



Nutrient management impacts on organic carbon pool in soils under different cropping systems in the Indo-Gangetic Plains in South Asia

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Abstract

Nutrient management impacts the dynamics of organic carbon (C), C sequestration and various C pools in soils and sustainability of cropping systems through biomass input and organic matter addition through organic manures. We reviewed long-term field experiments on different cropping systems in the Indo-Gangetic Plains of South Asia to study the effect of balanced and imbalanced application of mineral fertilizers applied either alone or conjointly with organic manures on different soil organic C pools. Application of mineral fertilizers not only enhanced crop productivity, but also C input and accumulation in the total organic C (TOC) pool with a significant impact on C fractions of differential lability or oxidizability. Balanced use of nitrogen, phosphorus, and potassium through fertilizers alone, or conjointly with organic manures or crop residues enhanced plant-mediated C input, TOC pool, and stocks, amount of biomass C required to maintain TOC levels, net C sequestration rate, and C fractions such as permanganate oxidizable C, water-extractable organic C, microbial biomass C, and C fractions of variable oxidizability. The amount of C input (plant mediated + exogenous) added was 0.88–12.2 Mg C ha⁻¹ year⁻¹ in the 0–15 cm plough layer soils under rice–wheat, 1.37–6.68 Mg C ha⁻¹ year⁻¹ under other rice-based systems (rice–berseem/rice–wheat–jute/rice–mustard–sesame/rice–fallow–rice) and 0.51–8.07 Mg C ha⁻¹ year⁻¹ in soils under non-rice-based cropping systems. In general, C sequestration rate was high in soils with low initial TOC content and high silt + clay fraction. Balanced application of mineral fertilizers conjointly with organic manures enhanced the percentage of macro-aggregates (> 0.25 mm), with simultaneous decrease in the percentage of micro-aggregates (< 0.25 mm). The stable or passive C pool (less labile + recalcitrant C) was the largest pool, comprising of about 50.5–80.3% of TOC in soils under different rice–wheat systems; almost similar (44.2–80.8% of TOC) to that for maize–wheat, but higher compared with those under cotton–wheat (44.1–61.9% of TOC) cropping system. The amount of C input required to maintain TOC stocks at steady state varied between 2.30 and 4.59 Mg C ha⁻¹ year⁻¹ for soils under rice-based systems, as compared with 1.10 and 3.47 Mg C ha⁻¹ year⁻¹ in soils under non-rice-based cropping systems. On an overall basis, balanced application of mineral fertilizers conjointly with organic manures exhibited an overwhelming role in enhancing C accumulation in recalcitrant C pool, while enlarging the labile C pool for increased crop productivity due to increased nutrient cycling.

Keywords Carbon input · Total organic carbon stocks · Soil organic carbon · Net carbon sequestration rate · Carbon pools

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Introduction

The Indo-Gangetic Plains (IGPs) in South Asia spread over 0.70 million km² of fertile land stretching about 2400 km from Punjab in Pakistan in the west to the Brahmaputra floodplains of Bangladesh in the east. Although the IGPs are a relatively homogeneous ecological region, yet based on physiography, bioclimate, and social factors these can be divided into four broad transects. Large parts of Punjab in Pakistan and Punjab and Haryana states in India constitute the trans-IGPs. While the regions comprising of west-central

and eastern Uttar Pradesh and Bihar constitute middle IGPs, and the Tarai in Uttaranchal in India and Nepal is designated as upper IGPs, the West Bengal in India and most parts of Bangladesh make lower IGPs (Gupta et al. 2002). The South-Asian basins of the three main rivers Indus, Ganga, and the Brahmaputra and their tributaries are home to about one billion people and are amongst the world's most densely populated areas. With continental monsoon climate throughout the IGPs, soils are normally coarser in the trans- and upper IGPs, primarily calcareous and micaceous alluviums with sandy loam to loam in texture. Finer textures of soils are found adjacent to the entrance of river streams (Gupta et al. 2002). Most of the soils are deficient in nitrogen (N) and phosphorus (P). Due to the micaceous nature of the soils in IGPs, the use of potassium (K) fertilizers has been started in some parts only in recent decades. However, due to low and imbalanced use of fertilizers, a decline in soil fertility is being observed in the middle and lower IGPs. On the other hand, due to heavy subsidies on N fertilizers in South Asian countries, in some regions of the IGPs farmers have developed a tendency to apply excessive amounts of fertilizer N to crops like rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.). About 85% of the annual rice–wheat cropping system as accomplished in South Asia is in the IGPs. While rice–rice is the dominant cropping system in the lower IGPs, farmers in the trans-, upper and middle IGPs grow crops like mung bean (*Phaseolus aureus* Roxb.) during the transition phase between wheat and rice, and on a small area replace wheat with crops like oilseeds [*Brassica* sp.], sugarcane (*Saccharum officinarum* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medikus), potato (*Solanum tuberosum* L.) and pigeon pea [*Cajanus cajan* (L.) Huth].

The IGPs are one of the largest cereal producing regions in the world, but the content of soil organic matter (SOM), a critical component of soils for supplying nutrients and maintaining the soil structure and water holding capacity, is generally low in IGPs (Pal et al. 2009; Singh et al. 2023). While the average total organic carbon (TOC) in the soil in trans- and upper IGPs is 3.0 g kg⁻¹, it is 4.0 g kg⁻¹ in the middle IGPs and 7.0 g kg⁻¹ in the lower IGPs (Bijay-Singh and Varinderpal-Singh 2012). Because of historic loss of organic C, estimated to be 45–50 Pg from the cultivated soils, the soils have an immense potential to sequester C. Low SOM levels in the soils of IGPs are due to sub-tropical climate, intensive cultivation of soils, crop residue removal, and diverse management of fertilizers and organic manures including imbalanced use of N, P, and K in crop production (Lal 2004c; Sapkota et al. 2017). Since field crops obtain more than 50% of N from the mineralization of SOM (Gardner and Drinkwater 2009; Dourado-Neto et al. 2010) and applied fertilizer N is used more efficiently in organic matter-rich soils than in organic matter-poor soils, maintenance of SOM is critical for increasing eco-efficiency in

crop production (Balasubramanian et al. 2013). Due to fundamental coupling between microbial C and N cycling in the soil, any management practice that leads to C loss may prove inherently detrimental to crop productivity.

Several long-term experiments conducted in the IGPs and elsewhere show a decrease in crop production due to significant loss of TOC and nutrient imbalance/depletion in agricultural soils (Dawe et al. 2000; Regmi et al. 2002; Ladha et al. 2000; Hobbs et al. 2008; Lal 2013). However, Bijay-Singh (2018) has cited several studies in which fertilizer application increased SOM levels. Ghimire et al. (2017) have also reported that in many long-term fertility experiments from India and Nepal, the application of optimum N, P, and K through fertilizers increased in TOC from 0.2 to 3.5 g kg⁻¹ over no-fertilizer control (CK). Potentially, fertilizer-based nutrient management can influence SOM both constructively and destructively (Ladha et al. 2011). Fertilizer application as per the need of the crop may increase SOM by promoting plant growth and increasing the amount of litter and root biomass in the soil. However, accumulation of inorganic N in the soil due to the application of excess fertilizer N to crops may accelerate the decomposition of SOM through microbial mineralization of litter and indigenous forms of organic C already present in the soil (Recous et al. 1995; Poffenbarger et al. 2017). According to Lupwayi et al. (2012), the nutrient addition to soil, in general, enhances microbial degradation of SOM by providing nutrients for microbes. Nitrogen and P fertilization into soil-crop system induces changes to soil microbial community structure, microbial growth, and activity (Contosta et al. 2015). However, the omission of fertilizer N and P over a long period of time not only significantly reduce the crop yields, but also affect the biochemical processes of soil microbes (Dai et al. 2013). The heterotrophic micro-organisms which are considered responsible for soil respiration consume dissolved organic C and a portion of readily available SOM as C substrate to reduce the equivalent energy for cell biosynthesis and growth (Sylvia et al. 2005). Apparently, a large fraction of released C and N during the process of mineralization is consumed by soil microbes to meet the preservation energy requisite of microbial biomass (Zheng and Marschner 2017). Nutrient acquisition is energetically a luxurious process and is compulsory for soil microbes to degrade the recalcitrant C pool to establish new access to C substrate (Moscatelli et al. 2005). The food web model of N mineralization revealed the production efficiency value of 0.30 assigned to bacteria and fungi, which showed that about 30% of C utilized is apportioned to microbial biomass production, whilst the remaining 70% is subjected to soil respiration (de Ruiter et al. 1993).

Therefore, nutrient management strategies play a crucial role in defining the TOC pool determined by the equilibrium amongst the C input into the soil from above- and



below-ground plant biomass and exogenous C inputs e.g., organic manure and composts, and the rate of C lost from the soils via decomposition of SOM (heterotrophic soil respiration). As reduced crop productivity will significantly influence plant-mediated C input into the soil and in turn impact the sustainability of the soil ecosystem, TOC build-up and sequestration constitutes one of the most realistic agricultural strategies to mitigate greenhouse gas emissions, enhance food security, and improve agricultural sustainability. Carbon sequestration refers to securely storing C into long-lived C pools in the soil that it is not immediately re-emitted as carbon dioxide (CO₂) (Lal 2016). In the agricultural sense, C sequestration is its storage in the soil as SOM (Minasny et al. 2017).

We have attempted to synthesize existing knowledge on the effects of various nutrient management practices on the status of different soil C pools under different crops and cropping sequences in the IGPs in South Asia. We analyzed data contained in peer-reviewed research papers, which report the effect of balanced and imbalanced application of chemical fertilizers applied either alone or conjointly with organic manures on TOC pool in long-term field experiments. It has been attempted to understand the mechanisms governing C sequestration in the soil as associated with nutrient management practices. The challenges and research gaps linking C accumulation with food security and climate change mitigation in soils of IGPs have also been discussed.

Plant mediated carbon input in soils under different cropping systems

Carbon input in soils is primarily a process through which atmospheric CO₂ is transferred to the soil and stored in the soil C pool (Bhatt et al. 2023). Except in arid and semi-arid climates where to a very small extent conversion of CO₂ from air entrapped in soil into inorganic C forms may also occur, this progression is principally facilitated by plants through the process of photosynthesis. Increasing global temperatures and atmospheric CO₂ concentration may impact C input in the soil through check on photosynthetic activity and C losses via microbial respiration and degradation (Ontl and Schulte 2012). SOM incoming the highly dynamic soil system is produced by plants, and it spreads the soil via the root biomass (as dead roots or root exudates) or as leaf litter and through restitution of un-harvested above-ground plant parts (Basile-Doelsch et al. 2020). The conceptual and experimental evidences suggest that net primary production (NPP) influences C sequestration by maintaining a balance of C inputs (e.g., net C gain by plants) and losses (e.g., microbial decomposition) (Diaz et al. 2009; Hooper et al. 2012). Besides, NPP is increased by elevated C inputs, particularly below-ground biomass C and increasing

microbial community, diversity, and activity, and by suppressing C losses via decomposition (Lange et al. 2015; Fornara and Tilman 2008). Therefore, C returns to soils under a given cropland ecosystem increase with NPP, but the restitution/yield ratio decreases as the yield increases. Although, the below-ground C fluxes are relatively small, yet are considered significant to share more towards SOM compared to C input as above-ground biomass components e.g., leaf litter and shoot biomass (Clemmensen et al. 2013; Rasse et al. 2005). The below-to above-ground biomass ratio (i.e., root/shoot) that apparently signifies as an indicator of plant mediated C input into the soils is extremely reliant on ecological conditions and is highly inconsistent (10–30%) (Basile-Doelsch et al. 2020). However, the rhizodeposition, which describes the C contribution to the soil by living plants via roots, is an extra C input factor. The rhizodeposition flux can be about 0.2–0.5 times the net root biomass production (Nguyen 2003; Jones et al. 2009; Balesdent et al. 2011).

Annual C input (Mg C ha⁻¹ year⁻¹) through above-and below-ground plant biomass, as well as exogenous C input (as manure and rhizodeposition) in response to nutrient management under various cropping systems as reported in different studies conducted in the IGPs of South Asia, are listed in Table 1. The plant-mediated C input into soil varied widely through different above-and below-ground components within a cropping system. The annual plant mediated C input into the soil plough layer (0–15 cm) through different components under rice–wheat cropping system varied between 2.16 and 10.6 Mg C ha⁻¹ year⁻¹ under different nutrient management treatments (Benbi et al. 2012a). Below-ground biomass in the surface (0–15 cm) depth varied from 0.82 and 1.90 Mg ha⁻¹ year⁻¹ for rice and from 0.71 to 1.67 Mg ha⁻¹ year⁻¹ for wheat in an annual rice–wheat cropping system. Balanced application of fertilizer N, P, and K increased the annual root biomass by 84.1% and 88.7%, respectively for rice and wheat crops over their respective control (CK) treatments (Benbi et al. 2016).

As reviewed by Bijay-Singh and Ali (2020), many research papers on long-term experiments from South Asia including from the IGPs region, prove that combined application of mineral fertilizers and organic manures such as farmyard manure (FYM) over a long period of time leads to accumulation of SOM in different cropping systems. In a rice–wheat cropping system, the application of FYM for 5 years increased the root biomass of rice by 52.4% (0.43 Mg ha⁻¹ year⁻¹) and that for wheat by 53.5% (0.38 Mg ha⁻¹ year⁻¹) over the CK treatment (Table 1). The combined NPK + FYM application increased root biomass by 1.08 Mg ha⁻¹ year⁻¹ in rice and 0.96 Mg ha⁻¹ year⁻¹ in wheat. Carbon input as root and leaf + stubble biomass varied between 0.90 and 2.03 Mg C ha⁻¹ year⁻¹, with an average of 1.32 Mg C ha⁻¹ year⁻¹

Table 1 Annual C input (Mg C ha⁻¹ year⁻¹) through above- and below-ground plant biomass, as well as exogenous C input (as manure and rhizodeposition) in the surface (0–15 cm) soil layer under different cropping systems in the Indo-Gangetic Plains of South Asia

Cropping system (study period)	Annual C input (Mg C ha ⁻¹ year ⁻¹) (data pooled for different nutrient, manure or integrated management practices)						Reference
	Crop residue C	Manure C	Root biomass C	Stubble biomass C	Rhizodeposition C	Total C input	
Rice–wheat (11 years)	2.95–3.69	0–3.98	0.66–0.93	0.18–0.24	1.31–1.78	2.16–10.6	Benbi et al. (2012a)
Rice–wheat (7 years)	2.57–4.91	0–3.93	0.43–1.04	0.10–0.26	0.84–2.06	1.36–12.2	Benbi and Senapati (2010)
Rice–wheat (25 years)	1.49–3.12	0.25–0.38	0.42–1.08	0.06–0.14	0.47–1.37	1.49–3.50	Ghosh et al. (2012)
Rice–wheat (5 years)	0–4.00	–	0.87–1.49	0.71–1.28	1.76–3.25	3.34–9.78	Sharma et al. (2020a)
Rice–wheat (5 years)	–	0–2.25	1.53–3.57	0.79–1.63	–	0.90–4.28	Benbi et al. (2016)
Rice–wheat (5 years)	–	–	0.61–1.43	0.28–0.60	0.56–1.27	1.46–3.30	Singh and Benbi (2021)
Rice–wheat (18 years)	–	0.73–6.07	0.13–1.18	0.09–0.32	0.56–1.72	0.88–3.22	Das et al. (2014)
Rice–wheat (16 years)	0.09–0.18	–	0.56–1.42	0.08–0.18	0.62–1.80	2.05–4.28	Ghosh et al. (2010)
Rice–rice (33 years)	0.10–0.15	–	0.85–1.64	0.12–0.20	0.66–1.33	3.13–4.96	Ghosh et al. (2010)
Rice–fallow–berseem (20 years)	–	–	0.42	–	0.34	1.51	Mandal et al. (2007)
Rice–berseem (20 years)	0.13–0.17	0.67–1.33	0.82–1.32	0.33–0.45	0.79–1.49	2.82–5.55	Majumder et al. (2008b)
Rice–wheat–jute (34 years)	0.13–0.25	–	0.75–2.37	0.06–0.19	1.06–3.18	2.69–6.68	Majumder et al. (2007)
Rice–wheat–jute (31 years)	0–0.25	–	0.75–2.37	0.06–0.19	1.06–3.18	2.69–6.68	Ghosh et al. (2010)
Rice–wheat–jute (34 years)	–	–	0.43	–	0.35	1.53	Mandal et al. (2007)
Rice–mustard–sesame (7 years)	–	–	0.41	–	0.33	1.49	Mandal et al. (2007)
Rice–wheat–fallow (19 years)	–	–	0.37	–	0.36	1.37	Mandal et al. (2007)
Rice–fallow–rice (36 years)	–	–	0.47	–	0.37	1.60	Mandal et al. (2007)
Soybean–wheat (30 years)	0.08–0.55	0–1.59	0.38–1.21	–	0.41–1.41	3.01–4.85	Bhattacharyya et al. (2010)
Soybean–wheat (30 years)	–	–	0.20–0.51	0.04–0.07	0.28–0.70	0.51–1.29	Kundu et al. (2007)
Maize–wheat–cowpea (9 years)	–	–	–	–	–	2.16–8.07	Purakayastha et al. (2008)

(Benbi et al. 2016). After 25 years of experimentation on nutrient management in rice–wheat cropping system, there was about 2.5-times higher crop C input to the soil with NPK + FYM application over CK treatment (Ghosh et al. 2012). Benbi et al. (2012b) reported a 1.31-times higher root biomass C input in soils by applying NPK + FYM to rice–wheat cropping system in north-western India. In annual system, total C input in soil plough layer varied between 0.90 and 4.28 Mg C ha⁻¹ year⁻¹ (Table 1) (Benbi

et al. 2016). Root index (root fraction of total aboveground biomass) for surface (0–15 cm) soil varied from 15 to 23% for rice and 10 to 15% for wheat (Singh and Benbi 2022). On a system basis, total C input as roots and shoot biomass and rhizodeposition in different treatments varied between 1.5 and 3.3 Mg C ha⁻¹ year⁻¹. They reported that root C input in surface soil was higher by about 19.6% in rice than in wheat. Carbon input through roots in the surface soil was 1.4- to 3.3-times higher than through shoot after



harvesting. Of the total root C input, 85–89% occurred in the surface and 11–15% in the sub-surface soil (Singh and Benbi 2022).

