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# Soil Organic Carbon Sequestration and Carbon Pools in Rice Based Cropping Systems in Indo-Gangetic Plains: An Overview

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

Carbon sequestration in the agricultural lands is possible through different soil management strategies and could be substantial with widespread implementation. Sequestration of historic carbon emissions is now essential as mitigation alone is not enough to stabilize our atmosphere. There are numerous management strategies for drawing carbon out of the atmosphere and holding it in the soil. Effectiveness of these strategies vary across different climates, soil types, and geographies. Still, it is a controversy about the durability of sequestration in soil and about the precise conditions that maximize drawdown of carbon emissions. Carbon sequestration in soil is the potential strategy which can reduce or mitigate the impacts of the global warming. The Asian countries are having more than 90% of rice fields, they are being blamed for their contribution in the methane emission and associated climate change. A major part of rice is grown under the continuous submergence condition that may influence the active and passive pools of soil carbon besides methane emission. In this paper we have reviewed the carbon sequestration potential of

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rice-based soils besides discussion on the mechanisms and strategies that promote accumulation of soil carbon while minimizing carbon emissions. The strategies *viz.* System of Rice Intensification, Integrated Nutrient Management, promoting mycorrhizal symbiosis in aerobic rice system besides enhancement of phytolith-occluded carbon are some of the key areas facilitating better carbon sequestration in rice ecosystem.

*Keywords: Carbon sequestration; passive pools; rice-based soils; soil carbon.*

## 1. INTRODUCTION

Soils can sequester carbon from the atmosphere with a proper management. On the basis of global estimates of historic carbon stocks and projections of rising emissions, the use fulness soil as a carbon sink and drawdown solution seems to be essential [1]. Since over one third of the arable land comes under agricultural production system, globally (World Bank, 2015), finding ways to increase soil carbon in agricultural production systems will be a major component of using the soils as a sink. A number of agricultural management strategies appear to sequester soil carbon by increasing carbon inputs to the soil and enhancing various soil processes that protect carbon from microbial turnover. Uncertainties about the extent and permanence of carbon sequestration in these systems are still remaining, but existing evidences are sufficient to warrant a greater global focus on the agricultural soils as a potential climate stability wedge and drawdown solution. Furthermore, the ancillary benefits of increasing soil carbon, including improvements to soil structure, fertility, and water-holding capacity, outweigh potential costs. In this paper, we'll discuss the basics of soil carbon, how it can be sequestered, management strategies that appear to show promise, and the debate about the potential of agricultural soils to be a climate stability wedge. Carbon sequestration in agricultural soils is a complex process controlled by the environmental factors and farming practices. Global warming is a prime factor associated with the climate change that is likely to have serious impacts on the earth. Such event is closely coincided with greenhouse gas emissions encompassing $CO_2$, $CH_4$ and$N_2O$ that contribute to the tune of 76%, 16% and 6% towards enhanced greenhouse effect [2]. Emission of $CO_2$ is considered as a 'kingpin' which was increased from 280 ppm (1850) to 395 ppm (2014) that commensurate with global mean temperature rise of $0.85^0C$ in the time period of 1800 to 2012 [2]. This trend continues to increase at an alarming rate which may result in serious consequences. Thus, there is a strong interest in stabilizing the atmospheric abundance of $CO_2$ and other GHGs to mitigate the unforeseen risks [3]. There are three strategies of lowering $CO_2$ emissions to mitigate the climate change viz. Reducing the global energy use, Developing low or no-carbon fuel and Sequestering $CO_2$ from point sources or atmosphere through some natural and engineering techniques [4]. Carbon sequestration is a most promising approach to minimize the emission of GHG, while conserving the carbon in the permanent pools of soil strata. Within the terrestrial ecosystems, rice soils are considered as the most important sites in global carbon cycling. Carbon sequestration is a process of transferring the atmospheric $CO_2$ into other long-lived global pools viz. oceanic, pedologic, biotic and geological strata [5]. The agricultural soils are considered as a source of GHG emissions, thereby, its potential role as a sink cannot be neglected. McConkey et al., [6] stated that every kg of soil organic carbon removes 3.7 kg of $CO_2$ from the atmosphere. Major paddy growing areas viz., India, China and other South East Asian countries are often blamed for their intensive emission of greenhouse gases. In India, rice is continued to be a major food crop and the area under rice cultivation is about 43.79 million hectares in the country which is mainly under submerged system of cultivation [7]. This facilitates methane emission which has a global warming potential of 28 times as that of $CO_2$ for 100-years' time horizon [2]. On other hand, the rice ecosystem is known to retain high amount of the resilient carbon among all the terrestrial ecosystems [8]. Organic matter preferentially accumulates in continuous rice systems as a result of submerged conditions. Slow rate of organic matter decomposition and higher net productivity of submerged rice soils lead to net carbon accumulation [9]. This situation warrants the scientists to identify the eco-friendly system of rice cultivation to promote carbon sequestration vis-à-vis lessen the global warming impacts.

