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Soil Organic Carbon Sequestration and Greenhouse Gas Emission with Conservation Agriculture under Subtropical India: Potential and Limitations: An overview

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ABSTRACT

Subtropical India is faced with the challenge of improving current food security on highly degraded land. At the same time, the region has to develop strategies to ensure future food security for the increasing population under worsening climate change. Conventional tillage (CT) has for many years resulted in the deterioration of soil quality through depletion of soil organic matter. In India, agriculture contributes about

17 per cent of the country's total GHGs emission. An intensive agricultural practice during the post-green revolution era without caring for the environment has supposedly played a major role towards enhancement of the greenhouse gases. Due to increase in demand for food production the farmers have started growing more than one crop a year through repeated tillage operations using conventional agricultural practices. Increase in carbon emission is the major concern, which is well addressed in kyoto protocol. This review of literature provides an overview of the impact of conservation agriculture (CA) on soil organic carbon (SOC) sequestration of the major agricultural strategies to mitigate greenhouse gas emissions, and improve agricultural sustainability. An overview synthesizes the much-needed state-of-knowledge on the effects of conservation agriculture practices on SOC sequestration and greenhouse gas emission identifies potential research gap, and limitations in studying SOC dynamics in rice –wheat cropping systems in subtropical India.

Key words: *Carbon sequestration, Climate change, Conservation agriculture, GHG emission*

INTRODUCTION

With the anthropogenic global farming[53], land surface temperatures may be increasing more rapidly than over the ocean[22]. The rapid rate of warming implies a major challenge for ecosystems to adjust with regards to land use and degradation and other biotic and abiotic stresses.

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Global food insecurity, already affecting about 1 billion people, may be exacerbated. The abrupt climate change (ACC) could disrupt the progress towards a hunger-free world[117]. Prevalence of drought and other extreme events can exacerbate food insecurity in several global hotspots (e.g., Sub-Saharan Africa, and South Asia), including India.

Soil carbon dynamics play a crucial role in sustaining soil quality, promoting crop production and protecting the environment[77]. The soil organic carbon (SOC) pool, a significant indicator of soil quality, has many direct and indirect effects on such quality. Increases in the SOC pool improve soil structure and tilth, counter soil erosion, raise water capacity and plant nutrient stores, provide energy for soil fauna, purify water, denature pollutants, improve the crop/crop residue ratio and mitigate the effects of climate[64]. Conservation tillage systems (such as minimum and no-till) have been observed to contribute to the role of soil as a carbon sink. By minimizing soil disturbance, reduced tillage decreases the mineralization of organic matter. The result is a larger store of soil organic carbon than with conventional tillage[78,116].

The effects of tillage on soil carbon dynamics are complex and often variable, however. Franzluebbers and Arshad[32] reported that there may be little to no increase in SOC in the first 2–5 years after changing to conservation management, but a large increase in total carbon in the following 5–10. Diuker and Lal[29], in turn, found that after 7 years the application rate of residue had a positive linear effect on soil organic carbon in all the tillage systems they studied. The adoption of conservation tillage practices and the cultivation of crops with a high potential for contributing to C biomass are further prerequisites for SOC accumulation[98]. Increases in soil organic carbon may also depend on the type of crop and the quality and quantity of crop residues[119]. Baker *et al*[7]., observed that under long-term management based on NT and low-addition cropping systems, soils failed to accumulate SOC, while NT in conjunction with legume-based cropping systems yielded SOC accumulation rates of around 0.8 mg ha^{-1} year^{-1}. The relative contribution of these two factors is heavily dependent on both soil and climate conditions.

Fertilization of crops is needed to overcome deficiencies in nutrients supplied by soils, especially in those soils exhausted by years of soil erosion, intensive disturbance with tillage, and continuous harvest of products that remove large quantities of nutrients. Excessive fertilization can also occur when agronomic prescriptions exist without regard for economic and environmental consequences. The N fertilizer rate to achieve maximum soil organic C sequestration (0.28Mg Cha^{-1} yr^{-1}) was 171 kg N ha^{-1} yr^{-1}(35), well within the range of values often reported to maximize cereal crop yields. However, when considering the C costs of N fertilizer (i.e., manufacture, distribution, and application), the optimum N fertilizer rate was 107-120 kg Nha^{-1}yr^{-1} based on C costs of 0.98 [0.86 + 0.08 + 0.04 for production, application, and liming components, respectively[115]] to 1.23 kg C kg^{-1} N fertilizer[54]. These calculations did not include the global warming potential of N_2O emission that is a near inevitable consequence of N fertilizer application. With N_2O 296 times more potent than CO_2 and assuming 1.25% of applied N would be emitted as N_2O[52], then an additional C cost of 1.59 kg C kg^{-1} N fertilizer would be an appropriate calculation. Optimum N fertilizer application to maximize C offset should then be reduced to as low as 24 kg N ha^{-1}yr^{-1} to achieve soil organic C sequestration of only 0.07 Mg C ha^{-1}yr^{-1}(35).

