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# Toward optimal soil organic carbon sequestration with effects of agricultural management practices and climate change in upland soils of subtropical India: A review

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## Abstract
Soil degradation, caused by land misuse and soil mismanagement, has plagued humanity since the dawn of settled agriculture. An understanding of the dynamics of soil organic carbon (SOC) as affected by agricultural management practices is imperative for maintaining soil productivity and mitigating global warming. Resource-poor and small-size land-holders can neither afford the expensive input nor are they sure of their effectiveness because of degraded soils and the harsh, changing climate. Consequently, crop yields are adversely impacted by accelerated erosion, and depletion of soil organic matter (SOM) and nutrients because of the extractive farming practices. The carbon (C) sequestration is a cost-effective strategy to mitigate climate change during the first few decades of the 21st century. There are five global C pools, and the third largest pool exists in soil and is estimated at 2.5 trillion tons (1-m depth). The conversion of natural ecosystems to agricultural ecosystems disturbs the soil ecological balance, soil processes, organic C, and biotic C pools. Globally, agricultural soils are estimated to potentially sequester 0.4–0.8 Pg C $yr^{-1}$ by the adoption of recommended management practices on croplands, 0.01–0.03 Pg C $yr^{-1}$ on irrigated soils, and 0.01–0.3 Pg C $yr^{-1}$ on grasslands. Globally, there is a C crisis in soil especially in subtropical ecosystems because of increased carbon dioxide emissions from soil.

**Keywords:** Climate change, Land management practices, Soil organic carbon

## Introduction
Soil carbon is considered one of the most important indicators of the productivity of low input farming systems and in assessing the soil health. It is the key to soil fertility, productivity and quality, as decline in carbon content not only affects sustainability of agricultural ecosystems, but also extremely important in maintaining overall quality of the environment. Soil contains a significant part (3.5%) of global carbon stock. There is a growing interest in assessing the role of soil as a sink for carbon under different land use practices as increase in soil organic carbon content by 0.01% could lead to sequestration of carbon that can compensate the annual increase of atmospheric carbon dioxide concentration. Sequestering 1 tonne carbon in humus can conserve nutrients to the tune of 83.3 kg N, 20 kg P and 14.3 kg S per hectare Singh *et al*., (2012) [81]. Thus, carbon management is the essential to environment management and sustainability of soil health *vis-a-vis* agricultural productivity.

The northeast India is equally vulnerable in terms of eco-fragility, marginality and inaccessibility making the future agricultural scenarios more uncertain and risk prone. The erratic pattern of rainfall (spatio-temporal), higher frequency of extreme rainfall events, less rain in June-Aug, and more in Sept/Oct, and more frequent flash floods and longer dry periods in various parts of the region manifests the impact of climate change (Borthakur *et al*., 1989) [10]. Summer monsoon rainfall has been decreasing significantly during the last century at an approximate rate of 11 mm per decade. On the other hand, the annual mean maximum temperature in the region is rising at the rate of +0.11 °C per decade. The annual mean temperature is also increasing at a rate of 0.04 °C per decade in the region (Das, 2009) [24].

Soil organic matter (SOM) plays a key role in the improvement of soil physical, chemical and biological properties Ouédraogo *et al*., (2007) [67].

Conservation of the quantity and quality of soil organic matter (SOM) is considered a central component of sustainable soil management and maintenance of soil quality Doran *et al*., (1996). Land-use changes, especially the conversion of native forest vegetation to cropland and plantations in tropical region, can alter soil C (Chen *et al.* 2003) [12]. Therefore, soil organic C (SOC) concentrations reflect soil and ecosystem processes as well as past management practices for both agricultural and nonagricultural soils (Collins *et al.* 2000) [13]. However, Murty *et al.* (2002) [56] found no significant overall change in SOC due to land use change from forest to pasture, although changes in soil C at individual sites ranged from −50% to +160%. These findings showed a high variability in soil C stocks in the changed ecosystems and possibly even within one ecosystem. Hence, ecosystems may lose or gain C, depending on soil type, tillage operations, plant residue retention or removal, fertiliser applications, organic manures/residues additions, and integrated nutrient management (Fearnside and Barbosa 1998) [20].

**Greenhouse gases and their management**

Amongst various GHGs that contribute to global warming, carbon dioxide is released from agriculture by way of burning of fossil fuel for agricultural operations; methane is emitted through agricultural practices like inundated paddy fields, nitrous oxide through fertilizers, combustion of fossil fuels etc. Nitrous oxide has a global warming potential 296 times greater than $CO_2$. In India, it is estimated that 28% of the GHG emissions are from agriculture; about 78% of methane and nitrous oxide emissions are also estimated to be from agriculture. As per the IPCC, every quintal of nitrogen applied in farming emits 1.25 kg of nitrous oxide. Half of the nitrogen applied to crops is lost to the environment. Burning of crop residues also impacts the soil fertility. Heat from burning straw penetrates into the soil up to 1 cm, elevating the temperature as high as 33.8-42.2 °C of the world's total emission of 16-34 Teragram (Tg) from rice cultivation alone, India contributes 2.4-6.0 Tg. The average methane flux from paddies ranges from 9 to 46 g/m$^2$ over a growing periods of 120 to 150 days. Reported that the atmospheric concentration of $CO_2$ has increased from 280 ppm in 1750 to 367 ppm in 1999 and is currently increasing at a rate of 1.5 ppm or 3.3 Pg C yr$^{-1}$ (IPCC, 2001) [29]. Similarly the atmospheric concentration of $CH_4$ has increased from 700 to 1745 ppb and that of $N_2O$ has increased from 270 to 314 ppb during the same period. This anthropogenic increase of GHGs in the atmosphere and the cumulative radioactive forcing of all GHGs has led to an increase in the global surface temperature of 0.6 °C since 19th Century with the current warming rate of 0.17°C per decade (IPCC, 2001) [29], which is higher than the critical rate of 0.1 °C per decade. Nieder and Benbi, (2008) [63]; Schaufler *et al*., (2010) [78] concluded that Carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) are important climate-relevant trace gases. While being highly unequally distributed (Âof 3–4 orders of magnitude for C), about 1500 Pg of total C and136 (92–140) Pg of total N are stored in the uppermost meter of the global soil layer, representing the largest terrestrial carbon and nitrogen pools.

