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Enhancing carbon sequestration potential and nutrient release dynamics under conservation agriculture in the Indo-Gangetic Plains, India: A review

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Abstract

Conservation management approaches focusing on minimizing soil disturbance maximizing soil cover, and stimulating biological activity can be achieved with different cropping choices and production goals in different environments all around the Indo-Gangetic Plains, India. Average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+FYM treatment and increased enzyme activities, which potentially influence soil nutrients dynamics under field condition. Compared to F_1 (first time, u need to indicate treatment details, otherwise, F1-ns not understood) control treatment the RDF+FYM treatment sequestered 0.28 Mg C ha^{-1} yr^{-1} whereas the NPK treatment sequestered 0.13 Mg C ha^{-1} yr^{-1}. As tillage intensity increased there was a redistribution of SOC in the profile, but it occurred only between ZT and PRB since under CT, SOC stock decreased even below the plow layer. Average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+FYM treatment. Compared to F_1 control treatment the RDF+FYM treatment sequestered 0.33 Mg C ha^{-1} yr^{1} whereas the NPK treatment sequestered 0.16 Mg C ha^{-1} yr^{-1}. The atmospheric carbon reservoir is significantly affected by change in lithogenic carbon reservoir (????) we did not do this, as we did not have data??). Carbon reservoir of soil is strongly influenced by the interaction between different biogeochemical cycles and environmental processes. At the local scale land use and soil management have also a significant impact on the soil carbon pool. Soil carbon is the major determinant of soil quality and agronomic viability because of its influence on other soil features. Soil carbon separation includes physical and chemical methods and their combinations in a sequence. These are not based on review or data presented in the paper.

Keywords: carbon sequestration, soil organic carbon, total carbon stocks, crop residue, no-tillage, IGP

Introduction

Atmospheric concentration of CO_2 has increased from ~ 280 ppm in pre-industrial era to ~ 385 ppm in 2008 (+ 37.5%) and is presently increasing at the rate of ~ 2 ppm/yr or 3.5 Pg/yr (1 Pg or pentagram = 1 Gt = 1 gigaton = 1 billion metric ton). The increase in CO_2 emission by human activity is attributed to fossil fuel combustion, deforestation and biomass burning, soil cultivation and drainage of wetlands or peat soils. Increase in fossil fuel combustion is caused by high global energy demand of 475 Quads (1 quad = 1015 BTU) and increasing at the rate of ~ 2.5%/yr, especially in emerging economies including China, India, Mexico, Brazil, etc. There exists a strong positive correlation between population growths on the one hand and CO_2 emission or the energy demand on the other. The world population of 6.7 billion in 2008 is increasing at the rate of 1.3%/yr and is projected to be 9.5 billion by 2050 before stabilizing at ~ 10 billion towards the end of the 21st century [1]. The sequestration of atmospheric CO2 into terrestrial soils is a vital solution for mitigating climate change. The soil organic carbon (SOC) storage in the global agro-ecosystem nearly accounts for 10% of the total terrestrial SOC storage (Tang *et al.*, 2010), and thus agricultural soils play an important role in the global carbon (C) cycle.

Global plant biomass captures ~110 Pg (10^{15}g) C yr^{-1} from the atmosphere through photosynthesis. Maintenance and decay of plants and animals occurs simultaneously and returns ~110 Pg C yr^{-1} as CO_2 to the atmosphere through autotrophic respiration (50 PgC yr^{-1}) and heterotrophic respiration (60PgCyr^{-1}). Soil to a depth of 1 m stores about 1600 Pg of X in organic matter; an addition 700 Pg of C stored in soil as carbonate minerals[2]. The atmosphere contains ~800 Pg of C as CO_2 and has been increasing in CO_2 concentration since the beginning of the 20th century. Estimates from the first decade of the 21st century indicate emissions of 7.7 Pg Cyr^{-1} from burning of fossil fuels and 1.4 Pg Cyr^{-1} from deforestation [2].

Sinks for this additional CO2 in the atmosphere have been 2.3 Pg Cyr^{-1} in the oceans and 2.7 Pg Cyr^{-1} to land biomass, leaving behind 4.4 Pg Cyr^{-1} accumulating in the atmosphere [2].

Assuming a global loss of 20% SOC (i.e. 400 Pg from an original level of 2000 Pg)via historical land cleaning that caused erosion and oxidation of organic matter [3, 4], there is an enormous potential to recapture at least 400 Pg of SOC with technological innovations and restoration activities. Assuming that an aggressive global restoration could occur within the next century, nearly the entire current rate of CO_2 increases in the atmosphere (i.e. 4.1 Pg Cyr^{-1}) could be mitigated through soil restoration (400 Pg C/ 5 billion ha of agricultural land/ 100 yr = mean soil organic carbon sequestration rate of 0.8 Mg C ha^{-1} yr^{-1}; certainly a tremendous goal, but also plausible). Clearly the potential for soil restoration with SOC could have a major impact on the atmosphere; it is our collective willingness to achieve this goal that may be questioned. Obviously, the time required to fully restore SOC may be longer than a century and the rate of release of fossil fuel- derived CO_2 cannot be considered static. In addition [5], more conservatively suggested that only 42-78 Pg of C might have been lost from soils worldwide, although estimates have varied from 44 to 537 Pg of C. Estimated total GHG emission, i.e. global warming potential per hectare in terms of CO2 equivalent (CO2-eq) varied amongst different crop production systems. On an average, rice-wheat system emitted 1,823 kg CO2-eq, whereas maize-wheat, fodder, vegetables and horticulture emitted 410, 245, 188 and 117 kg CO2-eq from the respective areas of these cropping systems. The total emission from 1.8 ha area under diversified cropping system was 2,784 kg CO2-eq as compared to 5,152 kg CO2-eq from the rice– wheat system in the same area. On hectare basis, diversified agriculture system emitted 1,547 kg CO2- eq/ha as compared to 2,862 kg CO2-eq/ha in rice-wheat system. The global warming potential under diversified agriculture system was 46% (1,316 kg CO2-eq/ha) less than that of rice-wheat.

The Indo-Gangetic Alluvial Plains (IGP) of India extends from 21^0 $45^/$ to 31^0 $0^/$ N latitudes and 740 $15^/$ to 91^0 $30^/$ E longitudes and includes the states of Punjab, Haryana, Delhi, Uttar Pradesh, Uttrakhand, Bihar, West Bengal, Himachal Pradesh, northern parts of Rajasthan and Tripura. The plains cover a total area of about 43.7 m ha and represent 8 agro-eco regions (AERs) and 14 agro-eco sub-regions (AESRs) [6]. The IGP, with about 13% geographical coverage in India, produces nearly 50% of the food grains for 40% of the total population of India. However, recent reports of the land use and soils of the IGP indicate a general decline in soil fertility [7]. Soils which earlier rarely showed any nutrient deficiency symptoms are now deficient in many nutritional elements. TOC is a key soil quality indicator, since high levels of TOC are linked to improvements of nutrient supply to crops, soil physical properties (improving soil structure) and biological properties (widening biodiversity and enhancing microbial activity). It also reduces pollution risks, by raising soils' buffering capacity. Hence increasing TOC has the potential to substantially increase crop production and reduce its variability [8]. In addition, increasing the storage or sequestration of carbon in agricultural soils has substantial potential to mitigate increases in atmospheric carbon dioxide (CO_2) concentrations [9]. Thus, enhancement of TOC in agricultural soils could not only improve soil quality and increase crop productivity, but also alleviate global warming, providing “win–win” benefits [9]. TOC levels in soils reflect the long-term balance between additions and losses of organic carbon. Various studies have shown that increases in TOC levels are directly related to the amount of organic residues added to soils, e.g. in fertilizer and manure application [10, 11]. In addition, changes in land use can significantly affect TOC dynamics, for example, the conversion of natural soil to cropland affects C storage [12].

Long term soil fertility studies have shown reduction in soil organic matter content as well as in the other essential nutrients that had higher levels of nutritional elements in the earlier years [13]. The biological activity of soils has gradually declined resulting in reduced efficiency of applied inputs [13]. As a consequence, parts of the IGP have an acidic environment at present [14]. It is in this context that the soils of the IGP of the Indian subcontinent require focused attention. Soils under arid and semi-arid climates in IGP cover 16.4 m ha and lack in organic carbon due to high rate of decomposition. Interestingly, the soils in the arid and semi-arid environments prevailing in some parts of the IGP are abundant in inorganic carbon in the form of calcium carbonate. The adverse climatic conditions in arid and semi-arid agro-eco-regions induce the precipitation of $CaCO_3$, thereby depriving the soils of Ca^{2+} in soil exchange complex with a concomitant development of soil sodicity in the sub-soils. The subsoil sodicity impairs the hydraulic conductivity of soils. This self-terminating process will lead to the formation of sodic soils with exchangeable sodium percentage (ESP) that decreases with depth. Therefore, the formation of pedogenic (secondary) $CaCO_3$ has been identified as a basic process that initiates the development of sodicity. The process of $CaCO_3$ formation in soils is now considered as a basic and natural process of soil degradation [15]. In soils of IGP the $CaCO_3$ has been formed during the semiarid climate prevailing for the last 4000 year B.P. and the rate of formation is proceeding at a very fast rate, i.e., 0.8-0.9 mg per 100 g of soil per year in the first 100 cm of the profile [16]. Improving agronomic and ecological benefits of greater SOC storage requires more information on management practices that increase C inputs and mitigate the loss of accrued benefits. This paper summarizes state-of-knowledge on the effects of tillage, nutrients, and residue management practices on carbon sequestration potential and nutrient release dynamics in the Indo-Gangetic Plains, India. Our objectives were to (I) briefly discuss the status of Total organic carbon stock in the IGP, India, (II) compare the conventional and conservation practices, mainly tillage, residue and nutrient management to improve SOC pools, and (III) highlight the opportunities, challenges, and research gaps to increase potential of SOC in IGP, India**.**

Soil organic matter dynamics (SOM)

The SOM concentration differs among climate, soil type and land uses. The carbon dynamics also depends on the microbial population, the intrinsic properties of plants and the availability of nutrients. Soil microbes tangibly organize soil particles together and enrich soil clump which protects C in macro aggregates. Soil organic matter is physically protected within aggregates. Aggregates have a major impact on microbial community structure, gaseous exchange, water maintenance and nutrient cycling. Depletion of SOM, a widespread problem on croplands and grazing lands in the region, is exacerbated by soil degradation. Most soils have extremely low levels of soil organic carbon (SOC) contents, ranging from 8 to $10gkg^{-1}$. Depletion of SOC pool is caused by fertility-exploitative practices and soil degradation processes. Low external input of chemical fertilizers and organic amendment causes depletion of SOC pool because nutrients harvested in agricultural products are not replaced, and are made available through mineralization of SOM. In some cases, soil is burnt to release nutrients contained in SOM. Fuel for household use is limited, and crop residue and animal dung are used as fuel. Crop residues are also used as fodder for livestock. Poultry manure is more effective in building soil C than rice straw and cow dung, possibly due to the presence of more humified and recalcitrant C forms in poultry manure [17].

West and Post [18] demonstrated that transitioning from conventional tillage to no-tillage could result in SOC sequestration of (0.57±0.14) Mg C ha^{-1} yr^{-1}. The potentials of SOC sequestration ranged from 0.10 to 0.50 Mg ha^{-1} yr^{-1} for humid temperate regions and from 0.05 to 0.20 Mg ha^{-1} yr^{-1} for semiarid and tropical regions [9]. Tillage, crop residue, and nutrient management practices are likely to influence SOC dynamics in agricultural soils. Studies suggest that soil management practices, such as intensive tillage and crop residue burning or removal, contribute to SOC loss [5, 19, 20]. Conservation practices such as reduced- and no-tillage are interlinked with crop residue and nutrient management (fertilizers, manure, and green manures), which influences SOC accrual and C dynamics in cropping systems [21-23].