Soil health is an indispensable quality for agricultural sustainability, and conservation agriculture (CA) intends to achieve the latter for livelihood security through minimal soil disturbance and retention of crop residues as soil cover. Soil organic matter (SOM) and soil biochemical properties are the most widely accepted indicators of soil quality[40]. SOM is involved in the enhancement of soil quality by improving soil structure, nutrient storage and biological activity.

Improved management of agricultural lands such as adoption of improved residue management practices, and lessened tillage intensity can result in greater carbon sequestration in soils Nieder and Benbi[79]. The intensively cultivated soils lose their organic matter and nutrients when crop residues (CR) are removed or burnt after crop harvest. In addition, burning also causes atmospheric pollution due to the emission of toxic and greenhouse gases like CO, CO_2 and CH_4 that pose a serious threat to human and environmental health. SOM is also important for the supply of N, P and S through mineralization, the retention of some micronutrient elements, enhanced cation exchange capacity, favorable water relations and aggregate stability.

Conventional tillage or plow tillage (PT)

Conventional tillage, generally involves ploughing and intensive soil disturbance. It is defined as the tillage type that leaves less than 15% of the crop residues on the soil surface after planting the next crop[30]. This type of tillage has been recognized as the major driver of soil degradation through the depletion of soil organic matter and associated nutrients loss[74]. It relies heavily on moldboard plow followed by secondary tillage[30] which is often drawn by heavy tractors. Plow tillage (PT) is primarily practiced by commercial farmers in Subtropical India with huge capital investments on mechanized machinery and inorganic inputs such as fertilizers and herbicides. In small holder famers, this type of agricultural practice is not prevalent due to low incomes, land limitation and limited access to implements. They usually use animal drawn moldboard plow, small tractors and hand hoe for soil tillage.

The benefits associated with soil PT system have been summarized by Hobbs *et al*[49]. These authors cited that soil tillage was traditionally considered to be the first step in seed bed preparation and it is used to incorporate previous crop residues, weeds, soil amendments added to soil such as organic and inorganic fertilizers. Soil disturbance as results of PT helps to aerate SOM which in turn release nutrients through mineralization and oxidation after exposure of SOM. They further reported that it controls soil- and residue-borne pest and diseases since residue burial and disturbance have been shown to alleviate this problem. Lastly, the authors highlighted that PT system can provide temporary relief for soil compaction through the use of implements that could shatter below ground formed compaction layers. The disadvantage of this tillage system is its impacts on soil quality characteristics. Conventional tillage system has been widely reported to negatively affect soil physical, chemical and biological properties[71,75].

Conservational tillage (CT)

Conservation tillage (CT) is defined as any tillage practice that minimizes soil loss and water, which often require the presence of at least 30% of the crop residues throughout the year[8]. Hobbs[49] on the other hand, stated that CT is a collective umbrella term that is commonly given to no-tillage,

direct drilling and minimum tillage and ridge tillage to denote that the specific practice has a conservation goal of some nature. Baker *et al*[7]., further argued that this term is not adequately defined as it also involves the conservation of fuel, time, soil water, soil structure, earthworms and nutrients. With this tillage type, traditional implements used to prepare soil for cultivation, such as plows, disks, chisel plows, and various types of cultivators are eliminated and replaced by drills and direct seeders capable of cutting stumble and roots, leaving the seed properly placed in the soil[64].

Conservation agriculture

Food Agriculture Organization has defined CA as an approach of managing agro-ecosystem for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and environment[31]. According to Verhulst *et al*[109]., this cultivation system has been proposed as a widely adapted set of management principles that can assure more sustainable agricultural production. This system has been adopted as a result of a realization that agriculture should not only be based only on high yield but it must also be sustainable. The adoption of this management principle has been pushed further by ever increasing prices of production cost, scarcity of water, climate change and degradation of ecosystem services which force farmers to look for alternatives that can reduce cost while improving natural resource base and productivity[58].

According to the definition, minimum soil disturbance refer to low disturbance, no tillage and direct seeding. The disturbed area must be less than 15 cm wide or less than 25% of the cropped area[109]. In this practice, there should be no area disturbed (by tillage) greater than the set limit. The aim for permanent soil cover is to protect the soil from water and wind erosion; reduce water run-off and evaporation; to improve water productivity and to enhance soil properties associated with long term sustainable productivity[109]. Conservation agriculture on the other hand maintains permanent soil cover and this can be a decomposed organic matter or it can be growing mulch. In its definition, CA contributes to environmental conservation as well as improved and sustained agricultural production as compared with CT. In addition, the area less than 30% ground cover is not considered as CA. As results, CT system is considered as the transitional stage towards and/one leg of CA.