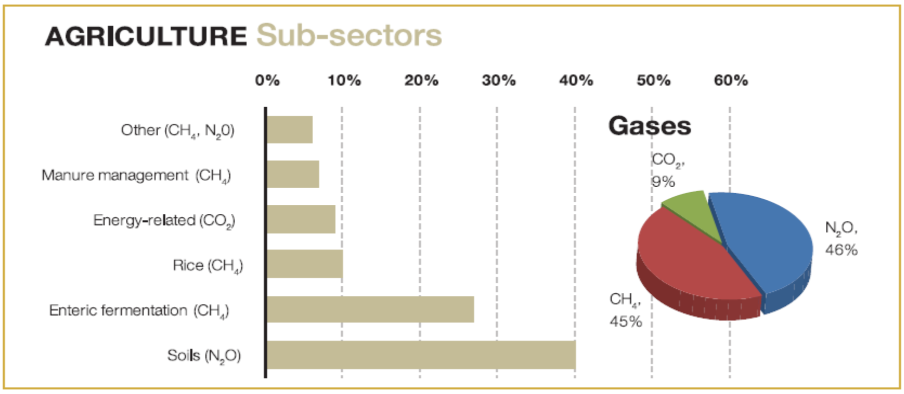


**Fig 1:** Greenhouse gas emissions from agriculture
***Source***: Kasterine and Vanzetti (2010)

Most of the cultivated soils have lost half to two thirds of the original SOC pool with a cumulative loss of 30-40 Mg C ha$^{-1}$. Depletion of SOC pool has contributed to 78±12 Pg C to the atmosphere. The depletion of soil C is accentuated by soil degradation and mismanagement of soil. Adoption of recommended management practices (RMPs) on agricultural soils can enhance carbon sequestration and reduce the rate of enrichment of atmospheric $CO_2$ and will have positive impacts on food security, water quality and environment. Lal (2004b) [41] reported that C emissions 2.20 kg CE ha$^{-1}$ for different tillage operations, 1.1.4 kg CE ha$^{-1}$ for spraying chemicals, 2.4 kg CE ha$^{-1}$ for seeding and 6.12 kg CE ha$^{-1}$ for combine harvesting. Similarly, estimates of C emissions in kg CE per kg for different fertilizer nutrients are 0.9.1.8 for N, 0.1.0.3 for $P_2O_5$, 0.1.0.2 for $K_2O$. Sustainable agricultural practices increase the soil organic carbon by incorporating organic materials into the soil. Soil can be a major source of storage of carbon, about twice as much carbon as in the atmosphere. Crop, tree and livestock integration with a systematic recycling of organic wastes is an integral part of sustainable agriculture and helps in reducing GHG emission. Conservation agriculture involving reduced tillage and residue recycling promote sequestration of carbon dioxide and thereby reduce global warming. In the irrigated agricultural system of subtropical India, system of alternate wetting and drying in rice is a feasible alternative to the existing practice of cultivation in continuous submerged conditions since AWD can cope with irregular intervals of rainfall and thus methane emission can be reduced in the anaerobic-aerobic transformation cycle. Agro-forestry is also a desired practice which further adds to the potential of sustainable agriculture in carbon sequestration.

An increase of soil temperature leads to higher emissions and to higher soil respiration rates as a positive feedback response of increased microbial metabolism. Methane and $N_2O$ emissions are additionally forced by increasing soil respiration rates with increasing soil temperatures, leading to decreasing $O_2$ concentrations in the soil. Nitric oxide and $CO_2$

emissions increase exponentially with temperature (Tang *et al*., 2003) [86]. Emissions of $CO_2$ and $CH_4$ positively correlate with the C/N-ratio (Shi *et al*., 2014; Weslien *et al*., 2009) [80, 89]. Yet, depending on the availability of other electron donors such as $Fe_3^+$, $Mn_4^+$, $SO_4^{2-}$and $NO_3^-$, the $CH_4$ production in soils may be reduced (Kögel-Knabner *et al*., 2010) [32], which is of particular relevance in many sub- tropical soils and particularly in rice paddies. Revealed that using controlled-release fertilizers or denitrification inhibitors prevents increased $N_2O$ emissions. Higher soil moisture during no-till practice leads to higher $N_2O$ emissions. Higher $N_2O$ emissions under no-till cannot be balanced by higher C sequestration and $CH_4$-uptake rates (Li *et al*., 2005) [43]. However, there are discordant findings on the influence of the tillage system: $N_2O$ emissions decreased with no-till practice (Omonode *et al*., 2011) [66] and were explained by lower soil temperatures, while others found a positive effect of no-till on $N_2O$ emissions and explained this with higher microbial activity (Baggs *et al*., 2003) [2]. Soil organic carbon (SOC) accumulation largely depends on vegetation cover. Any change in land use may significantly alter related source or sink characteristics for atmospheric $CO_2$ and other GHG's (Poeplau and Don, 2013) [70]. Vermeulen *et al*., (2012) [88] reported that using a conservative average of 300 mg $CO_2$ e $m^{-2}h^{-1}$for all land-cover types combined as compiled from our literature review, global annual soil emissions of ≥350 Pg $CO_2$ e result, corresponding to roughly 21% of the estimated global soil C and N pools Figure 2.