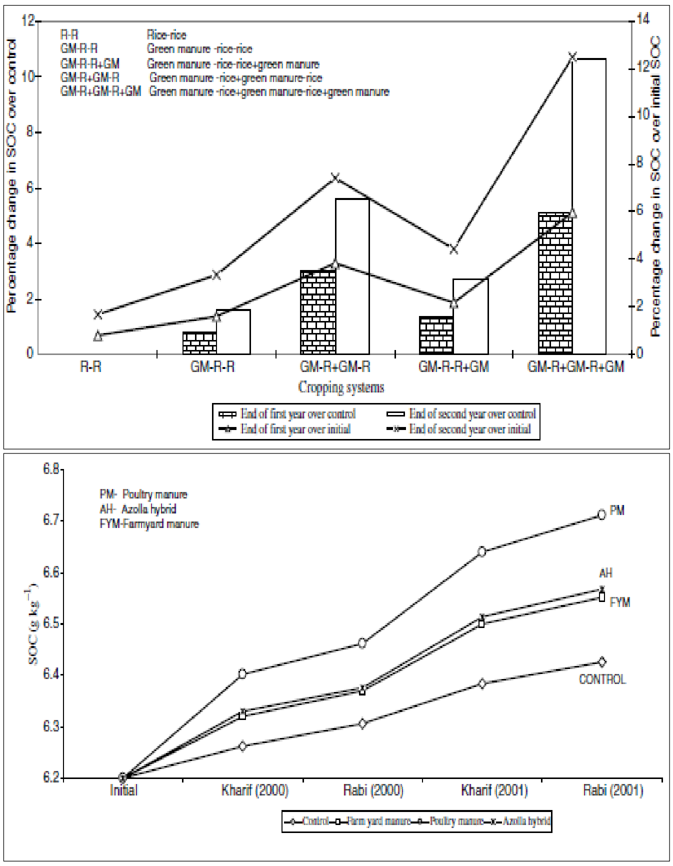


Fig 1a: Effect of cropping on soil organic carbon, **b:** Effect of organics/ bio-species on soil organic change compared with initial and final conten in different seasons

Lal *et al.* [24] reported that the increase in SOC (Figure 1a) through sequestration had two positive effects – enhancement of soil quality and regulatory capacity of the soil. These formed the basis for sustainable management of soil resources. Narain [25] as ascribed to the fact that PM owing to its higher organic matter content could have increased moisture-holding capacity of the soil and resulted in considerable residual carbon, leading to higher SOM and its fractions (Figure 1b). Besides, synergistic effect between organic and inorganic form of nutrients and formation of stable complex with humic substances supplied through PM might have also enhanced SOM.

Soil organic carbon pools

In terrestrial ecosystems the amount of carbon in soil is usually greater than the amount in living vegetation. It is therefore important to understand the dynamics of soil carbon as well as its role in terrestrial ecosystem carbon balance and the global carbon cycle. The loss of soil organic carbon by conversion of natural vegetation to cultivated use is well known. Soil organic carbon includes plant, animal and microbial residues in all stages of decomposition. Many organic compounds in the soil are intimately associated with inorganic soil particles. The turnover rate of the different soil organic carbon compounds varies due to the complex interactions between biological, chemical, and physical processes in soil. Although there may be a continuum of soil organic carbon compounds in terms of their decomposability and turnover time, physical fractionation techniques are often used to define and delineate various relatively-discrete soil organic carbon pools.

World soils constitute the third largest global C pool, comprising of two distinct components: (i) soil organic C (SOC) estimated at 1550 Pg, and (ii) soil inorganic C (SIC) pool estimated at 950 Pg, both to 1-m depth. Other pools include the oceanic (38,400 Pg), geologic/fossil fuel (4500 Pg), biotic (620 Pg), and atmospheric (750 Pg) [9]. Thus, the soil C pool of 2500 Pg is 3.3 times the atmospheric pool and 4.0 times the biotic pool. However, soils of the managed ecosystems have lost 50 to 75% of the original SOC pool. Conversion of natural to managed ecosystems depletes SOC pool because C input into the agricultural ecosystems is lower, and losses due to erosion, mineralization and leaching are higher than those in the natural ecosystems. The magnitude of SOC depletion is high in soils prone to erosion and those managed by low-input or extractive farming practices. The loss of SOC pool is also high in soils of coarse texture and those with a high initial pool. Most agricultural soils have lost 20 to 40 Mg Cha^{-1} due to historic land use and management. The SOC pool is at a dynamic equilibrium under a specific land use and management system. At equilibrium, the C_{input} into a system equals C_{output}. Upon conversion to another land use and management, depletion of SOC pool occurs if $C_{input} < C_{output}$, and sequestration if $C_{input} > C_{output}$ (Eq. 1 to Eq. 3).

Steady state . . . . $C_{input} = C_{output}$ . . . . Eq. 1

Depletion . . . . $Cinput < C_{output}$ . . . . Eq. 2

Sequestration . . . . . . $C_{input} > C_{output}$ . . . . Eq. 3

Land use and soil management techniques which lead to C sequestration are retention of crop residues, NT farming and incorporation of cover crops in a diversified rotation cycle, INM techniques of using compost and other biosolids, erosion control, water conservation, contour hedges with perennials, controlled grazing, etc. An average long term rate of SOC sequestration with these techniques is 200 to 1000 $kgha^{-1}yr^{-1}$ for humid temperate regions and 50 to 250 $kgha^{-1}yr^{-1}$ for dry tropical regions. In addition, the rate of SIC sequestration as secondary carbonates is about 5 to 25 $kgha^{-1}yr^{-1}$ in arid and semi-arid regions. In contrast, depletion of SOC pool occurs with the use of excessive plowing, residue removal and biomass burning, and extractive farming practices where nutrient balance is often negative. Kukal *et al.* [26] also observed that SOC concentration in the 0–60 cm soil profile was higher under FYM application (1.8 to 6.2 g kg^{-1}) followed by NPK application (1.7 to 5.3 g kg^{-1}) when compared to control plots.

Tian *et al.* [27] found that rotary tillage with straw return had higher SOC than plowing tillage with straw return at 0–10 cm soil depth in wheat field. The diverse results might be due to the different regional climate, soil type, crop rotation and the length of study. Under different field trials, Du *et al.* [28] and Mishra *et al.* [29] revealed that higher SOC and N concentrations in the surface layer under NT than those under RT and PT systems can be attributed to a combination of less soil disturbance and reduced litter decomposition due to less soil/residue interaction. Furthermore, the presence of mulch may have improved soil structure by stabilizing aggregates and protecting SOM against microbial degradation and reduced the rate of SOC decomposition. Luo *et al.* [30]; Verhulst *et al.* [31] also reported that the retention and management of preceding crop residue had a significant influence on SOM content under long-term of conservation agriculture. N was lost in TTSR through soil disturbance, rapid consumption and volatilization.

Naresh *et al.* [20] reported that the highest SOC stock of 72.2Mg C ha^{-1} was observed in F_4 with T_6 followed by that of 64Mg C ha^{-1} in F_6 with T_2 > that in F_3 with T_4 (57.9Mg C ha^{-1})> F_5 with T_1 (38.4Mg C ha^{-1})= F_7 with T_5 (35.8Mg C ha^{-1}),and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_4 with T_6 treatment (56.3Mg C ha^{-1}) followed by F_6 with T_2 (51.4Mg C ha^{-1}) and F_3 with T_1 (48.4Mg C ha^{-1}).

Table 1: Changes in soil organic carbon (SOC) (g kg^{-1}) concentration in soil after 12 yr of tillage crop establishment and fertilization (± standard deviation from mean).

At the end of experiment (in 2012)									
Soil Depth (cm)	Initial (2001)	F_1 Control	F_2-50% RDF	F_3-100% RDF	F_4-100% organic (FYM)	F_5-50% RDF +50% (foliar)	F_6-50% organic (FYM)+ 50%RDF	F_7-Farmers practice	Mean
0-15	4.7±0.26	3.7±0.19^{Db‡}	3.9±0.18^{Db}	5.1±0.21^{Ab}	5.8±0.28^{Aa}	4.9±0.23^{Ca}	5.4±0.26^{Ba}	4.8±0.23^{Cb}	4.8±0.23^{Cb}
15-30	4.5±0.25	3.1±0.18^{Cc}	3.2±0.17^{Ca}	4.6±0.19^{Cb}	5.5±0.23^{Aa}	4.1±0.21^{Cb}	5.2±0.22^{Ba}	3.3±0.18^{Cc}	4.2±0.20^{Cc}
30-60	3.1±0.19	2.1±0.13^{Cd}	2.4±0.13^{Fa}	3.3±0.18^{Cc}	5.1±0.21^{Ab}	3.1±0.18^{Cc}	4.5±0.19^{Bb}	2.8±0.15^{Bc}	3.3±0.17^{Cc}
60-80	2.3±0.13	1.1±0.07^{Cb}	1.9±0.11^{Aa}	2.8±015^{Cd}	3.4±0.19^{Ac}	2.3±0.14^{Ea}	2.7 ± 0.15^{Ca}	1.9±0.11^{Ca}	2.3±0.13^{Ca}
80-100	1.4±0.09	0.9±0.05^{Cc}	1.1±0.07^{Db}	1.6±0.10^{Ab}	2.3±0.13^{Ad}	1.5±0.09^{Bb}	1.9±0.12^{Cb}	1.2±0.07^{Cb}	1.5±0.09^{Bb}
Mean	3.2±0.18	2.2±0.12^{Cc}	2.5±0.13^{Db}	3.5±0.18^{Cb}	4.4±0.21 ^{Aa}	3.2±0.17^{Cc}	3.9±0.19 ^{Bb}	2.8±015 ^{Bc}	-

** Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

***Source*:** Naresh *et al.* [20]

Table 2: Profile soil organic carbon (SOC) as affected by 12 yr of tillage crop establishment and Fertilization

Tillage crop establishment	Initial SOC stock	2012 Mg C ha^{-1} Fertilization							
		F_1**	F_2	F_3	F_4	F_5	F_6	F_7	Mean
T_1*	20.9±1.6	19.2±1.3^{D†}	26.9±1.6^{D}	54.1±1.7^{D}	70.5±3.7^{D}	36.9± 1.5^{C}	63.3+2.8^{C}	35.1±1.7^{D}	43.7±2.0^{D}
T_2		23.0±1.7^{B}	33.5+2.5^{D}	65.8±2.0^{B}	81.6±4.2^{B}	44.9±1.9^{B}	70.9+3.7^{A}	39.8±1.3^{D}	51.4±2.5^{B}
T_3		16.7±1.3^{D}	23.4±1.9^{B}	52.0±1.6^{D}	63.5±3.3^{E}	33.2± 1.5^{C}	58.6±1.6^{D}	31.3±0.1^{B}	39.9±1.6^{D}
T_4		20.5±1.5^{C}	30.7±2.4^{B}	62.6±1.9^{C}	79.1±4.1^{C}	39.7±1.3^{B}	69.4+3.3^{B}	36.7±1.5^{C}	48.4±2.3^{C}
T_5		18.0±1.3^{D}	25.5±2.1^{A}	53.4±1.7^{D}	67.0±1.4^{B}	34.4± 1.3^{D}	61.3±2.1^{A}	32.1±0.1^{B}	41.7±1.4^{D}
T_6		26.5±1.9^{A}	42.5±3.1^{A}	68.5±2.1^{A}	85.7±4.5^{A}	49.7±1.8^{C}	73.0+3.6^{A}	48.2±2.1^{A}	56.3±2.7^{A}
T_7		15.8±1.2^{E}	19.3±1.8^{C}	49.0±1.5^{E}	58.0±1.3^{C}	29.8±1.2^{E}	51.7+2.5^{D}	27.4±1.7^{D}	28.7±1.6^{E}
Mean		19.9±1.5^{D}	28.8±2.2^{B}	57.9±1.8^{D}	72.2±3.2^{C}	38.4±1.5^{C}	64.0±2.8^{C}	35.8±1.2^{D}	-

** Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

***Source*:** Naresh *et al.* [20]

Srinivasarao *et al.* [32] observed that the application of FYM alone or in a combination with chemical fertilizers contributed to higher amounts of C inputs and subsequently to build up of higher SOC pool. Application of 10 Mg ha^{-1} of FYM and a recommended dose of chemical fertilizer (25:21.8:20.7 and 50:21.8:20.7 kg N, P, K ha^{-1} for groundnut and finger-millet, respectively) increased soil SOC pool by 41.2% to 73.0 Mg ha^{-1} with an increase of 9.3 Mg ha^{-1} over 13 years. Naresh *et al.*[23] reported that higher SOC 8.14 g kg^{-1} of soil in reduced tilled residue retained plots followed by 10.34 g kg^{-1} in permanently wide raised bed with residue retained plots. While, lower SOC 5.49 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots.

Total organic carbon stock (TOC stock)

Organic carbon content in the soils of warmer areas (arid and semi-arid) is less, the SOC stock is high (Table 3). This is due to more aerial coverage of dry and warmer areas in the IGP. In an earlier attempt to delineate the sufficient and deficient zones, 1 per cent level of organic carbon was considered as the tentative boundary between sufficient and deficient zones [33] considering OC equilibrium value at 1- 2 per cent [34]. In an effort to identify systems for carbon sequestration in semi-arid tropics of India, it was reported that forest and horticultural systems reach a quasi-equilibrium value of nearly 0.9-1.0 per cent SOC in shrink-swell soils [35]. This observation further supports 1 per cent value of SOC as a limit of sufficient or deficient zones of organic carbon. On the basis of 1 per cent SOC, it has been observed that 5 AERs (13.2, 15.3, 16.1, 16.2 and 17.2) comprising only 6 per cent area of the IGP falls in sufficient zone of organic carbon and the remaining 9 AERs comprising 94 per cent area of the IGP are under deficient zone. Soils under all categories of humid climate do not, however, fall under sufficient zone of SOC except in about 6% of the area. The remaining areas under humid climate are deficient in SOC due to intensive agricultural practices [13]. However, when point data on OC content were compared it was found that the cooler humid tracts of the IGP (AESR 13.2 and the AESRs 15.3, 16.1 and 16.2) have sufficient OC in the first 30 cm of soil depth (Table 2).