Soil structure and aggregation

Plow tillage is one of the major drivers of soil destruction through physical breakdown of the soil structure as compared to reduced tillage[28]. As a result, soil becomes susceptible to soil erosion due to dis-integration of soil aggregates[14]. Although plow tillage results in better structural distribution than reduced tillage and no-till, the components of the soil structure in PT are very weak to resist water slacking resulting in structural deterioration[99,109]. These can also results in reduced aggregation and increase turnover of aggregates and fragments of roots and mycorrhizal hyphae which are the major binding agents in soil. In conservation agriculture, soil is protected by permanent residue cover and this protects the soil from the impact of the rain drop, water and wind erosion[99]. In PT there is no protection of soil by the soil cover which increases chances of further destruction.

Bulk density and total porosity

Bulk density of the soil top layer (the top 30 cm) is usually lower in PT soils than in continuous no-till, reflecting the rapture effect of tillage near the surface[24]. According to So *et al*[102]., PT loosens the soil structure causing the immediate increase on the soil macro pores resulting in lower bulk density and higher total porosity which can benefit seedling establishment and crop growth. On the other hand, long term trials have indicated that on the lower surface of the soil, below 30 cm (under the plow layer), soil bulk density and total soil porosity between no-till and PT is generally similar[24]. Verhulst *et al*[109]., stated that a new "steady state" may be expected as a result of reduction in tillage, with a progressive change in total porosity with time. Moreover, the implement used in PT system makes soil more compact and after repeated tilling, the hardpan is usually formed underneath the plow layer[37]. This in turn can affect the movement of air, water and inhibits root growth. Hardpan has a high bulk density with a few macro-pores for roots to grow through[36,37] and tend to reduce macro-aggregates[57]. This can significantly reduce root length and trigger the formation of lateral roots[37]. As a result, growth, development and yield of crops may be reduced due to inefficient contact of roots with water which transport nutrients required for plant growth. In the long run yields may become unstable especially in drier areas.

Soil organic carbon (SOC)

Soil organic carbon (SOC) has been widely reported[78] as a primary factor that indicates soil quality because of its effect on soil key quality parameters. Soil properties are intrinsically linked to SOC and this in turn influences soil quality especially on the top layer of the soil. The top layer of the soil is important because it is where most of the cropping and soil management practices take place. Therefore, soil management practices are amongst the most important factors influencing changes in SOC[23]. Soil tillage, residue retention, crop rotation and the interactions of these factors, as in the case of CA, has been widely reported to influence SOC concentration[48,109,120].

Under no-till CA, the amount of SOC generally increases compared with PT[109]. This increase in SOC is more pronounced in the top soil. The soil layer from 0 to10 cm has high SOC compared to the subsoil[12,25]. In the subsoil, there may be either no significant difference in SOC or even in some cases decreases. In contrast to no-till system where SOC is usually stratified on the top 0–5 cm layer, a uniform distribution of SOC has been reported to up to 20 cm in PT system[34]. However, over time, PT system generally exhibit a significant decline in SOC concentration due to destruction of the soil structure, exposing SOM protected within soil aggregates to microbial organisms[63,120]. Thus, the adoption of no-till system can minimize the loss of SOC leading to higher or similar concentration compared to PT.

Some long term studies (>10 years), however, have reported no increase in SOC under no-tillage system, even when the residues have been left on the soil surface[112]. In a review of literature to determine the influence of the three different components of CA on SOC, Govaerts *et al*[41]., reported that in 7 of 78 (9%) cases, the SOC was lower in no-tillage compared to PT; in 40 (51%) cases it was higher and in 31 (40%) of the cases there was no significant differences. Verhulst *et al*[109]., concluded that the mechanisms that govern the balance between increased, similar or lower SOC after conversion to no-tillage are not clear but attributed the differences to climate and soil properties, differences in root development and rhizodeposits, and the stabilization of C in micro-aggregates-within-macro-aggregates. Dikgwatlhe *et al*[23]., further argued that the amount of SOC storage depends on the balance between the quantity and quality of SOM inputs outputs which is largely determined by the combined interaction of climate, soil properties and land use management.

Moreover, residue retention on soil surface has also been shown to increase the amount of SOC concentration[118]. In a long term study (11 years) conducted by Dikgwatlhe *et al*[23]., it was found that zero-tillage with residue retention resulted in an increase of SOC in the 0–10 cm soil layer compared to rotary tillage with residues incorporated and PT with residue retention and removed. Similar results were observed by Blanco- Canqui and Lal[12] in a CA study conducted over a period of 10 years. The rate of residue decomposition depends not only on the amount retained but also on the characteristics of the soil and the composition of the residues[109].