The carbon sequestration in the soils is considered a win-win situation because it improves soil quality and mitigates greenhouse gases in the atmosphere. However, the carbon sequestration in soil is often associated with the increasing greenhouse gas emissions in lowland rice soils, which can be detrimental to climate change mitigation. Incorporation of rice straw into the soil increases soil organic carbon and is considered important for recycling of the nutrients, and is advisable over burning as the latter causes respiratory health problems. However, the decomposition of straw under submerged conditions causes formation of phenolic compounds, which affect availability of nitrogen and crop growth, and increases greenhouse gas emissions, particularly methane. Production of methane under anaerobic decomposition of organic matter in lowland rice contributes about 10% of the global anthropogenic methane emissions through agricultural practices. Nitrogen fertilizers increase rice yields and soil organic carbon, but also increase methane emissions which depends on the application rate. This poses challenges on how to improve the productivity of rice system and foster soil organic carbon sequestration while reducing the emission of greenhouse gases, and finding the optimum balance remains fundamental for rice ecosystems. The following questions remain pertinent for lowland rice systems:

1. Is it possible to simultaneously sequester carbon in rice soils and reduce greenhouse gas emissions?
2. Can the carbon sequestration-greenhouse gas reduction benefits be achieved concurrently?
3. Are we chasing contradictory aims?

## 2. SOIL CARBON SEQUESTRATION

The soil carbon sequestration has immense potential to mitigate the increase in atmospheric $CO_2$ concentration. Global soil carbon is 3.3 times the size of the atmospheric pool and 4.5 times the size of the biotic pool [1]. The carbon sequestration potential of agricultural soils was duly recognized in article 3.4 of the Kyoto Protocol and itis now considered as a possible means of reducing atmospheric CO2 [10]. Watson et al. [11] estimated that 0.4-0.8 Pg C $y^{-1}$ is sequestered in agricultural soils globally by implementation of appropriate management practices. Numerous studies have also shown that croplands oils may serve as a large sink for atmospheric $CO_2$ by enhancing SOC ([12]; [13]). Generally, the process of soil carbon sequestration implies that pools of soil organic carbon and soil inorganic carbon as secondary carbonates get enhanced. However, the role of soil inorganic carbon in carbon sequestration is less well understood than that of soil organic carbon and there are also concerns of degradation of fertile agricultural soils as a result of enhancing the soil inorganic carbon. Hence, research in the field of soil carbon sequestration currently focuses on improving the SOC content of the soils, which can improve the quality of soil and crop productivity while improving the environment [5]. With respect to soil carbon sequestration, it is most desirable to fix atmospheric C (upon photosynthesis) in passive pools that have long turnover times in contrast to active carbon pools [14].

## 3. ACTIVE CARBON POOLS

The active carbon pool of soil is the accumulation of carbon in the labile form with short residence period of time. Active pools of soil organic carbon consist living microbes and microbial products along with soil organic carbon with a short turnover time period of 1-5 years [15]. Stevenson [16] reported that Carbohydrates represent approximately 5-20% of the total SOC and originate from plants, animals and microorganisms. Soil carbohydrates are mixture of complex polysaccharides that is important for the formation of stable soil structure and aggregation. According to Vivek [17] the major fractions of active pools of SOC include soil microbial biomass carbon, water-soluble carbohydrates and water-soluble organic carbon. Active carbon fractions are the energy source for soil food web and thus influence in nutrient cycling. The labile fractions of SOC respond faster to the changes in the supply of carbon and are considered as the important indicators of the soil quality [18]. The soil microbial biomass normally constitutes about 1-5% of the total soil carbon and can provide an early warning for a possible degrading and/or aggrading effect of different management practices on soil quality [19]. The water-soluble organic carbon seldom exceeds 200 mg/kg but it appears to be immediate organic substrate for the soil microorganisms. Turnover of soil microbial biomass therefore requires replenishment of water-soluble organic carbon supplies [17]. Swarup and Singh [20] stated that the C:N ratio of microbial biomass carbon (MBC) is about 5-15providing the mineral nutrients and life to the soil.

## 4. PASSIVE CARBON POOLS

Passive pools of soil organic carbon (SOC) include most recalcitrant fraction of the soil organic matter. The fractions which are chemically recalcitrant are humic acid and fulvic acid having the longest turnover time period. These humic substances are relatively stable fraction of SOM pool and are able to partly resist microbial decomposition and hence, they help to maintain the level of SOM [21]. According to Stevenson [16] these fractions possess a considerable chemical reactivity through which they contribute to the properties and productivity of soils. Passive pools are also called highly recalcitrant and these are very slowly altered by microbial activities [22]. C:N ratio of passive pools ranges from 7:1 to 9:1 [20]. Thus humification (the alteration of biologically derived carbon to chemically complex forms) also represents a critical process driving carbon sequestration. Subramanian [23] stated that Glomalin, a recalcitrant mycorrhiza specific glycoprotein produced by symbiotic arbuscular mycorrhizal fungi substantially contributes for soil carbon sequestration besides facilitating soil fertility. Glomalin which is a component of the hyphal wall, accumulates in soils considered to have a slow turnover as a consequence of its long resilient time which varies from 50 to 500 years [24]. The total contribution of glomalin carbon to the total organic carbon pools was estimated to be3.77-7.84% of total carbon depending on land-use type and total soil carbon [25]. In addition, it contains about 5% of iron and enhances soil aggregation, protecting carbonaceous material from rapid degradation in the soil ([26] and [27]). Recently, scientists have identified that carbon occluded within phytoliths of crop plants such as rice and sugarcane are important fraction of soil organic carbon (SOC) that can remain in the soil fora longer period [28]. Phytoliths, a plant stone, are silica bodies produced by plants in biomineralization process and thereby facilitates in the occlusion of carbon within the phytoliths. Therefore, the terrestrial carbon sequestration can be achieved by enhancing the phytolith-occluded carbon (PhytOC) production in plants and subsequent accumulation in the soil. The main objective of the soil carbon sequestration is to convert the atmospheric $CO_2$ into stable soil carbon pools which help to mitigate the impact of global warming besides facilitating in carbon