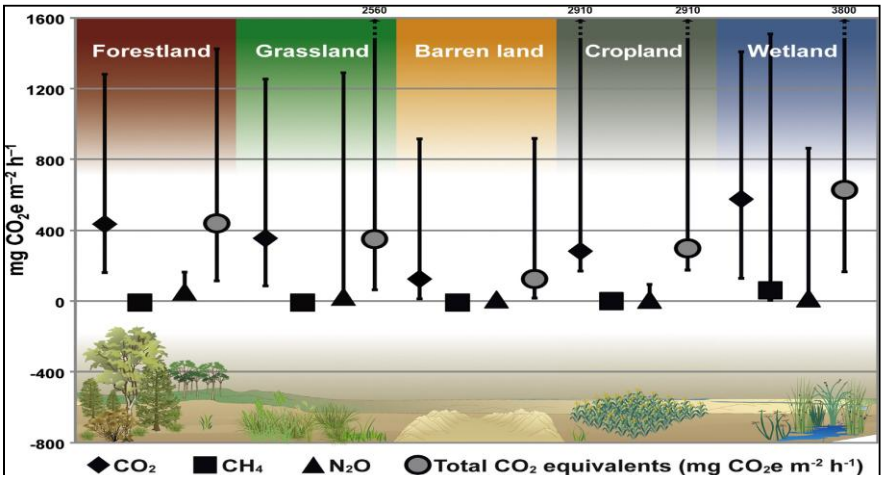


**Fig. 2:** GHG emissions ($CO_2$-eq) of $CO_2$, $N_2O$ and $CH_4$ from soils with different land cover. Median values for the sub-collectives are shown with the symbols; the range is indicated with solid lines

**Conservation tillage and carbon sequestration**

In India, the potential of soil C sequestration is estimated at 39-52 million tonne Cyr$^{-1}$ of which 7.2-9.8 million tone C yr$^{-1}$ for restoration of degraded soils and ecosystems, 5 to 7 Tg C yr-1 for erosion control, 6 to 7 million tonne C yr$^{-1}$ for adoption of improved management practices (IMP) on agricultural soils, and 22 to 26 million tonne C yr$^{-1}$ for secondary carbonates (Lal, 2004) [38]. ICAR and NAAS have estimated of about 121 million hectare of degraded lands including salt affected wasteland in India (Maji *et al*., 2010) [47]. Lal (2004) [38] suggested that up to 2 billion tonne C could be sequestered in India by reclamation of salt affected soils. The potential carbon sequestration in world soil is 0.4-1.2 GtC yr$^{-1}$, in cropland 0.4-0.8 GtC yr$^{-1}$, in restoration of degraded and desertified soils 0.20-0.85 GtC yr$^{-1}$, in irrigated soil 0.01-0.03 Gt C yr$^{-1}$ and in grasslands it is 0.01-0.3 Gt C yr$^{-1}$.Therefore, agricultural practices collectively can make a significant contribution at low cost to increasing soil carbon sinks and reducing GHG emissions. Batjes and Sombroek (1997) [5] concluded that soils contained1550 Pg of organic C upto 1 m depth, 2500 Pg of organic C up to 2 m and 750 Pg of inorganic carbon at 1 m depth. This total soil C pool of 2300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg. Carbon storage in soils is the balance between the input of dead plant material (leaf and root litter) and losses from decomposition and mineralization processes.

Vanden Bygaart *et al*. (2003) [87] found that reduced tillage increases the amount of carbon sequestered by an average of 320-150 kg C ha$^{-1}$. Reported that carbon emission from conventional tillage (CT), reduced tillage (RT) and no tillage (NT) were 72.02, 45.27, 23.26 kg C ha$^{-1}$, respectively in case of corn cultivation and 67.45, 40.70, 23.26 kgCha$^{-1}$, respectively, 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. Lal *et al*. (2004) [38] computed carbon sequestration potential of Indian soils by assuming converting degraded soils to restorative land use and estimated total potential of 39 to 49 (44± 5) TgCy$^{-1}$. Estimated the average net C flux for U.S. at +168 kg C ha$^{-1}$ yr$^{-1}$, when continuing 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$^{-1}$. Lal *et al., (*1998) [36] reported that CA improves agriculture by reducing erosion, increasing water infiltration, improving soil surface aggregates, reducing compaction through promotion of biological tillage, increasing surface soil organic matter and carbon content. West and Post (2002) [90] concluded that by converting conventional tillage to no-till sequestered an average of 0.57±0.14 t C ha$^{-1}$ yr$^{-1}$.

