-5 and 5-15 cm soil depths (Figures 5.1 and 5.2). Several other researchers reported an improvement of labile SOC pools upon retention of CR under ZT conditions (Bhattacharyya *et al*., 2013).



LSD (p = 0.05): Crop residue management: 0.14 (0-5 cm); 0.54 (5-15 cm)
Nutrient management: NS (0-5 cm); NS (5-15cm)

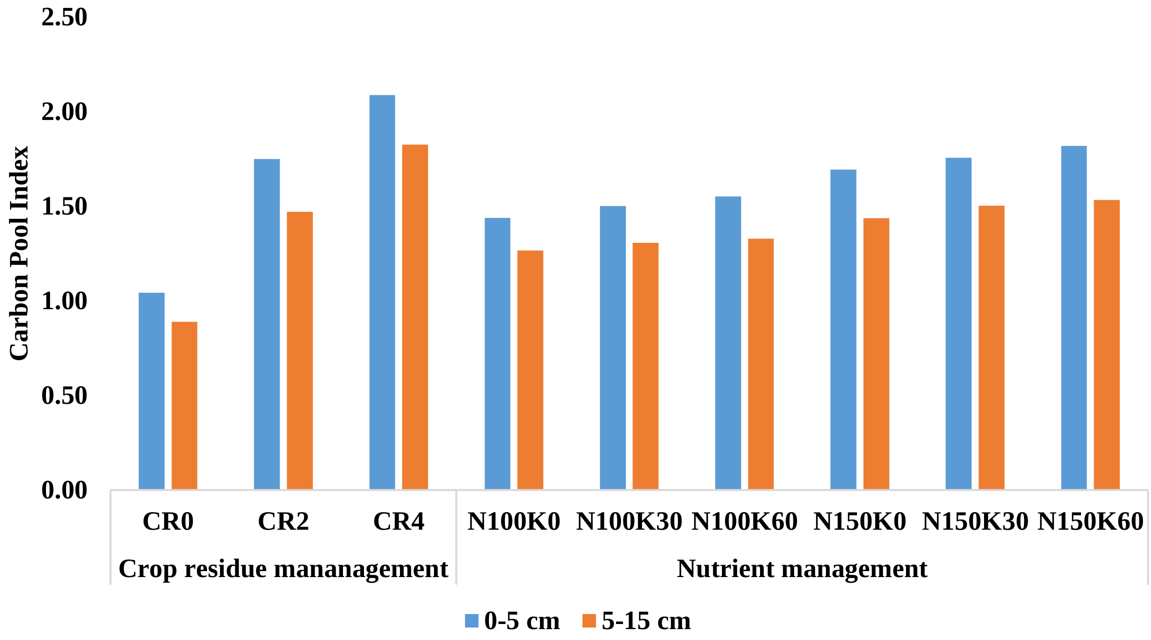
Fig 5.1. Effect of crop residue retention and nutrient management options on lability of soil organic carbon after 6 years of maize-wheat-mungbean cropping under conservation agriculture



LSD (p = 0.05): Crop residue management: 0.08 (0-5 cm); 0.34 (5-15 cm)
Nutrient management: NS (0-5 cm); NS (5-15cm)