The cumulative C input under rice–wheat cropping (7 years) varied from about 9.5 Mg ha⁻¹ in the CK treatment, compared to as high as about 85.4 Mg ha⁻¹ in rice straw (RS) incorporated plots along with the recommended fertilizer N application rate (Table 1) (Benbi and Senapati 2010). Annual total C input in the surface soil (0–15 cm) under rice–wheat cropping system (5 years) varied between 3.34 and 9.78 Mg C ha⁻¹, which was higher by 4.4 Mg C ha⁻¹ year⁻¹ (2.3 times) in RS incorporation at 10 Mg ha⁻¹ year⁻¹ (RS_{10.0}) when compared with CK (Sharma et al. 2020a). The C input through root, stubble, and rhizodeposition significantly responded to fertilizer N application. Application fertilizer at 90 kg N ha⁻¹ without RS incorporation (RS₀N₉₀) increased the total C input by 47.3% as compared to CK (Table 1). With a further increase in fertilizer N application rate to 120 kg N ha⁻¹ (RS₀N₁₂₀), total C input increased by 9% than in RS₀N₉₀. Increasing fertilizer N application to 150 kg N ha⁻¹ (RS₀N₁₅₀), however, did not significantly increase the total C input, compared with RS₀N₁₂₀ (Sharma et al. 2020a).

In the rice–wheat–jute cropping system (34 years), C input as plant biomass ranging between 1.1 and 4.6 Mg C ha⁻¹ year⁻¹ due to integrated nutrient management based on organic manures and inorganic fertilizers has been reported (Majumder et al. 2007; Mandal et al. 2007). The component-wise (leaf, stubble, root, rhizodeposition, aquatic growth in rice) annual cumulative C inputs into the soil through the rice, wheat, and jute crops under continuous rice–wheat–jute cropping (34 years) ranged from as low as 2.69 Mg C ha⁻¹ year⁻¹ in the CK treatment to as high as 6.68 Mg C ha⁻¹ year⁻¹ in the NPK + FYM treatment (Table 1) (Majumder et al. 2007). On an average, 3.26 ± 0.78 Mg ha⁻¹ of the left over above-ground biomass of berseem in rice–fallow–berseem (20 years) and 1.8–2.0 Mg ha⁻¹ of biomass (leaves, tops, and branches) of jute in a 34-year-old rice–wheat–jute system were added annually to the soils under different nutrient management treatments (Mandal et al. 2007) (Table 1). The leaf biomasses of berseem (in rice–fallow–berseem cropping), mustard, and sesamum (in rice–mustard–sesamum cropping) were estimated to be 10.8, 4.3, and 4.8% of above-ground biomass. Annual crop residue C input in soils under different treatments across the cropping systems was the highest in the NPK + FYM (4.5 Mg C ha⁻¹ year⁻¹) followed by the NPK (3.6 Mg C ha⁻¹ year⁻¹) and CK (2.3 Mg C ha⁻¹ year⁻¹) treatments (Mandal et al. 2007). In 20 years of continuous rice–berseem cropping, annual cumulative C inputs into the soil through the two crops under different nutrient management treatments ranged from 2.82 Mg C ha⁻¹ year⁻¹ in the CK to 5.55 Mg C ha⁻¹ year⁻¹ in the NPK + FYM treatment (Majumder et al. 2008b) (Table 1). Bhattacharyya et al. (2010) reported that in

a 30-year-old soybean–wheat cropping system, the average annual total C input varied with above-ground yield and was the highest under NPK + FYM and the lowest under unfertilized CK (Table 1). The average C input from soybean to soil was 29% of the harvestable above-ground biomass (R² = 0.99*, *p* < 0.01). Apart from C input of 1.59 Mg C ha⁻¹ year⁻¹ from FYM application, an additional gain of 0.88 Mg C ha⁻¹ year⁻¹ occurred under soybean with NPK + FYM compared to NPK only. The total C input from unfertilized wheat was 520 kg ha⁻¹ year⁻¹ and that from wheat grown on residual fertility of NPK + FYM was 1286 kg ha⁻¹ year⁻¹ (Bhattacharyya et al. 2010). The average annual C input from wheat to soil was about 24% of the annual harvestable above-ground biomass (R² = 0.98*, *p* < 0.01). The residual effect of applied manure leads to an additional accrual of 563 kg C ha⁻¹ year⁻¹ in wheat over that under fertilizer NPK alone. The harvestable above-ground biomass yield of wheat varied with residual fertility in fertilizer treatments applied to soybean. Kundu et al. (2007) reported that C input from wheat into the soils comprised 32% of total above-ground harvested biomass (Table 1). A considerable amount of C input of 445 kg C ha⁻¹ year⁻¹ from wheat to soil occurred as rhizodeposition (Kundu et al. 2001). The studies conducted with ¹⁴C revealed that rhizodeposition during the wheat growing season accounted for 30% of the total C accumulated by above-ground biomass (Lucas et al. 1977; Jenkinson and Rayner 1977; Keith et al. 1986).

The results of these long-term experiments showed that nutrient management has a significant impact on plant-mediated C input into the soils, with significantly higher C input under balanced than the imbalanced application of nutrients. The greater C accumulation in soils with FYM application was ascribed to addition of relatively more stabilized SOM to the soils (Dick and Gregorich 2004; Ghosh et al. 2010, 2012; Benbi et al. 2016). Farmyard manure being microbially degraded C substrate gets sequestered in soils aggregates. The increased C input, particularly under the rice–wheat cropping system helped enhance C sequestration and C stocks into the soil than the non-rice-based cropping systems. Although, in the rice soils, wet-tillage (puddling) accentuates destruction of soil structure and provide plenty of fine particles for coating particulate SOM (Tisdall and Oades 1982; Singh and Benbi 2016) but it distributes SOM and soil mineral components (silt + clay) more uniformly and allows organic matter to rigorously interact with mineral fraction (Sollins et al. 1996; Kögel-Knabner et al. 2010; Singh and Benbi 2023).

Cumulative carbon input and sequestration

The cereals can transfer 20 to 30% of total assimilated C into the soil (Jansson et al. 2021), and 50% of it is allocated in the roots and up to 30% in CO₂ evolved from the soil

by root respiration and microbial utilization of root borne organic substances (Kuzyakov and Domanski 2000; Lorenz et al. 2008; Turner et al. 2013; Kaiser et al. 2015). In a typical soil–plant system, plant’s investment in below-ground C allocation is improved with increased plant nutrient availability, in particular N and P, as well as enhanced tolerance to abiotic stress viz. drought, heat, and salinity (Kaiser et al. 2015; Begum et al. 2019). The plant mediated C input, especially the below-ground C cycling as root-C and rhizodeposition help enhanced C sequestration in soils.

Linear relationship has been reported to exist between TOC and the annual plant-mediated C inputs from different cropping systems, highlighting the overwhelming significance of C input on TOC stock in soils (Rasmussen and Parton 1994; Kuo et al. 1997; Majumder et al. 2007; Kundu et al. 2007; Mandal et al. 2007; Benbi and Senapati 2010; Bhattacharyya et al. 2010; Benbi et al. 2012a; Ghosh et al. 2012) (Table 2). The amount of C accumulated in soils reveals the long-term balance between C input and loss as CO₂. The linear relationship is evident from high levels of C depletion (30–60%) due to intensive cropping in subtropical regions of South Asia (Lal 2004a, b; Mandal et al. 2007). In a 33-year long-term rice–wheat cropping system, Kukal et al. (2009) reported high C sequestration due to the application of FYM as well as because of high C input through enhanced productivity. Similarly, Ghosh et al. (2012) reported the existence of a strong positive linear relationship ($R^2 = 0.98$) between the amount of C sequestered and the cumulative C input thereby indicating that the soil still has the capacity to sequester more C with the increase of C inputs through organic amendment as well as crop C inputs. Sharma et al. (2020a) also reported a linear positive relationship between total annual C input (through above- and below-ground biomass) into the soil plough layer and TOC after 5 cycles of the rice–wheat cropping system. After 7 years of rice–wheat cropping system, Benbi and Senapati

(2010) observed that C sequestration was linearly related to the cumulative C input. For C input less than 53.5 Mg ha⁻¹, a net decline in TOC was observed in rice–wheat soils, while the plots receiving FYM either alone or conjointly with RS showed a net C sequestration of 0.44–1.53 Mg ha⁻¹ (Benbi and Senapati 2010). A significant positive linear relationship observed between sequestered C and the total cumulative plant-mediated C inputs (2.82–5.55 Mg ha⁻¹ year⁻¹) to the soils during 20 years of rice–berseem cropping suggested the possibility of still more C sequestration in the soil (Majumder et al. 2008b). Similarly, Majumder et al. (2007) observed a significant direct relationship between the changes in TOC and the total cumulative plant-mediated C inputs and reported that even after 34 year of C additions through FYM (at 10.0 Mg ha⁻¹ year⁻¹) and crop residues (2.7–6.7 Mg ha⁻¹ year⁻¹) under rice–wheat–jute cropping, the soils still have a hunger for storage of C and therefore, have immense potential for further C sequestration.

The significant positive linear relationships between the changes in TOC and the cumulative C input to the soil (Table 2) suggest that soils can store C even more than added through FYM and RS at a reasonably high rate, and therefore, possess the potential to further sequester C (Benbi and Senapati 2010; Benbi et al. 2016; Sharma et al. 2020a). The rate of conversion of 6.3% for C input into TOC concentration has been reported by Benbi et al. (2016), which was higher compared to 4.4% reported by Benbi and Senapati (2010) and 5% by Majumder et al. (2007) for soils under rice–wheat cropping system under sub-tropical climatic conditions in the IGPs in India. In the hot and humid sub-tropics of the lower IGPs in India, Majumder et al. (2008b) reported a rather low rate of conversion (2.8%) of C input to TOC even after 20 years of rice–berseem cropping on a sandy loam soil. However, in a silty loam soil under a similar climate in the lower IGPs, Ghosh et al. (2012) showed a high (11.5%) rate of conversion of input C to TOC after 25 years of rice–wheat cropping system. The lower

Table 2 Relationship between cumulative carbon input (X, Mg C ha⁻¹) into the surface (0–15 cm) soil depth and quantities of total soil organic carbon (TOC) sequestration (Y, Mg C ha⁻¹) in soils under contrasting nutrient management practices followed in different cropping systems in the Indo-Gangetic Plains of South Asia

Cropping system	Study period	Regression equation	R ²	Reference
Rice–wheat	7 years	Y = 0.082X – 2.087	0.92	Benbi et al. (2012a)
Rice–wheat	11 years	Y = 0.044X – 2.301	0.75	Benbi and Senapati (2010)
Rice–wheat	5 years	Y = 0.0626X – 0.0016	0.57	Benbi et al. (2016)
Rice–wheat	25 years	Y = 0.1151X – 11.362	0.98	Ghosh et al. (2012)
Rice–wheat	5 years	Y = 0.298X + 3.414	0.73	Sharma et al. (2020a)
Rice–wheat	5 years	Y = 0.0626X – 0.0016	0.58	Benbi et al. (2016)
Rice–wheat	19 years	Y = 0.14X – 9.19	0.98	Majumder et al. (2008a)
Rice–wheat–jute	34 years	Y = 0.05X – 7.41	0.85	Majumder et al. (2007)
Rice–berseem	20 years	Y = 0.24X – 14.91	0.95	Majumder et al. (2008b)
Rice based systems [†]	7 to 36 years	Y = 0.064X – 3.60	0.40	Mandal et al. (2007)
Soybean–wheat	30 years	Y = 0.191X – 61.3	0.99	Kundu et al. (2007)
Groundnut mono-cropping	29 years	Y = 0.081X – 0.0727	0.72	Anantha et al. (2022)

[†]Pooled data for 5 different long-term (7 to 36 years) field experiments



C sequestration efficiency from crop residues into soils was possibly due to the hot and humid climate, which leads to the rapid oxidation of TOC (Majumder et al. 2007).

Paustian et al. (1992) ascribed preferential retention of C in manure amended soils to a high degree of decomposition and a high proportion of chemically recalcitrant organic compounds. According to Jenkinson (1988), the relationship between the addition and storage of C in the soil followed the first-order kinetics: $\frac{\delta C_s}{\delta t} = h * A - k * TOC$, where, 'Cs' is C storage, 't' is time, 'h' is the rate constant of annual C inputs incorporated into soil organic matter, A is annual C input to the soil, TOC is soil organic matter, and 'k' is the decay rate constant of native TOC. In a 30-year-old soybean–wheat cropping system in the upper IGPs, Kundu et al. (2007) observed that the annual rate of change in TOC increased linearly ($p < 0.01$) when plotted against cumulative C input. The intercept of the plot ($-61.3 \text{ kg C ha}^{-1} \text{ year}^{-1}$) represented the annual loss of C from native SOM. By equating the intercept with ' $k \times C_s$ ' in the Jenkinson (1988) model and keeping initial TOC content at $33.3 \text{ Mg C ha}^{-1}$, the decay rate of native TOC was estimated as 0.0018, which translates into C loss from native TOC during 30 years of soybean–wheat cropping to be 0.18% of the initial C content (Kundu et al. 2007).

According to Benbi et al. (2012a, 2016), the rise in C build-up in a surface (0–15 cm) layer of the soil due to FYM application was due to supplementary C input as manure. As organic material undergoes some decomposition, the organic C contained in it is already transformed to recalcitrant forms (Dick and Gregorich 2004). The application of NPK conjointly with FYM allows sequestration of even more C in the soil. Bhattacharyya et al. (2007) estimated that annual C inputs in wheat–soybean system by roots and rhizodeposition were 1542, 2339, and 2771 kg ha^{-1} with N, NPK, and NPK + FYM, respectively, and 25% of the added plant-mediated C was annually humified to contribute towards increase in TOC. Therefore, bulging of TOC pool in soils following manure application can be ascribed to supplementation of relatively stabilized C input with relatively lower oxidation and/or C mineralization potential. Figure 1 exemplifies the linear function of total annual C input into soil plough layer and TOC pool in rice–wheat soils in the IGPs. These relationships highlight the significance of best nutrient management practices in enhancing the crops' above-and below-ground biomass and eventually the biomass mediated C input for increased C storage into the soils.

Carbon sequestration and steady-state carbon stocks

It is considered that if the TOC stocks are not at steady state, the rate of C accrual requisite to accomplish the expected level would depend upon the TOC stocks trend prior to the

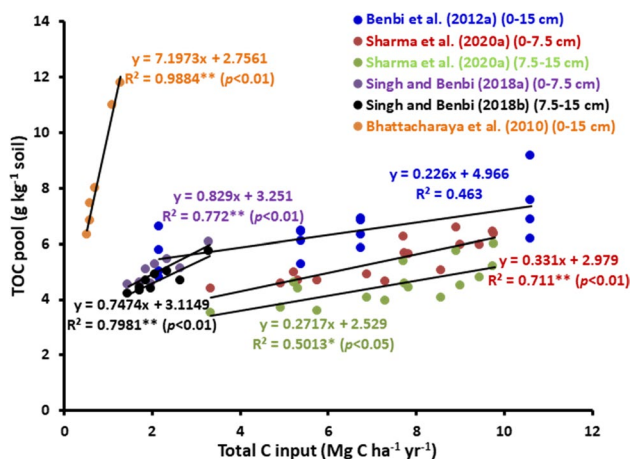


Fig. 1 Relationships between annual total C input into the soil plough layer (0–15 cm) and total organic C (TOC) pool in soils under rice–wheat cropping system in the Indo-Gangetic Plains of South Asia. Data in six studies pooled for different nutrient management treatments including inorganic and organic manures applied alone or conjointly

employment of better nutrient management intervention (Soussana et al. 2019). Under such circumstances, the burden would set on soils showing decreasing C stocks, because the rate at which they would have to increase will be greater compared to the soils characterized by stable or increasing TOC stocks (Soussana et al. 2019). Conversely, the increasing TOC stocks compared with the baseline (a reference) apparently indicates that the rate of increase in TOC to reach the target will be fixed, i.e., independent of the previous TOC stock trend (Pellerin et al. 2019). A decrease in SOC stocks is associated with increasing atmospheric CO_2 and a loss of soil fertility, while the opposite is the case when TOC stocks are built up (Lal 2016). Soil management and crop production practices are considered important to increase TOC stocks to a new steady-state, casing strategies both to enhance organic C input while reducing C mineralization (Minasny et al. 2017). Such management practices are believed to be sustained to preserve the benefit of increased TOC stocks.

Carbon sequestration in soil plough layer under different nutrient management treatments ranged from -1.1 to $+9.5 \text{ Mg ha}^{-1}$ over the initial TOC stocks after 11 years of rice–wheat cropping (Table 3) (Benbi et al. 2012a). About 8.2% of the added C was accumulated over the initial TOC stocks of 11.5 Mg ha^{-1} during the 11 years study period. The critical cumulative C input for zero change in TOC stocks was estimated to be 25.3 Mg ha^{-1} requiring an annual C input of 2.3 Mg C ha^{-1} (Benbi et al. 2012a). In a 19 years old rice–wheat cropping system in subtropical India, a minimum of $3.56 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ was required as organic amendments to compensate for TOC loss from cropping (Majumder et al. 2008a). Using data from five

Table 3 Annual carbon input ($\text{Mg C ha}^{-1} \text{ year}^{-1}$) required to maintain total soil organic carbon stocks at steady state for soils under different cropping systems in the Indo-Gangetic Plains of South Asia

Cropping system (study period)	Amount of carbon input required ($\text{Mg C ha}^{-1} \text{ year}^{-1}$)	Reference
Rice–wheat (11 years)	2.30	Benbi et al. (2012a)
Rice–wheat (19 years)	3.60	Majumder et al. (2008a)
Rice-based (7 to 36 years) [†]	2.90	Mandal et al. (2007)
Rice–berseem (20 years)	3.30	Majumder et al. (2008b)
Rice–wheat–jute (34 years)	4.59	Majumder et al. (2007)
Soybean–safflower (15 years)	3.47	Majumder et al. (2008a)
Sorghum based (22 years)	1.10	Srinivasarao et al. (2012a)
Groundnut mono-cropping (29 years)	0.32	Anantha et al. (2022)

[†]Pooled data for 5 long-term (7 to 36 years) cropping systems

long-term (7–36 years) fertility experiments on rice–wheat cropping in sub-tropical India, Mandal et al. (2007) reported that for sustenance of TOC level (i.e., zero change due to cropping), a minimum quantity of 2.9 Mg C ha^{-1} is required to be added as inputs (Mandal et al. 2007). In a 34 years long rice–wheat–jute ecosystem, Majumder et al. (2007) reported that $4.59 \text{ Mg C ha}^{-1}$ is required critical C input for zero change in TOC pool. A positive and linear relationship between changes in TOC stocks as a function of total cumulative C inputs to the soils (external organic manures + crop residue) implies that even after 11 years of continuous input of biomass C ranging from 0.6 to $3.4 \text{ Mg C ha}^{-1} \text{ year}^{-1}$, the soil C sink capacity was not filled. The relationship between cumulative C input and C sequestration showed that 8.2% of the added C was sequestered in the soil (Benbi et al. 2012a), which is lower than 14–21% reported for temperate semi-arid regions (Rasmussen and Collins 1991).