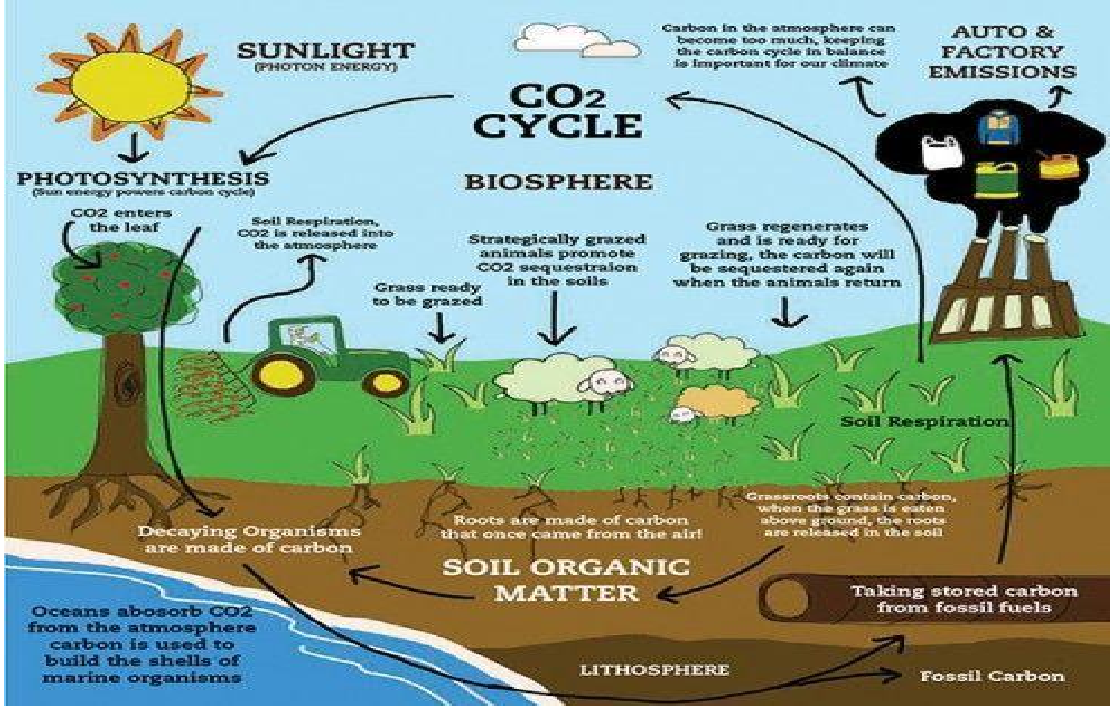

Fig. 1. Carbon cycle

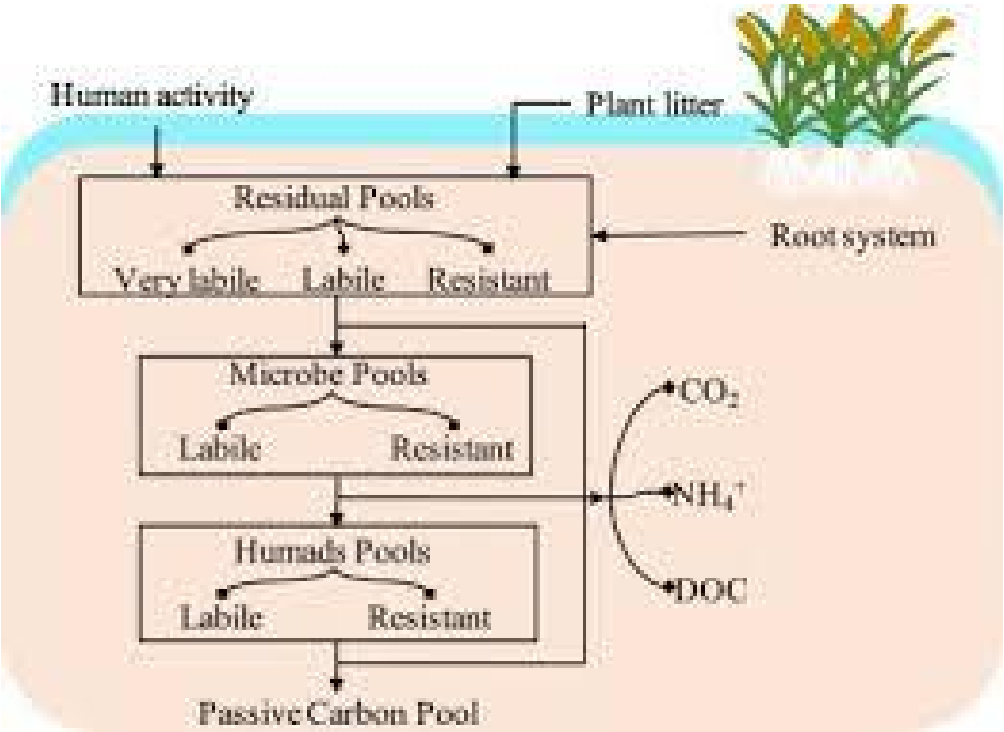

**Fig. 2. Passive carbon pools**

trading. But recently it is observed that the soil carbon sequestration is a less preferred area in carbon trading with the fact that there is lack of real and quantifiable assessment of carbon capture in this process. This is mainly due to the dynamic nature of soil organic carbon (SOC) and controversies surrounding the production of passive soil carbon pools like humic acid and fulvic acid on short term basis in the agro-ecosystems. More importantly, the available procedures for accurate quantification of these pools of carbon are far from satisfactory. On the other side, according to Phytolith-occluded carbon (PhytOC) research carbon occluded in phytoliths are easy to quantify as well demonstrating the benefits on long term basis. Therefore, it is understandable that future research must focus more on soil carbon sequestration in phytoliths in order to witness real time sequestration and promote the carbon trading.

### 4.1 Strategies for Enhancing Carbon Sequestration in Rice Ecosystem

1. System of Rice Intensification (SRI): The system of rice intensification improves humification process besides reducing $CH_4$ emissions.
2. Integrated Nutrient Management (INM): Practice of integrated nutrient management enhances humification process and increases SOC.
3. High yielding cultivars and hybrids: Use of improved seeds increases recalcitrant compounds.
4. Mycorrhizal inoculation: Inoculation of mycorrhiza improves glomalin content in aerobic rice soils.
5. High PhytOC yielding rice cultivars: Enhances phytolith occluded carbon.

## 5. MECHANISMS OF SOIL CARBON SEQUESTRATION IN RICE SYSTEM

Increasing evidence has shown a greater potential for carbon sequestration in paddy soils than in upland soils. However, the mechanisms underlying long-term accumulation and protection of soil organic carbon in paddy fields has not been well documented [29]. The classical literature by Ponnamperuma [30] explains that the decomposition of organic matter in a very submerged soil is slower than well drained soil. Under anaerobic conditions, both the decomposition of amended organic matter and mineralization of native SOC are not up to those under aerobic conditions ([31]; [32]). Intensive rice cropping assists in accumulation of phenolic lignin compounds that are immune to microbial decomposition under submergence [33]. They concluded that the changes in SOC quality under anaerobic conditions may contribute to the slowdown of C decomposition in paddy soils. During drying, iron species ($Fe^{2+}$) undergo oxidation and in wetting