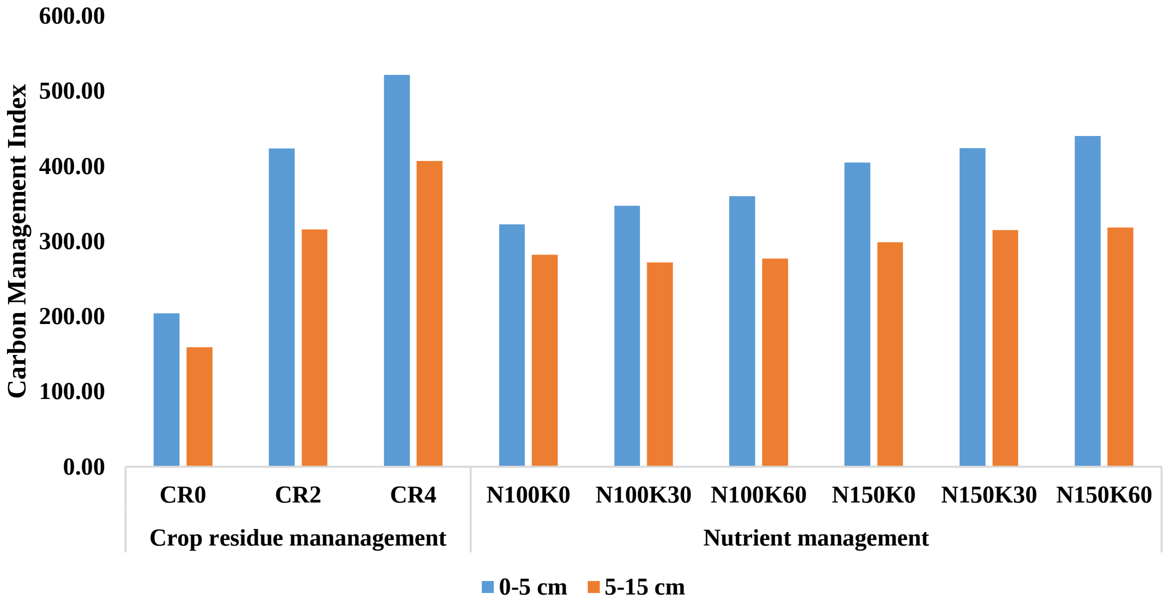
Fig 5.2. Effect of crop residue retention and nutrient management options on lability index after 6 years of maize-wheat-mungbean cropping under conservation agriculture

On the contrary CA promoted recalcitrant SOM formation due to moistened condition as a result of long-term mechanical non-disturbance. Thus, the labile SOC gets ample time to convert to non-labile pools of SOC, ultimately enhancing both labile and non-labile pools alike under adequate CR addition (Bhattacharyya *et al.*, 2012; Dey, 2016; Dey *et al.*, 2018). The SOC associated with free micro-aggregates, and micro-aggregates within macro-aggregates probably contributed to the SOC_{NL} build-up in CR_4 and CR_2 compared with no residue retention (Table 4.1). The sequestration of SOC in recalcitrant pools under 4 t ha^{-1} retention further improved CPI in both soil depths (Figure 5.3). By virtue of enhancements of LI and CPI, treatment CR_4 registered highest CMI, which was 155% and 23.2% higher compared with CR_0 and CR_2 in 0-5 cm soil depth, and 156.1% and 28.9% higher compared with CR_0 and CR_2 in 5-15 cm soil depth, respectively (Figure 5.4).



LSD (p = 0.05): Crop residue management: 0.13 (0-5 cm); 0.07 (5-15 cm)
Nutrient management: 0.09 (0-5 cm); 0.07 (5- 15cm)

Fig 5.3. Effect of crop residue retention and nutrient management options on carbon pool index after 6 years of maize-wheat-mungbean cropping under conservation agriculture



LSD (p = 0.05): Crop residue management: 33.49 (0-5 cm); 43.45 (5-15 cm)

Nutrient management: 33.76 (0-5 cm); 40.80 (5-15cm)

Fig 5.4. Effect of crop residue retention and nutrient management options on carbon management index after 6 years of maize-wheat-mungbean cropping under conservation agriculture

5.1.3. Organic carbon mineralization from bulk soil

In ZT conditions under CA, maximum of CR retained on surface did not get transferred or mixed into the deeper soil layers. This led to enhanced microbial activity in the 0-5 cm soil depth, compared with 5-15 cm depth, especially at high CR retention rates (Figures 4.1 and 4.2) (Dey, 2018). Therefore, greater Ct values were obtained from 0-5 cm depth compared with 5-15 cm depth (Table 4.3) (Parihar *et al.,* 2019). At both temperature regimes, highest Ct was obtained in CR_4 followed by CR_2 and CR_0 from both soil depths (Figures 4.1 to 4.4). As evident from Table 4.1, the plots with CR retention had higher concentration of labile SOC along with higher values of lability and LI (Figures 5.1 and 5.2), compared with those observed in no CR plots. Across temperature regimes, these higher labile SOC pools might have provided significantly higher C mineralization throughout incubation period in these treatments. Our results corroborate with other studies (Dey, 2016; Jat *et al.,* 2019; Parihar *et al.,* 2019), wherein the researchers established positive correlations between C mineralization and lability of SOC. Better substrate availability for microbes under CR retention encouraged C mineralization, as evident from higher values of Ct (Kumar *et al.,* 2018).