Soil organic C sequestration is strongly influenced by climatic conditions. For example, organic C sequestration under Mediterranean climate was 7.6% (Kong et al. 2005), 14% in humid IGP of India under irrigated rice–wheat cropping system (Majumder et al. 2008a), 5% for rice–wheat–jute system (Majumder et al. 2007), 6.4% for sub-tropical climatic conditions in India (Mandal et al. 2007). Rasmussen and Smiley (1997) reported C conversion rate of 14.8% in cooler and temperate climatic regions in USA and Canada. In a groundnut-based cropping system, the C sequestration potential defined as the rate of increase in TOC stocks *vis-à-vis* the antecedent baseline C stock in 0–20 cm soil layer ranged from $-0.18 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (unfertilized CK) to $0.57 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (50% recommended inorganic fertilizers + 4 Mg ha^{-1} groundnut shells) (Bhattacharyya et al. 2009). Regardless of the nutrient management treatment, the amount of C required to maintain initial organic C stocks varied between 2.30 and $4.59 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ in rice-based cropping systems, compared with between 1.10 and $3.47 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ in non-rice-based cropping systems in IGPs (Table 3). The extent of C sequestration into soils

was of greater magnitude in treatments involving exogenous C input through applied organic manures. The proportion of cumulatively added C input that gets sequestered into soil plough layer varied considerably among different nutrient management regimes, initial C status and the climatic conditions. Therefore, it can be concluded that C input of 2.6 – 4.6 Mg C ha^{-1} is required critical C input for zero change in TOC pool in soils for C restoration and long-term sustainability of different rice-based cropping systems.

Net carbon sequestration rate as influenced by nutrient management

Soil C sequestration implies transferring of atmospheric CO_2 into soil of a land unit through its vegetation. Over the past 12,000 years and particularly the last 200 years of agriculture has released 133 billion metric tons of CO_2 (Gt CO_2) from the soil into the atmosphere (Lutz and Welsh 2021). It is more than 3-times as much C as all human activities emitted in 2019 (43.1 Gt CO_2 (Lutz and Welsh 2021). Soil C sequestration is governed by implementation of robust nutrient management practices which aimed at increased plant productivity that increase the amount of C accrued as SOM. These C management practices work by enhancing the rate of C input to soils and/or by dropping the rates of turnover of organic C stocks already in the soil (Paustian et al. 2019). In addition to CO_2 removal potential, increases in SOM content are extremely advantageous from the perspective of soil health and fertility.

In an un-disturbed ecosystem, the rate of sequestration and C inputs is believed to be related to crop type and productivity of the crops, and is greatly influenced by climate, but also by nutrient accessibility and other growth decisive factors (Paustian et al. 2019). The C sequestration rates in soils under various cropping systems in IGPs are listed in Table 4. Nutrient management practices followed in different cropping systems influence C sequestration because it



is governed by plant-mediated C input. In the IGP of India and Nepal, soil C sequestration rates varying between 0.08 and 0.98 Mg C ha⁻¹ year⁻¹ under inorganic and organic fertilizers application in rice–wheat systems have been reported by Duxbury (2001). Brar et al. (2013) reported that in soil under rice–wheat cropping system, even the no-fertilizer treatment contributed 1.94 Mg C ha⁻¹ toward C sequestration with C sequestration rate of 0.22 Mg C ha⁻¹ year⁻¹, and TOC accumulation of 7.84 Mg C ha⁻¹. The TOC pool, C sequestration, and rate of C sequestration with balanced fertilizer NPK application were significantly increased from 9.19 to 9.99 Mg C ha⁻¹, from 3.30 to 4.10 Mg C ha⁻¹, and from 0.37 to 0.46 Mg C ha⁻¹ year⁻¹, respectively when FYM manure was applied along with NPK. Rasool et al. (2007) observed that the C sequestration rate in a 32-year-old rice–wheat cropping system in northwestern India was maximum (0.31 Mg C ha⁻¹ year⁻¹) in FYM applied plots, followed by 0.26 Mg C ha⁻¹ year⁻¹ in NPK plots, 0.19 Mg C ha⁻¹ year⁻¹ in NP, and the lowest (0.13 Mg C ha⁻¹ year⁻¹) in fertilizer N alone plots (Table 4). Nayak et al. (2012) observed that C sequestration rate varied between 0.231 and 0.332 Mg C ha⁻¹ year⁻¹ in NPK applied plots under continuous rice–wheat cropping system in four different agro-climatic zones of IGPs. The conjoint application of NPK + FYM leads to a significantly higher C sequestration rate, while the C sequestration rates in NPK + FYM and NPK + crop residues incorporation treatments were at par.

The application of manures along with inorganic fertilizer resulted in a net C sequestration of 0.44 Mg C ha⁻¹ in plough layer of the soil after 7 years of rice–wheat cropping. Carbon build-up was greater (1.53 Mg C ha⁻¹) with conjoint application of RS and FYM along with inorganic fertilizers that were applied annually (Benbi and Senapati 2010). This rate of input of biomass C was lower as compared to 4.6 Mg C ha⁻¹ year⁻¹ for rice–wheat–jute cropping system (Majumder et al. 2007), 3.6 Mg C ha⁻¹ year⁻¹ for rice–wheat cropping system (Majumder et al. 2008a) and 2.9 Mg C ha⁻¹ year⁻¹ for rice-based cropping system (Mandal et al. 2007). Benbi et al. (2012a) reported that after 11 years, C sequestration in the 0–15 cm layer ranged from –1.1 to +9.5 Mg C ha⁻¹ over the initial TOC stocks in rice–wheat cropping system. Data pooled for different fertilizer N application rates revealed that the highest C sequestration (8.2 Mg C ha⁻¹) occurred under FYM + RS, trailed by FYM (3.7 Mg C ha⁻¹) and the lowest under RS application treatment (2.8 Mg C ha⁻¹). During the 11-year period, about 8.2% of the added C was sequestered in rice–wheat cropping system over the initial stocks of 11.5 Mg C ha⁻¹ (Benbi et al. 2012a). Mandal et al. (2007) compared NPK and NPK + FYM treatments in different cropping systems and reported large differences in C sequestration rate (Table 4). Their results revealed that difference in C sequestration rate among NPK and NPK + FYM treatments

was 7.3% for rice–mustard–sesamum, 37.0% for rice–fallow–wheat, 176.9% for rice–fallow–berseem, 127.3% for rice–wheat–jute and 60.7% for rice–fallow–rice. This shows that balanced fertilization helps in sequestering more C than that sequestered by unbalanced fertilization (Rasool et al. 2007).

Kukul et al. (2009) reported that TOC sequestration rates in rice–wheat and maize–wheat cropping systems were the highest in FYM applied plots followed by NPK plots. In both the cropping systems, NPK application enhanced C sequestration rate, but the increase was more in rice–wheat compared to the maize–wheat cropping system. Averaged across the nutrient management treatments, TOC sequestration rate was about 3-times higher in rice–wheat than in maize–wheat cropping system. In the soil under rice–wheat cropping, FYM application sequestered 0.31 Mg C ha⁻¹ year⁻¹ compared to 0.14 Mg C ha⁻¹ year⁻¹ in maize–wheat cropping system. Similarly, with balanced fertilization (NPK), C was sequestered at 0.26 Mg C ha⁻¹ year⁻¹ under rice–wheat system as compared to 0.08 Mg C ha⁻¹ year⁻¹ for the soil under maize–wheat cropping system. Thus, soils under rice–wheat system sequestered 55% higher TOC in FYM applied plots than the respective treatment in maize–wheat cropping system. The NPK plots exhibited a higher TOC accumulation by 70% in soils under rice–wheat than in maize–wheat cropping system. The higher C sequestration rate in rice–wheat soils was ascribed to anaerobic (flooded) moisture regime prevailing consecutively for 3–4 months during rice growing season, and secondly due to higher crop biomass production in rice as compared to maize (Kukul et al. 2009). Higher above-ground biomass production in rice–wheat system also resulted in greater biomass of roots and rhizodeposition leading to greater C input in the soil (Singh and Benbi 2022). The response to below-ground (root) biomass yield and rhizo-deposition under different nutrient management regimes has been related to the above-ground biomass harvests (Bronson et al. 1998; Majumder et al. 2007; Sharma et al. 2020a; Singh and Benbi 2022). Witt et al. (2000) reported 11–12% greater C sequestration in soils continuously cropped with rice for 2 years than in the maize–rice rotation with the higher amounts sequestered in N-fertilized treatments.

Brar et al. (2015) reported the highest C sequestration rate of 0.186 Mg C ha⁻¹ year⁻¹ in a soil under maize–wheat cropping system (36 years) when 100% NPK and FYM were applied together (Table 4). Carbon sequestration under NP was about 11.3% higher than in plots to which only N was applied. Interestingly, C sequestration under 50% NPK treatment was about 27.2% lower than the 100% NPK treatment but there was non-significant ($p < 0.05$) difference in C sequestration rate among 100% NPK and 150% NPK treatment. Another long-term (34 years) study on maize–wheat cropping system revealed that C sequestration rate for

Table 4 Carbon sequestration rate ($\text{Mg C ha}^{-1} \text{ year}^{-1}$) for soils under different cropping systems in the Indo-Gangetic Plains of South Asia

Cropping system (study period)	Soil properties	Soil properties	Treatment	Carbon sequestration rate ($\text{Mg C ha}^{-1} \text{ year}^{-1}$)	Reference
Rice–wheat (32 years)	Sandy loam, <i>Typic Ustipsamment</i>	Tropical, semi-arid, mean maximum temperature 39.4°C , mean minimum temperature 4.4°C	N* NP NPK FYM [§]	0.13 0.19 0.26 0.31	Rasool et al. (2007)
Maize–wheat (36 years)	Sandy loam, <i>Typic Ustochrepts</i> , Initial TOC [†] 2.4 g kg^{-1}	Semi-arid, sub-tropical	CK N NP 50% NPK 100% NPK 150% NPK 100% NPK + FYM	0.033 0.097 0.108 0.075 0.103 0.106 0.186	Brar et al. (2015)
Rice–wheat (34 years)	Sandy loam, <i>Typic Ustipsamment</i> , Initial TOC 2.90 g kg^{-1} , B_D 1.69 g cm^{-3}	Tropical, semi-arid, mean annual rainfall 700 mm, mean maximum temperature 39°C , mean minimum temperature 4°C	CK N NP NPK FYM	– 0.130 0.190 0.260 0.310	Kukul et al. (2009)
Maize–wheat (34 years)	Sandy loam, <i>Typic Ustipsamment</i> , Initial TOC 2.70 g kg^{-1} , B_D 1.69 g cm^{-3}	Tropical, semi-arid, mean annual rainfall 700 mm, mean maximum temperature 39°C , mean minimum temperature 4°C	CK N NP NPK FYM	– 0.030 0.040 0.080 0.140	Kukul et al. (2009)
Rice–mustard–sesamum (7 years)	Silty clay, B_D 1.18 g cm^{-3} , Initial TOC 15.8 g kg^{-1}	Sub-humid, tropic, mean annual rainfall 1470 mm, mean maximum temperature 36.5°C , mean minimum temperature 12.0°C	NPK NPK + FYM	1.91 2.05	Mandal et al. (2007)
Rice–fallow–wheat (19 years)	Silty clay, B_D 1.20 g cm^{-3} , Initial TOC 14.2 g kg^{-1}	Sub-humid, tropic, mean annual rainfall 1480 mm, mean maximum temperature 36.2°C , mean minimum temperature 12.5°C	NPK NPK + FYM	0.27 0.37	Mandal et al. (2007)
Rice–fallow–barseem (20 years)	Silty clay, B_D 1.15 g cm^{-3} , Initial TOC 13.2 g kg^{-1}	Sub-humid, tropic, mean annual rainfall 1470 mm, mean maximum temperature 36.5°C , mean minimum temperature 12.0°C	NPK NPK + FYM	0.13 0.36	Mandal et al. (2007)
Rice–wheat–jute (34 years)	Sandy loam, B_D 1.35 g cm^{-3} , Initial TOC 10.4 g kg^{-1}	Sub-humid, tropic, mean annual rainfall 1492 mm, mean maximum temperature 35.4°C , mean minimum temperature 12.4°C	NPK NPK + FYM	0.11 0.25	Mandal et al. (2007)
Rice–fallow–rice (36 years)	Sandy clay loam, B_D 1.38 g cm^{-3} , Initial TOC 11.4 g kg^{-1}	Sub-humid, tropic, mean annual rainfall 1556 mm, mean maximum temperature 32.0°C , mean minimum temperature 14.0°C	NPK NPK + FYM	0.28 0.45	Mandal et al. (2007)



Table 4 (continued)

Cropping system (study period)	Soil properties	Soil properties	Treatment	Carbon sequestration rate (Mg C ha ⁻¹ year ⁻¹)	Reference
Maize–wheat (34 years)	Sandy loam, <i>Typic Ustochrept</i> , Initial TOC 2.4 g kg ⁻¹	Sub-tropical	CK N NP NPK NPK + FYM	0.32 0.34 0.46 0.73 0.105	Kaur et al. (2008)

†Total organic carbon

‡ Bulk density

§ Farmyard manure

¶ Check (no N, P, K or farmyard manure)

*N, NP, NPK represent nitrogen, nitrogen + phosphorus, and nitrogen + phosphorus + potassium, respectively

treatments involving imbalanced fertilizer application (N, NP) was lower (by 37.0–53.4%) than the balanced use of chemical fertilizers (NPK). Kukul et al. (2009) reported that after 34 years of maize–wheat cropping, C sequestration rate under NPK treatment was significantly increased by about 167 and 100%, respectively than application of N and NP, respectively (Table 4). Application of only FYM significantly enhanced the C sequestration rate by about 75% than application of NPK in maize–wheat cropping system. However, in rice–wheat cropping system (34 years), C sequestration rate was 2.2 to 4.8 times higher than in the soils under maize–wheat cropping system (Kukul et al. 2009). In rice–wheat cropping system, NP application enhanced the C sequestration by about 46.2% than N alone. However, NPK application increased the C sequestration rate by 36.8 and 100% than NP and N application. Application of only FYM increased the C sequestration rate by 19.2% than in the NPK treatment (Kukul et al. 2009). Under maize–wheat cropping system, the C sequestration rate in the soil was the highest (997 kg C ha⁻¹ year⁻¹) with combined application of NPK + FYM when compared with application of NPK alone (553 kg C ha⁻¹ year⁻¹) (Purakayastha et al. 2008). It was estimated that 17.1–34.0% of gross total C input over 10 years contributed towards the increased organic C content, while C sequestration efficiency in particulate organic C varied between 1.28 and 2.58% and was lower than KMnO₄-C that varied between 1.42 and 3.72%.

In a soybean–wheat cropping system, the annual rate of increase in TOC content over initial condition was 74, 328, 711, and 900 kg C ha⁻¹ under unfertilized, NPK, N + FYM, and NPK + FYM treatments, respectively (Kundu et al. 2007). In another long-term experiment on soybean–wheat annual cropping system, Kundu et al. (2002) reported that after 27 cycles about 26% of annual plant mediated C input was humified in the soil and increased TOC content but C loss from the native SOM of 36 kg ha⁻¹ year⁻¹ with decay rate of 0.11% of the initial TOC content was also recorded. Rudrappa et al. (2006) reported that the amount of sequestered organic C in soil under maize–wheat–cowpea (fodder) cropping system in New Delhi was the highest in NPK + FYM (731 kg C ha⁻¹ year⁻¹) followed by 150% NPK (462 kg C ha⁻¹ year⁻¹) and 100% NPK (169 kg C ha⁻¹ year⁻¹). Application of N and NP sequestered 106 and 134 kg C ha⁻¹ year⁻¹, respectively. In a 34 years maize–wheat cropping system, Kaur et al. (2008) observed that net change in TOC was positive for all nutrient management treatments (N, NP, NPK and NPK + FYM), and the steady state C varied between 5.8 and 9.9 Mg C ha⁻¹. The C sequestration rate increased significantly in NPK and NPK + FYM treatments to 0.73 and 1.05 Mg C ha⁻¹ year⁻¹, compared with 0.12 Mg C ha⁻¹ year⁻¹ in the fallow or no crop treatment.

The large differences in C sequestration rates for NPK and NPK + FYM treatments reported by Mandal et al.

(2007) was ascribed to the difference in soil texture and initial TOC concentration (Table 4). For example, the silty clay soil (initial TOC concentration of 15.8 g kg^{-1}) under rice–mustard–sesamum showed a 7.3% increase in C sequestration rate with NPK + FYM application rather than NPK alone. Although, soil texture for the experimental site under rice–fallow–wheat was also silty clay but had lower initial TOC concentration (14.2 g kg^{-1}). Nonetheless, the study period after which soil samples were analyzed for sites under rice–rice–fallow–wheat was 12 years more than rice–mustard–sesamum cropping system. Apparently, the experimental site under rice–fallow–wheat had higher C input through exogenous (FYM) and indigenous (root mediated C input and rhizodeposition) sources than the rice–mustard–sesamum, which had resulted in such large difference in C sequestration rate among two treatments for different cropping systems. The large difference in C sequestration rates among NPK and NPK + FYM treatments under rice–fallow–wheat (19 years; silty clay, initial TOC 14.2 g kg^{-1}) and rice–fallow–berseem (20 years, silty clay, initial TOC 13.2 g kg^{-1}) could be ascribed to the inclusion of leguminous (berseem) crop in annual cropping system. However, higher difference in C sequestration rate among treatments for soils in rice–wheat–jute (34 years, sandy loam) and rice–fallow–rice (36 years, sandy clay loam) was ascribed to the difference in initial TOC concentration (Table 4).

A relatively lower difference in C sequestration rates for soils having high initial (pre-existing) TOC levels and fine fraction (silt + clay) fraction) of the soil corroborates the concept of C saturation, which implies that C stabilization efficiency of applied C inputs at steady state depends on the C saturation deficit (Stewart et al. 2009; Angers et al. 2011). A relative decrease in C stabilization efficiency of soils receiving high C input in field experiments over a long-period of time or with high pre-existing C concentration is soils across different agro-climatic conditions, cropping systems, soil texture (silt + clay fraction) and mineralogy has been well established (Kool et al. 2007; Stewart et al. 2007; Gulde et al. 2008; Kimetu et al. 2008; Heitkamp et al. 2012). As the silt + clay fraction increased, the proportion of macro-aggregates ($> 0.25 \text{ mm}$) increased with a concomitant decrease in the proportion of micro-aggregates ($< 0.25 \text{ mm}$) (Singh and Benbi 2021). A linear response function highlighting increased stable C pool [(silt + clay)-C and NaOCl-C] as a function of silt + clay fraction implies that fine fraction of the soil controlled the soil organic matter stabilization (Singh and Benbi 2021). Carbon stabilization practices are linked by intrinsic resistance to the decomposition of organic compounds and to interactions of SOM with the silt + clay (Sollins et al. 1996). According to von Lützow et al. (2007) about 50–75% of TOC is associated with clay-sized particles ($< 2.0 \text{ }\mu\text{m}$), about 20–40% with silt-sized particles ($2.0\text{--}63 \text{ }\mu\text{m}$) and $< 10\%$ with sand sized

particles ($> 63 \text{ }\mu\text{m}$). Therefore, resistant C pool is linked not only to the presence of compounds that are hardly attractive for micro-organisms, but also to the dissimilar responses leading to the SOM humification process (Jastrow et al. 2007). The humification process is considered an important mechanism of SOM stabilization (Krull et al. 2003). Carbon accrual in soils, believed to be a function of soil texture and aggregation, with the silt and clay size fractions is highly protected from decomposition (Gulde et al. 2008; Hassink 2016). During the process of SOM decomposition, organic matter binds with silt and clay to form aggregates, which protects the organic matter from decomposition (Churchman 2018; Gulde et al. 2008; Singh and Benbi 2021). The highest amount of soil C is found in the silt and clay size fractions, whilst the sand sized fraction is low in soil C (Gabarrón-Galeote et al. 2015; Tiessen and Stewart 1983).