Balota *et al*., (2004) [4] showed that residue retention and no tillage increased total C by 45% and soil microbial biomass (SMB) by 83% at 0–50 cm depth as compared to traditional tillage. Similarly, also indicated that SMB was 7-36%higher with no tillage than conventional tillage. Naresh *et al*., (2015) [60] reported that higher carbon stocks were recorded in the direct seeded rice (DSR) as compared to the transplanted rice (TPR) treatments, because of the effects of puddling on aggregation/SOC losses. If only normal tillage was used (on the basis that deep tillage is not practiced) then DSR led to an increase in soil C of 2.63 t/ha compared to TPR. As a result, without puddling of soil, the annual increase in soil C was 0.375 t/ha, which can also be applied to soils of similar texture. White and Rice (2009) [92] indicated that reduced tillage promoted higher carbon sequestration. They also observed increased levels of soluble carbon, enzyme activity and aggregate stability in no tilled soil as compared with tilled soil. Similar results were reported by Roldan *et al.* (2005) [75] and observed that substantial amounts of carbon could be sequestered in irrigated cotton-growing soil where stubble was incorporated under a minimal tillage regime. Found that the values of SOC and total N were the highest in the minimum tillage and residue retained treatment and the lowest in conventional tillage and residue removed treatment. Tillage reduction from conventional to minimum and zero conditions along with residue retention increased the proportion of macro-aggregates over 21-42% over control in soil.

Motta *et al.* (2001) [55] observed that tillage had no effect on the soils chemical properties but affected SOC, particulate organic matter (POM) and microbial biomass (MB) and SOC, POM and MB values for the upper soil layer were higher by 86-130%, 78-113% and 44-183%, respectively for conservation tillage system as compared to conventional tillage. Also conservation tillage sequestered 3-7 kgha$^{-1}$ more C within 0-24cm depth than conventional tillage. Mosier *et al.* (2006) [54] reported that based on soil C sequestration, only NT soils were net sinks for Global Warming Potential (GWP). Thus, economic viability and environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer. Ghosh *et al*. (2010) [24] reported that double no till practice in rice-based system is cost-effective, restored soil organic carbon (70.75%), favored biological activity (46.7%), conserved water and produced yield higher (49%) than conventional tillage. Rochester (2011) [74] concluded that higher rates of C sequestration were observed in systems including legume crops. Greater C sequestration occurred in the sub-soil than in the surface soil (0-300mm).

## Crop rotations and carbon sequestration

Santos *et al.,*(2011) [77] reported on the basis of research done for 17 years that the forage-based rotations of semi-perennial alfalfa and annual rye grass for hay production contributed more to soil organic C sequestration than rotations based on cover crops (oat or vetch). Rochester, (2011) [74] observed that growing legumes in crop rotation benefited greenhouse gas abatement in two ways firstly by conversion of stubble carbon to soil SOC and secondly $N_2O$ emission was less because little or no nitrogen fertilizer was added. Baker *et al.,* (2007) [3] found that crop rotation systems along with conservation tillage accumulated about 11 tha$^{-1}$ of carbon after nine years. Whereas, according to the report of FAO (2001) [19], the carbon liberation into the atmosphere was about 1.8 t ha$^{-1}$yr$^{-1}$ of $CO_2$ under conventional tillage with monoculture systems. Richards and Stokes (2004) [73], concluded that forest land can fix about 250 million metric tonnes of carbon each year (12% of total $CO_2$ emissions), crop land can sequester about 4-11% of atmospheric C yr$^{-1}$, and grazing land can sequester about 5% of atmospheric C yr$^{-1}$. Aggarwal, (2007) [1] reported that Bamboo is an especially effective agro-forest sink of CO2 with a C sequestration rate as high as 47% amounting to 12-17 t $CO_2$ per hectare per annum. It also generates 35 per cent more oxygen than other timber species. Rotenberg and Yakir, (2010) [76] revealed that dry land forests apparently manage to sequester carbon by reducing respiration rates and growing rapidly in early spring to take advantage of temperatures most favorable for growth. Franzluebbers *et al*., (2006) [23] describes scenarios that could lead to different interpretations of how effective a conservation agricultural system might be in terms of soil organic C sequestration. In all three scenarios, soil organic C sequestration under conservation agriculture was 0.15 Mg C ha$^{-1}$ yr$^{1}$. a conventional system, the soil organic C sequestration rate could have been realistically increased to 0.25Mg C ha$^{-1}$yr$^{-1}$ in Scenario A, because soil organic C declined by 0.10 Mg C ha$^{-1}$yr$^{-1}$ under conventional agricultural practices following degradation from a previously elevated condition. In Scenario B (the most often presumed condition), soil organic C sequestration under conservation agriculture would have been effectively the same as that observed without comparison with conventional agriculture, because soil organic C under conventional agriculture was at a steady-state condition. In Scenario C, soil organic C sequestration under conservation agriculture would have to be adjusted to 0.05 Mg C/ha/yr, because the conventional system was improved by other practices similar to that under conservation agriculture, which sequestered soil organic C at 0.10 Mg C ha$^{-1}$ yr$^{-1}$.

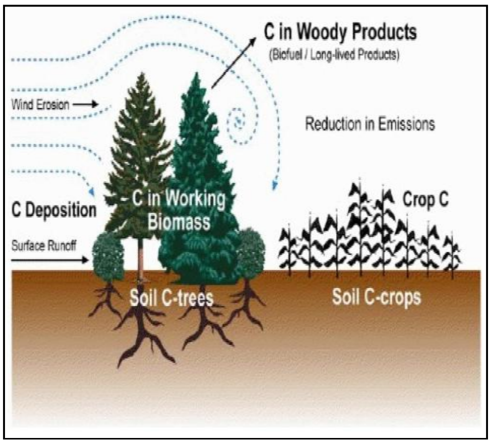


**Fig. 3a:** Agro-forestry and carbon sequestration
***Source***: IGUTEK (2011)

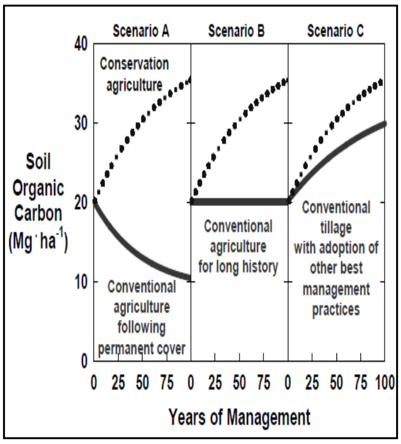


**Fig. 3b:** Hypothetical examples of soil organic C content under conservation agriculture and three different baseline conditions of conventional agriculture.