On the contrary, when the proportion of total SOC mineralized is considered *in lieu* of Ct, altogether different trends were obtained. A major portion of the CR load under CR_2 or CR_4 gets converted to stable SOC, either in the form of C associated with macro-aggregates, micro-aggregates, or micro-aggregates within macro-aggregates (Table 4.2) (Balesdent *et al.,* 1990; Lamparter *et al.*, 2009). Greater physical protection of SOC under ZT conditions with CR retention restricted its availability to microbial degradation (Six *et al.*, 2002b). In the present study, the C input is comprised of an array of materials with varying C:N ratios and degradability, which often promoted formation of recalcitrant SOM, along with an improvement in the labile pools. A better CPI and CMI under CR_4 supported the contention, and corroborated with lower proportion of SOC mineralization with respect to total SOC (Figures 5.3 and 5.4). The values of Kc were also significantly lower under CR_4 and CR_2 compared with those under CR_0 treatment at 20 and 30 °C in 0-5 and 5-15 cm soil depth (Table 4.5).

5.1.4. Soil organic carbon mineralization from aggregates

According to the life-cycle theory of macro-aggregates (Six *et al.,* 2000), soil micro-aggregates from previous cycles combine with fresh organic input to form newer macro-aggregates which become stabilized under ZT conditions. The retained CR gets converted to the coarse iPOM in the due process, which is labile in nature. Loss of C as CO_2 as a result of microbial respiration from the macro-aggregates leads to breaking of C-rich macro-aggregates and formation of C-poor micro-aggregates. In the process, the C associated with the micro-aggregates at the end of the cycle attains greater recalcitrance. Thus, irrespective of temperature regime or CR level, higher SOC mineralization occurred from macro-aggregates compared with micro-aggregates (Table 4.3), obviously due to greater abundance of substrate for microbial decomposition associated in macro-aggregates. On the other hand, if the proportion of accumulated C mineralized is considered, due to higher C content *per se* in macro-aggregate compared with micro-aggregates, the proportion of C mineralized out of total SOC in 64 days incubation was lower from the former than the latter (Table 4.4).

Since the study was conducted under ZT conditions, the life cycle or mean residence time of macro-aggregates was invariably high (Six *et al.,* 2000). Therefore, the iPOM under CR retained treatments is fairly stable in nature, and less prone to breaking and loss as CO_2. As a result, the proportion of macro-aggregate associated C mineralized was minimum under CR_4 followed by CR_2 and CR_0 (Table 4.4), in spite of higher Ct *per se* from the former (Table 4.3). The enhanced stability of C associated with micro-aggregates within macro-aggregates might also be responsible for this phenomenon. The Kc values were also reported to be lower in macro-aggregates, thus imparting greater stability of accumulated SOC compared with micro-aggregates (Table 4.5). Lowest values of Kc associated with macro-aggregates under CR_4, followed by CR_2 and CR_0 support this contention (Table 4.5) (Ghosh *et al.,* 2019). Similarly the proportion of C mineralized from micro-aggregate associated C was lower under CR_4, implying slower decomposition and greater stability of SOC compared with CR_0 across temperature regimes (Table 4.5).