Table 3: Total carbon stock in soils of the IGP, India

AESR No.	AESRs/Characteristics	Carbon	Depth Range (cm)	Carbon stock (Pg)		
			0-30	0-50	0-100	0-150
2.1	Marusthali plains, hot hyper-arid very low AWC, LGP<60 days	SOC	0.0008	0.0022	0.0039	0.0074
		SIC	0.0168	0.0164	0.0360	0.0581
		TC	0.0176	0.0186	0.0399	0.0655
2.3	Kachch Peninsula, hot hyper-arid, low AWC and LGP <60 days	SOC	0.0214	0.0310	0.0413	0.0157
		SIC	0.0029	0.0060	0.3341	0.5802
		TC	0.0243	0.0370	0.3754	0.5959
4.1	North Punjab Plain, Ganga-Yamuna Doab, hot semi-arid, medium AWC, LGP90-120 days	SOC	0.0609	0.1056	0.1770	0.2307
		SIC	0.1103	0.1769	0.3636	0.9422
		TC	0.1712	0.2825	0.5406	1.1729
4.3	Ganga-Yamuna Doab, Rohilkhand and Avadh Plain, hot moist semi-arid, medium to high AWC, LGP 120-150 days	SOC	0.0517	0.0773	0.1535	0.2032
		SIC	0.0000	0.0285	0.1523	0.8566
		TC	0.0517	0.1058	0.3058	1.0598
9.1	Punjab and Rohilkhand Plains, hot/dry moist sub-humid transition, medium AWC and LGP 120-150 days	SOC	0.0786	0.0497	0.0997	0.1376
		SIC	0.0020	0.0046	0.0065	0.0098
		TC	0.0806	0.0543	0.0162	0.1474
9.2	Rohilkhand, Avadh and south Bihar Plains, hot dry sub-humid, medium to high AWCand LGP 150-180 days	SOC	0.0639	0.0961	0.1472	0.2391
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0639	0.0961	0.1472	0.2391
13.1	North Bihar and Avadh Plains, hot dry to moist sub-humid with low to medium AWC and 180-210 days LGP	SOC	0.0649	0.1370	0.2265	0.3440
		SIC	0.0000	0.4925	1.0187	2.0733
		TC	0.0649	0.6295	1.2452	2.4173
13.2	Foothills of Central Himalayas, warm to hot moist, high AWC and LGP 180-210 days	SOC	0.1024	0.1391	0.2503	0.3054
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.1024	0.1391	0.2503	0.3054
15.1	Bengal Basin and north Bihar Plains, hot moist sub-humid with medium to high AWC and LGP 210-240 days	SOC	0.0985	0.1530	0.2474	0.2407
		SIC	0.0050	0.0251	0.0488	0.0598
		TC	0.1035	0.1781	0.2962	0.3005
15.3	Teesta, lower Brahmaputra Plain, hot moist humid to per-humid medium AWC and LGP 270-300 days	SOC	0.0542	0.0698	0.1511	0.1908
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0542	0.0698	0.1511	0.1908
16.1	Foot-hills of Eastern Himalayas, warm to hot per-humid, low to medium AWC and LGP 270-300 days	SOC	0.0096	0.0136	0.0208	0.0279
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0096	0.0136	0.0208	0.0279
16.2	Darjeeling and Sikkim Himalayas, warm to hot per-humid, low to medium AWC and LGP 270-300 days	SOC	0.0087	0.0091	0.0176	0.0246
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0087	0.0091	0.0176	0.0246
17.2	Purvachal (Eastern Range), warm to hot, per-humid, low to medium AWC and LGP >300 days	SOC	0.0005	0.0008	0.0016	0.0020
		SIC	0.0005	0.0000	0.0000	0.0000
		TC	0.0005	0.0008	0.0016	0.0020
18.5	Gangetic delta, hot moist, sub-humid to humid, medium AWC and LGP 240-270 days	SOC	0.0122	0.0147	0.0221	0.0309
		SIC	0.0005	0.0000	0.0000	0.0000
		TC	0.0122	0.0147	0.0221	0.0309
	Total	SOC	0.6283	0.8990	1.5600	2.0000
		SIC	0.1317	0.7500	1.9600	4.5800
		TC	0.7600	1.6490	3.5200	6.5800

AESRs = agro-ecological sub-regions; SOC= soil organic carbon; SIC= soil inorganic carbon; TC = total carbon

Srinivasarao *et al.* [36] revealed that to develop a relationship between inputs of SOC with SOC stock. The input of SOC has been estimated based on biomass yield, input of organic residue, including FYM, fertilizers and leaf fall to soils. The input of organic matter is also well correlated with organic carbon stock (r = 0.732) (Figure 5). The C saturation level in the soil of semiarid tropics is estimated to be 73.21 Mg ha^{-1} up to 60 cm soil depth. Vertisols and associated soils have relatively greater total soil carbon stock than other soil types, whereas soils of regions with less rainfall show larger inorganic C content than those of regions with more rainfall. Amount of rainfall is significantly related with the amount of organic C stocks as well as soil N. Hao *et al.* [37] who observed that application of inorganic fertilizer alone did not significantly improve TOC content as compared to the control, while the application of inorganic fertilizer along with manure or straw significantly increased TOC content. Chen *et al.* [38] found that SOC stocks increased in topsoil of double rice-cropping systems with increases in experimental duration. Additionally the SOC sequestration rate in 0–30 cm soil depth was observed to be higher than in single-rice paddy soils or upland soils. Long-term straw mulching could build soil organic matter level and N reserves, increase the availability of macro- and micro- nutrients, and subsequent nutrient transformations.

While intensive tillage practices enhance the decomposition of SOM, no-till practices generally enhance the TOC concentration in surface soil. No-till provides greater physical protection to macro-aggregate protected TOC than with CT but mostly at soil surface [39]. The higher TOC content and stock found in CA were due to better preservation of the SOM originally present in the soil and/or less mineralization of surface retained organic residues [40]. Kanchikerimath and Singh [41] also found that inorganic fertilizers plus organic material increased the SOC content of the soil. The reasons for the higher SOC in manure soils at deeper depths include the following. First, the crop rooting depth between organic manure and inorganic fertilizer soils differ. The organic manure soils can be favorable for the growth of roots into deeper layers due to the relatively loose soil and high soil water content. Second, SOC in organic manure soils can also move to lower depths through earthworm burrows and leaching [42]. Fan *et al.* [43] reported that the SOC stock in the 0–60 cm depth displayed a net decrease over 20 years under treatments without fertilizer P or N, and in contrast, increased by proportions ranging from 3.7% to 31.1% under the addition of compost and fertilizer N and P. The stabilization rate of exogenous organic carbon (C) into SOC was only 1.5% in NPK-treated soil but amounted to 8.7% to 14.1% in compost-amended soils [compost (CM) and half compost N plus half fertilizer N (HCM)]. The total quantities of sequestered SOC were linearly related (P b 0.01) to cumulative C inputs to the soil, and a critical input amount of 2.04 Mg C ha^{-1} yr^{-1} was found to be required to maintain the SOC stock level.

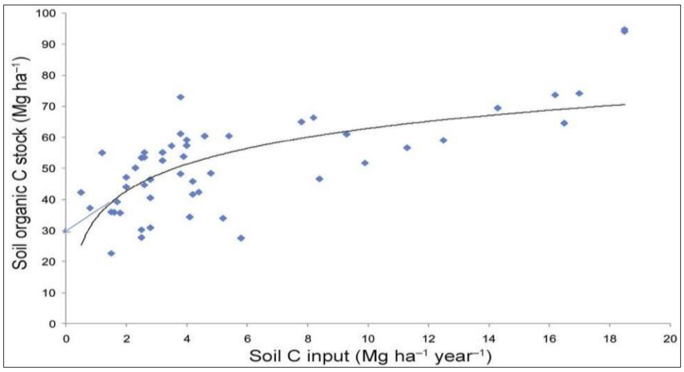


Fig 2: Soil organic carbon stock (Mg ha^{-1}) expressed as a function of carbon input levels (Mg ha^{-1} $year^{-1}$) for the semiarid tropical region of South India

Table 4: Organic carbon and calcium carbonate content of some representative soils from various agro-eco sub-regions (AESRs) of the IGP, India

Horizon	Depth (cm)	pH water	CEC {cmol(+)kg^{-1}}	Organic carbon (Percent)	Calcium carbonate equiv. (Percent)
AESR 13.2(MAT 22ºC; MAP 1500mm; LGP 180-210 days) *Aquic Hapludolls* (Uttar Pradesh)					
Ap	0-15	7.1	26.9	2.1	0.0
A1	15-38	8.0	24.3	1.4	0.0
Bg1	38-53	8.3	21.5	1.1	1.2
Bg2	53-66	8.3	13.9	0.7	2.7
Cg1	66-94	8.4	10.0	0.5	2.5
Cg2	94-135	8.4	8.9	0.4	2.6
AESR 9.1(MAT 25ºC; MAP 800mm; LGP 120-150 days) *Typic Haplustepts* (Punjab)					
A1	0-15	9.3	10.3	0.42	1.0
A2	15-28	10.1	11.1	0.21	1.0
Bw1	28-60	10.5	9.2	0.07	1.0
Bw2	60-72	10.5	11.7	0.08	1.0
Bw3	72-98	10.2	12.5	0.07	1.0
Bw4	98-135	10.0	14.0	0.08	1.0
AESR 4.1 (MAT 25ºC; MAP 700mm; LGP 90-120 days) *Typic Natrustalfs* (Haryana)					
A1	0-5	10.4	10.2	0.30	0.5
A2	5-24	10.3	12.8	0.30	0.9
Btn1	24-56	9.8	14.8	0.20	1.4
Btn2	56-85	9.8	14.6	0.20	3.3
BCkn	85-118	9.6	11.2	0.10	12.4
Ckn	118-140	9.2	9.8	0.10	20.5
AESR 2.1 (MAT 27ºC; MAP 218mm; LGP < 60 days) *Typic Camborthids* (Rajasthan)					
A	0-20	8.5	6.0	0.01	1.4
Bw1	20-53	8.5	6.1	0.01	6.4
Bw2	53-110	8.6	8.1	0.01	10.2
Ck1	110-144	8.6	7.0	0.01	11.0
Ck2	144-168	8.4	8.5	0.08	11.3
Ck3	168-180	8.5	10.2	0.01	3.9
AESR 15.1(MAT 26ºC; MAP 1500 mm; IGP 210-240 days) *Typic Endoaqualfs* (West Bengal)					
Ap	0-14	6.4	13.7	0.48	0.5
BA	14-38	6.9	15.0	0.20	0.9
Bt1	38-98	7.2	22.5	0.19	1.4
Bt2	98-150	7.5	25.6	0.10	2.3

AESR 16.1 (MAT 23ºC; MAP 2600-3000 mm; LGP 270-300 days) *Humic Dystrudepts* (West Bengal)					
Ap	0-25	5.0	6.5	1.4	Nil
Bw1	25-75	5.6	6.2	0.7	Nil
Bw2	75-150	5.7	7.5	0.6	Nil
AESR 16.2 (MAT 14ºC; MAP >2500 mm; LGP 270-300 days) *Humic Dystrudepts* (West Bengal)					
Ap	0-25	4.6	9.3	3.2	Nil
Bw1	25-75	4.6	7.2	1.3	Nil
Bw2	75-150	4.7	8.4	1.3	Nil
AESR 15.3 (MAT 25ºC; MAP 2000-3200; LGP 270-300 days) *Typic Dystrudepts* (Assam)					
Ap	0-25	4.5	13.6	1.84	Nil
B1	25-75	4.5	12.8	1.60	Nil
B2	75-150	4.6	14.4	0.86	Nil
AESR 18.5 (MAT ~26.7ºC; MAP 1900 mm; LGP 240 - 270 days) *Typic Haplaquept* (West Bengal)					
Ap	0-25	6.6	22.0	0.7	Nil
Bw1	25-75	7.5	25.7	0.2	Nil
Bw2	75-150	7.8	26.1	0.2	Nil
Bg3	43-65	5.0	14.6	0.6	Nil
Bg4	65-115	5.2	15.6	0.5	Nil
AESR 17.2 (MAT ~22ºC; MAP >3000 mm; LGP > 300 days) *Typic Epiaquept* (Tripura)					
Ap	0-13	5.5	7.8	1.3	Nil
Bg1	13-24	5.4	8.4	1.1	Nil
Bg2	24-43	5.3	8.9	0.4	Nil
Bg3	43-65	5.0	14.6	0.6	Nil
Bg4	65-115	5.2	15.6	0.5	Nil

MAT – Mean Annual Temperature; MAP – Mean Annual Precipitation; LGP – Length of Growing Period

The total carbon stock (TC) in different agro-ecological regions (Sehgal *et al.*, 1992) of the IGP indicates that the AERs 4 and 13 (hot semi-arid and hot sub-humid moist) have the highest carbon stock followed by AERs 2, 9 and 15 (hot arid, hot sub-humid, dry and hot sub-humid, moist to humid) (Table 3). The contribution of SOC stock in the overall total carbon stock decreases with depth and SIC stock increases, indicating an inverse relation between these two forms of carbon (Table 3). The SOC, SIC & TC stocks of each AESR at 30, 50, 100 and 150 cm depth of soils are shown in Table 3. The AERs 4 and 13 have the highest carbon stock followed by AERs 2, 9 and 15. Due to their low areal extent other AERs have poor TC stock. It is observed that the contribution of OC stock over the TC stock in the IGP decreases from 83% at 30 cm depth to 30% at 150 cm depth whereas SIC increases at the corresponding soil depth.