Nutrient management impacts on total organic carbon accumulation in the soil

An added thought which has emerged concerning restraints on persistent goals for soil C accumulation, has been the need for additional inputs of N (van Groenigen et al. 2017). In majority of mineral soils which had lost about 25–75% (equivalent to $10\text{--}30 \text{ Mg C ha}^{-1}$) of their antecedents TOC stocks (Lal 2013), SOM has a relatively narrow C:N stoichiometry, ranging between 8 and 20, with a C:N of 10–12 as a general “rule-of-thumb” for cropland ecosystems. Therefore, to sustain this equilibrium, if SOM pools must increase by per se 4 billion tons $\text{CO}_2 \text{ eq year}^{-1}$ ($1.1 \text{ Gt C year}^{-1}$), about 100 million tons N year^{-1} would be required to be added into the applied SOM (Paustian et al. 2019). According to van Groenigen et al. (2017), it would be comparable to about seventy-five percent of the current global synthetic N fertilizer production. Therefore, soil management and crop production practices such as inclusion of more legumes (e.g., N-fixing crops, legume pastures in cropping systems with annual crops) are required to be promoted which could aid meeting demands for additional N inputs into SOM with co-benefits of increased soil C accumulation (Rekhi et al. 2000; Chettri et al. 2003; Paustian et al. 2019). The application of inorganic and organic sources of plant nutrients for crop production is of fundamental importance for nutrition of crop plants as well as for soil health improvement through organic matter buildup. In most of the experiments conducted in the IGPs, TOC accumulation has been studied by estimating C by Walkey and Black’s method. It determines labile as well as a small part of non-labile organic C, which are readily accessible source of C to micro-organisms and directly influence plant nutrient supply. A good NPK fertility program helps sequester atmospheric CO_2 into TOC by increased plant growth and subsequently, the return of organic C



to the soil for storage as SOM. The balanced application of inorganic fertilizers along with organic manures (e.g., NPK + FYM) not only enhances root biomass, but additionally FYM as a source of organic matter contributed tremendously for enhancing TOC content.

Tables 5 and 6 list several experiments in which effect of different nutrient management strategies in different cropping systems in the IGPs on TOC accumulation are shown. The balanced application of inorganic fertilizers (NPK) to soils either alone or conjointly with FYM/RS significantly enhanced TOC (Majumder et al. 2007; Singh and Benbi 2018a; Sharma et al. 2020a), while imbalanced application of fertilizer nutrients either decreased or resulted in a non-significant change in TOC concentration (Singh and Benbi 2018a). Benbi et al. (2012a) reported that FYM application conjointly with RS incorporation resulted in about 70.8% higher TOC accumulation than application of only FYM (Table 5). Incorporation of RS enhanced TOC accumulation in the 0–15 cm soil layer by 34.6% than FYM alone. Fertilizer N application (180 kg N ha⁻¹) increased TOC accumulation by 4.5% as compared with the no-fertilizer plot (Benbi et al. 2012a). Brar et al. (2013) reported that after 9 years of rice–wheat cropping the TOC in the 0–15 cm layer increased from the initial status of 2.42 g kg⁻¹ to 3.26 g kg⁻¹ in the CK treatment and to 4.11 g kg⁻¹ with the application of NPK and to 4.55 g kg⁻¹ in the NPK + FYM treatment plot (Table 5). Soil organic C content was increased by 34.7% in the CK, and by 69.8 and 88.0% in NPK and NPK + FYM treatments, respectively. The application of N and NP significantly increased TOC content over the CK, although both these treatments did not differ significantly in TOC content. Rasool et al. (2007) reported that under rice–wheat cropping system the application of 120 kg N ha⁻¹ through mineral fertilizers resulted in 19.7% higher TOC than the CK plots. Application of fertilizers P and PK improved the TOC pool by 28.6 and 39.0%, respectively (Table 5). Yadvinder-Singh et al. (2004) reported 18.4% increase in TOC accumulation in 0–15 cm soil layer under rice–wheat system with N + green manure treatment as compared with CK (Table 5). However, wheat straw incorporation enhanced TOC accumulation by 39.5% than CK. The FYM + green manure treatment resulted in 71.1% higher TOC accumulation in soil than the CK treatment. The imbalanced application of fertilizers (N, NP and NK) did not result in considerable accumulation of TOC in soils under rice–wheat cropping system (Rekhi et al. 2000). Singh and Benbi (2018a) reported that as compared to the application of NPK alone, NPK + FYM application increased TOC concentration by 19% and 23%, respectively in surface and sub-surface soil under rice–wheat cropping system (Table 5). Soil organic C increased by 18.0 and 22.2%, respectively in FYM and N + FYM applied plots in the surface as compared with 17.3 and 18.9% in the sub-surface soil than the CK (Singh and Benbi 2018a).

According to Dick and Gregorich (2004), organic manures already undergo some decomposition and organic C in the manures is already converted to recalcitrant forms.

Nayak et al. (2012) studied rice–wheat cropping system in trans- (Ludhiana), middle (Kanpur) and lower (Sabour and Kalyani) IGPs and observed that continuous application of NPK for 23–26 years resulted in significantly higher TOC concentration than in the CK in the top 0–15 cm soil (Table 5). However, without the application of fertilizers (CK) a reduction in TOC by 22 and 35% over values recorded at initiation of the experiments was observed at Sabour and Kalyani. At Ludhiana and Kanpur, TOC levels in the CK treatments were maintained. Since the initial TOC at Sabour and Kalyani sites was comparatively higher than at Ludhiana and Kanpur, it was necessary to apply fertilizers and/or organic manure to maintain the TOC level (Table 5). The substitution of 50% N through FYM/CR/GM to rice significantly improved the TOC over the NPK alone treatment at all the four locations.

The conjoint application of NPK and FYM in rice–wheat–jute cropping system resulted in 6.2 and 24.9% higher TOC compared with NPK and CK treatments, respectively (Majumder et al. 2007). Even after 2 years of application in rice–rice cropping system, Rahman et al. (2016) reported 9.3% increase in TOC in a shallow red brown soil of Pakistan. The cow dung or poultry manure application increased the TOC accumulation by 28.7 and 34.4%, respectively. Haque et al. (2021) compared NPK + FYM, 75% NPK + biosolids and 75% NPK + FYM + biosolids in a silty loam soil of Bangladesh under rice-based cropping system, and reported about 22.5, 90.7 and 104.2% increase in TOC accumulation over NPK alone application (Table 5). Sharma et al. (2020a) reported that TOC concentration varied between 4.37 and 6.44 g C kg⁻¹ in the surface (0–7.5 cm) and 3.50 and 5.98 g C kg⁻¹ in the sub-surface (7.5–15 cm) soil layers under rice–wheat cropping system. Fertilizer N application with RS incorporation (RS₀N₉₀, RS₀N₁₂₀, and RS₀N₁₅₀) did not significantly increase the TOC concentration in the surface soil layer, as compared with CK. Average across the treatments, TOC in the surface soil layer was about 18% higher compared with sub-surface soil layer under rice–wheat cropping system (Table 5).

Bhattacharyya et al. (2010) observed that TOC build-up improved from the start of the experiment even in the unfertilized plots, but after 30 years of soybean–wheat cropping, the N + FYM and NPK + FYM treatment plots contained more TOC than those receiving NPK fertilizers only (Table 6). Soils under NPK + FYM treatment had 47% higher TOC concentration in 0–15 cm plough layer, 31% in the 15–30 cm and 35% in the 30–45 cm soil layers, compared with application of NPK alone. Another study conducted by Kundu et al. (2007) showed that after 30 years of soybean–wheat cropping, soils under NPK and NPK + FYM

Table 5 Effect of inorganic and organic fertilizer application on total soil organic carbon (TOC) accumulation in the surface layer (0–15 cm) of soils under rice–wheat cropping systems in the Indo-Gangetic Plains of South Asia

Climatic conditions	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Semi-arid, sub-tropical	Sandy loam, Initial TOC 4.8 g kg ⁻¹	11 years	FYM	4.89	Benbi et al. (2012a)
			Rice straw (RS)	6.58	
			FYM [§] +RS	8.35	
			N* ₀	6.20	
			N ₆₀	6.38	
			N ₁₂₀	6.29	
Semi-arid, sub-tropical	Sandy loam, Initial TOC 2.1 g kg ⁻¹	9 years	N ₁₈₀	6.48	Brar et al. (2013)
			CK [¶]	3.26	
			N	3.53	
			NP	3.60	
			NPK	4.11	
Semi-arid, sub-tropical	After rice Sandy loam, Initial TOC 2.9 g kg ⁻¹	32 years	NPK+FYM	4.52	Rasool et al. (2007)
			CK	3.00	
			FYM	6.20	
			N	3.40	
			NP	3.80	
Semi-arid, sub-tropical	After wheat Sandy loam, Initial TOC 2.9 g kg ⁻¹	32 years	NPK	5.30	Rasool et al. (2007)
			CK	2.90	
			FYM	5.10	
			N	3.90	
			NP	4.40	
Semi-arid, sub-tropical, mean annual rainfall = 800 mm	Loamy sand, Typic Ustipsament Initial TOC = 3.60 g kg ⁻¹	12-years	NPK	4.90	Yadvinder-Singh et al. (2004)
			CK	3.80	
			N	4.10	
			Green manure (GM)+N	4.50	
			Wheat straw (WS)+N	5.30	
			WS+GM+N	5.90	
			FYM+N	6.00	
			FYM+GM	6.50	
Semi-arid, sub-tropical	Loamy sand, Typic Ustipsament Initial TOC 1.80 g kg ⁻¹	13-years	CK	2.00	Rekhi et al. (2000)
			N ₁₂₀	3.00	
			N ₁₈₀	3.10	
			N ₁₂₀ P ₆₀	3.20	
			N ₁₈₀ P ₉₀	3.50	
			N ₁₂₀ P ₆₀ K ₃₀	3.70	
			N ₁₈₀ P ₉₀ K ₄₅	3.80	
			Hot humid, semi-arid, sub-tropical, monsoonal climate mean annual rainfall 713 mm	Soil depth 0–7.5 cm, sandy loam Eutric Cambisols Initial TOC 4.20 g kg ⁻¹	
N	4.46				
NP	4.56				
NK	4.60				
PK	5.09				
NPK	5.11				
FYM	5.25				
N+FYM	5.44				
NPK+FYM	6.08				



Table 5 (continued)

Climatic conditions	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Hot humid, semi-arid, sub-tropical, monsoonal climate, mean annual rainfall 713 mm	Soil depth 7.5–15 cm, sandy loam <i>Eutric Cambisols</i> Initial TOC 4.40 g kg ⁻¹	5-years	CK	4.21	Singh and Benbi (2018a)
			N	4.32	
			NP	4.38	
			NK	4.42	
			PK	4.67	
			NPK	4.68	
			FYM	4.94	
			N + FYM	5.00	
			NPK + FYM	5.75	
Sub-tropical, high temperature and humidity	Silty loam, pH 6.5	Not available	NPK	7.10	Haque et al. (2021)
			NPK + FYM	8.70	
			75% NPK + Biosolid	13.5	
			75% NPK + Biosolid + FYM	14.5	
Semi-arid, sub-tropical	Sandy loam, Initial TOC 2.1 g kg ⁻¹ , Soil depth 0–5 cm	10 years	NPK + FYM	3.33	Brar et al. (2013)
			75% NPK + Biosolid	3.77	
			75% NPK + Biosolid + FYM	3.90	
			NPK	4.33	
Semi-arid, sub-tropical	Sandy loam Initial TOC 2.1 g kg ⁻¹ , Soil depth 5–10 cm	10 years	NPK + FYM	5.07	Brar et al. (2013)
			CK	3.27	
			N	3.70	
			NP	3.77	
Semi-arid, sub-tropical	Sandy loam Initial TOC 2.1 g kg ⁻¹ , Soil depth 10–15 cm	10-years	NPK	4.23	Brar et al. (2013)
			NPK + FYM	4.70	
			CK	3.17	
			N	3.13	
Hot humid sub-tropical	Initial TOC 0.88%, Sandy loam	19-years	NP	3.13	Ghosh et al. (2010)
			NPK	3.77	
			NPK + FYM	3.87	
			Fallow	16.1	
Sub-tropical, semi-arid	Location-1 <i>Typic Ustochrept</i> , Initial TOC 3.1 g kg ⁻¹	26-years	CK	11.2	Nayak et al. (2012)
			NPK	16.0	
			NPK + FYM	19.5	
			NPK + RS	20.0	
Sub-tropical, semi-arid	Location-2 <i>Typic Ustochrept</i> , Initial TOC 2.9 g kg ⁻¹	25-years	NPK + GM	18.3	Nayak et al. (2012)
			CK	3.00	
			NPK	5.10	
			NPK + FYM	6.80	
Sub-tropical, semi-arid	Location-3 <i>Typic Ustochrept</i> , Initial TOC 4.6 g kg ⁻¹	25-years	NPK + Crop residue	6.10	Nayak et al. (2012)
			NPK + GM	5.90	
			CK	3.70	
			NPK	5.50	
Sub-tropical, semi-arid	Location-3 <i>Typic Ustochrept</i> , Initial TOC 4.6 g kg ⁻¹	25-years	NPK + FYM	6.30	Nayak et al. (2012)
			NPK + Crop residue	6.50	
			NPK + GM	6.10	
			CK	3.60	
Sub-tropical, semi-arid	Location-3 <i>Typic Ustochrept</i> , Initial TOC 4.6 g kg ⁻¹	25-years	NPK	5.60	Nayak et al. (2012)
			NPK + FYM	7.70	
			NPK + Crop residue	7.50	
			NPK + Green manure	7.40	

Table 5 (continued)

Climatic conditions	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Sub-tropical, semi-arid	Location-4 <i>Typic Ustochrept</i> , Initial TOC 4.6 g kg ⁻¹	23-years	Control	6.00	Nayak et al. (2012)
			NPK	8.40	
			NPK + FYM	9.90	
			NPK + Crop residue	9.60	
			NPK + GM	9.00	
Sub-humid, sub-tropical	<i>Aeric Haplaquept</i> , <i>Sandy loam</i> , Initial TOC 8.8 g kg ⁻¹	25-years	CK	14.7	Ghosh et al. (2012)
			NPK	17.8	
			NPK + FYM	21.3	
			NPK + RS	19.9	
			NPK + GM	18.3	
Sub-tropical, semi-arid, mean annual rainfall 700 mm	<i>Typic Ustochrept</i> , <i>Sandy loam</i> , TOC 3.91 g kg ⁻¹ , Soil depth 0–7.5 cm	5-years	CK	4.37	Sharma et al. (2020a)
			RS ₅ [‡]	4.69	
			RS _{7.5}	4.88	
			RS ₁₀	5.66	
			RS ₀ N ₉₀	4.56	
			RS ₅ N ₉₀	4.65	
			RS _{7.5} N ₉₀	5.06	
			RS ₁₀ N ₉₀	5.94	
			RS ₀ N ₁₂₀	4.69	
			RS ₅ N ₁₂₀	5.61	
			RS _{7.5} N ₁₂₀	5.94	
			RS ₁₀ N ₁₂₀	6.44	
			RS ₀ N ₁₅₀	4.97	
			RS ₅ N ₁₅₀	6.26	
			RS _{7.5} N ₁₅₀	6.58	
			RS ₁₀ N ₁₅₀	6.37	
			Sub-tropical, semi-arid, mean annual rainfall 700 mm	<i>Typic Ustochrept</i> , <i>Sandy loam</i> , TOC 3.91 g kg ⁻¹ , Soil depth 7.5–15 cm	
RS _{7.5}	3.59				
RS _{10.0}	4.05				
RS ₀ N ₉₀	4.56				
RS ₅ N ₉₀	3.68				
RS _{7.5} N ₉₀	3.96				
RS ₁₀ N ₉₀	4.05				
RS ₀ N ₁₂₀	4.79				
RS ₅ N ₁₂₀	4.37				
RS _{7.5} N ₁₂₀	4.42				
RS ₁₀ N ₁₂₀	4.51				
RS ₀ N ₁₅₀	5.20				
RS ₅ N ₁₅₀	4.60				
Sub-tropical, semi-arid, irrigated	<i>Sandy loam</i> , <i>Typic Ustochrept</i> , Initial TOC 2.40 g kg ⁻¹	34 years	Fallow	4.90	Kaur et al. (2008)
			CK	6.20	
			N	6.80	
			NP	6.70	
			NPK	7.70	
			NPK + FYM	9.00	



Table 5 (continued)

Climatic conditions	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Sub-tropical, semi-arid, irrigated, hot summer, cool winter	<i>Typic Haplustepts</i> , Sandy loam, Soil depth 0–7.5 cm	18 years	CK	11.5	Das et al. (2016)
			NPK	12.2	
			NPK + FYM	14.2	
			NPK + pressmud	13.5	
			NPK + green gram residue	13.0	
			NPK + cereal crop residue	16.0	
Sub-tropical, semi-arid, irrigated, hot summer, cool winter	<i>Typic Haplustepts</i> , Sandy loam, Soil depth 7.5–15 cm	18 years	CK	9.6	Das et al. (2016)
			NPK	11.0	
			NPK + FYM	13.0	
			NPK + pressmud	12.4	
			NPK + green gram residue	12.3	
			NPK + cereal crop residue	13.2	

[§]Farmyard manure

[¶]Check (no N, P, K, or organic manure)

*N, NP, NPK represent nitrogen, nitrogen + phosphorus, and nitrogen + phosphorus + potassium, respectively. Subscripts of N represent the dose in kg N ha⁻¹

[‡] Rice straw, subscripts of RS denote dose in Mg ha⁻¹

treatments contained about 38 and 89% higher TOC in the 0–45 cm soil layer, respectively, over that observed at the initiation of the experiment. They reported that soils under the NPK + FYM treatment contained 47.2% higher TOC concentration in the 0–15 cm plough layer than under the NPK plots (Table 6). Hossain et al. (2016) also reported a significant increase in TOC concentration in soils with the application of organic manures than the NPK application under wheat-mungbean-rice, wheat-black gram-rice, wheat-soybean-rice and wheat-fallow-rice cropping systems (Table 6). In a silt loam soil in Nepal, Regmi et al. (2002) reported increase in TOC concentration by 1.5 g kg⁻¹ (20.5%) under NPK over CK under rice-rice-wheat cropping system. Another long-term study in Nepal showed an increase in TOC concentration by about 37% in soil under rice-rice-wheat, 6.6–8.1% in soil under rice-wheat cropping system with the application of NPK, compared with the CK (Table 6) (Gami et al. 2009). Nutrient application through organic manures has been reported to enhance TOC by 18–62% over that observed by NPK application through chemical fertilizers in a rice-wheat system (Gami et al. 2001). The highest TOC under poultry litter and cattle manure application in a rice-wheat-legume cropping system as compared to farmers' practice of applying no manure and fertilizer was reported in eastern IGPs in Bangladesh (Hossain 2009).