5.1.5. Temperature sensitivity of soil organic carbon mineralization

As evident from Figures 4.1 to 4.12, cumulative C mineralization was higher at 30 °C, compared with that at 20 °C, irrespective of treatments in bulk soil as well as macro- and micro-aggregate size fractions. Similar increases in SOM mineralization with an increase in temperature were obtained by other researchers (Ghosh *et al.,* 2016; Dey, 2017; Jat *et al.,* 2019; Bhattacharyya *et al.,* 2020). The increase in temperature augmented the physiological reaction rate of organisms and microbial activity (Verma, 2009), which led to higher C mineralization *per se* at higher temperature. Greater proportion of total SOC was mineralized at elevated temperature, registering higher decay rates compared with lower temperatures (Tables 4.4 and 4.5), irrespective of treatments, sampling depths or aggregate size fractions. The Q_{10} values suggested that the macro-aggregate associated SOC was less temperature sensitive, compared with the SOC associated with micro-aggregates (Table 4.6). The C quality (CQT) hypothesis suggests greater Q_{10} of the recalcitrant C pools, requiring higher activation energy compared with labile C pools (Craine *et al.,* 2010; Ghosh *et al.,* 2020). The micro-aggregates strongly adsorb SOM through ligand exchange, polyvalent cation bridges and large surface areas, and lead to acquired recalcitrance of micro-aggregate associated C, that requires higher activation energy for mineralization compared with the labile SOM associated with macro-aggregates (Ghosh *et al.,* 2016). The micro-aggregate associated C is inherently recalcitrant in nature, as it is the remnant from the C decay, and is released from the larger soil macro-aggregates (Six *et al.,* 2000). Several other researchers reported higher temperature sensitivity of SOC degradation in micro-aggregates than macro-aggregates (von Lützow *et al.,* 2007; Ghosh *et al.,* 2016).

The probable mechanism of SOC stabilization might also be different in macro- and micro-aggregate size fractions. The physical protection might have played a crucial role in the macro-aggregates, whereas the bio-chemical recalcitrance was the main mechanism in micro-aggregates. This difference in stabilization mechanism leads to temperature insensitivity of physically protected C in macro-aggregates, whereas the temperature-mediated increment in SOC mineralization was very prominent in micro-aggregates (von Lützow and Kögel-Knabner, 2009). Residue retention in ZT plots might have promoted the C build-up mainly though physical protection, rather than developing bio-chemical recalcitrance (Jat *et al.,* 2019). This phenomenon resulted in significantly lesser Q_{10} values of macro-aggregate associated C with CR retention at 4 t ha^{-1} under CR_4 compared with that under no residue (CR_0) plots (Tables 4.6).

5.2. Effect of nutrient management on soil organic carbon dynamics

Treatments with 150 kg ha^{-1} N application registered significantly higher total SOC and WBC compared with those having 100 kg ha^{-1} N application, irrespective of fertilizer K rates in both 0-5 and 5-15 cm soil depths (Table 4.1). Adequate N input enhanced biomass production leading to addition of higher amounts of fresh organic residue through stubble and root mass, which ultimately contributed to build-up of SOC (Cotrufo *et al.,* 2013; Jat *et al.,* 2019). Adequate N input promoted root formation, proliferation and rhizo-deposition, resulting in SOC accumulation (Ghosh *et al.,* 2019). In 0-5 cm soil depth, treatment $N_{100}K_{60}$ had 7.86% higher total SOC compared to $N_{100}K_0$, whereas $N_{150}K_{60}$ had 6.79% higher total SOC than $N_{150}K_0$ treatment. However, different rates of K application at similar N did not affect SOC significantly in 5-15 cm layer, possibly due to greater accumulation of aboveground biomass and root exudates in 0-5 cm soil depth.

Alike total SOC, the SOC pools of varying lability (SOC_{VL}, SOC_L, SOC_{LL} and SOC_{NL}) were higher under N_{150} compared with N_{100} at both 0-5 and 5-15 cm soil depths, irrespective of K rates (Table 4.1). The aboveground biomass, when retained as CR along with fertilizer input under CA, ensured availability of enormous amount of substrate for soil microbes. The SOC_{VL}, SOC_L and SOC_{LL} were enriched under N_{150} compared with N_{100} plots due to partial oxidation. Post-harvest stubbles and litter fall added substantial amounts of fresh organic matter even under CR_0.

Thus, there was an apparent relationship between N fertilization and labile SOC, owing to higher biomass yield with incremental N application. The N_{150} treatments resulted in significantly greater CPI and CMI compared with N_{100} (Figures 5.3 and 5.4). Least mechanical disturbance across experimental plots masked the effect of different rates of N fertilization on soil aggregates and aggregate associated C (Table 4.2).

Fertilizer K application did not affect soil aggregation status, different pools of SOC and mineralization pattern of SOC at different temperature regimes (Tables 4.1 and 4.2; Figures 4.1 to 4.12). In fact, K fertilization is generally not expected to influence SOC dynamics directly. There could, however, be an indirect effect by way of changed balance of fertilizer nutrients due to graded K application rates and its influence on total biomass (aboveground + belowground) production. In order to test this hypothesis, effect of graded K levels long with varying CR treatments was evaluated on SOC mineralization and temperature sensitivity. Relatively higher native K supply in the illite-dominated soil of experimental site might have masked the effect of K fertilization in the present investigation, resulting in no apparent effect of K application on different parameters studied.