Soil organic carbon (SOC) fractions

Soil organic carbon based on physically defined fractions is increasingly used to interpret the dynamics of SOC in the soil[100]. Hermle *et al*[47]., distinguished three fractions in which C may be available. These are easily decomposable fraction (libile), material stabilized by physical-chemical mechanisms (intermediate) and the biochemically recalcitrant fraction (stable). Easily decomposable fraction, consisting mainly of particulate organic matter (POM) and some dissolved C is readily available and rapidly decomposed, represents early stage of humification and can stimulate decomposition of (hemi) cellulose[106]. On the other hand, resistant SOC such as lignin is old and in close contact with mineral surface and is resistant to microbial decomposition. Sanger *et al*[96]., reported that resistant SOC promote the formation of a complex phenyl-propanol structure which often encrust cellulose-hemicellulose matrix and slow decomposition on these components. POM plays a crucial role in soil aggregation and it can be used as an early indicator of changes in soil management because of its rapid turnover time[100,109]. Thus, Haynes and Beare[46] (1996) suggested that it can be used as an indicator of early changes of SOM.

Macrofauna

Macrofauna includes those organisms with an average body width greater than 2 mm[59,65]. This group of organisms is divided into two, based on their function. These are litter transformers and ecosystem engineers[65]. Litter transformers consist mostly of larger arthropods and soil mesofauna while ecosystem engineers on the other hand comprised mainly of termites and earthworms. Verhulst *et al*[109]., stated that ecosystem engineers have a large impact on influencing soil structure and aggregation as compared with litter transformers. In contrast, litter transformers concentrate their activity on the soil surface where they physically fragment litter and deposit mainly faecal organic pellets. In addition, ecosystem engineers ingest mixture of organic matter and mineral soil and are reported to be responsible for gradual introduction of dead organic material onto the soil[109]. Plow tillage has been widely reported to affect the availability of soil macrofauna through direct physical disruption as well as habitat destruction[59]. The impact has been more pronounced on larger organisms with less negative impact on species with high mobility and higher population growth potential[20].

Earthworms

Earthworms play a key role in formation of the soil structure. This, according to Six *et al*[101]., has been recognized since Charles Darwin times in the late 1800s. The effect of earthworms on the soil structure is not only mediated by abundance but also by the functional diversity of their communities[109]. Therefore, they vary in their ecological behaviour, thus, their effect on soil structure is different[59]. Epigeic earthworms concentrate their activity on the soil surface while anaecic earthworms have their activities mainly confined inside the soil surface[59].

Moreover, earthworms play a major role in the recycling of nutrients and formation of stable aggregates. They remove organic material from the soil and incorporate them as a stable aggregate. They ingest the organic matter and incorporate them with inorganic material, pass the mixture through their gut and excrete it as a cast. Earlier research in temperate pastures has shown that up to 50% of surface layer soil aggregates are earthworm casts[107]. Earthworms mediate soil aggregates through burrowing and cast formation[15]. External pressure is exerted during burrowing on the surrounding soil and the mucus is deposited on the burrow walls[101]. This in turn assist in formation of stable macro aggregates (>250 mm), when allowed to dry and age, due to organic mucilage and/stable organo-mineral complexes and oriented clays left lined in the burrowing walls[101]. In contrast, when cast is exposed to rainfall, it can be easily dispersed and contribute to nutrient loss and soil erosion[13]. Several studies have shown more stable structure of soil aggregation when the cast are present than the same soil with no cast[65,67,70]. In addition the stability of cast depends on the quality of ingested material[101].

Microbial biomass

Maintaining SMB and micro-flora activity and diversity is a fundamental for sustainable agricultural management[51]. Soil microbial biomass is a reflection of soil to store and recycle nutrients, such as C, N, P & S and SOM and has a high turnover rate relative to total SOM[17]. Microorganisms plays an important role in physical stabilization of soil aggregates[26] and this was found to be linked to glomalin content which is an indication of degree of hyphal network development[27]. These fungal hyphae form extended network in cultivated soil and are activated by contact with seedlings[89]. Zuberer[121] further reported that SMB produces polysaccharides which promote cementation of soil aggregates. The hyphae produced by fungi growing in soil allows for entanglement of soil properties[121]. During tillage, the fungal networks are fragmented and this potentially results in the loss of cell content[89]. In contrast to tillage system, in no-till conservation agriculture, the mycorrhizal system is more stable[103]. In addition, SMB contributes to soil health, in generally, through disease suppression by being antagonistic to potential plant pathogens[113].

The dominant factor controlling the availability of SMB is the rate of C input[16] and also availability of N resources in the soil[101]. A uniform and continuous supply of C from organic crop residues serves as the energy source for microorganisms. Previous studies has shown that as the total organic C pool increased or decreases, as results of changes in C input in the soil, the microbial pool also increases or decreases[33]. Plow tillage promote the release and decomposition of previously protected SOM in the soil, initially increasing soil microbial biomass[89].