Banger et al. (2009) reported that FYM application increased TOC by 27.6% as compared with the CK, whereas NPK increased TOC by 15.9% in rice-cowpea

(17 years) cropping system. Soil organic C concentration in 0–7.5 cm soil layer under maize-wheat-cowpea increased by 61.3% with NPK + FYM application as compared with the CK (Kaur et al. 2008). In the 0–15 cm soil plough layer, TOC concentration increased by 45.7% with NPK + FYM application as compared with the CK treatment (Table 6). Rudrappa et al. (2006) reported that application of super optimal dose of NPK (150%) showed higher TOC content (12.9 g C kg⁻¹) when compared with either 50% NPK (9.3 g C kg⁻¹) or 100% NPK (10.0 g C kg⁻¹) in 0–15 cm soil layer under maize-wheat-cowpea (fodder) cropping system (Table 6). There was an improvement in TOC in 100% NPK or 100% NP (9.3 g C kg⁻¹) over 100% N (8.7 g C kg⁻¹). Application of FYM with 100% NPK showed 15.2 g C kg⁻¹ in 0–15 soil layer. Moharana et al. (2012) reported that the soils under NPK + FYM had significantly higher TOC in the 0–15 cm soil layer over those under NPK application. Soil organic C level was 11.5 g kg⁻¹ in FYM, 11.1 g kg⁻¹ in NPK + FYM, 8.50 g kg⁻¹ in NPK and 7.53 g kg⁻¹ in unfertilized CK. The increase in TOC concentration in FYM and NPK + FYM treatments was 52.5 and 47.1% higher as compared to the CK, while about 35.0 and 30.3% higher over NPK treatment, respectively (Table 6).

Bhattacharyya et al. (2007) reported that TOC concentration with FYM application was 20–26% higher compared with no-FYM in soybean-wheat cropping system. The overall increase in TOC concentration in NPK + FYM applied plots as compared with NPK and unfertilized CK

Table 6 Effect of inorganic and organic fertilizer application on total soil organic carbon (TOC) concentration in surface layer (0–15 cm) of soils under cropping systems other than rice–wheat system in the Indo-Gangetic Plains of South Asia

Cropping system	Climate	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Soybean–wheat	Semi-arid, tropical	Sandy loam, B _D [‡] 1.32 g cm ⁻³ , Initial TOC 5.08 g kg ⁻¹ , Typic <i>Haplaquept</i>	30 years	CK [¶]	6.30	Bhattacharyya et al. (2010)
				NP*	7.46	
				NK	6.84	
				NPK	8.01	
				N + FYM [§]	11.0	
				NPK + FYM	11.8	
Wheat–mungbean–rice	Sub-tropical	Silty clay loam, TOC 8.1 g kg ⁻¹	2 years	NPK	8.1	Hossain et al. (2016)
				Poultry manure (3 Mg ha ⁻¹)	8.3	
				Poultry manure (6 Mg ha ⁻¹)	9.3	
				Cow dung (5 Mg ha ⁻¹)	8.1	
				Cow dung (10 Mg ha ⁻¹)	9.2	
				Farmers Practice	7.5	
Wheat–mungbean–rice	Sub-tropical	Silty clay loam, TOC 8.1 g kg ⁻¹	2 years	NPK	8.2	Hossain et al. (2016)
				Poultry manure (3 Mg ha ⁻¹)	9.3	
				Poultry manure (6 Mg ha ⁻¹)	9.8	
				Cow dung (5 Mg ha ⁻¹)	8.3	
				Cow dung (10 Mg ha ⁻¹)	9.6	
				Farmers Practice	7.6	
Wheat–black gram–rice	Sub-tropical	Silty clay loam, TOC 8.1 g kg ⁻¹	2 years	NPK	8.4	Hossain et al. (2016)
				Poultry manure (3 Mg ha ⁻¹)	10.2	
				Poultry manure (6 Mg ha ⁻¹)	11.1	
				Cow dung (5 Mg ha ⁻¹)	9.8	
				Cow dung (10 Mg ha ⁻¹)	10.7	
				Farmers Practice	7.8	
Wheat–fallow–rice	Sub-tropical	Silty clay loam, TOC 8.1 g kg ⁻¹	2 years	NPK	7.4	Hossain et al. (2016)
				Poultry manure (3 Mg ha ⁻¹)	8.2	
				Poultry manure (6 Mg ha ⁻¹)	8.8	
				Cow dung (5 Mg ha ⁻¹)	7.9	
				Cow dung (10 Mg ha ⁻¹)	8.6	
				Farmers Practice	7.2	
Rice–rice–wheat (Location-Bhairahawa)	Sub-tropical, mean annual rainfall 1735–1836 mm	Typic <i>Hapluquepts</i> , calcareous, Silt plus clay 890 g kg ⁻¹ soil	25 years	CK	8.1	Gami et al. (2009)
			NPK	11.1		
			FYM	20.1		



Table 6 (continued)

Cropping system	Climate	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Rice–rice–wheat (Location-Tarahara)	Sub-tropical, mean annual rainfall 1735–1836 mm	<i>Typic Hapluquepts</i> , calcareous, Silt plus clay 670 g kg ⁻¹ soil	25 years	CK	9.1	Gami et al. (2009)
				NPK	9.7	
				FYM	13.7	
Rice–rice–wheat (Location-Parwanipur)	Sub-tropical, annual rainfall 1735–1836 mm	<i>Typic Hapluquepts</i> , calcareous, Silt plus clay 670 g kg ⁻¹ soil	25 years	CK	6.2	Gami et al. (2009)
				NPK	6.7	
				FYM	11.2	
				NPK + FYM	8.3	
				NPK + RS	8.0	
Rice–rice–wheat	Sub-tropical, annual rainfall 1687 mm	<i>Typic Hapluquepts</i> , Calcareous	20 years	CK	7.3	Regmi et al. (2002)
				NPK	8.8	
Rice–cowpea	Tropical, semi-arid, monsoonal	Sandy loam, <i>Typic Rhodualf</i> , Initial TOC 3.5 g kg ⁻¹	17 years	CK	3.60	Banger et al. (2009)
				N	4.00	
				NP	4.10	
				NPK	4.30	
				NPK + FYM	4.80	
Soybean–wheat	Sub-temperate	Sandy loam, <i>Typic Hapluquept</i> , Initial TOC 5.77 g kg ⁻¹	30 years	CK	6.30	Kundu et al. (2007)
				NP	7.46	
				NK	6.84	
				NPK	8.01	
				N + FYM	11.0	
Soybean–wheat	–	<i>Silty clay loam</i> , Initial TOC 7.31 g kg ⁻¹	8 years	CK	7.01	Bhattacharyya et al. (2007)
				N	7.42	
				NPK	7.58	
				FYM	8.45	
				N + FYM	9.27	
Pearl millet–wheat	Semi-arid, sub-tropical	Sandy loam, <i>Typic Inceptisol</i> , Initial TOC 2.9 g kg ⁻¹ , alkaline	6 years	Control	4.90	Moharana et al. (2012)
				FYM	7.30	
				NPK	5.10	
				NPK + FYM	6.50	
Sorghum–sunflower	Semi-arid, tropical	<i>Typic Rhodustalfs</i> , Initial TOC 2.70 g kg ⁻¹ , average annual rainfall 738 mm	10 years	CK	3.05	Venkateswarlu et al. (2007)
				N	3.60	
				P	3.50	
				NP	4.80	
Maize–wheat–cowpea	Semi-arid, sub-tropical	<i>Typic Haplustept</i> , Initial TOC 4.40 g kg ⁻¹ (0–45 cm)	10 years	CK	4.49	Purakayastha et al. (2008)
				50% NPK	4.71	
				100% NPK	4.90	
				150% NPK	5.40	
				100% NP	4.79	
				100% N	4.71	
100% NPK + FYM	5.83					

Table 6 (continued)

Cropping system	Climate	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Rice–cowpea	Tropical semi-arid mean annual rainfall = 765 mm	<i>Typic Rhodalfs</i> , Initial TOC 0.354%, Sandy loam soil	16 years	CK	3.60	Banger et al. (2010)
				N	4.00	
				NP	4.10	
				NPK	4.30	
				NPK + FYM	4.80	
Rice–fallow–rice	Sub-tropical, hot and humid	Shallow red brown terrace soil	2 years	FYM	4.91	Rahman et al. (2016)
				CK	10.8	
				NPK	11.8	
				Cow dung	13.9	
				Poultry manure	14.5	
Sorghum–mungbean	Semi-arid sub-tropical, mean annual rainfall 746 mm	Sandy loam, Alfisols,	8 years	RS	13.2	Sharma et al. (2008)
				CK	5.70	
				N	6.10	
				N + Compost	6.60	
				Gliricidia loppings + N	6.40	
Rice–wheat–jute	Hot moist, sub-humid mean annual rainfall = 1666 mm	<i>Typic Eutrochrept</i> , B _D 1.35 g cm ⁻³ Sand 54%, Silt 28%, Clay 18%	32 years	Compost + 2 Gliricidia loppings	6.90	Chaudhury et al. (2005)
				CK	4.81	
				N	4.89	
				NP	5.64	
				NPK	6.27	
Maize–wheat–cowpea (fodder)	Sub-tropical	<i>Typic Haplustept</i> , Initial TOC 4.40 g kg ⁻¹ , B _D 1.67 g cm ⁻³	32 years	NPK + FYM	4.69	Rudrappa et al. (2006)
				CK	9.30	
				50% NPK	10.0	
				100% NPK	12.9	
				150% NPK	9.30	
Rice–cowpea	Semi-arid tropics	Sandy loam, <i>Typic Rhodalf</i>	16 years	100% NP	8.70	Banger et al. (2010)
				100% N	15.2	
				100% NPK + FYM	8.30	
				CK	3.60	
				N	4.00	
Maize–wheat–cowpea	Sub-tropical, semi-arid, irrigated	<i>Typic Ustochrept</i> , Initial TOC 2.40 g kg ⁻¹ , Sandy loam, soil depth 0–7.5 cm)	34 years	NP	4.20	Kaur et al. (2008)
				NPK	5.00	
				NPK + FYM	5.10	
				Fallow	3.10	
				CK	3.50	
Maize–wheat–cowpea	Semi-arid, sub-tropical	Sandy loam, Initial TOC 2.40 g kg ⁻¹ , Soil depth 7.5–15.0 cm	34 years	NP	3.20	Kaur et al. (2008)
				NPK	3.50	
				NPK + FYM	4.00	
				N	3.30	
				CK	3.10	



Table 6 (continued)

Cropping system	Climate	Soil properties	Study period	Treatment	TOC (g kg ⁻¹)	Reference
Maize–wheat-	Semi-arid, sub-tropical	Sandy loam, Initial TOC 2.40 g kg ⁻¹	36 years	CK	3.08	Brar et al. (2015)
				N	3.34	
				NP	3.52	
				NPK	3.71	
Soybean–wheat	Sub-humid, moist summer and mild winter	Vertisols, <i>Typic Haplustert</i> , sand 253 g kg ⁻¹ , silt 179 g kg ⁻¹ , clay 568 g kg ⁻¹	39 years	NPK + FYM	5.20	Manna et al. (2013)
				CK	6.30	
				N	6.40	
				NP	7.00	
Soybean–wheat	Sub-humid, mean annual rainfall 1450 mm	Sandy clay loam, <i>Typic Haplustalf</i> , Alfisol	30 years	NPK	8.60	Manna et al. (2007)
				NPK + FYM	12.4	
				CK	3.50	
				N	3.40	
Pearl millet–wheat	Sub-tropical, semi-arid, hot and dry summer	Sandy loam, <i>Typic Haplustept</i> ,	6 years	NP	4.20	Moharana et al. (2012)
				NPK	4.50	
				NPK + FYM	4.70	
				NPK + Lime	4.50	
				CK	7.53	
				FYM	11.5	
				NPK	8.50	
				NPK + FYM	11.1	

‡ Bulk density

§ Farmyard manure

¶ Check (no N, P, K or organic manure)

*N, NP, NPK represent nitrogen, nitrogen + phosphorus, and nitrogen + phosphorus + potassium, respectively

plots was 11.0 and 14.0 Mg C ha⁻¹ after 8 years, respectively (Table 6). Banger et al. (2009) reported that FYM application increased the TOC by about 27.6% than the CK, whereas NPK application increased it by 15.9% in rice–cowpea cropping system. Manna et al. (2005) observed that TOC in the unfertilized soil decreased by 16–42% at three sites (Barrackpore, Ranchi and Akola) in India when compared to initial values, whereas the application of FYM conjointly with NPK either maintained or improved it over the initial TOC values at these sites.

Figure 2 illustrates the percent increase in TOC concentration with different nutrient management practices over the CK in the surface (0–15 cm) soil layer under rice–wheat cropping system. Data pooled for different locations revealed that in the soils under rice–wheat cropping system, application of fertilizer N alone increased the TOC pool by 0.2–75.9% when compared with CK. The application of NP increased TOC pool by 2.5–65.0% than the CK. The pooled data showed that balanced use of fertilizers (NPK) increased TOC by 6.1 to 87.5% over the control. The magnitude of increase in TOC pool in 0–15 cm plough layer

under rice–wheat cropping system was the highest with conjoint application of inorganic fertilizers and organic manures: 22.1–126.7% with NPK + FYM, 24.5–105.6% with NPK + GM and 35.4–108.3% with NPK + crop residues incorporation (Fig. 2). However, in soils under non-rice-based cropping systems, application of only fertilizer N increased the TOC pool by up to 63.4% over the CK (Fig. 3). Balanced use of fertilizers (NPK) resulted in 4.1–42.9% increase in TOC than in the CK plots. Application of FYM alone in the non-rice-based cropping systems in the IGP resulted in increased TOC pool by almost same magnitude (4.1–49.0%) as with NPK treatment. The integrated use of inorganic fertilizers and organic manures resulted in the highest increase in TOC pool in 0–15 cm plough layer under non-rice-based cropping systems.

Not only the fertilizer application, but also the method of fertilizer application and inclusion of leguminous crops in annual cropping systems affect the TOC pool in the IGPs (Rekhi et al. 2000; Chettri et al. 2003; Thuy et al. 2008). Gaihre et al. (2015) reported that deep placement of fertilizer N in a soil under rice–rice cropping system in Bangladesh



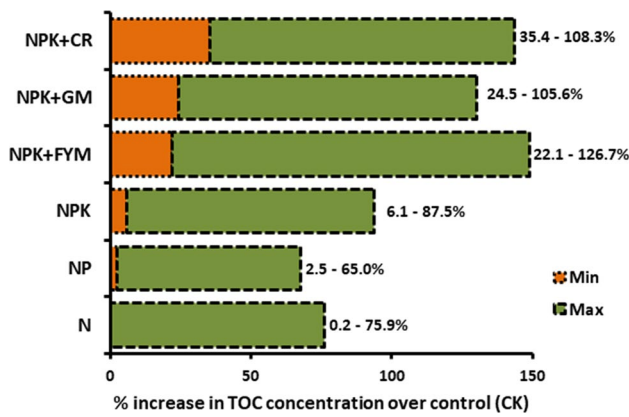


Fig. 2 Percent increase in total organic C (TOC) concentration over the control (CK) in the surface (0–15 cm) soil layer under rice–wheat cropping system in Indo-Gangetic Plains of South Asia. Data pooled from Rekhi et al. (2000), Yadvinder-Singh et al. (2004), Rasool et al. (2007), Kaur et al. (2008), Ghosh et al. (2010, 2012), Nayak et al. (2012), Brar et al. (2013), Das et al. (2016), Singh and Benbi (2018a), and Sharma et al. (2020a). Acronyms: FYM (farmyard manure), GM (green manure), CR (crop residues), NPK (nitrogen, phosphorus, and potassium supplied through mineral fertilizers)

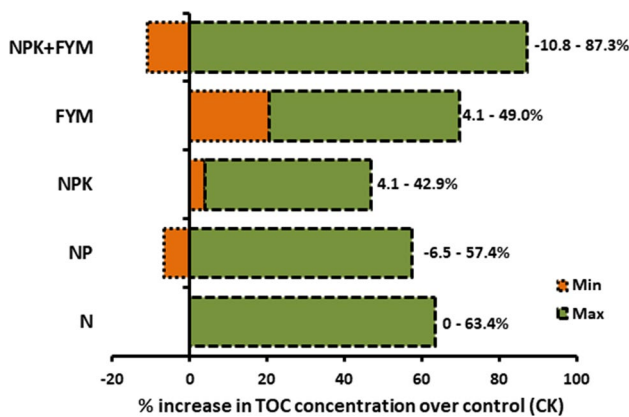


Fig. 3 Percent increase in total organic C (TOC) concentration over the control (CK) in the surface (0–15 cm) soil layer under non-rice-based cropping systems in Indo-Gangetic Plains of South Asia. Data pooled from Chaudhury et al. (2005), Rudrappa et al. (2006), Bhattacharyya et al. (2007), Kundu et al. (2007), Venkateswarlu et al. (2007), Kaur et al. (2008), Purakayastha et al. (2008), Sharma et al. (2008), Banger et al. (2009, 2010), Bhattacharyya et al. (2010), Moharana et al. (2012), Srinivasarao et al. (2012a, b), and Brar et al. (2015). Acronyms: NPK (nitrogen, phosphorus, and potassium supplied through mineral fertilizers)

increased TOC content due to higher NPP as compared with the conventional method of application of fertilizer N. Rekhi et al. (2000) reported that the TOC content was increased by > 2-folds after 13 years of rice–wheat cropping with the inclusion of leguminous crop in the annual crop rotation. Regardless of the cropping system and soil texture, balanced application of chemical fertilizers conjointly with organic

manures helps enlarge the TOC pool and its labile and non-labile fractions into the soils.