periods, iron species undergo reduction ($Fe^{3+}$). Thus, iron cycling has the potential to both limit carbon oxidation and limit methane release (by acting as a subsurface oxidative agent and a competing electron acceptor in microbial respiration). Net retention of organic matter and plant debris are often observed in most wetlands [34]. Consequently, a protracted period of soil submergence promotes the formation of passive pools of SOC vis-a-vis carbon sequestration [18]. In contrast, the formation of humic compounds is maximized under partly oxidizing conditions: If there's an excessive amount of oxygen, full mineralization occurs; if there's deficient, oxidative polymerization is stifled. Frequent wetting and drying cycles avoid the stagnation that happens under either oxidizing or reducing conditions and promote the oxidative polymerization reaction that stabilizes carbon [35]. The mechanisms involved in preferential accumulation of organic matter in wetland soils are ascribed mainly to an aerobiosis and also the associated chemical and biochemical changes [36]. In submerged soils, the formation of recalcitrant complexes with organic matter renders them less available for microbial attack. Moreover, the biological organic process including overall higher primary productivity and decreased humification result in net accumulation of organic matter in wetland soils and sediments. Hydrologic regimes that produce seasonal wetting and drying like rice can provide the motive force for iron cycling [37].

## 6. POTENTIAL CARBON SEQUESTRATION OF RICE SOILS

Globally, rice cultivation covers a total area of about 153 mha and it has been proposed to have a great potential in sequestrating atmospheric $CO_2$ ([1]; [38]). Among all terrestrial ecosystems, rice soils have the highest carbon density [39] and therefore they constitute an important carbon stock. Ramesh et al. [10] investigated various land use systems of semi-arid tropics, they have shown rice systems had highest content of organic carbon and nitrogen irrespective of bioclimatic zones, land use under agricultural and horticultural systems. The high productivity, high water table, and low decomposition rate associated with wetlands favour carbon storage within the soil, sediment and detritus [40]. Great potential for soil carbon sequestration has been found in rice paddies [41]. Jarecki and Lal [42] reported the potentials for SOC sequestration for rice as 401 kg C $ha^{-1}$ $yr^{-1}$. Evidence has also shown that carbon density in paddy soils was higher than that in upland soils ([43] and significant amount of carbon is sequestrated in rice soils over the last two decades in China [44].