The poor base soils under humid tropical climate with relatively high annual rainfall (*Dystrustepts* / *Haplustepts* and Ultisols) with similar pH and CEC can differ in terms of content of OC due to cool or warm winter months [33]. The mere presence of cool winter in many parts of the IGP covering northern states of Punjab and Haryana, does not, however, allow a higher SOC build up except in the cooler *Terai* areas (AESR 13.2) with Mollisols (Tables 5 and 6).

Higher accumulation of OC in soils is related to vegetative cover supported by high rainfall. The combined influence of rainfall, temperature and other substrate (soil) quality determines the amount of OC accumulated in soils to qualify them as Mollisols, or other orders like Alfisols, Aridisols, Entisols and Umbric intergrades of Inceptisols commonly observed in the IGP (Table 6). This indicates that the most conducive condition favouring accumulation of OC in soils of the IGP should be humid to per-humid climate punctuated with a cool winter for 2-3 months.

Venkanna *et al.* (2014) reported that the soil organic carbon (SOC) stock was highest in Alfisols (52.84 Mg ha^{-1}) followed by Inceptisols (51.26 Mg ha^{-1}) and Vertisols and associated soils (49.33 Mg ha^{-1}), whereas soil inorganic carbon (SIC) stock was highest in Vertisols and associated soil (22.9 Mg ha^{-1}) followed by Inceptisols (17.5 Mg ha^{-1}) and Alfisols (12.4 Mg ha^{-1}). Among the different land-use systems, total C stock was highest in forest soils followed by fodder system, paddy, maize, cotton, redgram, intercrop, chilli, permanent fallow and lowest in castor system. Bhattacharyya *et al.* [4] reported that the SOC stock of Entisols ranges between 0.08 and 0.27 Pg in the upper 30 cm to 150 cm depth, respectively. The SIC stock increases down the depth (Table 7). Total SIC stock in these soils is 1.05 Pg (Table 7). The total carbon (TC) stock in Entisols is 1.32 Pg in the first 150 cm soil depth which is approximately 20 percent of the TC stock in the IGP (Tables 5 and 7).

Table 5: Carbon stock in various soil orders of the IGP, India *(Values in Pg)*

Soil orders	Carbon	Soil depth range in cm			
		0-30	**0-50**	**0-100**	**0-150**
1. Entisols	SOC	0.080	0.130	0.250	0.274
	SIC	0.010	0.270	0.610	1.050
	TC	0.090	0.400	0.860	1.324
2. Inceptisols	SOC	0.330	0.480	0.790	1.152
	SIC	0.030	0.310	0.660	1.444
	TC	0.360	0.790	1.450	2.596
3. Alfisols	SOC	0.100	0.150	0.250	0.284
	SIC	0.080	0.160	0.340	1.372
	TC	0.180	0.310	0.590	1.656
4. Mollisols	SOC	0.120	0.150	0.250	0.269
	SIC	0.000	0.000	0.000	0.115
	TC	0.120	0.150	0.250	0.385
5. Aridisols	SOC	0.001	0.020	0.023	0.021
	SIC	0.008	0.014	0.348	0.610
	TC	0.009	0.03	0.371	0.631
TOTAL	SOC	0.630	0.910	1.560	2.000
	SIC	0.130	0.750	1.960	4.587
	TC	0.760	1.660	3.520	6.587

Table 6: Carbon stock in Mollisols of the IGP, India *(Values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Aquic Hapludolls	SOC	0.0980	0.1211	0.2083	0.2201
	SIC	Nil	Nil	Nil	0.1155
	TC	0.0980	0.1211	0.2083	0.3356
Typic Hapludolls	SOC	0.0183	0.0260	0.0420	0.0492
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0183	0.0260	0.0420	0.0492
Total	SOC	0.1163	0.1471	0.2503	0.2693
	SIC	0.0000	0.0000	0.0000	0.1155
	TC	0.1163	0.1471	0.2503	0.3848

Table 7: Carbon stock in Entisols of the IGP, India *(Values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Typic Torripsamments	SOC	0.0007	0.0011	0.0016	0.0021
	SIC	0.0049	0.0084	0.0180	0.0286
	TC	0.0056	0.0095	0.0196	0.0307
Typic Ustipsamments	SOC	0.0025	0.0037	0.0073	0.0098
	SIC	0.000	0.000	0.000	0.000
	TC	0.0025	0.0037	0.0073	0.0098
Typic Ustifluvents	SOC	0.0610	0.0999	0.1941	0.2097
	SIC	0.0029	0.2590	0.5815	0.9946
	TC	0.0639	0.3589	0.7756	1.2043
Typic Fluvaquents	SOC	0.0179	0.0266	0.0433	0.0524
	SIC	0.0000	0.0015	0.0104	0.0261
	TC	0.0179	0.0281	0.0537	0.0785
Total	SOC	0.0821	0.1313	0.2463	0.2740
	SIC	0.0078	0.2689	0.6099	1.0493
	TC	0.0899	0.4002	0.8562	1.3233

The SIC stock for other three subgroups namely *Typic Haplustepts*, *Aeric Endoaquepts*, and *Udic Haplustepts* are also substantial in the first 150 cm depth of soils. The SIC stock of the Inceptisols in the first 30, 50, 100 and 150 cm depth of soils is shown in Table 8. The total C stock in the Inceptisols is 2.52 Pg in the first 150 cm which is 38 per cent of the total C stock of the soils of IGP (Tables 5 and 8). The total carbon stock in the Alfisols ranges from 0.1823 to 1.6536 Pg in the first 30 to 150 cm depth of soils, respectively. The highest content of total carbon at 150 cm of Alfisols corresponds to about 29 per cent of the total carbon stock of the IGP (Tables 5 and 9).

Table 8: Carbon stock in Inceptisols of the IGP, India *(Values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Aquic Haplustepts	SOC	0.0199	0.0277	0.0466	0.0592
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0199	0.0277	0.0466	0.0592
Fluventic Haplustepts	SOC	0.0380	0.0598	0.1086	0.2036
	SIC	0.0000	0.2212	0.3686	0.7584
	TC	0.0380	0.2810	0.4772	0.9620
Udic Haplustepts	SOC	0.0314	0.0500	0.0957	0.1441
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0314	0.0500	0.0957	0.1441
Vertic Endoaquepts	SOC	0.0341	0.0503	0.0669	0.0827
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0341	0.0503	0.0669	0.0827
Typic Endoaquepts	SOC	0.0297	0.0280	0.0621	0.0822
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0297	0.0280	0.0621	0.0822
Aeric Endoaquepts	SOC	0.0214	0.0297	0.0547	0.0714
	SIC	0.0000	0.0286	0.1142	0.2570
	TC	0.0214	0.0583	0.1689	0.3284
Typic Haplustepts	SOC	0.1479	0.2247	0.3351	0.4845
	SIC	0.0307	0.0561	0.1801	0.4283
	TC	0.1786	0.2808	0.5152	0.9128

Humic Dystrudepts	SOC	0.0096	0.0136	0.0208	0.0278
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0096	0.0136	0.0208	0.0278
Total	SOC	0.3320	0.4798	0.7905	1.1520
	SIC	0.0307	0.3059	0.6629	1.4437
	TC	0.3630	0.7857	0.7857	2.5292

Table 9: Carbon stock in Alfisols of the IGP, India *(Values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	**0-50**	**0-100**	**0-150**
Typic Natrustalfs	SOC	0.0547	0.0827	0.1293	0.1317
	SIC	0.0159	0.0345	0.2154	1.0289
	TC	0.0706	0.1172	0.3447	1.1594
Aquic Natrustalfs	SOC	0.0112	0.0187	0.0331	0.0442
	SIC	0.0666	0.1084	0.1039	0.3094
	TC	0.0778	0.1271	0.1370	0.3536
Aeric Endoaqualfs	SOC	0.0165	0.0258	0.0418	0.0580
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0165	0.0258	0.0418	0.0580
Typic Endoaqualfs	SOC	0.0153	0.0228	0.0422	0.0501
	SIC	0.0021	0.0147	0.0257	0.0337
	TC	0.0174	0.0375	0.0679	0.0838
Total	SOC	0.0977	0.1500	0.2464	0.2840
	SIC	0.0846	0.1576	0.3450	1.3720
	TC	0.1823	0.3076	0.5914	1.6536

The total carbon stock ranges from 0.1163 to 0.3848 Pg in the first 30 to 150 cm depth of soils, respectively. The total carbon stock in Mollisols has a share of 8.1 per cent of the total carbon stock of the IGP (Tables 6 and 7). The SIC stock ranges from 0.0076 to 0.6096 Pg in first 30 to 150 cm of soils, respectively. The total carbon stock ranges from 0.0088 to 0.6306 Pg in similar depth ranges and account for 1 per cent to 9.6 per cent of the total carbon stock of the IGP (Tables 6 and 10).

Table 10: Carbon stock in Aridisols of the IGP, India *(Values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	**0-50**	**0-100**	**0-150**
Typic Camborthids	SOC	0.0001	0.0010	0.0023	0.0053
	SIC	0.0048	0.0080	0.0181	0.0295
	TC	0.0049	0.0090	0.0204	0.0348
Typic Calciorthids	SOC	0.0011	0.0174	0.0206	0.0157
	SIC	0.0028	0.0060	0.3296	0.5801
	TC	0.0039	0.0234	0.3502	0.5958
Total	SOC	0.0012	0.0184	0.0229	0.0210
	SIC	0.0076	0.0140	0.3477	0.6096
	TC	0.0088	0.0324	0.3706	0.6306

SOC and SIC stock in the IGP, India and World

The SOC and SIC stock of the IGP, India, tropical regions and the world shows in Table 11. It is interesting to note that SOC stock of the IGP constitutes 6.45% of the total SOC stock of India, 0.30% of the tropical regions and 0.09% of the world in the first 30 cm depth of soils. The corresponding values for SIC are 3.20% for India, 0.17% for tropical regions and 0.06% for world, respectively. Therefore it indicates that IGP has only 3% SOC stock of the country. The impoverishment of SOC in the IGP as compared to tropical regions and world in general and to India in particular is thus apparent.

Table 11: Carbon stock in IGP, India and other regions

Region IGP, India	Soil depth range (cm)		
	0-30	**0-100**	**0-150**
	<——————————---------- Pg——————————------------->		
SOC	0.63 (6.45/0.30/0.09)*	1.56 (6.23/0.39/0.10)*	2.00 (6.67/0.32/0.08)*
SIC	0.13 (3.20/0.17/0.06)*	1.96 (8.76/0.93/0.27)*	4.58 (—/—/—)*
Total	0.76 (5.50/0.27/0.0.08)*	3.52 (7.42/0.58/0.16)*	6.58 (10.28/—/—)*
India[1]			
SOC	9.77	25.04	29.97
SIC	4.06	22.37	34.03
Total	13.83	47.41	64.00
Tropical Regions[2]			
SOC	207	395	628
SIC	76	211	—
Total	283	604	—
World[2]			
SOC	704	1505	2416
SIC	234	722	—
Total	938	2227	—

* Values in parentheses indicate % of stock in India, Tropical Regions and the world respectively, Bhattacharyya *et al.* [44] and Batjes [45]

Carbon pools in different size aggregates

Different carbon pools influence aggregation differently and also SOM is influenced by aggregate turn over [46, 47]. Thus C content in aggregates and their size are interdependent. C pools in soil aggregates provide substantial view on decomposition and the storage capacity of carbon in different aggregate size fractions. Suitable management practices help in protection of carbon pools in soil aggregates. The distribution of the C fraction among soil aggregate size fractions is variable [48]. On the basis of turn over time C pool is classified as Active, Slow and Intermediate pools. Active pools change seasonally and influence aggregation [39]. Soil carbon concentrations alter gradually over time because of their bulk quantity [49]. Particulate organic carbon is reflected as transitional pools in soil carbon dynamics and acts as a substrate for microbial activity (Six *et al.*, 1999). Results show that, except for maize–wheat system, cultivation resulted in significant decline (10 to 17%) of macro-aggregates compared to uncultivated soils. Whereas, the proportion of micro-aggregates were higher under croplands than in uncultivated soils. Ploughing causes aggregates to break down resulting in increase in the proportion of micro-aggregates and silt and clay-sized particles in the soil [50]. Maysoon and Rice [51] also showed that manure application increased macro-aggregate- protected labile C as compared with mineral fertilizer. It seems that physical protection of labile C in macro-aggregates is a dominant factor for SOC enhancement and thus for C sequestration in paddy soils. Jin *et al.* [52] indicated that OC in sediments was associated with the fine silt and clay primary particles and that these particles were probably found in the field within 250–20 µm aggregates in the deposited sediments.