Soil organic carbon fractions

SOM is composed of labile and non-labile C pools. It is a heterogeneous mixture of materials, ranging from active or labile fractions (e.g., microbial biomass, particulate organic matter, and soluble organic matter) decomposing in a matter of months and the more resistant or non-labile fractions remaining in the soil with turnover rates measured in millennia (Christensen and Johnston 1997). About 20–40% of organic C exists as a slow pool with decadal turnover times, while less than 5% comprise rapidly cycling active pool with turnover time ranging between hours and months (Shaffer et al. 2001). Change in C input to soil can promptly influence these TOC pools (Bolinder et al. 1999). The labile (very labile and less labile C) pools decompose readily and serve as nutrient source in soils for growing plants, whilst the non-labile (less labile and recalcitrant C) pools are important for C sequestration in soil (Bolinder et al. 1999; Ghosh et al. 2012; Singh and Benbi 2018a, b; Sharma et al. 2020a, b). Among the labile C pools, water extractable organic C (WEOC), microbial biomass C (MBC), potassium permanganate oxidizable organic C (KMnO₄-C) and organic C fractions of varying oxidizability are considered important (Blair et al. 1995; Chan et al. 2001; Benbi et al. 2012b). Although changes in total SOM content in response to soil management are difficult to apprehend because of large background levels and natural soil variability (Haynes and Beare 1996), the changes in different labile and non-labile C pools are apparently more discernible (Benbi et al. 2015a, b). The labile C pool acts as energy source for microbes (Chan et al. 2001), and therefore, could C dynamics better than TOC alone (Singh and Benbi 2018a, b). It has been suggested that hot water extractable C could be used as a sensitive indicator of the fertility status of soils (Haynes 2005). The organic C oxidizable with KMnO₄ is believed to a useful index of labile soil C (Blair et al. 1995). The KMnO₄-C fraction includes labile humic material and polysaccharides and is sensitive to soil management induced change in SOM quality and quantity (Blair et al. 1995; Singh and Benbi 2018a; Sharma et al. 2020a). The chemical characterization of SOM based on extraction of labile C pools with different solutions and strong acids of variable strength provides relatively easy and quick estimates of management induced changes in SOM composition (Chan et al. 2001).

As nutrient management substantially impacts C inputs and losses, it influences both the quantity and quality of SOM (Benbi et al. 2015a). Thus addition of C into the soil not only influences TOC but also different pools of C such as potassium permanganate oxidizable C, water extractable



organic C, hot water C, and microbial biomass C. Labile C fractions act as sensitive indicators to soil management induced changes in TOC pool under short to medium term effects. These fractions have relatively shorter turnover times and are more sensitive indicators to soil management practices compared with TOC (Yan et al. 2007; Chen et al. 2016). Conversely, the recalcitrant pools are difficult for soil micro-organisms to decompose and have relatively long turnover times (Yan et al. 2007).

Permanganate oxidizable carbon

Several studies have shown that potassium permanganate extractable C (or $\text{KMnO}_4\text{-C}$) and microbial biomass C is sensitive to changes in soil and crop management (Culman et al. 2012). Therefore, $\text{KMnO}_4\text{-C}$ is now widely used in the IGPs and South Asia as indicator of changes in C pools in the soil ecosystem. Singh and Benbi (2018a) reported that FYM application in rice–wheat cropping system significantly increased $\text{KMnO}_4\text{-C}$ by 229% in the surface (0–7.5 cm) and 180% in the sub-surface (7.5–15 cm) soil than in the CK plot. In the surface soil, $\text{KMnO}_4\text{-C}$ increased significantly by 589 and 811 mg kg^{-1} with N + FYM and NPK + FYM application, respectively. The corresponding increase in the sub-surface soil was 345 and 534 mg kg^{-1} , respectively (Table 7). Averaged across treatments, surface soil had 25.6% higher $\text{KMnO}_4\text{-C}$ than the sub-surface soil. In surface soil layer (0–15 cm) under rice–wheat cropping, $\text{KMnO}_4\text{-C}$ increased significantly by 24.1, 42.3, 53.5 and 75.7% with the application of N, NP, NPK and NPK + FYM, respectively over the CK (Brar et al. 2013). It was observed that conjoint application of FYM and NPK significantly improved $\text{KMnO}_4\text{-C}$ by 14.5% in 0–15 cm plough layer than in the NPK treatment (Table 7). The increase in $\text{KMnO}_4\text{-C}$ with application of fertilizer N was ascribed to the priming effect of applied fertilizer N on fresh organic material in the soil, which stimulates the microbial activity resulting in the decomposition of SOM (Rudrappa et al. 2006). While studying the effect of fertilizer N application along with RS incorporation, Sharma et al. (2020a) reported significantly lower $\text{KMnO}_4\text{-C}$ in the CK, while the highest value of $\text{KMnO}_4\text{-C}$ was recorded with combined application of fertilizer N and RS incorporation ($\text{RS}_{10.0}\text{N}_{150}$) (Table 7). The $\text{KMnO}_4\text{-C}$ concentration in the surface (0–7.5 cm) soil layer was about 34.9% higher than in the sub-surface (7.5–15 cm) soil layer. The $\text{KMnO}_4\text{-C}$ comprised about 8.9–10.1% of TOC. The non-labile C comprised the major proportion of TOC in soil under rice–wheat cropping system, and 10% higher in the surface as compared to in the sub-surface soil layer (Table 7).

In 0–15 cm plough layer under maize–wheat–cowpea (fodder) cropping system, 150% NPK resulted in significantly higher $\text{KMnO}_4\text{-C}$ concentration as compared to in

the 50 and 100% NPK treatments (Rudrappa et al. 2006). The balanced applications of NPK resulted in higher $\text{KMnO}_4\text{-C}$ than that in unbalanced fertilization (N and NP) (Rudrappa et al. 2006; Singh and Benbi 2018a). Rudrappa et al. (2006) reported that $\text{KMnO}_4\text{-C}$ comprised 7.6–21.9% of TOC pool in the soils. The application of NPK + FYM showed the highest accumulation of $\text{KMnO}_4\text{-C}$, while the CK treatment had the lowest value. Moharana et al. (2012) reported that $\text{KMnO}_4\text{-C}$ comprised 10.5–12.3% of TOC, and the $\text{KMnO}_4\text{-C}$ concentration was higher in NPK + FYM than under NPK or CK treatments under pearl millet–wheat cropping system. The increased $\text{KMnO}_4\text{-C}$ concentration with FYM application as well as higher turn-over of root biomass was ascribed to better plant growth and yield of pearl millet and wheat crops under combined application of NPK + FYM, compared to the application of FYM alone (Table 7). The percent increase in $\text{KMnO}_4\text{-C}$ in FYM and NPK + FYM treatments was 27.7 and 44.7% over NPK, and 51.9 and 72.2% over unfertilized CK, respectively. The large variations in $\text{KMnO}_4\text{-C}$ concentration in soils under NPK + FYM application indicate that this labile C pool of TOC was more sensitive to changes in manuring and fertilization (Rudrappa et al. 2006; Singh and Benbi 2018a). The $\text{KMnO}_4\text{-C}$ constituted 10–13% of TOC (Lou et al. 2011; Singh and Benbi 2018a; Sharma et al. 2020a).

Water extractable organic carbon

Water extractable organic C (WEOC), the soluble fraction of organic matter extracted from the soil, is the most active and mobile fraction of soil organic matter. It comprises of 0.3–0.6% of TOC, contains labile organic C and N and is sensitive to soil management. Singh and Benbi (2018a) reported that WEOC content in a soil in trans-IGPs under rice–wheat cropping system was 11.4–17.4 mg kg^{-1} in the surface (0–7.5 cm) and 10.9–17.0 mg kg^{-1} in the sub-surface (7.5–15 cm) soil. As compared to the WEOC content in the CK, application of fertilizer N alone resulted in 9.7 and 6.4% increase in WEOC in the surface and sub-surface soil layers, respectively. Balanced fertilizer application with N, P and K significantly increased the WEOC concentration as compared to with imbalanced fertilizer application (N, NP and NK). Application of FYM alone significantly increased WEOC at both the soil depths by 3.5–5.3%, over that observed with application of NPK (Table 7). Brar et al. (2013) reported that fertilizer N application increased the WEOC by 8.3% as compared to with the value observed in the CK plot. The application of NP and NPK significantly enriched the 0–15 cm plough layer with WEOC by 58.9 and 110.1%, respectively over the CK (Table 7). The highest WEOC concentration was observed with conjoint application of organic manure and inorganic fertilizers (NPK + FYM) than NPK alone. The increased concentration

Table 7 Effect of inorganic and organic fertilizer application on different soil organic carbon (TOC) fractions viz. potassium permanganate oxidizable C (KMnO₄-C), water extractable organic C (WEOC) and microbial biomass C (MBC) in surface layer (0–15 cm) of soils under different cropping systems in the Indo-Gangetic Plain of South Asia

Cropping system	Climatic conditions	Soil properties	Study period	Treatment	KMnO ₄ -C (mg kg ⁻¹)	WEOC (mg kg ⁻¹)	MBC (mg kg ⁻¹)	Reference
Rice–wheat	Semi-arid, Sub-tropical	Sandy loam, Initial TOC 2.1 g kg ⁻¹ , Soil depth 0–5 cm	10 years	CK [¶]	898	16.8	–	Brar et al. (2013)
				N [†]	1114	18.2	–	
				NP	1278	26.7	–	
				NPK	1378	35.3	–	
				NPK + FYM [§]	1578	37.2	–	
Rice–wheat	Semi-arid, sub-tropical	Sandy loam, Initial TOC 2.1 g kg ⁻¹ , Soil depth 5–10 cm	10 years	CK	824	13.6	–	Brar et al. (2013)
				N	1024	14.7	–	
				NP	1122	22.4	–	
				NPK	1176	29.6	–	
				NPK + FYM	1390	31.3	–	
Rice–wheat	Semi-arid, sub-tropical	Sandy loam, Initial TOC 2.1 g kg ⁻¹ , Soil depth 10–15 cm	10 years	CK	752	12.8	–	Brar et al. (2013)
				N	934	13.8	–	
				NP	996	20.9	–	
				NPK	1022	27.2	–	
				NPK + FYM	1222	28.4	–	
Rice–wheat	Hot humid, semi-arid, sub-tropical, monsoonal climate mean annual rainfall 713 mm	Soil depth 7.5–15 cm, Sandy loam, <i>Eutric Cambisols</i> Initial TOC 4.40 g kg ⁻¹	5 years	Control	265	11.4	150.2	Singh and Benbi (2018a)
				N	279	12.5	164.6	
				NP	338	13.7	174.7	
				NK	411	12.7	175.5	
				PK	417	14.8	178.0	
				NPK	840	14.5	188.0	
				FYM	873	15.0	208.8	
				N + FYM	854	16.5	218.0	
Rice–wheat	Hot humid, semi-arid, sub-tropical, monsoonal climate mean annual rainfall 713 mm	Sandy loam, Soil depth 7.5–15 cm, <i>Eutric Cambisols</i> , Initial TOC 4.40 g kg ⁻¹	5 years	Control	245	10.9	128.4	Singh and Benbi (2018a)
				N	250	11.6	144.5	
				NP	274	13.5	156.9	
				NK	404	12.5	152.6	
				PK	363	13.5	165.3	
				NPK	671	13.2	171.6	
				FYM	687	13.9	182.0	
				N + FYM	590	15.5	186.3	
				NPK + FYM	779	17.0	234.4	
				Rice–wheat	Sub-tropical, semi-arid, mean annual rainfall 700 mm	Sandy loam, <i>Typic Ustochrept</i> , TOC 3.91 g kg ⁻¹ , Soil depth 0–7.5 cm	5 years	
RS ₅ [‡]	460	27.0	253.5					
RS _{7.5}	480	27.5	267.6					
RS ₁₀	560	32.0	319.2					
RS ₀ N ₉₀	450	25.9	246.9					
RS ₅ N ₉₀	460	25.5	254.3					
RS _{7.5} N ₉₀	500	28.1	282.0					
RS ₁₀ N ₉₀	590	33.7	288.1					
RS ₀ N ₁₂₀	460	26.7	247.7					
RS ₅ N ₁₂₀	550	31.8	304.2					
RS _{7.5} N ₁₂₀	590	33.6	310.2					
RS ₁₀ N ₁₂₀	640	36.2	347.3					
RS ₀ N ₁₅₀	500	28.5	275.3					
RS ₅ N ₁₅₀	620	35.4	321.2					
RS _{7.5} N ₁₅₀	650	36.5	373.2					
RS ₁₀ N ₁₅₀	720	39.7	408.1					



Table 7 (continued)

Cropping system	Climatic conditions	Soil properties	Study period	Treatment	KMnO ₄ -C (mg kg ⁻¹)	WEOC (mg kg ⁻¹)	MBC (mg kg ⁻¹)	Reference
Rice–wheat	Sub-tropical, semi-arid, mean annual rainfall 700 mm	Sandy loam, <i>Typic Ustochrept</i> , TOC 3.91 g kg ⁻¹ , Soil depth 7.5–15 cm	5 years	RS ₀ N ₀	310	19.7	193.6	Sharma et al. (2020a)
				RS ₅	320	20.4	194.9	
				RS _{7.5}	360	22.5	222.2	
				RS ₁₀	400	24.3	249.6	
				RS ₀ N ₉₀	330	21.7	202.2	
				RS ₅ N ₉₀	350	22.3	220.1	
				RS _{7.5} N ₉₀	360	23.9	234.6	
				RS ₁₀ N ₉₀	430	26.1	263.0	
				RS ₀ N ₁₂₀	390	24.9	237.3	
				RS ₅ N ₁₂₀	390	25.2	243.6	
				RS _{7.5} N ₁₂₀	400	25.7	243.4	
				RS ₁₀ N ₁₂₀	460	28.2	277.3	
				RS ₀ N ₁₅₀	410	26.1	254.3	
				RS ₅ N ₁₅₀	480	30.7	265.9	
RS _{7.5} N ₁₅₀	510	32.7	314.7					
RS ₁₀ N ₁₅₀	530	34.3	325.1					
Rice–wheat	Sub-tropical, semi-arid, irrigated, hot summer, cool winter	Sandy loam, <i>Typic Haplustepts</i> , Soil depth 0–7.5 cm	18 years	CK	580	–	135	Das et al. (2016)
				NPK	660	–	148	
				NPK + FYM	840	–	340	
				NPK + Pressmud	870	–	256	
				NPK + green gram residue	840	–	290	
				NPK + cereal crop residue	750	–	186	
Rice–wheat	Sub-tropical, semi-arid, irrigated, hot summer, cool winter	Sandy loam, <i>Typic Haplustepts</i> , Soil depth 7.5–15 cm	18 years	CK	400	–	133	Das et al. (2016)
				NPK	520	–	141	
				NPK + FYM	780	–	248	
				NPK + Pressmud	650	–	167	
				NPK + green gram residue	650	–	216	
Maize–wheat–cowpea	Semi-arid sub-tropical	Sandy loam, Initial TOC 2.4 g kg ⁻¹ , Soil depth 0–7.5 cm	34 years	CK	–	13.8	138.1	Kaur et al. (2008)
				N	–	25.6	167.2	
				NP	–	33.2	185.7	
				NPK	–	34.6	210.1	
				NPK + FYM	–	49.2	228.0	
Rice–cowpea	Semi-arid	Sandy loam, <i>Typic Rhodualf</i>	16 years	CK	–	20.4	170.5	Banger et al. (2009)
				N	–	24.1	212.2	
				NP	–	23.9	228.4	
				NPK	–	28.1	241.2	
				NPK + FYM	–	35.1	320.0	
				FYM	–	37.2	325.8	
Rice–wheat	mean annual rainfall = 1500 mm	Sandy clay loam, <i>Aeric Endoaquept</i>	4 years	CK	315.2	11.1	192.7	Bhattacharyya et al. (2012)
				N	367.1	29.5	317.0	
				RS + N	434.9	34.5	337.8	
				RS + GM	472.7	48.3	416.9	
Rice–wheat–jute	Tropical, Sub-humid, AAR = 1600 mm	Sandy loam, <i>Typic Eutrochrept</i>	31 years	NPK	–	–	344.0	Ghosh et al. (2010)
				NPK + FYM	–	–	475.0	

Table 7 (continued)

Cropping system	Climatic conditions	Soil properties	Study period	Treatment	KMnO ₄ -C (mg kg ⁻¹)	WEOC (mg kg ⁻¹)	MBC (mg kg ⁻¹)	Reference
Rice–wheat	Tropical, sub-humid, mean annual rainfall = 1500 mm	Sandy loam, <i>Aeric Hapluquepts</i>	16 years	NPK	–	–	571.0	Ghosh et al. (2010)
				NPK + FYM	–	–	549.0	
Rice–rice	Tropical, Sub-humid,	Sandy clay loam <i>Endoaquept</i>	33 years	NPK	–	–	495.0	Ghosh et al. (2010)
				NPK + FYM	–	–	523.0	
Rice–wheat	Sub-tropics, hot humid	Sandy loam, <i>Aeric Haplaquept</i>	25 years	CK	–	–	250.0	Ghosh et al. (2012)
				NPK	–	–	486.0	
				NPK + FYM	–	–	531.0	
				NPK + RS	–	–	776.0	
				NPK + green manure	–	–	565.0	
Soybean–wheat	Sub-humid, mean annual rainfall 1350 mm	<i>Typic Haplustert</i> , Vertisol	39 years	CK	–	25.1	156.0	Manna et al. (2013)
				N	–	23.3	218.0	
				NP	–	24.0	382.0	
				NPK	–	29.3	559.0	
				NPK + FYM	–	33.1	598.0	
Pearl millet–wheat	Sub-tropical, semi-arid, hot and dry summer	Sandy loam, <i>Typic Haplustepts</i> , Inceptisol	6 years	CK	178.0	–	–	Moharana et al. (2012)
				FYM	262.0	–	–	
				NPK	182.0	–	–	
				NPK + FYM	270.0	–	–	

‡ Rice straw, subscripts of RS denote dose in Mg ha⁻¹

§ Farmyard manure

¶ Check (no N, P, K or organic manure)

† N, NP, NPK represent nitrogen, nitrogen + phosphorus, and nitrogen + phosphorus + potassium, respectively. Subscripts of N denote dose in kg N ha⁻¹

of WEOC with fertilizer N application was ascribed to the priming effect of applied N on the fresh organic material in the soil, which stimulates the microbial activity helping in the decomposition of SOM with rapid release of the WEOC fraction (Yagi et al. 2005).