However, the long-term effects are less obvious because they depend on the amount of C re-injected in the soil each year to compensate for mineralization[89]. In the early stages of CA adoption, the availability of nitrogen usually decrease in the soil due to increase in microbial activity due to surface residue decomposition and lack of incorporation in the soil and this is more pronounced in organic material with higher C/N ratios. In the long-run, however, studies have shown they may be a significant increase in C or SMB in the top soil in various CA systems[110]. The effect of tillage practice on SMB-C and N seems to be mainly confined in the surface layers with stronger stratification when tillage is reduced[95]. Aslam *et al*[4]., found that SMB content was twice in permanent pasture and no-till treatments in 0–5 cm depth as in 5–20 cm depth soil after 2 years of cropping following permanent pasture in a silt loamy soil[31]. Similar results were reported by Alvear *et al*[3]., and Pankhurst *et al*[83]., in different soil types. This can be attributed to higher level of C substrate available for microorganism growth, better soil physical condition and water retention under reduced tillage.

Enzyme activity

Soil enzymes play a crucial role in catalysing reactions associated with organic matter decomposition and nutrient cycling[56]. They have been suggested as potential indicators of soil quality because of their important function in soil biology, ease of measurements and rapid response to changes in soil management practices and environmental conditions[21]. They respond to management practices such as tillage, fertiliser application, crop rotation, residue management and pesticides and in this way they may alter the availability of plant nutrients[109]. They are a valuable tool for assessing soil's ability to function or bounce back after disturbance[56].

Generally, the activities of enzymes decreases with soil depth[43] and they vary with seasons and depend on soil physical, chemical and biological characteristics of the soil[80]. No-till management practice increase stratification of soil enzyme activities near the soil surface, perhaps due to the similar vertical distribution of SOM in NT than in PT and the activity of microbes[43]. The activities of enzymes is mainly confined in the 0–5 cm depth in NT practice for different soil in different environmental conditions than in PT and below 5 cm depth, no difference has been found in enzyme activities between NT and PT[3,91]. Furthermore, seasonal variability also affects the enzyme activity. As a result, single enzyme assay may not be a representative of overall microbial community activity and do not take into account seasonal changes and inherent differences in enzyme activity[90].

Conservation tillage and carbon sequestration

Several studies compare soil organic carbon (SOC) in conventional and conservation tillage systems. The results from analysis suggest that switching from conventional cultivation to zero till would clearly reduce on-farm emissions. Vanden Bygaart *et al*[105]., found that reduced tillage increases the amount of carbon sequestered by an average of 320-150 kg C ha^{-1} in 35 studies of western Canada and that the removal of fallow enhanced soil carbon storage by 150-60 kg C ha^{-1} based on 19 Studies. West and Marland[115] reported that carbon emission from conventional tillage (CT), reduced tillage (RT) and no tillage (NT) were respectively 72.02, 45.27, 23.26 kg C ha^{-1} in case of corn cultivation and 67.45, 40.70, 23.26 kg C ha^{-1} for soybean cultivation based on annual fossil fuel consumption and CO_2 emission from agricultural machinery. Thus there was 67.70% and 65.41% reduction in CO_2 emission as compared to conventional tillage for corn and soybean cultivation respectively. West and Marland[115] reported that no-till emitted less CO_2 from agricultural operations than did conventional tillage and estimated that net relative C flux, following a change from CT to NT on non-irrigated crops was –368 kg ha.

Mosier *et al*[73]., reported that based on soil C sequestration, only NT soils were net sinks for GWP and economic viability and environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer. West and Marland[115] estimated the average net C flux for U.S. at +168 kg C ha^{-1} yr^{-1} due to CT practices. The net C flux following a change from CT to NT was –200 kg C ha^{-1} yr^{-1}. Thus, the total change in the flux of CO_2 to the atmosphere, following a change from CT to NT on non-irrigated crops, was expected to be about –368 kg C ha^{-1} yr^{-1}. In India, zero-till drills, strip till drills, roto till drills are used for direct drilling of wheat after paddy. Comparative study of zero till, strip trill and roto-till was carried out and their performance was compared with conventional tillage. In no-till plots, fuel consumption was found to be 11.30 l ha^{-1} as compared to 34.62 l ha^{-1} by conventional method resulting in fuel saving of 24 l/ha. There was 67 % saving in fuel due to no-tillage as compared to conventional method[76]. Lal[62] reported that, conversion of conventional tillage to minimum tillage or no tillage practices can lead to drastic reductions in C emissions.

Ghimire *et al*[39]., studies suggest that soil management practices, such as intensive tillage and crop residue burning or removal, contribute to SOC loss. 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[10,38,61,78]. Hossain[50]; Naresh *et al*[77]., revealed that in a 3-year study in a rice-wheat system, SOC content was 0.22% greater under no-tillage raised bed than under conventional tillage. 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. Pandey *et al*[82]., in a rice-wheat system at Varanasi, India observed that no-tillage before sowing of rice and wheat could increase SOC by 0.59 Mg C ha^{-1} yr^{-1}. Greater SOC content under reduced- and no-tillage systems are largely due to higher soil aggregation and conservation in micro- and macro-aggregates[9,77].