Chapter 6 Summary and conclusions

Conservation agriculture (CA) is reported to improve SOC contents, although the CR load and nutrient management protocols for CA need to be standardized. Information on SOC dynamics under varying rates of CR retention and nutrient supply is scanty. Sporadic information is available on the effect of different CR loads and fertilization options on SOC pools in soil and aggregates, and temperature sensitivity of SOC mineralization under CA, although such effects need to be studied in detail for understanding SOC dynamics so as to standardise the CA management practices. Present investigation was, therefore, undertaken to understand the effect of CR and nutrient management options on (i) dynamics and sequestration of SOC, and (ii) distribution and temperature sensitivity of SOC within aggregates. To accomplish the objectives, an on-going CA experiment established during 2013 at ICAR-IARI, New Delhi was chosen. The experiment was comprised of 18 treatments laid in a split-plot design with three CR retention rates (0, 2 and 4 t ha^{-1}) and six fertilizer NK rates ($N_{100}K_{0}$, $N_{100}K_{30}$, $N_{100}K_{60}$, $N_{150}K_{0}$, $N_{150}K_{30}$ and $N_{150}K_{60}$). Salient findings of the study are summarized hereunder:

- Retention of CR had significant effect on total SOC content. Treatment CR_4 (4 t ha^{-1}) had the highest total SOC, followed by CR_2 (2 t ha^{-1}) and CR_0, in all soil depths. In 0-5 cm soil depth, total SOC was almost double, and 67.5% higher in CR_4 and CR_2 treatments, respectively compared with that under no residue retention (CR_0).
- All SOC fractions of varying lability viz., SOC_{VL}, SOC_{L}, SOC_{LL}, SOC_{NL} and WBC were affected by both CR levels and nutrient management practices under CA in both soil depths (0-5 and 5-15 cm). Treatment CR_4 had the highest value of all these fractions followed by CR_2 and CR_0.
- CR retention on soil surface under CA had significant impact on macro-aggregate percentage. In 0-5 cm soil, the CR_4 treatment had 25.5% and 9.13% higher macro-aggregates percentage compared with CR_0 and CR_2, respectively. Similar enhancements in macro-aggregates percentage due to CR addition were also recorded in 5-15 cm soil depth.
- Higher macro-aggregate percentage under CR retained plots was accompanied by significantly lower micro-aggregate percentage. Highest amount of micro-aggregates (%) was found in CR_0 in 0-5 cm (37.86%) and 5-15 cm (34.37%) soil depth, which was significantly greater than those in CR_2 and CR_4 treatment.