Sharma et al. (2020a) reported that WEOC constituted only 0.6% of TOC, although the concentration of WEOC was 20.4% higher in the surface (0–7.5 cm) than the sub-surface (7.5–15 cm) soil layer (Table 7). In the rice–wheat cropping system, the WEOC concentration was significantly lower in the CK, and increased by 14.9 and 14.6 mg C kg⁻¹ in the surface and sub-surface soil layers, respectively in plots receiving fertilizer N combined with RS incorporation (RS_{10.0}N₁₅₀). The beneficial effects of organic manures application under rice–wheat cropping system on WEOC content were also reported by Manna et al. (2006). Banger et al. (2009) reported that although WEOC constitutes a very low percentage of TOC pool (0.55% in the CK and 0.77% with integrated fertilization), the greater variation in its content may act as a useful tool to evaluate the impact of management systems on gross C accumulation or depletion in soil under rice–cowpea cropping system. It represents the labile C pool with rapid turnover rates and composed of an array

of molecules in a soluble phase (Chantigny 2003). Kaur et al. (2008) reported that after 34 years of maize–wheat cropping, the WEOC accounted for 0.5–1.1% of TOC and increased significantly with an application of organic fertilizers along with inorganic fertilizers. Moharana et al. (2012) reported increased accumulation of WEOC with FYM and NPK + FYM application by 43.1 and 27.5%, respectively than in the plots receiving NPK alone in the soil under pearl millet–wheat cropping system. However, increased accumulation in WEOC concentration was 49.0 and 32.7% greater than the treatment receiving no fertilizer or manure (CK) (Table 7). Higher WEOC concentration in FYM treated soil indicates that added FYM contains significant amount of soluble organic matter (Chantigny et al. 2002). A significant increase in labile C pools such as KMnO₄-C and WEOC under the influence of balanced application of nutrients conjointly with organic manures highlights increased C mineralization and nutrient cycling in crop production (Fig. 4).

Soil microbial biomass carbon

The MBC consists of C contained in bacteria and fungi—the living micro-organisms smaller than 5–10 μm³ (Banger



et al. 2009). Generally, up to 5% of the TOC and organic N in soil exist in the MBC and about half of the MBC is in the surface layer of the soil. Return of organic matter to the soil such as through application of organic manures and above- and below-ground plant residues increases soil MBC. It provides an effective early indicator of the improvement or deterioration of soil quality because of different management practices (Powlson 1994). According to Alvarez and Alvarez (2000), MBC in the soil increased with the increase in TOC, particularly the light fraction C of the soil. In the IGPs, Ghosh et al. (2010) reported that MBC constituted 2.8–4.3% of TOC pool in the 0–15 cm soil plough layer. MBC as a proportion of TOC has been reported to range between 0.8 and 5.0% of TOC pool in several other studies (Tables 5, 6 and 7). Although MBC comprises of a small fraction of TOC, yet a large variation in MBC in response to crop production and soil management and cropping systems reflects the quality of soil, because the turn-over of SOM is controlled by this pool (Powlson and Brooks 1987).

Singh and Benbi (2018a) reported that applications of FYM alone or in combination with NPK significantly improved soil MBC. Soil MBC ranged between 150 and 297 mg kg⁻¹ in surface (0–7.5 cm) and between 128 and 234 mg kg⁻¹ in sub-surface soil (7.5–15 cm). MBC increased significantly with fertilizer N application compared to the CK but did not differ significantly among other treatments involving imbalanced application of fertilizer nutrients (NP, NK and PK). The balanced application of fertilizer N, P, and K significantly increased soil MBC. Compared with the application of NPK alone, NPK + FYM application increased MBC by 58.2% in the surface and 36.6% in the sub-surface soil. Averaged across treatments, surface soil had 15.3% higher MBC than the sub-surface soil (Table 7). The differences in MBC levels within the treatments were associated to the differences in C input. Increased C input results not only in higher MBC and TOC, but also increased MBC: TOC ratio (Witter and Kanal 1998). Nayak et al. (2012) reported that conjoint application NPK + FYM resulted in a significantly higher soil MBC over NPK at four locations under rice–wheat cropping system in the IGPs. MBC in plots receiving crop residue along with NPK was at par with NPK + FYM at all places except at Ludhiana (trans-IGPs) (Table 7). However, MBC of surface soil in NPK + GM was significantly lower than NPK + FYM at Ludhiana, Sabour and Kalyani except at Kanpur where it was at par. Sharma et al. (2020a) reported that fertilizer N application and RS incorporation significantly increased MBC, basal soil respiration rate and mineralization quotients as compared with CK (Table 7). The highest MBC was observed in plots receiving combined application of fertilizer N and RS incorporation (RS_{10,0}N₁₅₀) (408.1 mg kg⁻¹ soil), and the lowest under the CK (243.9 mg kg⁻¹ soil).

After 34 years of maize–wheat cropping system, MBC varied between 137 and 228 mg kg⁻¹ in 0–15 cm soil plough layer at Ludhiana in the north-western India (Kaur et al. 2008). As compared to in the CK plot, MBC was 21.1, 34.5, 52.1 and 65.1% higher under N, NP, NPK and NPK + FYM treatments, respectively (Table 7). The MBC increased significantly with fertilizer N application and comprised 4.5–5.7% of TOC. Rudrappa et al. (2006) reported that NPK increased MBC by 18 and 9% over N and NP treatments, respectively in soil under maize–wheat–cowpea (fodder) cropping system at New Delhi, India. MBC in NPK + FYM treatment increased by 19 and 17% than in the 100% NPK and 150% NPK treatments, respectively. Under pearl millet–wheat cropping system, Moharana et al. (2012) observed that MBC in surface soil varied from 155 mg kg⁻¹ in the unfertilized CK plot to 273 mg kg⁻¹ in the NPK + FYM plots, while it varied from 113 mg kg⁻¹ in CK to 156 mg kg⁻¹ in the subsurface soil. As shown in Table 7, it increased by 56.3 and 76.5% under FYM and NPK + FYM treatments over the CK; the increases in MBC over NPK treatment were 26.7 and 43.0%, respectively (Table 7). The application of NPK fertilizer not only enhanced the plant growth, but also favors the synthesis of cellular components of micro-organisms. The size and activity of the soil microbial biomass depend on quantity and quality of SOM and crop management practices viz. synthetic fertilizers and residue incorporation (Weigand et al. 1995; Schjøning et al. 2002). The extent of increase in MBC concentration was higher in the surface (0–7.5 cm) than sub-surface (7.5–15 cm) soil layer (Moharana et al. 2012; Singh and Benbi 2018a; Sharma et al. 2020a). Greater increase in MBC concentration in the surface, compared with the subsurface

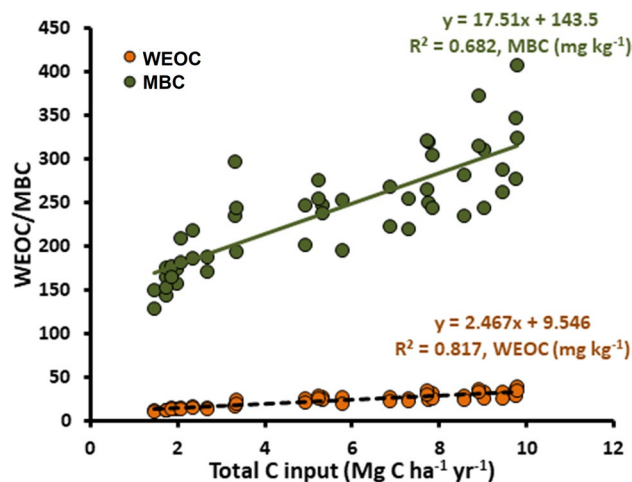


Fig. 4 Soil microbial biomass C (MBC; mg kg⁻¹) and water extractable organic C (WEOC; mg kg⁻¹) in 0–15 cm plough layer as a function of total annual C input (Mg C ha⁻¹ year⁻¹) under rice–wheat cropping system in the Indo-Gangetic Plains of South Asia. Data pooled from Singh and Benbi (2018a) and Sharma et al. (2020a)

soil indicates higher substrate availability and microbial activity in surface soil layer.

The application of organic manures provides more favorable environment for rapid microbial growth, which results in an increase in MBC (Moscatelli et al. 2005; Moharana et al. 2012). Therefore, higher root biomass under NPK + FYM treatment results in higher MBC values than when only mineral fertilizers are applied (Dezhi et al. 2007; Benbi et al. 2016; Singh and Benbi 2018a). The increased plant mediated above- and below-ground biomass C linearly increase WEOC ($R^2=0.82$) and MBC ($R^2=0.68$) pools in the plough layer of the soil under rice–wheat cropping system in the IGP (Fig. 4). Similarly, there exists a linear relationship between the WEOC and MBC ($R^2=0.88$) in soils under rice–wheat cropping system (Fig. 5).

Soil organic carbon fractions of variable lability

Soil organic C extracted with acid-aqueous solution ratios partition TOC in four fractions of decreasing oxidizability/lability as very labile C (Fract. 1), labile C (Fract. 2), less labile C (Fract. 3) and recalcitrant C (Fract. 4) (Chan et al. 2001). These fractions have been extensively used for quantifying the impact of soil management regimes on SOM quality. In soils under rice–wheat cropping system in IGPs, Ghosh et al. (2012) reported that very labile and labile (Fract. 1 and Fract. 2) fractions comprised of 58% of TOC in the plough layer of the soil; the remaining 42% consisted of the less labile and non-labile fractions (Table 8). Under the same cropping system, Majumder et al. (2008b) reported relative preponderance different SOC fractions as: Fract. 4 (36.3%) > Fract.1 (34.0%) >> Fract. 3(18.4%) > Fract. 2 (11.3%). The two easily oxidizable fractions (Fract. 1 and Fract. 2) together constituted 45.3% of TOC. Ghosh et al. (2010) reported that recalcitrant C pool was the largest fraction of TOC under different nutrient management treatments and varied between 35 and 49% in soils under rice–wheat cropping system. Among the other C fractions, the contribution of Fract. 1 was higher (27–34% of TOC) than Fract. 2 and 3 (10–16% of TOC).

Majumder et al. (2007) reported that in a rice–wheat cropping system very labile and labile fractions consisted of 56.1% TOC. Singh and Benbi (2018a) observed that irrespective of the nutrient management strategy, the recalcitrant fraction comprised of larger pool of organic C than the other three fractions (Table 8). Averaged across different nutrient management treatments, the four fractions of organic C represented 15.2, 13.4, 30.9 and 41.0% of TOC concentration in soil plough depth. After 5 years of rice–wheat cropping, 72% of TOC was stabilized as Fract. 3 and Fract. 4. Benbi et al. (2012b) also reported a similar order of abundance of organic C fractions of varying oxidizability in soils under rice–wheat cropping system (Table 8). In a 25-year

long-term field experiment under rice–wheat cropping system, Ghosh et al. (2012) reported magnitude of different organic C fractions in the order of Fract. 4 > Fract. 1 > Fract. 3 > Fract. 2. Singh and Benbi (2018a) reported that the proportion of TOC stabilized as Fract. 3 + Fract. 4 (72% of TOC) was of higher magnitude compared with that reported earlier (63% of TOC) by Benbi et al. (2012b) in the soils under rice–wheat cropping. Averaged across soil depths, Das et al. (2016) reported that the contribution of very labile, labile, less labile and recalcitrant fractions towards TOC under different nutrient management treatments was in the range 6.6–16.5%, 11.6–24.4%, 4.04–11.8% and 53.5–70.8%, respectively (Table 8). The passive C pool (Fract. 3 and Fract. 4) contributed relatively higher proportion (about 70.1% of TOC) than the active C (Fract. 1 and Fract. 2) pool (29.9%). Majumder et al. (2007) reported that the magnitude of different fractions of TOC extracted under a gradient of oxidizing conditions was: Fract. 1 (36%) > Fract. 4 (33.6%) > Fract. 2 (20.1%) > Fract. 3 (10.3%).

Majumder et al. (2008b) reported that a large proportion (about 63%) of applied C stabilized into TOC in passive pool if the FYM was applied to rice (Table 8). Conversely, with the application of FYM to both rice and wheat in a cropping system, a higher proportion was stabilized in active C pool. Majumder et al. (2007) reported a similar trend of contribution of passive pool towards TOC under NPK and FYM application treatments. The conjoint application of FYM, GM or sulphitation pressmud along with inorganic fertilizers enlarged the active C pool, while the application of mineral fertilizers (NPK) or NPK + crop residues contributed more towards the passive C pool. A larger proportion

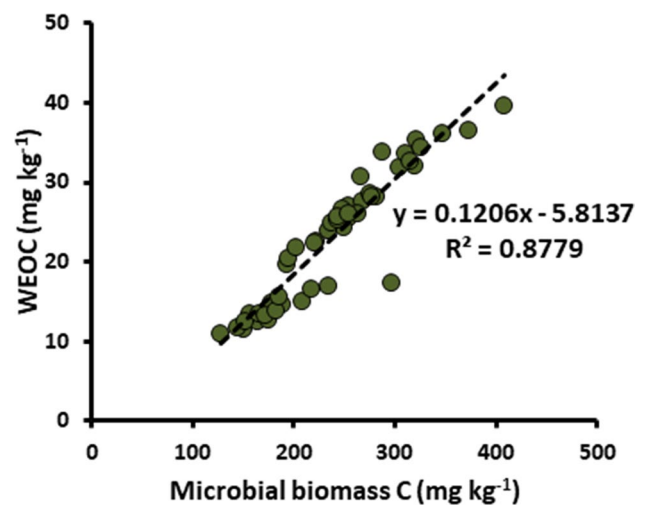


Fig. 5 Relationship between soil microbial biomass C (MBC) and water extractable organic C (WEOC) in 0–15 cm plough layer under rice–wheat cropping system in the Indo-Gangetic Plains of South Asia. Data pooled from Singh and Benbi (2018a) and Sharma et al. (2020a)



of Fract. 4 was observed in NPK + FYM compared with NPK alone application. The occurrence of high lability index for TOC with long-term application of only N fertilizer has been related to high respiratory quotient (qCO_2) values (Fauci and Dick 1994). Additional C inputs through FYM had no effect on the C lability because the substrate biochemistry of FYM revealed that high content of lignin and polyphenol in FYM form stable complexes with proteins of plant origin make the organic matter comparatively more resistant to decomposition and less labile so that the lability index value for NPK + FYM treatment should have been still lower than for the NPK (Tian et al. 1992). Singh and Benbi (2018a) reported that NPK + FYM treatment in rice–wheat cropping resulted in stabilization of C as Fract. 4 in higher amounts than the imbalanced application of fertilizer N with manure (N + FYM). The larger effect of NPK + FYM and NPK + RS treatments on Fract. 3 and Fract. 4 was attributed to the higher lignin and polyphenol content of applied organic sources which lead to formation of more stable complex with protein of plant origin and thus made FYM-C more resistant to decomposition than that of GM (Tian et al. 1992).

Figure 6 illustrates that the passive C pool (Fract. 3 and Fract. 4) was the largest and comprised of 50.5–80.3% of TOC in soils under rice–wheat/berseem cropping systems, 44.2–80.8% of TOC in maize–wheat and 44.1–61.9% of TOC in cotton–wheat cropping system. In soils under rice–wheat cropping system, Fract. 2 was the smallest fraction (13.0–18.7% of TOC), while in soils under maize–wheat and cotton wheat cropping system Fract. 2 was the smallest fraction (6.7–26.0% in maize–wheat and 14.6–30.1% in cotton–wheat). These results reveal that quality of SOM under rice–wheat and a maize–wheat cropping system is better than that under cotton–wheat cropping system (Fig. 6). The stabilization of SOM in soils under different cropping systems has significance in C cycling and sequestration with

co-benefits of nutrient mineralization. The characterization of rice–wheat soils with greater proportion of organic C existing in less labile and recalcitrant forms was ascribed to the retarded rate of C oxidation in these soils that remained inundated for about 90 days during the rice growing season (Jenkinson 1988; Watanabe 1984). Because of retarded rate of SOM decomposition under submerged soils, compared with the aerobic soils, plant biomass molecules that are more resistant to microbial degradation such as lignins might gradually accumulate in the organic matter of rice soils (Colberg 1988; Tate 1979). There is indirect evidence of the accumulation of lignin derived C substrates in anaerobic soils (Ye and Wen 1991). Soil organic matter becomes more lignified in rice soils because of the incorporation of lignin-derived phenols in submerged systems (Bierke et al. 2008). The predominance of recalcitrant vanillyl monomers indicates a high stability of lignin in upland rice rotation (Chen et al. 2018).

Water stable aggregates and mean weight diameter of soil aggregates

A soil aggregate is a group of primary soil particles that strongly cohere to each other. They are formed through the combined action of cohesion and fragmentation processes. During the first stage of macro-aggregate (> 0.25 mm) formation, flocculation of silt and clay particles and free micro-aggregates occurs around plant roots via biotic processes (such as root entangling, root and microbial binding agent production) and abiotic factors (i.e., electrostatic interactions between clay particles) (Denef and Six 2005). In the second stage, micro-aggregates (< 0.25 mm) are formed within established macro-aggregates (Oades 1984). The macro-aggregates are formed around roots or plant residues, and then fine root hairs grow into these aggregates which exude

Table 8 Distribution of soil organic carbon (TOC) in fractions of varying oxidizability viz. very labile C (Fract. 1), labile C (Fract. 2), less labile C (Fract. 3) and recalcitrant C (Fract. 4) in soils under different cropping systems in the Indo-Gangetic Plains of South Asia

Cropping system	C fraction as % of TOC				Reference
	Fract. 1	Fract. 2	Fract. 3	Fract. 4	
Rice–wheat	18.0	18.7	23.8	39.6	Benbi et al. (2012a)
Rice–wheat	15.2	13.4	30.9	41.0	Singh and Benbi (2018a)
Rice–wheat	16.8	14.6	19.1	49.4	Sharma et al. (2020a)
Rice–wheat	16.8	14.0	30.7	38.5	Singh and Benbi (2022)
Rice–wheat	6.6–16.5	11.6–24.4	4.0–11.8	53.5–70.8	Das et al. (2016)
Rice–wheat	37.1–47.1	10.4–22.6	11.3–20.0	19.5–30.7	Ghosh et al. (2012)
Rice–berseem	31.0	57.2	8.6	3.2	Majumder et al. (2008b)
Maize–wheat	26.0	29.8	26.1	18.1	Benbi et al. (2012b)
Maize–wheat	6.7	12.5	37.3	43.5	Singh and Benbi (2018a)
Maize–wheat	25.5	30.4	24.0	20.3	Singh and Benbi (2022)
Cotton–wheat	14.6	23.5	25.3	36.6	Singh and Benbi (2018a)
Cotton–wheat	30.1	26.0	16.1	28.0	Singh and Benbi (2022)

organic acids, enzymes, and other C rich compounds, which support higher microbial populations and thus act as the core of new micro-aggregates (Oades 1984; Six et al. 2000). These C rich organic compounds are then encapsulated by silt and clay particles inside of the macro-aggregates, forming occluded micro-aggregates that are enriched with C (Six et al. 2000; Miller and Jastrow 2000; Fonte et al. 2014).