## Crop residue and carbon sequestration

Lal, (1997) [37] reported that the annual production of crop residue in the world is estimated to be about 3.4×10$^{9}$ tonnes. If 15% of the C present in the residues can be converted to passive organic carbon fraction, this may lead to C sequestration of 0.2 × 1015 g $yr^{-1}$. Duxbury and Lauren (2004) [18] revealed that an average, soil C stock increased by 1.48 $tha^{-1}$ when residues were added. The total amount of residues added over the period of 7 years was 29.5 t/ha or 14.75 t C $ha^{-1}$. Thus, C retention was 10% of that added or 0.21 t C $ha^{-1}yr^{-1}$. In case of soybean-wheat system in sub-tropical central India, the annual contribution of C from aboveground biomass was about 22 percent for soybean and 32 percent for wheat (Kundu *et al.*, 2001) [34]. This resulted in 18% of the annual gross carbon input being incorporated into the SOM. Puget and Drinkwater (2001) [72] in their study with leguminous green manure observed that nearly half of the root derived C was still present in the soil after one growing season in comparison to only 13% of shoot-derived C. Singh and Sidhu, (2014) [82] found that zero-till sowing of wheat with rice residue as surface mulch, while maintaining yield, reduces tillage costs and time saving, avoids the need for burning.

**Organic agriculture and carbon sequestration**

Gregorich *et al.* (1998) [25] observed that manure soils had large quantities of soluble C with a slower turnover rate than in control or fertilized plots. Feng and Li (2001) [21] concluded that for the same carbon input, carbon storage in soil was higher by 1.18 t $ha^{-1}$ C with manure application than with plant residues. Whalen and Chang (2002) [93] reported that manure application promoted the formation and stabilization of soil macro aggregates. Liu *et al.* (2005) [43] found thatthe profile average SOC content (0- 90 cm) was only 0.9%, 4.1%, and 8.6% higher for manure, chemical fertilizers, and manure plus fertilizers, respectively, than that with no fertilizer application or control in the Chinese Mollisols. However, SOC at the 0- 15 cm soil layer was 6.2%, 7.7%, and 9.3% higher with manure, chemical fertilizers, and manure plus fertilizers, respectively, than with no fertilizer application. These results indicated that the annual rate of decline rate of SOC in the 0 15 cm layer without fertilizer was not very high (< 0.58%/yr) when a well-designed crop rotation was used. Kukal *et al.*, (2009) [33] revealed that application of FYM and inorganic fertilizer in rice-wheat and maize-wheat cropping systems. They reported that the SOC sequestration rate was higher in FYM plots in comparison to NPK plots in both the cropping systems. Also the sequestration rate was three times higher in rice-wheat than in maize-wheat cropping system. Who obtained 7-20% higher organic carbon in top soil layer (5 cm) in cotton-rye cropping system with poultry litter as compared to fertilizer. In organic agriculture, biomass is not burned. It reduces the $N_2O$ emissions by 0.6-0.7Gt $CO_2$ e $yr^{-1}$ in comparison to conventional agriculture (Smith *et al*., 2007) [83]. Organic systems are highly adaptive to climate change due to: (a) the application of traditional skills and farmers' knowledge, (b) soil fertility-building techniques, and (c) a high degree of diversity. Liu *et al*., (2013) [46] revealed that the average concentration of particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) in 0–60 cm depth were increased by 64.9–91.9%, 42.5–56.9%, and 74.7–99.4%, respectively, over the CK treatment. Niggli *et al.*, (2009) [64] found that an organic approach 40 per cent of the GHG emissions of agriculture could be mitigated by sequestering carbon into soils at rates of 100kg of C $ha^{-1}$ $yr^{-1}$ for pasture land and 200kg of C $ha^{-1}$ $yr^{-1}$ for arable crops. By combining organic farming with reduced tillage, the sequestration rate can be increased to 500kg of C $ha^{-1}$ $yr^{-1}$ in arable crops as compared to ploughed conventional cropping systems, but as the soil C dynamics reach a new equilibrium, these rates will decline in the future. This would reduce GHG emissions by another 20 per cent. Organic farming is an important option in a multifunctional approach to climate change.