## 7. SOIL ORGANIC CARBON SEQUESTRATION UNDER RICE-WHEAT SYSTEM

An emerging concern in the Rice-Wheat cropping systems is the reduction in soil organic carbon content and the associated reduced nutrient supplying capacity of the soil. In India, about 19.6 million tonnes of rice and wheat straw are burnt, if it is used as the recycled biomass, this potentially can translate into 3.85 mt of organic carbon, 59,000 tonnes of nitrogen, and 2,000 tonnes of the phosphorous and 34,000 tonnes of potassium and could be one of the potential options for improving the SOC stocks of soil. When residues are incorporated into the soil, mineral nitrogen is immobilized during decomposition, which may reduce nitrogen uptake and yield of the succeeding wheat crop by about 40% [45], whereas the combined use of rice or wheat straw and inorganic fertilizer in RW systems can increase the yield of rice and wheat [46] and build up SOC. Nambiar [47] reported that SOC in treatments not receiving farmyard manure declined in some long-term experiments in India, and that applications of FYM before either crop were effective in building up SOC and boosting crop yields. In the present rice-based cropping systems, crop residues are either burnt or removed from the field for stock feed and bedding, roofing and fencing.

Across the different agro-climatic zones of IGP, comparatively higher SOC content was observed in LGP followed by MGP, UGP and TGP, respectively. The higher SOC content in LGP and MGP over TGP and UGP is due to higher clay content in the soil, low land situation, reduced conditions due to incomplete drainage and humid climate [48]. Organic matter decomposition proceeds faster in sandy than in clayey soils [49], while the rate of soil organic matter decomposition is lessened in lowland rice fields, apparently due to excessively reduced conditions [50]. Because of the lack of oxygen under submerged conditions, even a modest oxygen demand for microbial activity cannot be met if large pores are filled with water, resulting in a decreased rate of decomposition [51]. Therefore, there is an incomplete decomposition of organic materials and decreased humification of organic matter under submerged conditions, resulting in net accumulation of organic matter in soils [52].

Continuous application of NPK for 23–26 year in Rice-Wheat cropping system has resulted in significantly higher SOC over control in 0–15 cm soil depth across different agro-climatic zones of IGP. Intensive RW system in IGP without application of fertilizers resulted in reduction (22 and 35% decrease) of SOC concentration over initial value in middle and lower IGP, respectively whereas at trans and upper IGP, it has more or less maintained the SOC level [48]. As initial SOC concentration was comparatively higher at middle and lower IGP than trans- and upper-IGP, it would be hard to maintain SOC contents without fertilization and/or organic matter addition in middle and lower IGP. However, because of very low initial value, the SOC concentration in the control plot was maintained at trans and upper IGP despite declining yield trend. Application of recommended dose of NPK resulted in increased SOC in surface soil over the initial level at all places except at LGP where a slight reduction was recorded. The higher stubble and root biomass retention comm. ensurating with higher yield in the NPK fertilized plot might have improved the SOC in surface soil at all sites except at LGP where initial SOC value was comparatively higher than others. However, compared to unmanured/unfertilized control, the fields receiving recommended NPK fertilizer resulted higher SOC concentration in surface soil at all the places. Results of other long-term experiments have also shown that with optimum application of inorganic fertilizers, the SOC content has either been increased ([53]; [54]) or maintained over the years [55]. Substitution of 50% N through FYM or crop residue (CR) or green manure (GM) to rice has improved SOC significantly over NPK treated plots at all the locations. The addition of FYM, CR, and GM complemented with NPK increased the organic carbon content of soil over that achieved with NPK alone, due to additive effect of NPK and organics and interaction between them [48]. A similar build-up of SOC due to cropping with the application of chemical fertilizer combined with manure [56], paddy straw [57], and green manure [58] were also reported from long-term experiments. Many long-term experiments have shown that both chemical fertilizer and manure application increased the SOC content in the soil, but the increases in SOC is seen much higher with organic manure.

Using the mass of SOC in the control treatment as reference point and number of years of interventions, Nayak et al. [48] estimated the sequestration rate (rate of net SOC increase), which varied from 0.231 to 0.332 t $ha^{-1}yr^{-1}$ in NPK treated plot under continuous RW cropping system in the different agro-climatic zones of IGP (Fig. 2). Among the treatments, NPK + FYM recorded significantly higher sequestration rate over all other treatments across all the agro-climatic zones except at LGP and UGP where the sequestration rate between NPK + FYM and NPK + CR were at par. Their study indicates that applications of NPK fertilizer with or without organics can sequester carbon in soils at all the sites of IGP. Response of SOC to carbon input has been controversial ([59]; [52]). Hao et al. [60] reported that combined applications of inorganic fertilizers (NP and NPK fertilization) with or without manure can sequester carbon in soils at most of the sites of northern China. The soil carbon sequestration rates as reported by Nayak et al. [46] vary from 0.08 to 0.98 t $ha^{-1}$ $yr^{-1}$ in IGP under the NPK, NPK + FYM, NPK + CR and NPK + GM treatments, which are comparable to those from other studies [61]. The soil carbon sequestration with response to application of fertilizer complemented with organics was higher in LGP and MGP in humid climate than in TGP and UGP lying in semiarid climate. While budgeting carbon stocks in different eco-regions of Asia indicated a possible conservation or even increase in carbon stock in soil in the lowland tropics, despite high temperature prevalent throughout the years, which favours rapid mineralization of carbon. They opined that this was due to the relatively slow rate of soil carbon mineralization under anaerobiosis and also the large carbon inputs from nonvascular plants in the soil–flood water ecosystem. Soils rich in clay may have more potential to sequester carbon than those rich in sand and silt in the similar climate zone, due to the physical protection of mineral on soil organic carbon which also partly explained the higher SOC sequestration rate at LGP having higher clay percent (Matus *et al*., 2008).