The organic carbon storage was the highest in the aggregate of < 0.25 mm in Ust-Sandiic Entisols and Los-Orthic Entisols, and in the aggregate of > 5 mm in Hap-Ustic Isohumisols and Eum-Orthic Anthrosols. The soil organic carbon content and storage under different types of vegetation had the trend of natural forestland > bare land > artificial forest land > farming land.

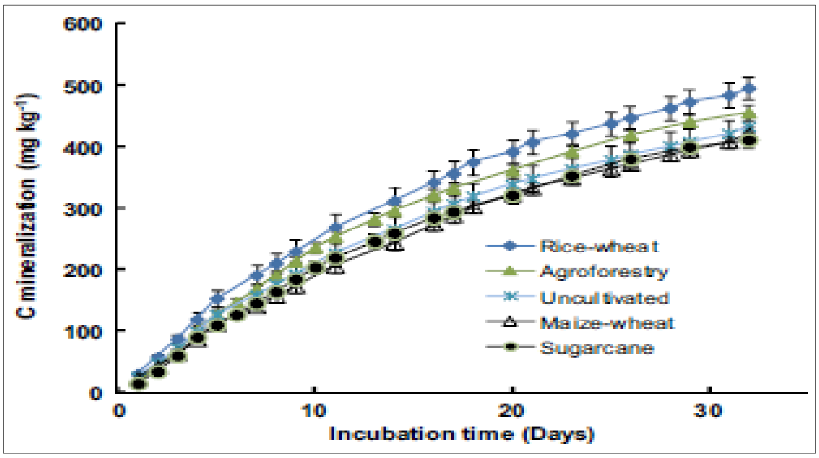
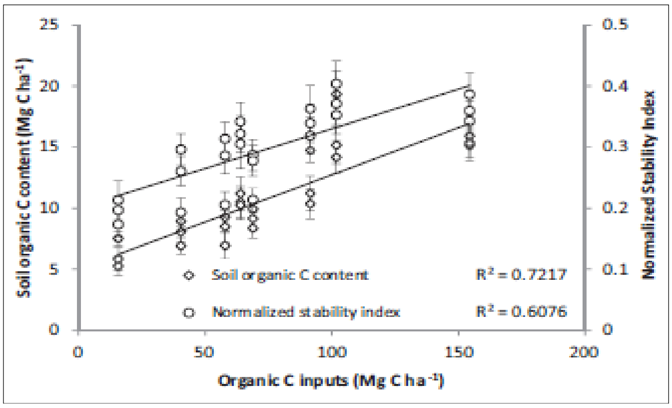


Fig 3: Cumulative C mineralization in 32 days of incubation at 25 °C in uncultivated soils and the soils under agro-forestry, maize–wheat, rice–wheat, and sugarcane agro-ecosystems. Line bars indicate standard error

Kushwa *et al.* [53] reported that in 0- to 5-cm soil layer, highest and lowest SOC was observed in no tillage (NT) (8.8 g kg^{-1}) and conventional tillage (CT) (5.9 g kg^{-1}), whereas in 5- to 15-cm soil layer, higher SOC was observed in mouldboard tillage (MB). The stratification ratio of SOC was higher in NT (2.20) followed by reduced tillage (RT) (1.93), MB (1.68) and CT (1.51). Higher available phosphorous concentration (12.8 g kg^{-1}) was recorded in NT with $N_{50\%}$ followed by NT with $N_{100\%}$.

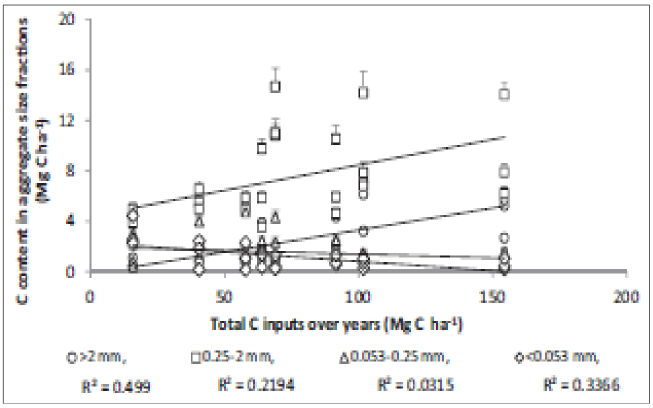
Carbon in bulk soil

The increase in SOC concentration at the soil layer is attributed to the presence of crop residue and relatively less soil disturbance by tillage operation in NT and RT. Besides this, the organic matter below the surface, including the previous crop's roots, was left undisturbed and thus was under slower decay process owing to less oxidative microclimate in conservation tillage (NT and RT) treatment [47]. The increase in SOC in mouldboard plough treatment at 5- to 15- and 15- to 30-cm depth interval might be the consequence of turning down crop residue to a depth between 15 and 20 cm annually during mouldboard ploughing, while with continuous no-tillage, plant residues remain on the surface [54] concentration in MB in top 5-cm soil depth was less compared to NT and RT due to heavy disturbance and fine tilth of the surface soil by rotavator tillage before sowing of wheat crop. This might have resulted in breakdown of the topsoil aggregates and promoted faster decomposition of the added residue due to more oxidative environment in the topsoil [55].



a

Fig 4a: Relations between organic C inputs, soil organic C content and stability index of aggregates

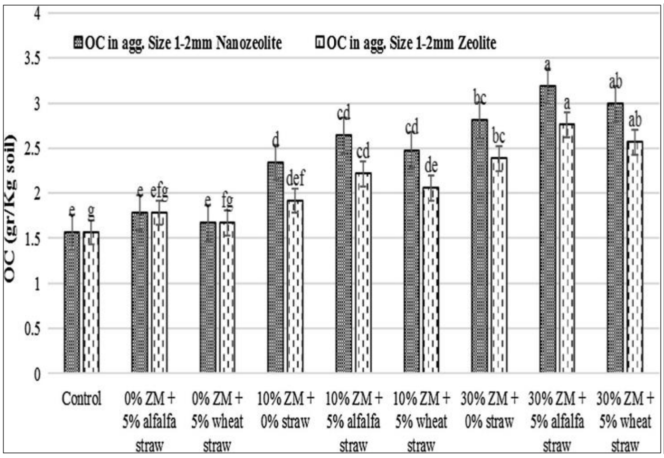


b

Fig.4b: The C contents in soil aggregate fractions as influenced by total C inputs to the soil.

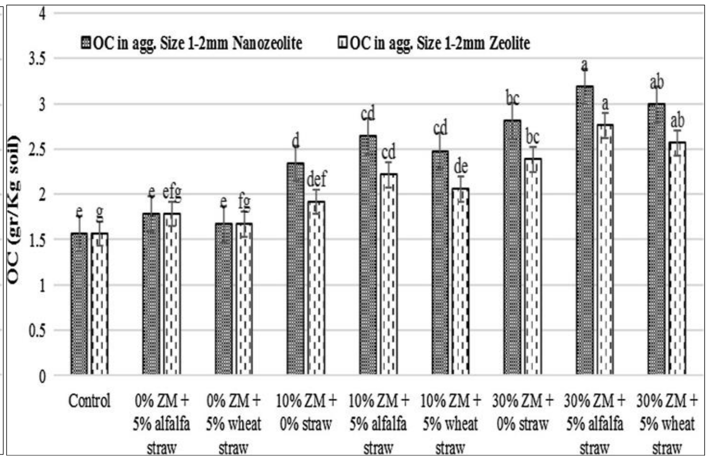
Soil organic C content linearly increased with C inputs (R^2 = 0.72; p < 0.001) (Figure 4a). Similarly, significant positive linear relationship was obtained between C inputs and aggregate stability (R^2 = 0.60; p < 0.001). Significant positive relations were also obtained between total C inputs and both the LM (R^2 = 0.50; p < 0.0001) and the SM (R^2 = 0.22; p = 0.004) C fractions (Figure 4b). However, no significant relation was obtained between mi-C and C inputs (R2 = 0.03; p = 0.41), but sc-C content decreased significantly with increase in C inputs (R^2 = 0.34; p = 0.003). Stewart *et al.* (2009) reported that the soil C saturation must take into consideration different pools of C in soil along with the bulk soil C. There is a preferential accumulation of C in macro-aggregates, while the soil structural stability improves with greater macro-aggregation. The small (0.025–2 mm) fraction comprises greater portions (33–65%) of the soil, and therefore has a larger contribution in soil C built up. While the coarse fractions of POM in macro-aggregates have greater C content, it consists of an insignificant 9–14% of macro-aggregate amount. On the contrary, the micro-aggregates fractions within macro-aggregates contribute to nearly 2/3rd of macro-aggregates, and might significantly contribute in C sequestration. However, variations among the treatments in terms of bulk soil and aggregate associated C fractions show the varying impact of kind and source of organic inputs, which need to be explored. It is imperative that the quality of C inputs is as important as its quantity to realize the short- and long-term C sequestration in soils through balanced fertilization.

Milad *et al.* [56] reported that the amount of OC increased with the additions of the higher percentages of nanozeolite, zeolite, and plant residues, particularly alfalfa straw, in aggregate size 1–2 mm (Figure 5b), OC was maximum compared with the control and other treatments. Figure 6a showed the amount of OC increased in aggregate size range of 0.25–1 mm with the additions of nanozeolite and zeolite, especially nanozeolite, and also addition of plant residues, particularly alfalfa straw; the amounts of OC were 2.76 and 2.36 (g Kg_{soil}^{-1}). However, the amounts of OC were higher in each aggregate size fraction in the treated soil with nanozeolite and alfalfa straw than that in the treated soil with zeolite and alfalfa straw (Figure 5a; 5b & 6a; 6b).



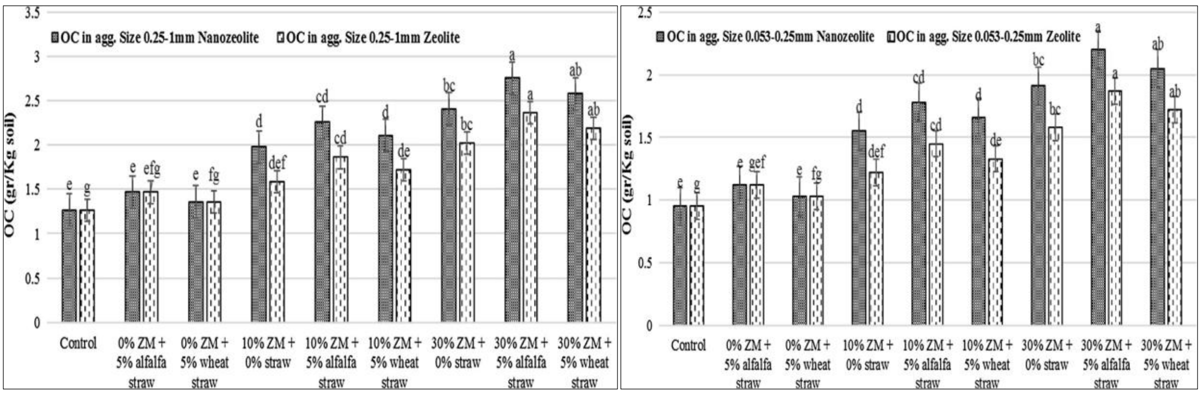
a

Fig 5a: Comparison of OC (g/Kg soil) in aggregate size>2 mm in treated soil by zeolitic size>2 mm in treated soil by zeolitic materials (ZM) and plant residues,



b

Fig 5b: Comparison of OC (g/Kg soil) in aggregate size (1–2) mm in treated soil by zeolitic materials (ZM) and plant residues



a b

Fig 6a: Comparison of OC (g/Kg soil) in aggregate (0.25–1) mm in treated soil by zeolitic materials (ZM) and plant residues, **Fig 6a**: Comparison of OC (g/Kg soil) in aggregate size (0.053–0.25) mm in treated soil by zeolitic materials (ZM) and plant residues

Sui *et al.* [57] reported that crop residue addition has the greatest impact on increasing LM-C content. Impact of green gram residue in rice followed by FYM in wheat is better than FYM in rice only, in increasing LM-C fraction. In general, C content decreased as LM > SM > sc > mi (with residue and/or FYM); SM > LM > mi > sc (SPM addition); and LM > SM > sc > mi (inorganic N only). The SOM is essential to control erosion, optimize water infiltration and conserve nutrients[58]. Stratification of SOM occurs when the soils remain undisturbed for a considerable period of time like the case of NT systems. Increasing cropping intensity and management with conservation tillage also result in greater stratification of different organic matter fractions [58]. Fewer disturbances and mixing of soil preserve crop residues and soil organic matter near the soil surface from decomposition, where it has the most beneficial impact. In a study Franzluebbers and Studemann [59], it was reported that during pasture development, stratification ratio of soil organic C (0- to 15-cm/15- to 30-cm depth) increased from 2.4 at initiation to 3.0 ? 0.7 at the end of 5 years to 3.6? 0.6 at the end of 12 years.