- In accordance with the level of CR retention, maximum amount of macro-aggregate and micro-aggregate associated C was found in CR_4 followed by CR_2 and CR_0 in both soil depths.
- Irrespective of temperature regimes and soil depth in incubation studies, highest Ct was recorded from soils and aggregates of CR_4, followed by CR_2 and CR_0. On the other hand, the soils and aggregates pertaining to highest level of CR retention *i.e.*, CR_4 registered lowest proportion of total SOC mineralized.
- Macro-aggregates showed greater Ct compared with micro-aggregates. Irrespective of aggregate size, treatment CR_4 had highest Ct, followed by CR_2 and CR_0 at both temperature regimes (20 ^oC and 30 ^oC) and soil depths.
- In macro-aggregates, CR_0 treatment had 5.21% and CR_4 had 4.38% total SOC mineralized at 20 ^oC, whereas the corresponding values were 6.11% and 4.97% respectively at 30 ^oC in 0-5 cm soil depth.
- For bulk soil, CR_0 had significantly higher Kc values compared with CR_4 and CR_2 treatments, irrespective of soil depth and temperature regimes. However, Kc was higher at 30 ^oC compared with that at 20 ^oC irrespective of depth. Lower depth had higher Kc value compared with surface 0-5 cm soil layer. Treatments CR_4 and CR_2 registered similar Kc at 20 ^oC and 30 ^oC in 0-5 cm soil depth.
- Micro-aggregates had higher value of Kc compared with bulk soil or macro-aggregates, irrespective of temperature regimes and soil depths. Generally CR_4 treatment had lower Kc compared with CR_0 treatment for both the aggregate fractions irrespective of depths and incubation temperatures.
- In bulk soil, and macro- and micro-aggregates, increment in CR loads did not bring significant variation in temperature sensitivity (Q_{10}) of SOC mineralization in 0-5 or 5-15 cm soil depth, except for macro-aggregates at 0-5 cm soil depth where CR_0 had 10.7% higher Q_{10} than CR_4 treatment. In bulk soil, and macro- and micro-aggregates, the Q_{10} values were greater in 5-15 cm soil layer compared with those in 0-5 cm soil layer.
- Among nutrient management options, treatment $N_{150}K_{60}$ registered the highest total SOC content in 0-5 cm (11.6 g kg^{-1}) and 5-15 cm (8.8 g kg^{-1}). Treatments receiving 150 kg N ha^{-1} application ($N_{150}K_0$, $N_{150}K_{30}$ and $N_{150}K_{60}$) registered significantly higher total SOC, WBC, $SOC_{VL,}$ $SOC_{L,}$ SOC_{LL} and SOC_{NL} compared with treatments fertilized at 100 kg N ha^{-1} application ($N_{100}K_0$, $N_{100}K_{30}$ and $N_{100}K_{60}$), irrespective of K rates in both

0-5 and 5-15 cm soil depths. Fertilizer K rates did not show any significant effect on total SOC, WBC, and SOC fractions of varying lability, irrespective of N rates in both soil depths. Also, K fertilization did not affect cumulative SOC mineralization as well as temperature sensitivity of SOC mineralization.

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

- Residue retention and incremental N rates improved both labile and recalcitrant SOC pools, with labile pools experiencing substantial improvement. To achieve the maximum C sequestration potential of CA, adequate CR and N input is critical in maize-wheat-mungbean cropping system.
- Decay rate of SOC mineralization was drastically reduced by increments in CR loads, indicating higher C stability by means of greater physical protection through soil aggregates, especially for C associated with micro-aggregates within macro-aggregates.
- The C stabilized in residue-retained plots of CA was found to be physically protected, especially inside macro-aggregates, and more importantly temperature insensitive. Therefore, in the present global warming scenario, CA holds the key for effective C capture from the environment.
- The findings underlined the need for detailed multi-location studies to evaluate the effect of CR and nutrient interactions on SOC dynamics so as to improve understanding in this area and evolve soil health-centric management practices for CA-based cropping systems.

Abstract

Soil organic carbon (SOC) plays important role in improving soil health, crop productivity and sustainability of the agricultural production systems. Conservation agriculture (CA) helps in restoration and accumulation of SOC through minimum mechanical disturbance, CR retention and crop diversification. The present study relates to the stability of accumulated SOC under different CR retention and nutrient management options under CA. Soil samples from 2 depths (0-5 and 5-15 cm) were collected from an on-going field experiment on CA under maize-wheat-mungbean cropping system established in 2013 at research farm of ICAR-IARI, New Delhi. The area represents Trans-Gangetic Plain (TGP) transect of the Indo-Gangetic Plain (IGP) region, and the soil is classified as Typic Haplustept. The field experiment was laid in a split-plot design having 3 levels of CR retention in the main plots [CR_0: no CR retention; CR_2: retention of CR @ 2 t ha^{-1} after harvest of each crop; CR_4: retention of CR @ 4 t ha^{-1} after harvest of each crop], and six combinations of nitrogen (N) and potassium (K) fertilizer rates in the sub-plots [N_{100}: 100 kg N ha^{-1}, N_{150}: 150 kg N ha^{-1}, K_0: no K_2O fertilizer applied, K_{30}: 30 kg K_2O ha^{-1} and K_{60}: 60 kg K_2O ha^{-1}].