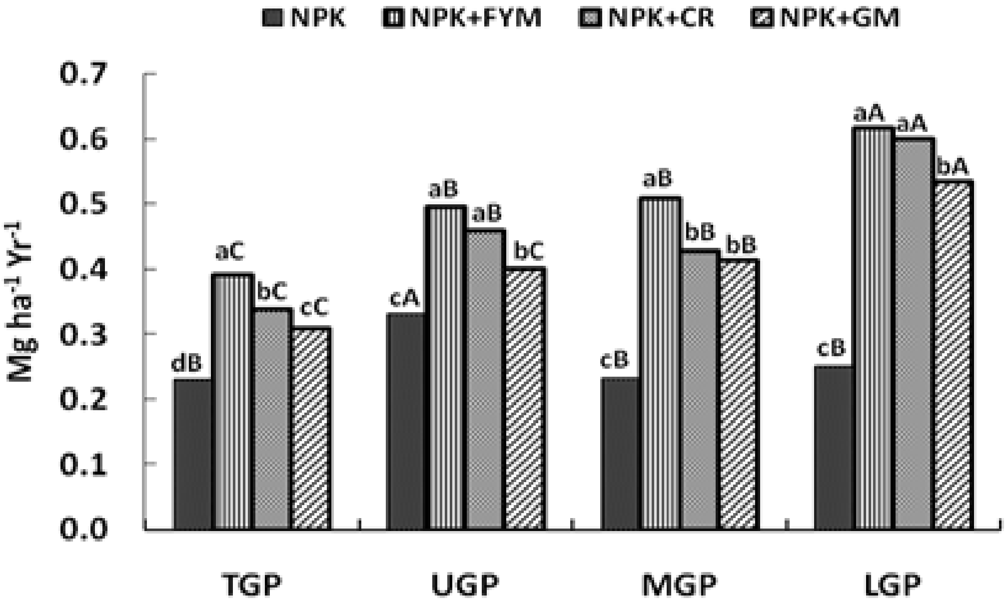

**Fig. 3. Changes in soil organic carbon pool (Mg ha$^{-1}$ Yr$^{-1}$) in different integrated nutrient management system over the control under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower-case letters are not significantly different in different treatments at same centre; means with the same uppercase letters are not significantly different in a treatment at different centres). Adapted from Nayak et al. [46]**

## 8. SOIL ORGANIC CARBON SEQUESTRATION UNDER SALT AFFECTED SOIL

Saline and sodic soils are of widespread occurrence in the arid and semiarid regions of northern India, limiting the productivity of more than 2.5 m ha of otherwise arable lands in the IGP (Abrol & Bhumbla, 1971). Afforestation and reclamation through agroforestry systems have been reported to increase soil organic matter content and improve the biological properties of sodic soils (Singh, 1996; Singh & Singh, 1997). Phytoremediation of sodic soil of IGP soil can sequester 0.826 Mg carbon ha$^{-1}$ yr$^{-1}$ under *Prosopis juliflora* plantations while intensive cropping of RW, including the application of gypsum amendments and optimum nutrient management, can sequester 0.689 Mg C ha$^{-1}$ yr$^{-1}$ (A.K. Nayak personal communication, 18 Feb, 2012). Kaur et al. (2002) suggested that various land use system can sequester organic C in the range of 0.2 to 0.8 Mg C ha$^{-1}$ year$^{-1}$. In long term experiment on a sodic soil, the changes in organic carbon under four tree species revealed that *Prosopis juliflora* is the most efficient species in terms of increasing SOC accumulation. However, the efficacy of application of amendments especially plant materials in enhancing soil organic carbon (SOC) status and amelioration of these soils depends on the plant species and their ability to grow and produce biomass (Qadir et al., 2002). In general, it has been found that the amelioration of sodic and saline soils through the use of plants in the form of vegetation and crop residues is a slow process and this process can be enhanced by the application of amendments such as gypsum to reclaim the sodic soils followed by phytoremediation by cultivating Rice-Wheat. However, phytoremediation is advantageous that in addition to supplying organic matter, it provides source of plant nutrients, which are released during their mineralization in the soil. Moreover, plant roots produce root exudates and mucilages, resulting in increased microbial activity and microbial products in and around rhizosphere for aggregate formation and stabilization. Growing roots also provide channels for enhanced infiltration and hydraulic conductivity for rapid leaching of excess salts. Remediation of even 10% area of salt- affected lands, achieving an estimated SOC sequestration of 0.2 Mg carbon $ha^{-1}$ $yr^{-1}$ over a 50-year period, may lead to 0.8 Pg carbon sequestered in SOC in these soils. Therefore, the potential for salt affected soils to sequester SOC is large and significant. It is expected that large proportion of C sequestration will occur or result in the formation and stabilization of soil aggregates such as SOM-$Ca^{2+}$ - clay aggregates, and as protected SOC against rapid microbial decomposition. However, research is required to validate this SOC sequestration mechanism after restoration of salt affected soils, since, besides SOC benefits other benefits occur in improved physical and chemical characteristics of the soil.