Nayak *et al.* [60] revealed that the significant linear positive response to C additions indicates potential of C sequestration in this soil. The slope of the relationship between total C inputs and soil organic C content indicates an additional 7.7%

of C can be accumulated with additional organic C inputs. However, the sequestration efficiency of added C **(**^SOC/DC input**)** in the nutrition treatments over control shows a logarithmic trend.

Sombrero and de Benito [61] reported that at a depth of 0–10 cm, the SOC content was significantly higher with no tillage (NT) than conventional tillage (CT) or minimum tillage (MT), by 58% and 11%, respectively. SOC values were 41% higher with MT, in turn, than with CT. At a depth of 10–20 cm, the SOC content was 30% higher with NT than with CT and 7% higher than with MT and at 20–30 cm, it was 7% higher with MT than with CT, 12% higher with NT than CT and 9% higher with NT than MT. Zhang *et al.* [62] revealed that the content of soil total organic carbon (TOC) and organic C fractions (that is, water soluble organic C, easily oxidizable organic C, particulate organic C, humus C and black C) were higher in the sustainable agricultural practices (SAP) than in the conventional agricultural practices (CAP) treatment, respectively. Huang *et al.* [63] observed significantly more macro-aggregates and higher SOM content in the bulk soil and the >2 mm aggregate fraction for the NPK plus OM treatment compared with the other treatments. Zhou *et al.* [64] concluded that the application of NPK plus OM increased the size of sub-aggregates that comprised the macro-aggregates. Also, they observed that long-term application of NPK plus OM improves soil aggregation and alters the three-dimensional microstructure of macro-aggregates, while NPK alone does not. Tripathi *et al.* [65] reported that higher C accumulation in macro-aggregates could be due to the lower decomposable SOM associated with these aggregates and also the direct contribution of SOM to the stability of macro-aggregates resulting in only C-rich macro-aggregates being able to withstand slaking due to zeolitic materials in the soil.

Potential of Soil Carbon Sequestration in IGP, India

Carbon sequestration in terrestrial ecosystems has two distinct but related components: sequestration in biomass (primarily trees comprising both the above ground and below ground components) and soil. A fraction of the biomass returned to the soil is converted into stable humic substances and related organo-mineral complexes with a long residence time. The effectiveness of soil C sequestration depends on the quantity and quality of biomass returned to the soil. In cropland soils, a principal source of biomass is the crop residues. It was reported that manure is more resistant to microbial decomposition than plant residues. Consequently, for the same carbon input, carbon storage is higher with manure application than with plant residues [66]. Among the organic materials treatments, the lowest organic carbon in soils was found in rice straw (RS) which attributed to the highest emission of CO_2 in this treatment. This may be due to the use of higher rates of N fertilizer in RS treatment compared to poultry manure (PM) and cow dung (CD), which may stimulate soil microbial activity and eventually increase the CO_2 emission. Therefore, treatments with inorganic nitrogen fertilizers favor degradation of organic matter, which ultimately result in low carbon content in soils. This is in agreement with the Halvorson *et al.* [67].

Grace *et al.* [68] reported that the simulations suggest a change to no-tillage across the rice-wheat region of India would increase SOC levels by an average of 5 Mg C ha^{-1} (or 19% when compared to the conventionally tilled wheat-rice systems) after 20 years. The largest change in SOC after 20 years was found in the high activity soils i.e. those with relatively higher clay contents in rice- wheat systems of West Bengal, where the IPCC model estimated that an additional 8.7 Mg C ha^{-1} was stored over 20 years when shifting from conventional tillage to no-tillage farming practices. The smallest gain in SOC over 20 years in response to changing tillage practices, 3.6 Mg C ha^{-1},was found in the coarser-textured soils of Punjab and Haryana States under both rice-wheat and cotton-wheat systems (Table 12).

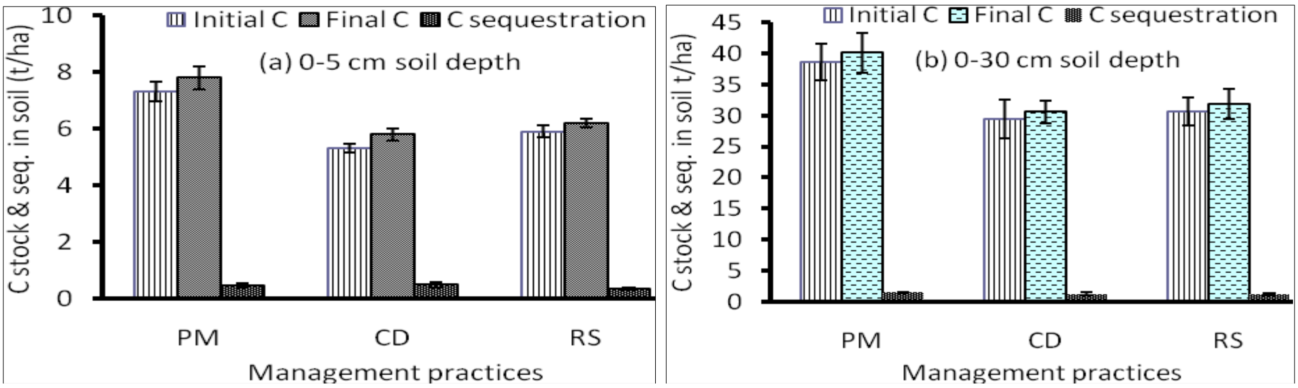


Fig 7: Carbon stock and sequestration (t ha^{-1}) in soils under different management practices after two crop seasons (Seq. = sequestration)

Table 12: Impact of tillage on SOC (0-30 cm) in Indian States of the Indo-Gangetic Plain.

Region/State	Soil type[a]	Gross SOC Stock [b] Mg C ha^{-1}		Net SOC Stock [c] Mg C ha^{-1}		SOC Change [d] Mg C ha^{-1}		SOC Change [e] Kg C ha^{-1} yr^{-1}	
Rice-Wheat		*Conv. till*	*No-till*	*Conv. till*	*No-till*	*Gross*	*Net*	*Gross*	*Net*
Bihar	lac	27.25	33.52	3.96	10.19	6.27	6.23	314	312
Haryana	lac	24.14	28.25	-7.96	-2.59	4.11	5.37	206	269
Haryana	san	21.39	25.03	-10.71	-5.81	3.64	4.9	182	245
Punjab	hac	26.22	30.68	-8.54	-2.84	4.46	5.7	223	285
Punjab	lac	24.15	28.25	-10.61	-5.26	4.1	5.35	205	268
Punjab	san	21.39	25.03	-13.37	-8.49	3.64	4.88	182	244
U.Pradesh	hac	26.22	30.68	-0.30	5.51	4.46	5.81	223	291
U.Pradesh	lac	24.15	28.25	-2.37	3.09	4.1	5.46	205	273
W.Bengal	hac	37.69	46.35	12.02	21.59	8.66	9.57	433	479
W.Bengal	lac	27.25	33.52	1.58	8.75	6.27	7.17	314	359

W.Bengal	san	22.61	27.81	-3.06	3.05	5.2	6.11	260	306
Maize-Wheat		*Conv. till*	*No-till*	*Conv. till*	*No-till*	*Gross*	*Net*	*Gross*	*Net*
U.Pradesh	lac	24.14	28.25	15.49	20.11	4.11	4.62	206	231
Cotton-Wheat		*Conv. till*	*No-till*	*Conv. till*	*No-till*	*Gross*	*Net*	*Gross*	*Net*
Haryana	lac	24.14	28.25	12.52	17.38	4.11	4.86	206	243
Haryana	san	21.39	25.03	9.77	14.16	3.64	4.39	182	220
Punjab	lac	24.14	28.25	10.98	15.83	4.11	4.85	206	243
Punjab	san	21.39	25.03	8.23	12.61	3.64	4.38	182	219

[a]lac = low activity soils, hac = high activity soils, san= sandy soil.
[b]Simulated SOC change (0-30cm) after 20 years.
[c]Simulated SOC change (0-30 cm) after 20 years and adjusted for associated greenhouse gas emissions.
[d]Net SOC change (0-30 cm) under the new technology relative to conservation tillage after 20 years.
[e]Average net SOC change (0-30cm) per annum under the new technology relative to conservation tillage.

Grace *et al.* [68] revealed that the average net SOC sequestration rate after 20 years for the rice-wheat system is estimated 15 to be 6.1 Mg C ha^{-1} under no-tillage, equivalent to a per annum SOC sequestration rates of 302 16 kg C ha^{-1} annum^{-1}. The conversion to no-till from conventional tillage in rice-wheat systems in West Bengal is the most productive in terms of potential carbon gains on an area basis. Whilst there is an average increase (across all soil types) of 7.6 Mg C after 20 years, the actual area under rice-wheat is small compared to the other States (Table 13). In terms of the total returns in C the implementation of no-tillage practices in rice-wheat systems across the IGP of India would sequester 44.1 Mt C over years (Table 13), with half of this in the State of Uttar Pradesh? India 2320 has more than 7.7 million hectares of conventionally tilled soils under rice-wheat with a potential of net C sequestration rate of 5.7 Mg C ha^{-1}. Chen *et al.* [69] have also reported that the RR/RI and application of organic manure increased the SOC concentration in soils under rice. Further, paddy soils play a key role in total C sequestration and a sink for global C [70]. Nath *et al.* [71] reported that the integrated use of organics with inorganic fertilizers enhances the productivity and appreciably increases the SOC over that in the control treatment.

Table 13: Distribution of tillage management and total net SOC sequestration potential and Proportion (%) of total net C sequestration achieved after (after 20 years) when implementing no-tillage practices in wheat based cropping systems of the Indo-Ganetic Plain

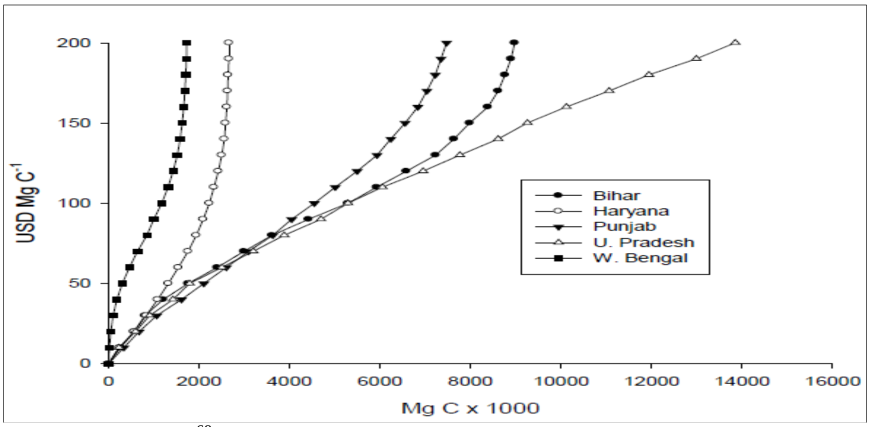
Region/State	**Land Area in System [a] ha x 1000**			**Proportion of Area %**		**Seq. Rate[b] Mg C ha^{-1}**	**Total C Seq.[c] Mt C**	**Carbon price (USD Mg C^{-1})**			
Rice-Wheat	*Conv.*	*No-till*	*Total[d]*	*Conv.*	*No-till*	*No-till*	*No-till*	*25*	*50*	*100*	*200*
Bihar	1493	18	1511	99	1	6.23	9.30	7.4	18.9	56.9	96.5
Haryana	517	350	867	60	40	5.14	2.66	26.4	49.8	84	100
Punjab	1535	215	1750	88	12	5.31	8.15	10.7	25.9	55.8	91.7
Uttar Pradesh	3948	175	4123	96	4	5.64	22.27	3.4	8	23.8	62.2
W. Bengal	233	0	233	100	0	7.62	1.78	4.5	17.3	66.4	97.5
Total R-W	7726	758	8484	89	11	-	44.15	7	16.5	42	78.6
Maize-Wheat											
Uttar Pradesh	570	0	570	100	0	4.62	2.63	4.9	13.6	35	77.8
Cotton-Wheat											
Haryana	603	0	603	100	0	4.62	2.79	1.9	4.2	12.2	31.6
Punjab	240	0	240	100	0	4.63	1.11	5.1	11.9	33.1	78
Total C-W	843	0	843	100	0	-	3.99	2.8	6.3	17.7	43.8