Greenhouse Gas Emission with Conservation Agriculture

Jain *et al*[55]., 2014 estimates, on farm burning of 98.4 Mt of crop residues led to the emission of 8.57 Mt of CO, 141.15 Mt of CO_2, 0.037 Mt of SOx, 0.23 Mt of NOx, 0.12 Mt of NH_3 and 1.46 Mt NMVOC, 0.65 Mt of NMHC, 1.21 Mt of particulate matter for the year 2008–0. CO_2 accounted for 91.6% of the total emissions. Out of the rest (8.43%) 66% was CO, 2.2% NO, 5% NMHC and 11% NMVOC (Fig. 1 (a). Burning of rice straw contributed the maximum (40%) to this emission followed by wheat (22%) and sugarcane (20%) (Fig.4(b). Highest emissions were from the IGP states with Uttar Pradesh accounting for 23%, followed by Punjab (22%) and Haryana (9%). Burning of agricultural residues, resulted in 70, 7 and 0.66% of C present in rice straw as CO_2, CO and CH_4, emission respectively, while 20, 2.1% of N in straw is emitted as NOx and N_2O, respectively, and 17% as S in straw is emitted as SOx upon burning. Emissions from open biomass burning over tropical Asia were evaluated during seven fire years from 2000 to 2006 by Chang *et al*[18]. Venkataraman[108], have inventoried the emissions from open biomass burning including crop residues in India using Moderate Resolution Imaging Spectro-radiometer (MODIS) active fire and land cover data approach. Sahai *et al*[93]., have measured the emission of trace gases and particulate species from burning of wheat straw in agricultural fields in Pant Nagar, Uttar Pradesh.

Sahai *et al*[94]., have estimated that burning of 63 Mt of crop residue emitted 4.86 Mt of CO_2 equivalents of GHGs 3.4 Mt of CO and 0.14 Mt of NOx. ZT reduced the C emission of farm operations with 74 kg C ha^{-1} y^{-1} compared to CT. This may seem a small difference, but while the amount of C that can be sequestered in soil is finite, the reduction in net CO_2 flux to the atmosphere by reduced fossil-fuel use can continue indefinitely[115]. The net GWP (taking into account soil C sequestration, emissions of GHG from soil and fuel used for farm operations and the production of fertilizer and seeds) was near neutral for ZT with crop residue retention (40 kg CO_2 ha^{-1} y^{-1}), whereas in the other management practices it was approximately 2000 kg CO_2 ha^{-1} y^{-1}.Rochette[87] concluded that N_2O emissions only increased in poorly-drained finely-textured agricultural soils under zero tillage located in regions with a humid climate, but not in well-drained aerated soils. Mosier *et al*[72]., also reported that a better aerated soil with no tillage and residue retention would also favor CH_4 reduction and inhibit CH_4 production. However, soil as a sink for CH_4 is far less important than as a source for N_2O.

Chatskikh *et al*[19]., found that the average daily soil CO_2 respiration was significantly higher for conventional tillage than for zero-tillage, whereas the N_2O emissions did not show consistent differences. The management practices such as AWD involved in alternative rice land preparation and crop establishment in the improved scenarios (S3-S4) in the present study were reported to cause lower methane emissions from rice paddies[2,66]. However since different factors interact and the magnitude of interactions results in temporal and spatial variability in emissions of CH_4, it is not possible to estimate a relative effect of any single factor. Land use change and emission reduction in agriculture will be key elements in achieving an 80% reduction in GHG emissions by 2050[88]. Patino-Zuniga *et al*[85]., reported that conservation agriculture, in its version of permanent raised bed planting with crop residue retention, decreased emissions of $N_2O$and CO_2 compared to soil under conventionally tilled raised beds.

Gupta *et al*[45]., revealed that the GWP (CH_4 + N_2O) of wheat–rice systems varied from 944 to 1891 kg CO_2 eq. ha^{-1} and 1167–2233 kg CO_2 eq. ha^{-1} in the first and second years of wheat–rice cropping respectively. The combination of ZTW followed by DSR showed significantly low GWP than other combination of wheat and rice treatments. These combinations led to about 44–47% reductions in GWP over the conventional CTW-TPR system in both the years. The order of GWP among the different combination of treatments was as follows: (ZTW + RR) - DSR < ZTW-DSR < ZTW-IWD < ZTW + NOCU-TPR + NOCU < CTWTPR < ZTW-TPR in both the years. The share of rice in total GWP was 72–81% in those combinations in which TPR was a treatment while it varied from 56 to 65% where DSR was a treatment. These results indicate that adoption of ZTW followed by DSR in the IGP in place of conventional CTW-TPR can be an efficient low carbon emitting option.