## 9. CARBON SEQUESTRATION IN SYSTEM OF RICE INTENSIFICATION (SRI)

System of Rice Intensification is a rice establishment technique which was developed by a French priest, Fr. Henri De Laulanie during early1980s in Madagascar. A set of agronomic practices followed in SRI viz. transplanting of 14-day old seedlings, square planting (25 x 25cm), criss-cross cono-weeding for four times with an interval of 10 days and irrigation scheduling with intermittent wetting and drying conditions up to PI stage [62]. The SRI reduces water requirements [63], raises input productivity [64], accessible to smallholders [65] thereby enhance yield of crop and is more favourable for the environment than conventional practice with its continuous flooding of paddies. Cono-weeding is the key component contributing nearly 40% towards the yield increase in SRI system of cultivation (Sudhalakshmi, 2002), such enhance productivity is closely associated with root proliferation and intense microbial activity. One of the key components of SRI is cono-weeding that aerates the rhizosphere of the soil which promotes microbial activities besides proliferating root growth. Roots are the prime location of carbon accumulation that would significantly contribute for the stable carbon pool in rice ecosystem. Barison [66] observed that SRI plants had considerably greater root length density in the lower soil horizons than the conventionally plants. RLD for SRI plants were 2.3 times more at 30–40 cm depth and 3.8 times more at 40–50 cm. They also had greater root pulling resistance (RPR) as SRI plants at the panicle initiation stage required 7.2 times more force per plant than rice grown with farmer methods. This disparity had increased to 14.2 times at the time of maturity. Such large phenotypical differences in root growth induced by SRI practices. Rupela et al., [67] observed that SRI plants had about 10times more root mass, about five times more root length density and about seven times more root volume in the top 30 cm of soil profile compared with roots of conventional rice plants. They also reported that the root length in the top 15 cm of the soil were 19.8 km $m^3$ and 2.4 km $m^3$ for SRI and conventional system, respectively. SRI practices in particular produce much larger and longer-lived root systems and these are associated with increased and modified populations of soil biota [68]. Rhizosphere microorganisms are efficient carbon sequester converting atmospheric $CO_2$ into biomass carbon. Rhizosphere soils of SRI had higher enzyme activities viz., dehydrogenase, urease, acid phosphate, alkaline phosphate and nitrogenase than conventional system [69]. Thiyagarajan et al. [62] stated that mechanical hand weeder mainly used for the weed control in a criss-cross pattern in SRI method. This implement buried the weeds in top 3–5 cm of soil. Decomposition of these weeds provides additional nutrients and beneficial aerobic microorganisms. Rajkishore [69] reported that larger proportions of passive pools of soil carbon such as humic acid, fulvic acid and glomalin retained by SRI method. It has unique features such as alternate wetting and drying and cono-weeding practice that are either favourable to enhanced humification processes or rapid decomposition of non-humic substances which might have contributed for higher humic acid and fulvic contents of SRI than conventional system of rice cultivation [70]. It is further explained that the components of SRI system such as alternate wetting and drying water management that provides irrigation after the development of hair line crack and the practice of cono-weeding that churns and aerates the soil are the important factors that facilitate humification process through the oxidation of phenolic substances in rice soils. As like Stevenson [16] reported that the sequential two-step of the humification process is the oxidation of phenolic groups followed by condensation of the resulting quinones with amino acids to form melanins. Importantly, the rate-limiting step in the humification process appears to be the oxidation of polyphenols to quinones. Then these quinones react with peptides and amino acids and form large melanin-like polymers that resist further degradation by microorganisms.

As a result of intense anaerobic conditions lower levels of passive pools of carbon in submerged rice cultivation suppress the humifications [70]. Continuous submergence restricts oxidation or decomposition of organic matter, reduces the biological activity besides excluding major portion of microbes that catalyse humification process. With increasing submergence, the humic acid fractions became less polycondensed and less oxidized or humified with higher sulphur and hydrogen and lower oxygen concentrations. Mahieu et al. [71] also demonstrated that proper aeration of soils promoted soil organic matter humification and that the humic acid fractions were less humified with irrigated rice cropping.

In SRI, irrigation is scheduled by alternate wetting and drying process in which moisture maintains at field capacity. This helps to reduce the methane emission from the rice field's and global warming impacts. Jayadeva et al. [72] estimated that $CH_4$ emission is 40% lower in SRI compared to submerged rice cultivation. Dumas-Johansen [73] evaluated the effect of SRI on the farmers' livelihood situation and reported through theoretically calculations that SRI inherits significant potentials for carbon storage and mitigation of greenhouse gases. Rajkishore et al. [70] have shown a consistent reduction in methane emission in SRI (31.8 and 37.7 kg ha$^{-1}$) than conventional system of rice cultivation (44.6 and 55.5 kgha$^{-1}$) in summer and kharif seasons, respectively. Rajkishore et al. [74] reviewed the potential methane mitigation strategies and highlighted the eco-friendly advantages of SRI components such as alternate wetting and drying system of irrigation, cono-weeding practice in reducing the methane emission. Overall, both resilient soil carbon pools and biological activities favoured by SRI management practices.