**Nutrient management in cropping system and carbon sequestration**

Manna *et al*., (2013) [50]; Kukal *et al*., (2009) [33]; Bhattacharyya *et al*., (2012) [8]; Naresh *et al*., (2017) [62] reported that long term application of NPK or farm yard manure (FYM) significantly increased the C sequestration rate in rice–wheat system (55% higher SOC in FYM plots and 70% higher in NPK plots) than in maize–wheat cropping system. Kukal *et al*., (2009) [33] revealed that the incorporation of green manure with FYM sequestered relatively low organic C as compared to green manure with FYM and crop residue. Liebig *et al*., (2002) [35] observed that high N rate treatments increased C sequestration rate by 1.0–1.4 Mg $ha^{-1}$ $yr^{-1}$. The application of FYM at 10–15 Mg $ha^{-1}$ $yr^{-1}$ along with NPK increased SOC sequestration at the rate of 50.7–900 kg $ha^{-1}$ $yr^{-1}$ over 28–33 years (Bhattacharyya *et al*., 2010; Mandal *et al*., 2007; Manna *et al*., 2005) [7, 48, 49]. Lal (2004) [38] concluded that globally, agricultural soils are estimated to potentially sequester 0.4–0.8 Pg C $yr^{-1}$ by adopting conservation agricultural practices, which represent 33.3–100% of the total potential of C sequestration in world soils. Srinivasarao *et al*., (2013) [84] observed that in a *Leucaena* agri-silvi system, C sequestration was the highest (13.7 Mg C $ha^{-1}$ yr−1) followed by *Prosopis* silvi-pasture system (2.36 Ta Mg C $ha^{-1}$ $yr^{-1}$). Nair *et al*., (2010) [59] reported that in agro-forestry systems, the C stored in soil ranged from 30 to 300 Mg C $ha^{-1}$ up to 1-m depth.

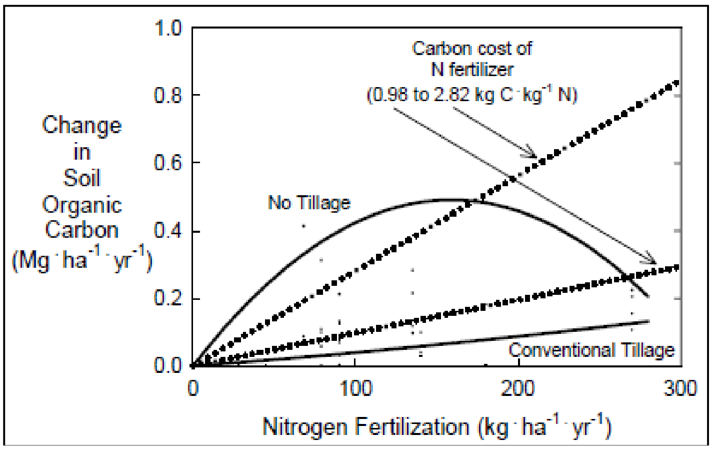


**Fig.4a:** Average change in soil organic C as affected by N fertilizer rate in the southeastern USA (Franzluebbers 2005).

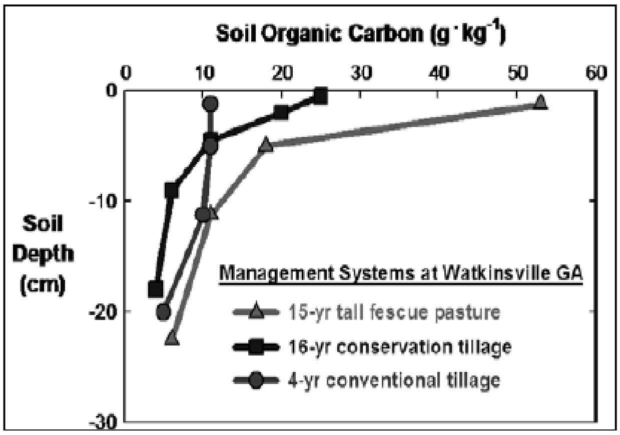


**Fig. 4b:** Depth distribution of soil organic C under conventional tillage, conservation tillage, and pasture (adapted from Schnabel *et al*., 2001) [79].

Franzluebbers, (2005) found that soil organic C sequestration during 15 + 17 years of pasture was estimated at 1.03 + 0.90 Mg C ha$^{-1}$ yr$^{-1}$ (Figure 4a). Soil organic C sequestration under pasture compared with conventional-tillage cropland averaged 0.53 Mg C ha-1 yr$^{-1}$ at a depth of 0-5 cm ($p$ < 0.01), 0.17 Mg C ha$^{-1}$ yr$^{-1}$ at a depth of 5-12.5 cm ($p$ < 0.01), and 0.05 Mg C/ha/yr at a depth of 12.5-20 cm ($p$ > 0.05) for a total of 0.74 Mg C/ha/yr to a cumulative depth of 0-20 cm (Schnabel *et al*., 2001 Figure 4b) [79]. Bhatia *et al*., (2010) [9] reported that the use of nitrification inhibitors such as: S. benzylisothiouronium butanoate (SBT butanoate) and S. benzyliso-thiouronium fluroate (SBT fluroate) increased yield of crop plants, reduced emissions of $N_2O$ by 4-5%, and, because $N_2O$ is a more potent greenhouse gas than $CO_2$, reduced global warming potential by 8.9-19.5% compared to urea treatment alone, thereby helping to mitigate $N_2O$ emission. Nitrification and urease inhibitors can reduce the loss of N as $N_2O$. The application of dicyandiamide (DCD) and Nitrapyrin to grassland reduced the emission of $N_2O$ from $NH_4^+$ based fertilizers by 64% and 52%, respectively. Snyder *et al*., (2007) [85] demonstrated that slow, control release and stabilized N fertiliser can enhance crop productivity and minimize the $N_2O$ emissions. Liu *et al*., (2006) [54] found that injection of liquid urea, ammonium nitrate at a deeper level in soil profile (10-15cm) resulted in 40-70% lower emission of $N_2O$ compared to shallow injection (5cm) or surface application. Hultgreen and Leduc (2003) [27] reported that the $N_2O$ emissions were reduced when urea was broadcast in mid-row rather than side-banded. Global warming potential in a no-N treatment of conventional transplanted rice was 1,419kg $CO_2$e ha$^{-1}$, whereas GWP under traditional nutrient application of NPK was 6,730kg $CO_2$e ha$^{-1}$ (Pathak, 2010) [69]. Suggested that the incentive for nitrous oxide emission reduction by application of lower nitrogen application rates within a profitable range ultimately could be financially remunerated through a carbon or nutrient market. That would bring economic and environmental advantages to compensate for lost productivity benefits due to the use of higher nitrogen application rates.