[a]estimate supplied by regional agronomists
[b]SOC sequestration per hectare after 20 years in response to management and derived from the net SOC change data in Table 10.
[c]Total additional SOC potentially sequestered after 20 years without economic constraints with all cropping area currently under conventional tillage converted to no-till cropping.
[d]Total area = conventional + no-tillage

Challenges in achieving potential of soil carbon sequestration in IGP, India

Climate change and food security posse's greatest challenge and threat in attaining the goals of sustainability with the present agriculture system. The world population of 6.7 billion in 2008 is increasing at the rate of 1.3%/yr and is projected to be 9.5 billion by 2050 before stabilizing at ~ 10 billion towards the end of the 21st century. Land degradation is a worldwide challenge, substantially affecting productivity in more than 80 countries and especially serious in developing countries. The impact of land degradation has already put at risk the livelihoods, economic well-being, and nutritional status of more than 1 billion people in developing countries [72]. Land degradation adversely affects the ecological integrity and productivity of about 2 billon ha, or 23 percent of landscapes under human use and up to 40 percent of the world's agricultural land are seriously degraded. India with 2.4% land area supports more than 17% of the world population. Achieving food security under the regime of climate change will require a holistic system approach, incorporating the principles of conservation agriculture (CA), and judicious crop rotation [73]. The potential soil C sink capacity of managed ecosystems approximately equals the cumulative historic C loss estimated at 55 to 78 Gt. However, the attainable soil C sink capacity is only 50 to 66% of the potential capacity [9]. Crop management (land preparation, variety, seed rate, sowing time, seed treatment, fertilizer, water, and pest management) has significant impact on carbon and nitrogen dynamics in soil[74]. As India with exploding population and depleting valuable resources, these objectives become crucial to solve the problems of reduced productivity and rapid loss of soil fertility influenced by climate change.

Therefore, carbon sequestration is caused by those management systems that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, enhance activity and species diversity of soil fauna, and strengthen mechanisms of elemental cycling. The stability of soil organic C with respect to microbial respiration is determined by inherent recalcitrance of organic compounds, interaction with stabilizing substances, and accessibility to microorganisms [75]. Conservation agriculture has the following four principles: (i) minimizing mechanical soil disturbance and seeding directly into untilled soil to improve SOM content and soil health; (ii) enhancing SOM using cover crops and/or crop residues (mainly residue retention). This protects the soil surface, conserves water and nutrients, promotes soil biological activity and contributes to integrated pest management; (iii) diversification of crops in associations, sequences and rotations to enhance system resilience and (iv) controlled traffic that lessen soil compaction [76]. Thus, CA avoids straw burning, improves SOC content, enhances input use efficiency and has the potential to reduce greenhouse gas emissions [77]. Crop residue management is key component of CT as well as CA and an important strategy for C sequestration. In India, over 620.4 million tons (Mt) of agricultural residues are produced every year (Jain *et al.*, 2014). In IGP, over 297.5 Mt of agricultural residues are produced every year, which is 47.9 % of the total CRs generated in India. However, 61.6 Mt of residue burnt every year in IGP, which is about 62.5 % of the total CRs burnt in India.



Source: Grace *et al.*[68]

Fig 8: Carbon supply curves (based on 20 year accumulation rates) for the Indo-Gangetic Plain of India when converting from conventional to no-tillage practices in rice-wheat cropping systems.

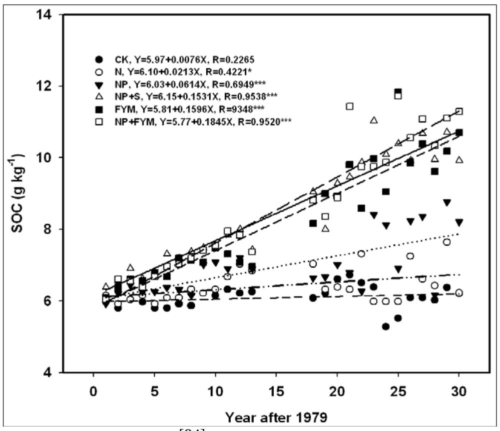
For maize-wheat, only one State (Uttar Pradesh) was analyzed, with an annual SOC sequestration rate under no-tillage of 206 kg C ha^{-1}. The sequestration rate in the cotton-wheat systems of Haryana and Uttar Pradesh ranged from 182-206 C ha^{-1} annum^{-1}. The relative magnitude of these changes are at the low end of the sequestration rates reported from the limited data that exists in northern India on the long-term impact of conservation tillage on SOC levels [78]. Grace *et al.* [68] reported that at this carbon price, a total of 34.7 Mt C (79% of the estimated C sequestration potential) could be sequestered over 20 years in rice-wheat systems of the IGP, with Uttar Pradesh contributing 13.9 Mt C. For the States of West Bengal and Haryana, where rice-wheat cropping only covers 750,000 ha (compared to nearly 4 Mha in Uttar Pradesh) there is little increase in the total amount of C sequestered across these States under no-tillage over 20 years once the carbon price exceeds USD 100 Mg C^{-1} (Figure 8). Collectively, maize-wheat and cotton-maize rotation systems are only found on 1.2 Mha of the IGP of India. In maize-wheat systems under no-till, a carbon price of USD 50 Mg C^{-1} would realize 252,000 Mg C, approximately 14% of the sequestration potential, increasing to 811,000 Mg C (or 35% of potential) at a carbon price of USD 100 Mg C^{-1}. For cotton-wheat, a carbon 15 price of USD 50 Mg C^{-1} would return 173,000 Mg C over 20 years, 6% of the simulated C 16 sequestration potential, increasing to 18% at a carbon price of USD 100 Mg C^{-1}(Figure 8).

The SOC sequestration potential for the NPK treatment was 1.54Mg C ha^{-1}, which was only 17% and 13% of the potential for the HCM and CM treatments, respectively. These results suggest that the studied soil would be saturated at a quite low level with long-term inorganic fertilizer application compared with long-term compost application. This was attributed mainly to the fact that compost application could improve soil aggregation and aggregate-associated organic C whereas inorganic fertilizer had no obvious effect [79]. Bhattacharyya *et al.* [80] found that the 15–30 cm soil layer was the most efficient in stabilizing applied organic C and that the proportion of applied manure C stabilized in this layer was 1.37 times the proportion in the 0–15 cm layer and 6.14 times the proportion in the 30–45 cm layer. However, with respect to the low C-retention capacity of the 20–40 cm soil layer (sandy soil) at the study site, organic C may have moved downward from the 0–20 cm layer, passed through the 20–40 cm layer, and been sequestered in the 40–60 cm soil layer. The results of the present study suggest that the SOC sequestration potential would be underestimated using topsoil only and that improving the depth distribution may be a practical way to achieve C sequestration.

Globally, principal residue management practices involve residue removal, residue incorporation and residue burning. Agricultural residues burning may emit significant quantity of air pollutants like CO_2, N_2O, and CH_4, which is responsible for global climate change and causes nutrient loss as well as soil degradation. One ton of wheat residue contains 4-5 kg N, 0.7-0.9 kg P, and 9-11 kg K (Singh and Sidhu [81]. Singh *et al.* [82] estimated 6 kg N ha^{-1} (15% of initial) in the sandy loam and 12 kg N ha^{-1} (27% of initial) in the silt loam from buried residue by maximum tillering stage. The amount of N released from the buried residue on the sandy loam increased to 12 kg ha^{-1} by the booting stage and to 26-28 kg ha^{-1} by maturity. The Indo-Gangetic Plain (IGP), breadbasket of South Asia also known as Indus-Ganga and the North Indian River Plain, is a 255 million hectare (630 million acre) fertile plain encompassing most of northern and eastern India, the most populous parts of Pakistan, Nepal and virtually all of Bangladesh. IGP now days are under serious stress due to stagnant productivity, loss of soil fertility, straw burning (soil degradation) and repercussions of climate change. To overcome these constrains the following objectives the drivers and indicators of soil carbon sequestration under CA of IGP. Tillage, residue incorporation (crop residue, cover crop, green manure, brown manuring) and crop diversification. Indicators: mineralogy, water stable aggregates, mean weight diameter, aggregate associated carbon, C:N ratio, DOC, DON, active and passive pool, MB-C, Earthworm (no. and height), carbon stock, C and N mineralization, SIC, fulvic and humic acid rate of nutrient release from different residue of crops under CA, Carbon and nitrogen mineralization, Residue decomposition and Nitrogen fixation and nitrate leaching loss. Naresh *et al.* [23] reported that higher SOC content of 8.14 g kg^{-1} of soil was found in reduced tilled residue retained plots followed by 10.34 g kg^{-1} in permanently wide raised bed with residue retained plots. Whereas, the lowest level of SOC content of 5.49 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots.

Soil organic C restoration in response to biomass-C input and no-till

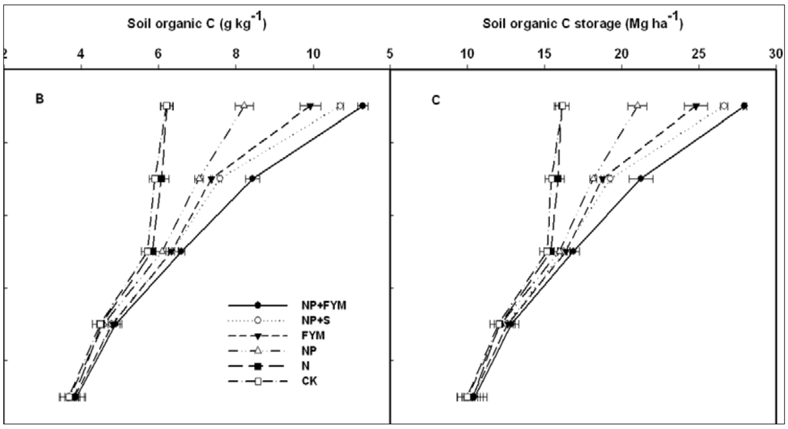
As widely reported in the literature, a strong correlation between SOC and total N is observed, emphasizing that SOC sequestration is closely related to N accumulation. Most of the increase in SOC stock observed in the soil under continuous no-till without any soil disturbance (CNT), as compared with that in the CT, was in the 0–5 cm (38%) and the 20–40 cm (48%) layers. In contrast, the same comparison showed an increase in SOC stock in the 2.5–5 cm (11%) and 20–40 cm (58%) layers under no-till with one chisel plowing (NTch) when compared with CT. These variations may result from different degree of mechanical disturbance amongst CNT and NTch treatments. While only the seedling zone is slightly disturbed in CNT, the chisel used in NTch disturbs the entire soil surface, increasing the decomposition rate of crop residues and the oxidation of SOC stock due high N mineralization rate. dos Santos *et al.* [83] also showed a close relationship between SOC stock and root C addition, and a poor relationship with total C addition and no relationship with shoot C addition.



Source: Liu *et al.* [84].

a

Fig 9a: Trend changes of soil organic carbon (SOC) at 0–20 cm top soil layer in a long-term fertilization experiment.



b

Fig 9b: Effect of long-term fertilizer applications on depth distribution of soil organic C (B) and soil organic C storage (C).

Liu *et al.* [84] reported that the topsoil (0–20 cm) had the maximum levels of cumulative SOC storage in the 1 m soil depth for the CK, N, NP, FYM, NP+S and NP+FYM treatments, accounting for 24%, 23%, 27%, 30%, 31% and 31%, respectively. At the 20–40 cm and 40–60 cm soil layers, the SOC stocks of the NP, FYM, NP+S and NP+FYM treatments were significantly higher by 17%, 21%, 25% and 37% and 5.3%, 8.1%, 7.3% and 11%, respectively, than that of the CK. The differences of SOC storage between different treatments were not significant in the 60–80 cm and 80–100 cm soil layers. SOC storages were significantly different between fertilization treatments in the 0–100 cm profile. Compared with the CK treatment, SOC storages of the NP+FYM, NP+S, FYM and NP treatments within the 0–100 cm soil depth were increased by nearly 30, 24, 20 and 12%, respectively. Wang *et al.* [85] indicated that soil organic matter was significantly greater to 30 cm in no-tillage with straw cover (NTSC), while total soil nitrogen was lower than traditional tillage with straw removal (TTSR) treatments. Han *et al.* [86] also observed that topsoil organic carbon (C) increased by 0.9 (0.7–1.0, 95% confidence interval (CI)) g kg^{-1} (10.0%, relative change, hereafter the same), 1.7 (1.2–2.3) g kg^{-1} (15.4%), 2.0 (1.9–2.2) g kg^{-1} (19.5%) and 3.5 (3.2–3.8) g kg^{-1} (36.2%) under UCF, CF, CFS and CFM, respectively. Naresh *et al.* [13] reported that the profile SOC stock differed significantly (P < 0.05) among treatments The highest SOC stock of 72.2Mg C ha^{-1} was observed in F_6 with T_6 followed by that of 64Mg C ha^{-1} in F_4 with T_2> that in F_3 with T_4 (57.9Mg C ha^{-1})> F_5 with T_1 (38.4Mg C ha^{-1})= F_7 with T_5 (35.8 Mg C ha^{-1}),and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_6 with T_6 treatment (56.3Mg C ha^{-1}) followed by F_4 with T_2 (51.4Mg C ha^{-1}) and F_3 with T_1 (48.4Mg C ha^{-1}).