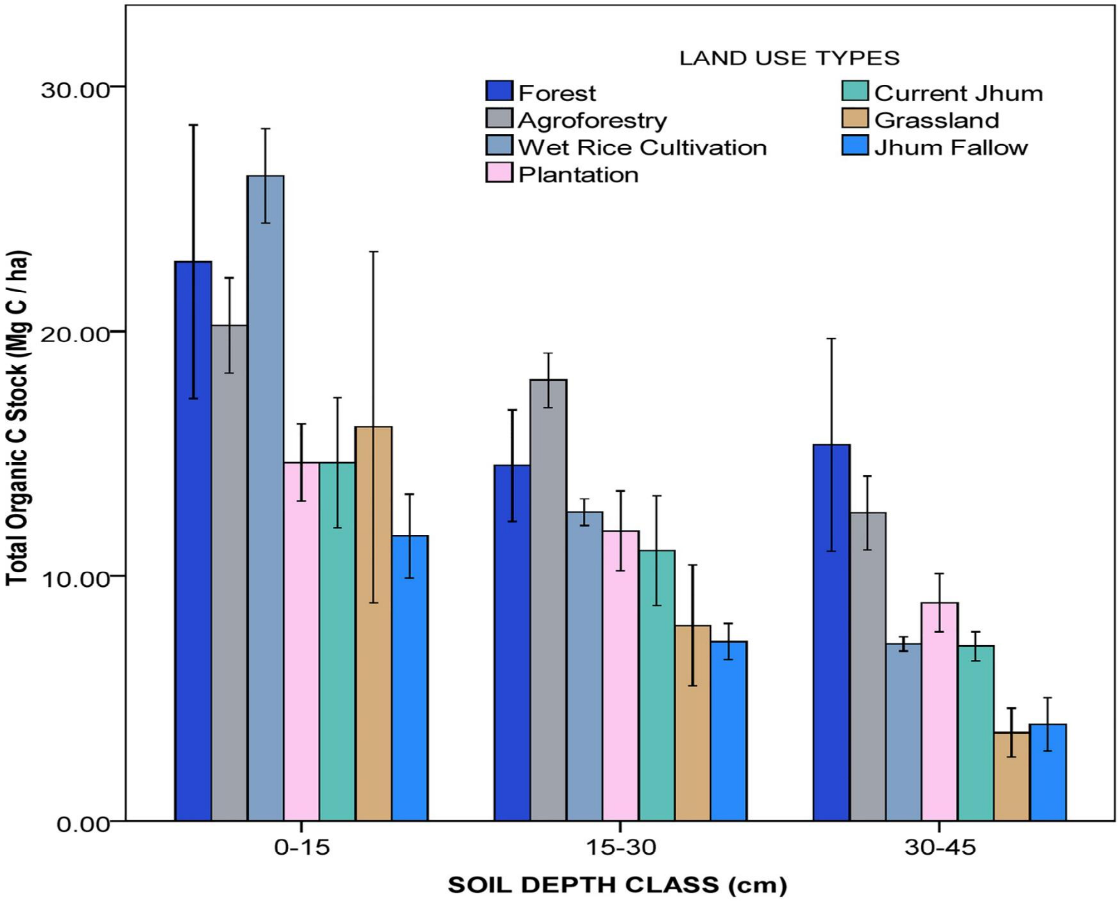

**Fig. 4. Soil organic carbon stock (Mg C ha$^{-1}$) at different soil depth in different land use types in Mizoram [75]**

## 10. STRATEGIES TO IMPROVE CARBON SEQUESTRATION IN RICE SOILS

Carbon sequestration potentials of rice soils can be further improved by the adoption of good agronomic practices. During the past decade of agronomic research, several strategies have been evolved and suggested to retain the carbon in fixed pools of soil while circumventing the emissions of greenhouse gases. Adoption of Integrated Nutrient Management practices to achieve the balanced crop nutrition, conserve carbon and increase the passive pools of soil carbon by enhancing the process of humification. Extension of the rice area under SRI system to minimize methane emission and improve passive pools of soil carbon in rice fields. In the State of Tamil Nadu government has implemented a policy to introduce SRI in the entire state to promote productivity of rice without associated environmental harms. Use of high yielding varieties, hybrids and GM crops with a good root: shoot ratio and harvest index with a large biomass production and profusely branched root system containing recalcitrant compounds (e.g., phenolics). Enhancement of soil processes involving biological nitrogen fixation and mycorrhizae. Better use of integrated farming systems that efficiently use resources, enhance biodiversity and mimic the natural ecosystems. Selection of high PhytOC-yielding rice cultivars over low PhytOC-yielding cultivars under different agro-ecosystems offers to enhance terrestrial carbon sequestration.

## 11. CONCLUSION

There is a need for more quantitative assessment of the carbon sequestration potential of agricultural soils of IGP under different management practices for different soil types, climates and agricultural systems by supporting existing long term cropping system trial sites and by establishment of new ones where appropriate; quantifying interactions of soil organic carbon (SOC) sequestration with the emissions of GHGs and developing soil carbon models that can account for locally relevant agricultural management practices. There is also a need for assessment of how rehabilitation processes affect carbon cycling and carbon stocks, and how to maximise the accumulation of carbon stocks in the salt affected areas of IGP where soil organic carbon (SOC) stocks are very small. Soil organic carbon accumulation is likely o be increased in rice soils, the fractionation of carbon in both, active or passive pools is quite complex. Therefore, more studies need to be conducted in order to gain insights into the chemistry of humification and its associated processes that govern the soil carbon sequestration. Moreover, the experimental investigations are to exploit the rice phytoliths to enhance the soil carbon sequestration. Rice soils also serve as a source of methane and therefore suitable region-specific methane mitigation strategies have to be evolved besides budgeting the GHG potentials of already identified management practices.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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