## Climate change and carbon sequestration

Concentration of $CO_2$ in the atmosphere has increased from 280 ppm in the pre-industrial era (~1750) to 385 ppm in 2009 (Normile, 2009) [65], and is presently increasing at the rate of about 2 ppm yr$^{-1}$ (0.50 %yr$^{-1}$). Atmospheric concentration of $CH_4$ has increased from the pre-industrial level of 700 ppb to 1789 ppb, at the rate of 13 ppb during the late 1980s, and 6 ppb from 2006 to 2007 (0.34%yr$^{-1}$). Similarly, the concentration of $N_2O$ has increased from 270 ppb in pre-industrial era to 321 ppb in 2007, and is increasing at the rate of 0.8 ppb yr$^{-1}$ (0.25%yr$^{-1}$). Because of the increase in concentration of GHGs, mean earth's temperature has already increased by 0.6 ± 0.2°C, and is projected to increase by 2 to 4°C towards the end of the 21$^{st}$ century under the business as usual scenario (IPCC, 2007) [30]. McKinsey and Co., (2009) [51] assuming that the SOC pool to 1-m depth can be increased by 10% on a global scale over the next 50 to 100 years, difficult and challenging as the task may be, transfer of 250 Pg of atmospheric C 910% of 2500 Pg of soil C pool to 1-m depth) is equivalent to reducing atmospheric $CO_2$ concentration by 118 ppm (250 Pg x 0.47 ppm/Pg). If the process can be presumably accomplished today increasing the soil C pool by 250 Pg would draw down the atmospheric $CO_2$ concentration from 383 ppm to 265 ppm, which is even lower than the pre-industrial concentration of 280 ppm. Indeed C sequestration in terrestrial ecosystems is the only cost-efficient process of reducing the atmospheric abundance of $CO_2$.

Globally, agriculture is responsible for about 20% of the greenhouse gas emissions. However, this percentage does not take into account the large role that agriculture plays in the opposing processes of photosynthesis and respiration, as well as contributions to soil organic C sequestration via animal manure application and crop residue inputs with conservation agricultural systems (Franzluebbers *et al*., 2006 Figure 5) [23]. Pacala and Socolow, (2006) [68] reported that C sequestration in terrestrial ecosystems is 3-4 Pg C Yr$^{-1}$ until 2050 through adoption of no-till farming and conservation agriculture, afforestation, and establishment of energy plantations.

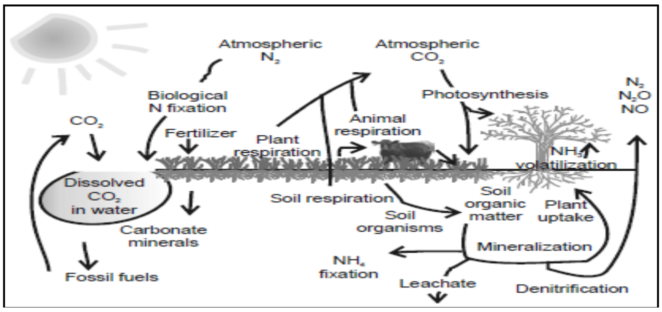


**Fig. 5:** Illustration of the terrestrial C cycle
***Source:*** alan.franzluebbers@ars.usda.gov

Naresh *et al*., (2015) [60] revealed that compared to conventional tillage (CT), zero-tillage and permanent raised beds (PRB) could significantly improve the SOC content in cropland. Lal (1989) [42] estimated that widespread adoption of conservation tillage on soil in 400 million ha cropland by the year 2020 may lead to C-sequestration of 1481 to 4913 Tg (1 Tera gram = $10^{12}$ g). It is estimated that agricultural intensification in India results in C sequestration of about 12.7 to 16.5 Tg yr$^{-1}$. The total potential of a SOC sequestration in India of 77.9 to 106.4 Tg yr$^{-1}$ (92.2 ±20.2 Tg yr$^{-1}$). Of this potential, 12.9% is through restoration of degraded soils and 45.6% through erosion prevention and management, 15.8% through agricultural intensification and 25.7% through secondary carbonates (Bhattacharya 2007) [6]. Mishra *et al*., (2010) [53] showed that the influence of tillage systems on SOC and total N storage can vary with the soil depth, cropping system, site specific characteristics and climate. Soil organic C sequestration rate was 0.28 + 0.44 Mg C ha$^{-1}$ yr$^{-1}$ without cover cropping and was 0.53 + 0.45 Mg C ha$^{-1}$ yr$^{-1}$

with cover cropping (Franzluebbers, 2006 Figure 6a) [23]. The average ratio of soil organic C with conservation tillage-to conventional tillage was 1.11 without cover cropping and 1.20 with cover cropping ($p$ = 0.02). It has been stated that conservation tillage alone creates an imperfect and incomplete system for conservation agricultural systems (Derpsch, 2007) [15]. concluded that mean soil organic C sequestration rate in cotton production systems was estimated at 0.48 + 0.56 Mg C ha$^{-1}$ yr$^{-1}$ (Figure 6b).