Results indicated significant improvement in total SOC and its' pools of varying oxidizability consequent to increment in CR load. Treatment CR_4 had 100% and 19.3% higher total SOC compared with treatments CR_0 and CR_2 in respectively 0-5 cm soil layer. Plots with residue addition (CR_4 and CR_2) had significantly higher labile and recalcitrant C pools in 0-5 and 5-15 cm soil layers compared with no residue retention (CR_0). Treatment CR_4 had 155% and 23.2 % higher values of carbon management index (CMI) compared with CR_2 and CR_0 in 0-5 cm soil depth. Similar trend was observed in sub-surface soil. Treatment CR_4 had the highest macro-aggregate percentage followed by CR_2 and CR_0 in both soil depths, whereas an opposite trend was recorded for soil micro-aggregate percentage, implying accumulation C-rich macro-aggregates under CR retained plots, with a subsequent depletion of micro-aggregates. Both macro-aggregate and micro-aggregate associated C followed the trend $CR_4 > CR_2 > CR_0$ in 0-5 and 5-15 cm soil depth. Retention of CR significantly affected cumulative C mineralization (Ct) ($CR_4 > CR_2 > CR_0$) in bulk soil, and macro- and micro-aggregates, irrespective of soil depth and incubation temperature regimes. Micro-aggregates had higher percentage of total SOC mineralized, decay rate (Kc) and Q_{10} compared with bulk soil and macro-aggregates, irrespective of temperature regimes and soil depth. Generally, CR_4 treatment had lower percentage of total SOC mineralized and Kc compared with that under CR_0 treatment for both

aggregate fractions. CR addition did not affect Q_{10} values, except for macro-aggregates in 0-5 cm soil layer.

Fertilizer N application enhanced total SOC and its' pools of varying lability. Application of 150 kg N ha^{-1} showed higher total SOC, and labile and recalcitrant pools compared with 100 kg N ha^{-1}, irrespective of K rates, in 0-5 and 5-15 cm soil depths. K fertilization did not affect SOC dynamics in soil. Present study suggested that, to achieve maximum C sequestration potential of CA-based maize-wheat-mungbean cropping system, adequate N input is critical along with 4 t ha^{-1} cereal CR retention. The C stabilized in residue-retained plots was found to be physically protected as the decay rate of SOC mineralization was drastically reduced.

सारांश

मृदा स्वास्थ्य सुधार, फसल उत्पादकता में वृद्धि और कृषि उत्पादन प्रणाली की स्थिरता हेतु मृदा जैविक कार्बन (SOC) महत्वपूर्ण भूमिका निभाता है। संरक्षण कृषि (CA) न्यूनतम यांत्रिक बाधा, फसल अवशेष (CR) अवधारण और फसल विविधीकरण के माध्यम से SOC के स्तर में सुधार तथा संचयन में मदद करती है। वर्तमान अध्ययन संरक्षण कृषि के तहत फसल अवशेषों और पोषक तत्व प्रबंधन विकल्पों के संचित SOC की स्थिरता पर प्रभाव से संबंधित है। मिट्टी के नमूने आईसीएआर-आईएआरआई, नई दिल्ली के अनुसंधान फार्म में 2013 में स्थापित मक्का-गेहूं-मूंग फसल प्रणाली के तहत CA पर आधारित एक प्रक्षेत्र परीक्षण से 2 गहराई (0-5 और 5-15 सेमी) से एकत्र किए गए। यह क्षेत्र सिंधु-गंगा मैदानी क्षेत्र (IGP) के अंतर्गत ट्रांस-गंगा मैदान प्रभाग (TGP) का प्रतिनिधित्व करता है, और यहाँ की मिट्टी “टिपिक हैप्लुस्टेप्ट” के रूप में वर्गीकृत की गयी है। स्प्लिट-प्लॉट डिज़ाइन में किए गए प्रक्षेत्र प्रयोग में फसल अवशेष (CR) अवधारण के तीन स्तर [CR_0: शून्य CR अवधारण; CR_2: प्रत्येक फसल की कटाई के बाद 2 टन/हे॰ CR का अवधारण; CR_4: प्रत्येक फसल की कटाई के बाद 4 टन/हे॰ CR का अवधारण] मुख्य-प्लॉट में, और नत्रजन (N) व पोटैशियम (K) उर्वरकों की छह संयोजन दरें [N_{100}: 100 किग्रा N/हे॰, N_{150}: 150 किग्रा N/हे॰, K_0: कोई पोटाश उर्वरक नहीं, K_{30}: 30 किग्रा पोटाश/हे॰ और K_{60}: 60 किग्रा पोटाश/हे॰] सब-प्लॉट में लिए गये।