The release of polysaccharides and organic acids produced during decomposition of organic sources plays a key role in the stabilization of soil macro-aggregates (Cheshire 1979; Six et al. 2000). Since polysaccharides and organic acids do not spread far from the site of production (Benbi et al. 2016), the freshly added crop residues acts as nucleation sites for the growth of fungi and other soil microbes (Puget et al. 1995; Jastrow 1996). These polysaccharides and mucilaginous substances result in the binding of residues and soil particulates into macro-aggregates. Sodhi et al. (2009) reported that in a sandy loam soil under rice–wheat cropping system proportion of water stable aggregates (WSA) varied between 77.6 and 80.1% (Table 9). At wheat harvest, the WSA ranged between 74.1 and 77.2% under different treatments involving application of organic manures and inorganic fertilizers either alone or in combinations and increased to 80.9–83.0% at rice harvest. The amount of WSA after rice and wheat harvest were significantly ($p < 0.05$) higher for plots receiving rice straw compost ($8 \text{ Mg ha}^{-1} \text{ year}^{-1}$) to both rice and wheat as compared to in the plots receiving inorganic fertilizers (Table 9). The mean weight diameter (MWD) of aggregates was significantly ($p < 0.05$) higher in rice straw compost applied plots as compared to the CK and plots with the application of inorganic fertilizers. Benbi et al. (2016) reported that WSA ranged between 72.0 and 77.8%, of which macro-aggregates ($> 0.25 \text{ mm}$) comprised of 37.1–49.3% of the WSA, while macro-aggregates ($< 0.25 \text{ mm}$) constituted 23.3–30.3% (Table 9). The application of inorganic fertilizers and FYM significantly ($p < 0.05$) increased the proportion of macro-aggregates, which were linearly related to TOC. The formation of macro-aggregates increased by 5.3–18.2% at the surface (0–7.5 cm) and 11.3–23.2% at the sub-surface (7.5–15 cm) soil with the application of FYM and NPK + FYM, respectively, over unfertilized CK. Micro-aggregates were significantly higher in the unfertilized CK and decreased with NPK + FYM application because of increase in the formation of macro-aggregates (Table 9).

Benbi and Senapati (2010) reported that total WSA ranged between 54.3 and 73.4% under different treatments involving RS incorporation and fertilizer N (120 kg N ha^{-1}) application at the three sampling depths in a 7-year long rice–wheat cropping system (Table 9). The macro-aggregates (0.25 to $> 2 \text{ mm}$) comprised 32.5–54.5% of the total WSA compared to 18.9–21.8% as micro-aggregates. Among the macro-aggregates, the 0.25–0.50 mm fraction

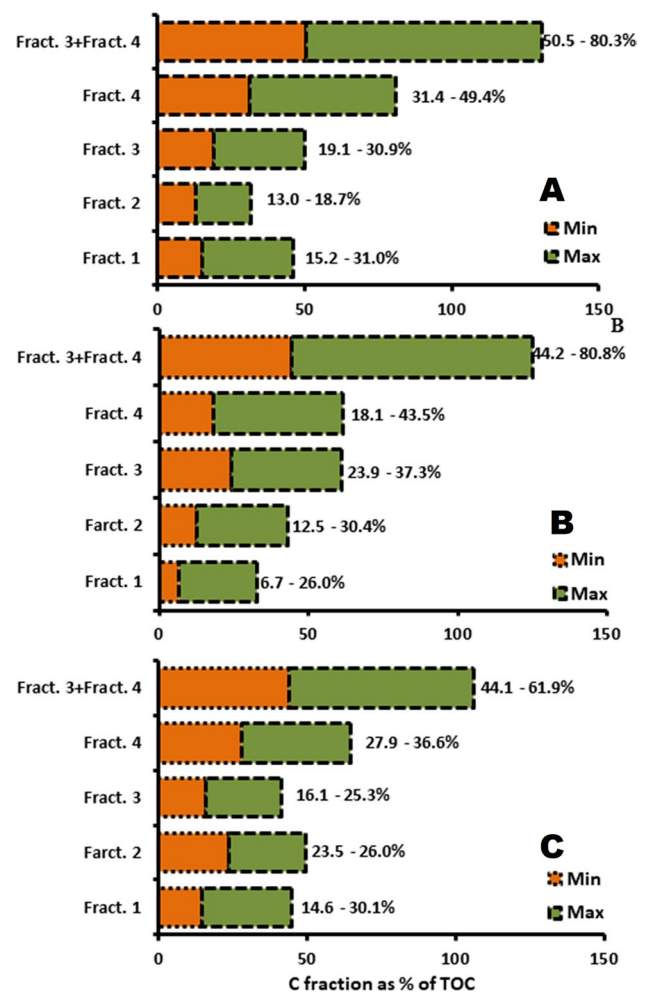


Fig. 6 Distribution of total organic carbon (TOC) in fractions of varying lability in the surface (0–15 cm) soil under rice–wheat/berseem (A), maize–wheat (B) and cotton–wheat (C) cropping systems in the Indo-Gangetic Plains of South Asia. Data pooled for Majumder et al. (2008a, b), Benbi et al. (2012a), Singh and Benbi (2018a), Sharma et al. (2020a), and Singh and Benbi (2021)

was the greatest in amount (17.4–22.1%) and aggregates of size $> 2.0 \text{ mm}$ were least in amount (1.9 and 4.4%). The effect of organic sources on aggregation was greatest in the plots that received both RS and FYM together (Table 9). Fertilizer N application did not influence aggregation significantly. The formation of macro-aggregates with concomitant decrease in the proportion of micro-aggregates and the encapsulation of C has immense significance for C budgets in cropland ecosystems. The organic C associated with aggregates remains protected from mineralization due to less physical and microbial degradation (Six et al. 2002; Benbi et al. 2016). A typical hierarchical model of aggregate formation provides insight with large differences in the distribution of TOC pool, with macro-aggregates typically containing more organic C than the soil micro-aggregates ($< 0.25 \text{ mm}$). The macro-aggregate-associated C increased



with an increase in the proportion of water stable macro-aggregates (Singh and Benbi 2021). In contrast, micro-aggregate-associated C did not show any relationship to the aggregate proportion. Notwithstanding the application effect of more lignified FYM-C, the polysaccharides and organic acids released during the microbial decomposition of SOM play a key role in the stabilization of macro-aggregates (> 0.25 mm) (Cheshire 1979). Similarly, crop residue acts as a substrate for soil food web and, therefore, greatly impacts nutrient cycling for maintaining soil quality and productivity due to the production of microbial metabolites (Sharma et al. 2021). These metabolites do not spread far from the site of production, freshly added residues function as nucleation sites for the growth of fungi and other soil microbes (Christensen 2001).

Total organic carbon and yield of crops

The C sequestration in soils of the tropics and subtropics is considered to vary between 100 and 500 kg C ha⁻¹ year⁻¹, but most soils under agro-ecosystems in South Asia are depleted of their antecedent TOC pool by 25–75%, which is equivalent to 10–30 Mg C ha⁻¹ (Lal 2013). Studies conducted in northern India revealed that the cultivated soils had loss of 21–36% TOC as compared to uncultivated soils (Benbi et al. 2015a), which is a little lesser than the values (30–60%) reported in various agro-climatic regions of India (Lal 2004a). In long-term field experiments in South Asia, an increase in crop productivity with the build-up of the TOC pool in the soil has been well established (Aggarwal et al. 1997; Shankar et al. 2002; Ghosh et al. 2003; Lal 2006). A yield gain of 0.5–1.0 kg ha⁻¹ for cowpeas, 20–70 kg ha⁻¹ for wheat, 10–50 kg for rice, and 10–300 kg ha⁻¹ for maize has been reported with every 1.0 Mg C ha⁻¹ increase in TOC pool in the root zone (Lal 2004a, 2006). The yield of pearl millet increased by about 100–200 kg ha⁻¹ Mg⁻¹ TOC in the soils of India (Aggarwal et al. 1997). The grain yield of mustard increased by 360 kg ha⁻¹ Mg⁻¹ TOC pool in the surface 0–15 cm layer with TOC varying between 6 and 12 Mg C ha⁻¹ (Shankar et al. 2002). Oldfield et al. (2019) developed a quantitative model to explore how SOM relates to crop yield potential of maize and wheat in light of co-varying factors of management, soil type, and climate, and reported that yields of these two crops are on average greater with higher concentrations of TOC; however, yield increases level off at about 2% TOC. Nonetheless, the decline in yield of the rice–wheat cropping system was the cause of the decline in the TOC pool at 200 to 624 kg ha⁻¹ year⁻¹ (Grace et al. 2003). Therefore, it could be concluded that C sequestration in soils has immense potential for enhancing yield and C sustainability of different cropland ecosystems.

Future research needs

To feed the burgeoning human population with reduced reliance on external inputs and with minimal environmental implications is the primary challenge among different countries in the IGPs. Review of the existing literature underpins some researchable issues and strategies for large scale adoption of different soil management and crop production practices in the IGPs for increased C sustainability with reduced C loss in crop production.

- There is a strong need to study the change in SOM quality within aggregate sizes (viz. macro- and micro-aggregates) in terms of alteration in different labile and non-labile C pools in response to nutrient management in rice- and non-rice-based cropping systems. It would help understand the underlying mechanism responsible for differential accumulation of SOM among different pools in response to nutrient management. Additionally, there is a need to study sequestration of plant mediated C input among different aggregate sizes in soils under different cropping systems. For example, the soils under rice-based cropping system had entirely different impact on physical properties due to destruction of soil structure, compared with the soils under non-rice-based cropping systems. There exists a considerable contradiction among researchers; some have reported loss of encapsulated C due to wet-tillage, whilst the others reported increased C sequestration in response to wet-tillage which provide plenty of fine particles for coating particulate SOM and distributes SOM and soil mineral components (silt + clay) more uniformly and allows organic matter to interact with mineral fraction more sufficiently.
- There is dearth of information on effect of different nutrient management practices on response of root development (growth, geometry, and architecture) in stressed and un-stressed soil environments, and quantification of plant mediated C input into the soil. It would help apprehend the differential response of nutrient management practices on root development in soils under contrasting rice-based and non-rice-based cropping systems in response to alteration in soil moisture regimes. Nonetheless, there is a need to study the biochemical characteristics of plant mediated C input (such as through roots, leaves + stubble) to understand the effect of biomass C composition on soil respiration and C loss from the ecosystem.
- There is a need to quantify the fraction of total plant mediated biomass C being sequestered in different water stable aggregates. It would help quantify the amount of C sequestered in soil micro-aggregate fraction which is considered relatively less susceptible to C loss by oxidative actions. Nonetheless, the size of soil microbial bio-

Table 9 Effect of inorganic and organic fertilizer application on water stable aggregates (WSA) and mean weight diameter (MWD) in surface layer (0–15 cm) of soils under rice–wheat cropping system in the Indo-Gangetic Plains of South Asia

Climatic conditions	Soil properties	Study period	Treatment	WSA (%)	MWD (mm)	Reference
Semi-arid, sub-tropical, mean annual rainfall 750 mm	Sandy clay loam <i>Typic Ustipsamment</i> Initial TOC 4.10 g kg ⁻¹	10 years	CK [¶]	77.6	0.335	Sodhi et al. (2009)
			NP*	77.7	0.320	
			NP + RS [†] compost	79.5	0.405	
			RS compost	80.1	0.460	
Hot humid, semi-arid, sub-tropical, mean annual rainfall 713 mm	Soil depth 0–7.5 cm, Sandy loam, <i>Eutric Cambisols</i> , Initial TOC 4.20 g kg ⁻¹	5 years	CK	72.0	0.544	Benbi et al. (2016)
			NPK	72.5	0.546	
			FYM [‡]	73.5	0.553	
			N + FYM	75.8	0.561	
			NPK + FYM	77.8	0.563	
Hot humid Semi-arid Sub-tropical, annual rainfall 713 mm	Soil depth 7.5–15 cm, Sandy loam, <i>Eutric Cambisol</i> , Initial TOC 4.40 g kg ⁻¹	5 years	CK	64.9	0.529	Benbi et al. (2016)
			NPK	66.2	0.545	
			FYM	66.3	0.561	
			N + FYM	68.1	0.576	
			NPK + FYM	69.0	0.572	
Semi-arid, sub-tropical, mean annual rainfall 700–800 mm	Soil depth 0–5 cm, Sandy loam, <i>Typic Ustorthent</i> , Initial TOC 4.80 g kg ⁻¹	7 years	CK	58.0	–	Benbi and Senapati (2010)
			N + RS	58.0	–	
			FYM	72.2	–	
			N + FYM	72.2	–	
Semi-arid, sub-tropical, mean annual rainfall 700–800 mm	Soil depth 5–10 cm, Sandy loam <i>Typic Ustorthents</i> , Initial TOC 4.80 g kg ⁻¹	7 years	CK	55.1	–	Benbi and Senapati (2010)
			N + RS	55.2	–	
			FYM	66.8	–	
			N + FYM	67.0	–	
Semi-arid, Sub-tropical, mean annual rainfall 700–800 mm	Soil depth 5–10 cm, Sandy loam, <i>Typic Ustorthents</i> , Initial TOC 4.80 g kg ⁻¹	7 years	CK	54.3	–	Benbi and Senapati (2010)
			N + RS	54.3	–	
			FYM	58.0	–	
			N + FYM	58.1	–	
Semi-arid, tropical	Sandy loam, Initial TOC 2.90 g kg ⁻¹ , B _D [‡] 1.69 g cm ⁻³	34 years	CK	–	0.129	Kukul et al. (2009)
			FYM	–	0.524	
			N	–	0.154	
			NP	–	0.244	
			NPK	–	0.309	
Hot humid, semi-arid, sub-tropical, monsoonal climate, mean annual rainfall 713 mm	Soil depth 0–7.5 cm, Sandy loam, <i>Eutric Cambisols</i> , Initial TOC 4.20 g kg ⁻¹	5 years	CK	72.0	0.544	Singh and Benbi (2018a)
			NPK	72.5	0.546	
			FYM	73.5	0.533	
			N + FYM	75.8	0.561	
			NPK + FYM	77.8	0.563	
Hot humid, semi-arid, sub-tropical, monsoonal climate, mean annual rainfall 713 mm	Soil depth 7.5–15 cm, Sandy loam, <i>Eutric Cambisols</i> , Initial TOC 4.40 g kg ⁻¹	5 years	CK	64.9	0.529	Singh and Benbi (2018a)
			NPK	66.2	0.545	
			FYM	66.3	0.561	
			N + FYM	68.1	0.576	
			NPK + FYM	69.0	0.572	

[‡] Bulk density

[§]Farmyard manure

[¶]Check (no N, P, K, or organic manure)

[†]Rice straw

*N, NP, NPK represent nitrogen, nitrogen + phosphorus, and nitrogen + phosphorus + potassium, respectively



mass pool is required to be studied separately for micro- and macro-aggregates for increased understanding of its impact on soil respiration and eventually C sequestration in stable pool.

- In the entire IGPs, especially in northwestern India, the development and implementing the legislation on monitoring of in situ crop residues burning is required. There should be an enforced complete ban on open field residue burning especially of rice, but with provisions of monetary incentives to the farmers based on C footprints and/or storage and other ecosystem services rendered by in situ residue retention.
- The possibilities of increased C sequestration in soils with co-benefits of reduced N needs of crops are explored with the inclusion of green manure leguminous crops during the intervening period between wheat harvesting and rice establishment. The inclusion of mung bean crop between the annual rice–wheat cropping system would help enhance the economic benefits to farmers, besides offering ecological benefits and numerous ecosystem services. The inclusion of sesbania would help improving soil health while ameliorating iron deficiency.

Biophysical limits and barriers

- Lack of awareness among farming community regarding balanced use of chemical fertilizers has been the major biophysical barrier for reduced crop productivity and nutrient use efficiency and the deterioration of soil health.
- In the entire IGPs, particularly in the north-western India, where rice–wheat cropping has been the predominant system, in situ rice residue burning has been causing environmental pollution due to large emission of greenhouse gases with high C costs. Additionally, residue burning escapes possibilities of increased C sequestration when these could otherwise be used to increase organic C inputs to the soils.

Conclusions

In the IGPs in South Asia, the amount of C input (plant – mediated + exogenous) into the soil has been recorded to be 0.88 to 12.2 Mg C ha⁻¹ year⁻¹ under rice–wheat cropping, 1.37 to 6.68 Mg C ha⁻¹ year⁻¹ under other rice based systems (rice–berseem/rice–wheat–jute/rice–mustard–sesamum/rice–fallow–rice) and 0.51 to 8.07 Mg C ha⁻¹ year⁻¹ under non-rice based cropping systems (maize–wheat, soybean–wheat, maize–wheat–cowpea). Plant-mediated C input increased significantly with balanced use of N, P and

K applied as mineral fertilizers as compared to no fertilizer or imbalanced use of fertilizer nutrients. The magnitude of plant-mediated C inputs further increased by the conjoint application with organic manures and balanced application of N, P and K. The long-term (5–25 years) rice–wheat experiments showed that 4.4–28.9% of the added C was sequestered in TOC pool, as compared with 5.0–24.0% in other rice-based systems (7–36 years), and 19.1–45.0% in non-rice-based cropping systems (13–30 years). The amount of C input required to maintain TOC stocks at steady state varied between 2.30 and 4.59 Mg C ha⁻¹ year⁻¹ for soils under rice-based systems, as compared with 1.10 and 3.47 Mg C ha⁻¹ year⁻¹ in soils under non-rice-based cropping systems. Application of only fertilizer N increased the TOC pool by 0.2–75.9% in the rice-based cropping systems, and up to 63.4% in the non-rice-based cropping systems. Balanced use of inorganic fertilizers (NPK) increased the TOC in soils under rice and non-rice-based cropping systems by 6.1–87.5% and 4.1–42.9%, respectively. The conjoint application of inorganic fertilizers and organic sources (NPK + FYM/CR/GM) increased the TOC pool in 0–15 cm plough layer by 22 to 127% in soils under rice-based systems, in contrast to -10.8 to 87.3% in soils under non-rice-based cropping systems. The passive C pool (less labile + recalcitrant C) was the largest pool, comprising of about 50.5–80.3% of TOC in soils under different rice–wheat; almost similar (44.2–80.8% of TOC) to that for maize–wheat, but considerably higher compared with those under cotton–wheat (44.1–61.9% of TOC) cropping system. The inclusion of leguminous crops during the intervening period between wheat harvest and rice establishment in an annual rice–wheat cropping system help enhanced C sequestration in soils with co-benefits of increased N availability. The conjoint application of fertilizers and organic manures leads to preferential C sequestration in passive C pool, besides enhancing soil respiration which leads to increased release of nutrients due to altered substrate availability. Balanced use of fertilizers conjointly with organic manures and/or crop residue management has noteworthy impact on C accumulation in soils for long-term sustainability of the ecosystems and restoration of soil fertility.

Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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