The rate of SOC sequestration, through adoption of recommended management practices and in comparison with the baseline, may range from 50–500 kgha^{-1}yr^{-1} for semi-arid tropics to 500– 1,000 kg ha^{-1}yr^{-1} for humid temperate environment [87] Figure 10.

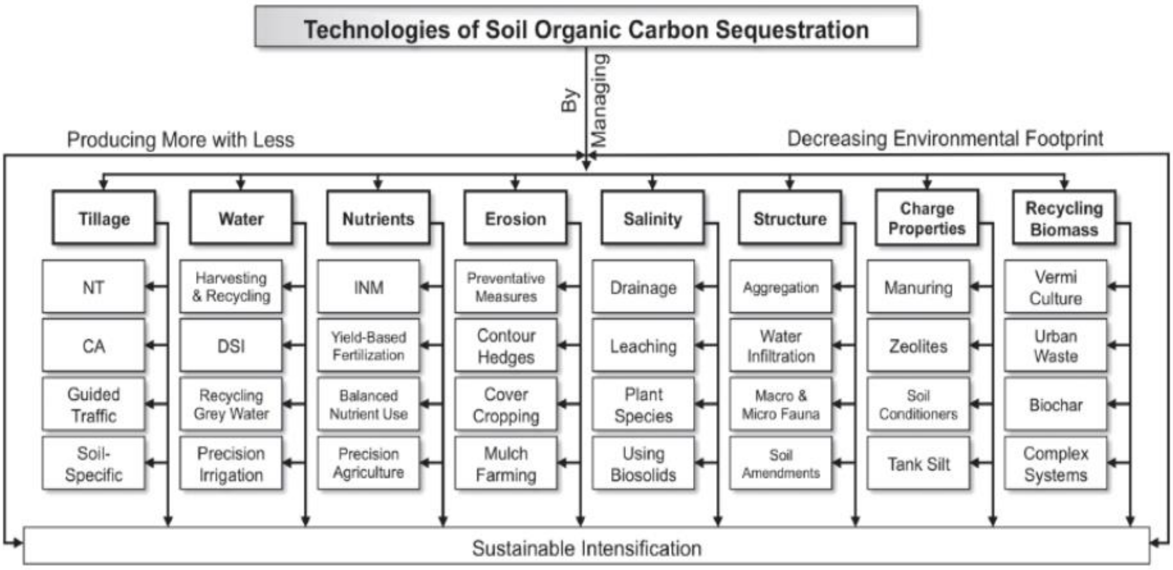


Fig 10: Strategies of creating a positive soil organic carbon budget and sequestering carbon in soil.

Gami *et al.* [88] also reported a significant increase in SOC stocks to 60 cm depth under three 23–25-year-old long-term fertility experiments in the Nepal, with application of manure and inorganic fertilizer. Within 1 m soil depth, the cumulative distribution of SOC in the CK, N, NP, FYM, NP+S and NP+FYM treatments were by 50%, 46%, 51%, 53%, 54% and 55% in the 0–40 cm layer, and 68%, 68%, 71%, 72%, 73% and 74% in the 0–60 cm layer, respectively. On average the estimate of soil C accumulation to 60 cm depth were 267% and 41% greater than that for soil C accumulated to 20 cm depth and to 40 cm depth, respectively. These findings suggest that the estimate of soil C accumulation to 60 cm depth was more effective than that for soil C accumulated to 40 cm. In this study, C input was increased under the N treatment compared to the CK. However, neither SOC concentration nor C storage was significantly changed under the N treatment. The reason for this is that the N treatment may stimulate soil microbial activity, therefore increasing the C output. The increase in C mineralization might offset the increase in C input. In a 3-yr study in a rice-wheat system, SOC content was 0.22% greater under no-tillage raised bed than under conventional tillage (Hossain, 2009). Studies on plains of Nepal revealed 9.89% greater SOC in 0–50 cm soil profile under no-tillage than under conventional tillage in a rice-wheat system [22].

The significant fraction of SOC under no-tillage was accumulated in surface soil with 28.3% greater SOC content in 0–5 cm depth of no-tillage system than that in the conventional tillage system. Tivet *et al.* [89] have reported that the humification degree of SOC in soil under CT can be higher than those under NT in 0–5 cm depth, indicating a release of labile SOC under CT as a result of the continuous and strong disruption of aggregates. In contrast, the higher protection of SOC by aggregates in soil under NT enhances labile SOC in each aggregate size fraction. Tivet *et al.* [90] showed that the difference in SOC stock among CT and NT systems is largely attributed to storage in large macro-aggregates, which are crucial for the physical protection of POC. Then, part of this fraction will become later stabilized through selective preservation by biochemical recalcitrance or interactions with mineral surfaces. Strategies of enhancing formation of secondary carbonates Figure 11. In comparison with SOC, however, there are a fewer options of SIC sequestration as secondary carbonates. There are 2 types of secondary carbonates: biogenic and geogenic. Formation of biogenic carbonates can be moderated through addition of manure and input of other sources of biomass-C, appropriate and crop rotations. The rate of formation of secondary carbonates, in soils of arid and semi-arid climates is 2-4 $kgC^{-1}ha^{-1}\ yr^{-1}$ [91, 92].

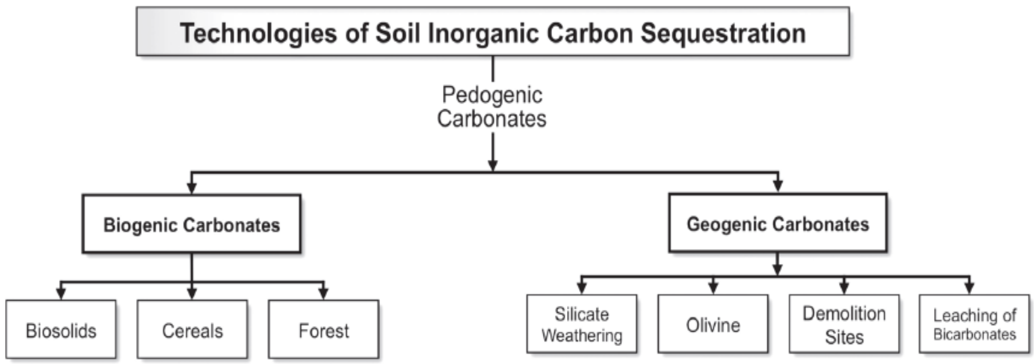


Fig 11: Techniques of sequestering inorganic carbon in soils as pedogenic carbonates.

Joao *et al.* [93] revealed that the magnitude of SOC fractions emphasized that the smaller fraction mineral-associated organic carbon (MAOC) is quantitatively essential to SOC sequestration, representing from 63 to 72% of the C concentration in the 0–5 cm layer and more in deeper layers. However, differences of POC among tillage treatments in soil surface layers highlighted the role of coarse fraction in SOC sequestration under CNT. The C stored in the POC fraction represents environmental and agronomic benefits, which depend on the maintenance of high and diverse biomass-C input under NT on the long-term, to preserve high surface-soil C fractions and to ensure a progressive protection of labile moieties within macro-aggregates. Thus, SOC may be relatively more labile in CNT than under CT. A study in a rice-wheat system at Varanasi, India compared four tillage treatments consisting of tillage timing and intensity, and revealed that no-tillage before sowing of rice and wheat could increase SOC by 0.59 Mg C ha^{-1} yr^{-1} [94]. The rate of SOC sequestration due to reduced- or no-tillage management in rice-based systems in South Asia varied from 0 to 2 114 kg ha^{-1} yr^{-1} [95, 22]. Greater SOC content under reduced- and no-tillage systems are largely due to higher soil aggregation and conservation in micro- and macro-aggregates [95, 23]. Conservation agriculture (CA) consisting of reduced tillage (RT)/ no-tillage (NT),retention of crop residues can accumulate soil C and N in the temperate, tropical and Mediterranean environments [96, 97].

Role of organic carbon in productivity of soil

Soil has an ability of renovation and accumulation of nutrients and their kinetics. The efficiency of an Agro-ecosystem depends on its productivity. SOM supports ecosystem function in terrestrial systems. Recalcitrant materials with lengthier residence times observably involve the major pools in soils. SOC has the capability to control water and air movement. SOC is closely associated with the soil's biological and physical status. Physico-chemical reactivity of soil is also influenced by the SOC. Soil carbon plays a vital role in regulating ecosystem services. Management systems influence all the internal and interrelated properties of soil over time [98]. Soil management practices to obtain various socio-economic and environmental benefits require decisive action that maintains and enhances soil carbon.

The adoption of conservation tillage practices offers soil carbon sequestration opportunity, more favorable plant growth environment and soil health improvement relative to conventional tillage [99]. Integrated policies and incentives are required to limit soil carbon loss due to bad management practices that results in loss and discharges of greenhouse gases to the atmosphere [100]. Soils are vulnerable to carbon losses and results in the release of carbon dioxide to the atmosphere as a consequence of accelerated degradation due to land use change or unsustainable management practices [87]. Microorganisms presented in the soil produce certain substances that act as binding material for soil particles [101]. These soil aggregates acts as a store house of soil carbon and also helps in the stabilization of soil carbon. Soil carbon is very essential for soil aggregate stability and plant nutrient intake [102, 103]. If more carbon is stored in the soil as organic matter, it will result in reduction of atmospheric carbon, which means reduction of greenhouse gases and global warming. The storage of carbon in soil as soil organic matter is called "soil carbon sequestration".

Adoption of RT/NT system with INM/IPNM and retention/ incorporation of 30% rice residues sequestered three times more SOC in soil system under RRS. The variation in SOC pool and sequestration were attributed largely to C addition through recycling of organic sources (FYM/GLM), tillage intensity (RT/NT), crop residues retention (30% residue), and production of root mass, nutrient-use pattern, soil texture and prevailing ecosystem [104]. Enhancement in SOC pool of the paddy soils can improve soil quality and mitigate global warming. Moreover, CT practice can enhance SOC and N mineralization by incorporating crop residues, disrupting soil aggregates, and increasing aeration, hence causing a reduction in SOC pool [105, 106]. The increase in SOC concentration might be due to the production of higher residues and root mass as well as addition of FYM [107].

Conclusion

Conservation tillage proved to be highly effective in enhancing SOC under the semi-arid conditions prevailing in western Uttar Pradesh. Treatment involving 50 per cent recommended dose of N supplied through chemical fertilizers and another 50 per cent through FYM reduced the depletion of SOC stocks and produced higher yields. Increase in SOC stock by 1 Mg ha^{-1} in 1-m depth increased cumulative grain yield by 0.46 Mg ha^{-1}. However, most ≥ (7 percent) of the C supplemented through FYM in this climate was mineralized and only a small fraction ≥ (23 per cent) was stabilized into SOC stock. The rate of addition of organic amendments should be at least doubled to reduce SOC depletion and increased considerably to enhance the SOC stock. SOC is a key element in the valuation of natural resources and the evaluation of how management affects soil quality and ecosystem services derived from soil. Stratified SOC with depth under conservation agriculture approaches helps soil function to an optimum. Conservation management approaches focusing on minimizing soil disturbance, maximizing soil cover, and stimulating biological activity can be achieved with cropping choices and production goals in different environments in the Indo-Gangetic Plains, India. A key to success will be to consider the agronomic, ecological, environmental, and economic constraints within a particular farm setting.

Studies also indicate that the OC content of soils sharply declines when put to cultivation even within 15 years of cultivation. Irrespective of the initial carbon level of soils, there is a tendency of soils to reach a quasi-equilibrium which has been reported as 1-2 per cent for red soils of eastern India and about 0.5 to 0.8 per cent in black soils of central India. The huge inorganic carbon stock in the form of $CaCO_3$ appears to be immobile since its apparent insolubility in the arid to semi-arid climate. It has been mentioned that the inorganic carbon present in sub-humid to humid ecosystem can be made available to plants by the dissolution of $CaCO_3$ through root exudates. For increasing SOC in soil, certain conservation practices may be adopted. Management and improvement of soil quality are imperative for the vastly growing population who conservatively depends on the soil resources for a constant supply of food and fiber. There is a need for farmers to be made aware them about the facts of soil carbon in agriculture so they can make a proper decision for adopting a suitable management practices for enhancement of productivity and fertility of soil simultaneously.

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