परिणामों ने संकेत दिया कि फसल अवशेषों के अवधारण में वृद्धि से SOC तथा उसके विभिन्न ऑक्सीकरण क्षमता वाले अंशों की मात्रा में वृद्धि होती है। उपचार CR_4 में क्रमशः 0-5 सेमी मिट्टी की परत में CR_0 और CR_2 की तुलना में कुल SOC 100% और 19.3% अधिक था। CR_4 और CR_2 उपचारों में बिना अवशेष (CR_0) की तुलना में 0-5 और 5-15 सेमी मिट्टी की परतों में रीकेल्सीट्रांट तथा अस्थिर कार्बन अंशों की अधिक मात्रा पायी गई। उपचार CR_4 के अंतर्गत 0-5 सेमी गहराई में CR_2 और CR_0 की तुलना में कार्बन प्रबंधन सूचकांक (CMI) क्रमश: 155% और 23.2% अधिक पाया गया। मिट्टी की निचली परत (5-15 सेमी) में भी इसी तरह की प्रवृत्ति देखी गई। CR_2 और CR_0 उपचारों की तुलना में CR_4 में मिट्टी की दोनों परतों में सर्वाधिक प्रतिशत स्थूल-समुच्चक पाये गए, जबकि सूक्ष्म-समुच्चकों के संबंध में विपरीत प्रवृत्ति दर्ज़ की गयी। अर्थात फसल अवशेषों के अवधारण से कार्बन-संपन्न स्थूल-समुच्चकों का संचय हुआ तथा सूक्ष्म-समुच्चकों में कमी आयी। कुल मिट्टी तथा सूक्ष्म एवं स्थूल-समुच्चकों दोनों से जुड़े कार्बन की मात्रा में 0-5 और 5-15 सेमी मिट्टी में $CR_4 > CR_2 > CR_0$ प्रवृत्ति का

अनुसरण हुआ। फसल अवशेष अवधारण ने मिट्टी की दोनो परतों और तापमानों से निरपेक्ष कुल मिट्टी, तथा सूक्ष्म एवं स्थूल- समुच्चकों में कुल कार्बन खनिजीकरण (C_t) को महत्वपूर्ण ढंग से प्रभावित किया, और उपचारों का क्रम $CR_4 > CR_2 > CR_0$ रहा। तापमान और मिट्टी की गहराई के निरपेक्ष कुल मिट्टी और स्थूल-समुच्चकों में Kc, Q_{10} एवं कुल खनिजीकृत SOC की अधिक मात्रा दर्ज की गयी। सामान्यतः CR_4 उपचार के अंतर्गत, CR_0 की तुलना में, दोनों समुच्चकों में प्रतिशत खनिजीकृत SOC और Kc की मात्रा कम थी। 0-5 सेमी मिट्टी की परत में फसल अवशेष संकलन का स्थूल-समुच्चकों के अलावा, Q_{10} पर कोई प्रभाव नहीं हुआ।

उर्वरक नत्रजन के इस्तेमाल से कुल SOC तथा इसके विभिन्न संघटकों में वृद्धि हुई। 0-5 और 5-15 सेमी गहराई में, पोटाश की दरों के निरपेक्ष 150 किग्रा नत्रजन/हे॰ के इस्तेमाल से 100 किग्रा नत्रजन/हे॰ की तुलना में कुल SOC एवं इसके अस्थिर और स्थिर संघटकों में वृद्धि हुई। उर्वरक पोटाश ने मिट्टी में SOC की गतिकी को प्रभावित नहीं किया। वर्तमान अध्ययन ने यह सुझाव दिया कि CA- आधारित मक्का-गेहूं-मूंग फसल प्रणाली में अधिकतम कार्बन संचयन क्षमता प्राप्त करने के लिए नत्रजन की पर्याप्त मात्रा और 4 टन/हे॰ फसल अवशेष का अवधारण अपरिहार्य है। अवशेष-अवधारित उपचारों में स्थिर कार्बन भौतिक रूप से संरक्षित पाया गया, क्योंकि SOC खनिजीकरण की क्षय दर में भारी कमी पाई गयी।

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