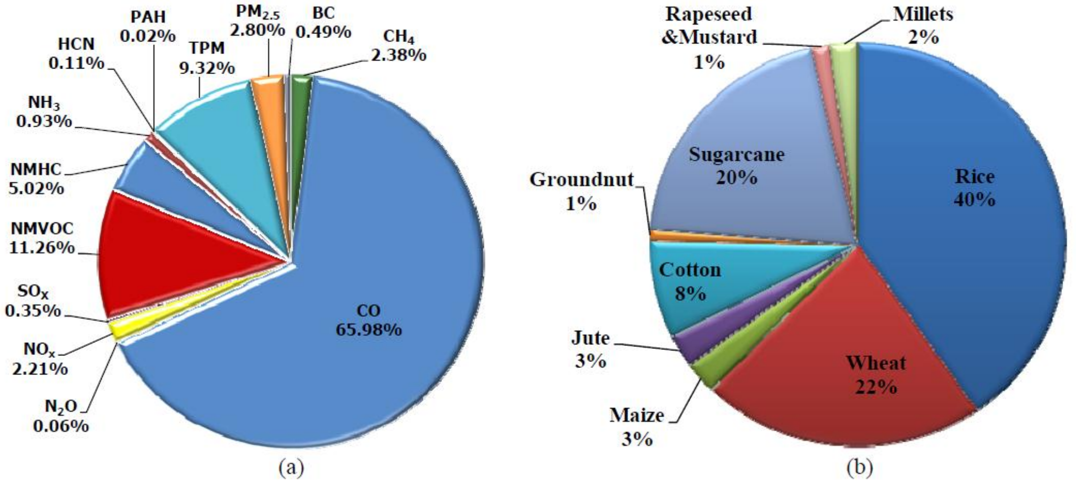

Fig. 1: (a) Emission of different pollutants and GHGs due to field burning of crop residues. (b) Contribution of different crops in burning[55].

Incorporation of cereal residues into paddy fields at optimum time before rice transplanting can help in minimizing the adverse effect on rice growth and CH_4 emissions. The incorporation of wheat straw before transplanting of rice showed no significant effect on N_2O emission due to immobilization of mineral N by high C/N ratio of the straw incorporated[68]. However, an increase in N_2O emission from fields with mulch compared to those with incorporated residue has been observed in subtropical Asian rice-based cropping systems[6]. Baggs *et al*[5]., speculated that timing residue return such that the N becomes available when needed by the upland crop should minimize N_2O emission as compared with residue return at the beginning of the preseason fallow. CRM is unlikely to have significant overall effects on CH_4 emission in upland crops like wheat. For any CH_4 to be produced there must be at least a small number of anaerobic microsites for methanogenic bacteria to grow, so any treatment that makes the soil more anaerobic is likely to increase the risk of CH_4 emission, including a rainfall event or mulch application. As in flooded systems, any action that causes residue to decompose before becoming anaerobic will lessen the risk of CH_4 emission. From the perspective of mitigating GHG emissions from wheat crop in RW cropping system, residues are not the primary crop management concern. When soil is at or near field capacity, there would be such little CH_4 formation and N_2O emission and the effect of CRM would be negligible[11]. Neither mulch nor incorporation of rice residue into wheat crop would be expected to have very significant impact on CH_4 emission in the following rice crop, because the incorporated or mulched residue would decompose considerably during the upland crop season[1]. It is estimated that the burning of one ton of straw releases 3 kg particulate matters, 60 kg CO, 1460 kg CO_2, 199 kg ash and 2kg SO_2. With the development of new drills, which are able to cut through crop residue, for zero-tillage crop planting, burning of straw can be avoided, which amounts to as much as 10 tons per hectare, potentially reducing release of some 13–14 tons of carbon dioxide[44]. Elimination of burning on just 5 million hectares would reduce the huge flux of yearly CO_2 emissions by 43.3 million tons (including 0.8 million ton CO_2 produced upon burning of fossil fuel in tillage). Zero-tillage on an average saves about 60 l of fuel per hectare thus reducing emission of CO_2 by 156 kg per hectare per year[42,44].

Pathak *et al*[84]., noticed that methane emissions from rice fields range from 16.2 to 45.4 kg ha^{-1} during the entire season, whereas nitrous oxide emission under rice and wheat crops amounts to 0.8 and 0.7 kg ha^{-1}. Incorporation of straw increases methane emissions under flooded conditions, but surface management of the straw under aerated conditions and temporary aeration of the soils can mitigate these effects. Thus, adoption of aerobic mulch management with reduced tillage is likely to reduce methane emissions from the system. The water regime can strongly affect the emission of nitrous oxide, another GHG, which increases under submergence, and is negligible under aeration. Any agronomic activity that increased nitrous oxide emission by 1 kg ha^{-1} needs to be offset by sequestering 275 kg ha^{-1} of carbon, or reducing methane production by 62 kg ha^{-1}. Sah *et al*[92]., revealed that the CO_2 emissions conventionally tilled (CT) wheat emitted the highest amount of CO_2 (224 kg ha^{-1}) followed by PRB (146 kg ha^{-1}) and the lowest from ZT (126 kg ha^{-1}). The highest CO_2 emission through CT attributed to higher tractor usage on land preparation and more pumping time on irrigation. However, ZT and PBP wheat emitted lower CO_2 to the atmosphere by 43.7 % and 34.9 %, respectively, as compared to CT. Sapkota *et al*[97]., found in both the years; total seasonal CH_4 emission was much higher in CT based system than ZT based system, irrespective of residue retention.