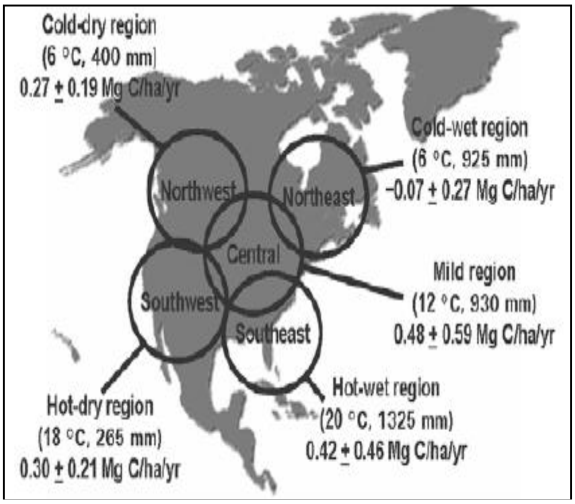


**Fig. 6a:** Mean + standard deviation of soil organic C sequestration rates in five different regions of the USA and Canada (adapted from Franzluebbers *et al*., 2006) [23]

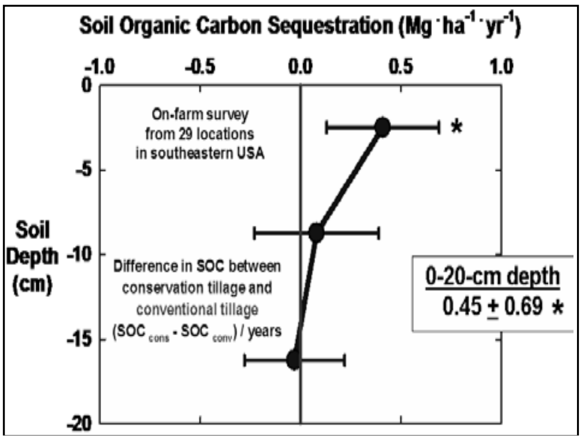


**Fig. 6b:** Difference in soil organic C sequestration between conservation-tillage and conventional tillage cropland (adapted from Causarano *et al*., 2008) [11].

Powlson *et al*., (2014) [71] concluded that the rates of SOC stock increase from reduced or zero tillage in the IGP (0.3 Mg C ha$^{-1}$ yr$^{-1}$, and zero tillage can have some value as a climate change mitigation strategy in some situations but its impact varies greatly between sites. Helgason *et al*., (2014) [26] found that the rate of residue decomposition, and hence SOC accumulation, is more sensitive to environmental conditions (temperature, moisture) for surface-applied residues, as in CA, than for those that are incorporated. Naresh *et al*., (2016) [61] reported that soil layers under FIRB and ZT with application rice straw and I5 treatments after 3 years. Hence, better aggregation was found with FIRB with 6t rice straw + I5 where macro-aggregates were greater than 30% of total soil mass. The same treatment also enhanced the labile C and N fractions such as water soluble C, particulate and light fraction organic matter from 7.1 mg·kg$^{-1}$ conventional tillage to 17.6 mg·kg$^{-1}$ in surface layer and from 6.5 to 16.3 mg·kg$^{-1}$ in subsurface layer after 3 years leading to the 42% and 39% higher water soluble C stocks over CT in 0-15 cm soil layers, respectively. The changes in water soluble C stocks after 4 years were 45% and 40%.

## Conclusions

Agricultural management practices and climate change i.e. conservation agricultural systems create a biologically intensive, yet ecologically protective interface between the soil profile and the atmosphere. Protection of the soil surface from natural physical forces that can cause degradation (i.e., wind, water, and traffic) is needed to allow soils to function to their highest potential. Sequestering organic C in soil, creating a nutrient-rich environment for the proliferation of plants, and allowing water to pass through and be filtered are some critical soil functions that can be enhanced with conservation agricultural systems. Soil organic C sequestration with agricultural management practices in upland soils of sub-tropical India can be relatively high (depending on management and soil conditions). Agricultural management practices, increased cropping system complexity, cover cropping; animal manure application, optimum fertilization, and rotation of crops with pastures are effective strategies to enhance soil organic C sequestration.

Soil organic C 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. A key to success will be to consider the agronomic, ecological and environmental constraints within a particular farm setting. The magnitude and severity of the depletion of SOC pool are exacerbated through decline in soil quality by accelerated erosion and other degradation processes. Perpetual use of extractive farming practices and mining of soil fertility also deplete the SOC pool. Conversion to a restorative land use and adoption of recommended agricultural management practices, which create positive C and nutrient budgets, can enhance SOC pool while restoring soil quality.

Soil carbon sequestration is a win-win-win strategy. Through its numerous co-benefits, it mitigates climate disruption, adapts agro-ecosystems to climate change, and improves the environment. This is a cost-effective strategy of moderating climate change, and is the only natural and viable option of reducing the atmospheric abundance of $CO_2$. The drawdown potential of soil C sequestration will help reducing atmospheric $CO_2$ concentration by 120 to 150 ppm over the next 50-100 years, and improving the environment. The amount of organic carbon stored in various soil pools is the balance between the rate of soil organic carbon input and the rate of mineralization in each of the organic carbon pools. However, the storage of carbon in soil profile is governed by the soil type, climate, management, mineral composition, topography, soil organisms and other unknown factors. 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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