Wassmann *et al*[111]., proposed that CH_4 emissions may be suppressed by up to 50% if DSR fields are drained mid-season. The net effect of direct seeding on GHG emissions also depends on N_2O emissions, which increase under aerobic conditions.

Impact of soil tillage, water and residue retention on GHG emission

Kumar and Ladha[60] reported reduction of CH_4 emission with ZT-DSR compared to CT-TPR ranging from 24 to 79% under flooded condition and reduction of 43–75% under intermittent irrigation. Rochette[87] found that ZT increases N_2O emissions relative to the CT only in poorly-aerated (fine-textured) soils. The zero-till practice in DSR made possible the addition of large amounts of residues as mulch on the soil surface, without increasing CH_4 and N_2O emissions[78]. Ogle *et al*[81]., concluded more specifically that soil C stocks would be expected to increase under zero-till only if C inputs increased, or decreased by only less than 15%. Mandal *et al*[69]., observed that the total quantity of soil C sequestered over a long period was linearly related to the cumulative crop residue C inputs, and, to sustain the SOC level (zero change due to cropping) in subtropical India, a minimum quantity of 2.9 Mg C should be added per hectare per annum as inputs, which is less than 10% of the residues.

Tubiello *et al*[104]., revealed that recent reports by the IPCC and FAO, synthetic fertilizers contribute 12-14% of global total GHG emissions from agriculture (680-725 Mt CO_2 eq per year in 2010/2011). About 70% of these emissions come from Brazil, China, India and Indonesia.

Richards *et al*[86]., found that N_2O emissions from soils are due to microbial N turnover processes in soils, with microbes competing with plants for N in the rhizosphere. Plant-microbe competition for N is low or not existing at the beginning of the growing season, when most fertilizer is applied. Timely meeting of the N demand of crops, as with SSNM, favors plant N uptake over microbial N processing and thus results in lowered N_2O emissions. Weller *et al*[114]. observed that Mid-season drainage, intermittent flooding, or rotation of flooded rice with upland cropping can mitigate CH_4 emissions from rice-based cropping systems

Obstacles to adoption of conservation agriculture by farming community

- The adoption of agricultural management practices capable of sequestering C is hampered both by environmental (weather, etc.) and socio-political factors. The latter constraints, including the supply and demand for agricultural products, production costs, subsidies, incentives to reduce environmental impacts and social, aesthetic and political acceptance for changes, may well be the most important factors in deciding whether or not suggestions are applied by producers. It must be understood though, that in the end, producers will only adopt new management practices if it is found to be economically feasible. Analyses of these factors are highly complex, and studies on this are in their infancy
- It should be emphasized that C sequestration, whether in vegetation or in soils, does not represent a ‘‘permanent’’ solution to the issue at hand. The C carbon sequestered should not ‘‘irreversibly’’ locked-up; but rather, that the build-up of offset terrestrial C stocks through changes in management is reliant on the long-term maintenance of those practices throughout time.
- Because C sequestration is a function of primary production and rate of organic matter decomposition, the most important factor influencing sequestration is weather (moisture and temperature). Thus, the amount of C sequestered depends on weather conditions over which we have no control.
- Alternate drying and wetting in some rice-based systems further complicated our understanding of the responses of alternative tillage, crop residue, and nutrient management practices. Similarly, knowledge gap in disentangling the soil C pools under diverse agro-ecosystems and management practices limits our

understanding of turnover rate, storage, and loss of SOC in rice-based production systems.

CONCLUSIONS

Resource Conservation Technologies can play a significant role in SOC sequestration by increasing soil carbon sinks, reducing GHG emissions, and sustaining agricultural productivity at higher level. Conservation agriculture sequesters maximum soil organic carbon near soil surface layer. Adoption of conservation agriculture with use of crop residues mulch, no till farming and efficient use of agricultural inputs help to conserve moisture, reduce soil erosion and enhance SOC sequestration. Rate and amount of SOC sequestration differ with soil types, depths and land use and varies from one region to another. Evaluating SOC dynamics of different rice-based systems under present and projected climate change scenario, alternative management practices, and their potential impacts on agricultural system sustainability would substantially benefit producers, researchers, and policy makers. Improved understanding of SOC dynamics and soil-plant-atmosphere interaction of GHGs in continuously flooded intermittently flooded and upland rice-based systems would help to estimate global warming potential of South Asian agriculture and other similar agro-ecosystems in the world. More research evaluating impacts of alternative management systems on SOC dynamics and GHG emissions is required. Specifically, understanding SOC and nutrient dynamics during transition from conventional to conservation systems are required.

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