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RK Naresh
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

M Sharath Chandra
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Pradeep Kumar Kanaujiya
Department of Agronomy, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India

Mahendra Pratap Singh
Department of Agronomy, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India

Aryan Baliyan
Department of Soil Science and Agricultural Chemistry, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Shakti Om Pathak
Department of Soil Science and Agricultural Chemistry, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Himanshu Tiwari
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Corresponding Author:
RK Naresh
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Temporal changes in biochemical indicators of soil quality and nutrient dynamics in conservation agriculture based rice-wheat systems in north western India: A review

RK Naresh, M Sharath Chandra, Pradeep Kumar Kanaujiya, Mahendra Pratap Singh, Aryan Baliyan, Shakti Om Pathak and Himanshu Tiwari

Abstract
Agricultural productivity relies on a wide range of ecosystem services provided by the soil biota. Sustainable management practices, such as tillage and residue management, can influence structure and function of the soil micro-biota, and nutrient dynamics with direct consequences for the associated ecosystem services. Although there is increasing evidence that different tillage regimes alter the soil biological indices, we only have a limited understanding of their temporal changes in rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system. However, agricultural intensification is placing tremendous pressure on the soil's capacity to maintain its functions leading to large-scale ecosystem degradation and loss of productivity in the long term. Therefore, there is an urgent need to find early indicators of soil health degradation in response to agricultural management. Our purpose was to review the literature in which a wide perspective of soil quality and the complex task of its assessment, considering the inherent and dynamic factors, are introduced. It focuses on the possibilities of applying and integrating the accumulated knowledge in agro-ecological land evaluation in order to predict soil quality. Land use change, especially from conservation agriculture ecosystem (CA) to intensive agriculture, is negatively impacting soil quality and sustainability. Soil biological activities are sensitive indicators of such land-use impacts. Land use and management practices affect microbial properties in topsoil but have no effects in subsoil.
The majority of the increases in biochemical properties were higher at vegetative growth (at 40-45 days after sowing) and flowering (at 80-85 days after sowing) stages compared to the initial and at maturity. The principal component analysis of the assayed variables showed that all the variables significantly contributed to the variability in parameters examined and were more related to maximum tillering stage of wheat growth than to maturity or at sowing of wheat. Three highly effective biological indicators were microbial biomass carbon, microbial quotient and mineralization quotient, which responded significantly to changes in tillage and residue management practices in the RWS. Studies showed that non-puddling significantly enhanced dehydrogenase activity (5%), microbial biomass carbon (3%) and potentially mineralizable nitrogen (5%) over puddling, whereas the latter treatment hugely benefited meta bolic quotient (41%) in rice. Notillage resulted in higher values of soil biological indicators under wheat cultivation. Partial substitution of fertilizer N by farmyard manure, sewage sludge and a combination of (FYM + biofertilizer + crop residues/green manure) increased indicators at higher magnitudes, like dehydrogenase activity (36%), microbial biomass carbon (33%) and potentially mineralizable nitrogen (57%), but reduced the metabolic quotient which implied an accumulation of stable organic C under organic nutrient management. In all soil layers the total SOC, WSOC, HWSOC, EOC, MBC, POC, and LFOC contents were 13.87-145.97% higher in the NPKS2 treatment than in the CK treatment. The CPMI was highest in the NPKS2 treatment in the top 20 cm soil. SOC correlated positively with labile C fractions and CPMI in the 0-5 and 5-10 cm soil layers ($p < 0.05$), with the exception of WSOC and LFOC in the 5-10 cm soil layer.

Keywords: Tillage practices, residue retention, soil quality, soil microbial activity, soil indicators

Introduction

Soil is an extremely complex ecosystem and a highly valuable resource from an ecocentric and anthropocentric perspective. Soil is undoubtedly one of our most essential and strategic resources, due to its many crucial functions, including: (i) provision of food, fiber, and fuel; (ii) decomposition of organic matter (e.g., dead plant and animal material); (iii) recycling of essential nutrients; (iv) detoxification of organic contaminants; (v) carbon sequestration; (vi) regulation of water quality and supply; (vii) habitat provision for myriad of animals and microorganisms (soil is an important biodiversity reservoir); (viii) source of raw materials (clay, sand, gravel). Unfortunately, soil has been and is currently being rapidly degraded at a global scale due to a range of invasive anthropic activities in intensive agriculture, with concomitant adverse effects on human and ecosystem health. This is concerning as soil is a non-renewable resource at a human temporal scale (i.e., soil loss and degradation are not recoverable within a human lifespan).

Rice-wheat system (RWS) is a major crop rotation for food security, employment, income and livelihood for millions of people in Asia (Singh *et al*., 2014) [5]. This system occupies about 13.5 million hectares in the Indo-Gangetic Plain (IGP) of South Asia (Gupta and Seth 2007) [16]. Intensive tillage, imbalance use of fertilizers, depletion of water resources and environment pollution have led to stagnation or declining trends in yields of the RWS in many parts of South Asia (Srinivasan *et al*., 2012) [52]. This calls for immediate solution by adopting better management practices for improving soil and environment quality, and maintain social ecosystem. Conservation agriculture (CA) practices (zero tillage and residue retention) are gaining momentum as alternate to conventional practices for addressing the issues of energy, labour, water scarcity, environment quality and climate change (Gathala *et al*., 2013; Jat *et al*. 2016) [13], and for sustained and improved productivity of RWS in South Asia (Dikgwatlhe *et al*. 2014; Zhang *et al*., 2014) [7, 61]. Nearly 44.5 Mt of rice residues are burned annually in North-West India causing serious environmental pollution (Yadvinder-Singh and Sidhu, 2014) [5]. In-situ management of rice residue as surface mulch is one practice for its effective disposal that can decrease air pollution and increase soil organic carbon (SOC) content (Soon and Lupwayi 2012) [51]. Zero tillage in combination with surface retention of rice residue conserves soil water and improves overall soil health through enhancing soil organic matter content (Gathala *et al*., 2013; Naresh *et al*., 2020) [13].

SOC plays an important role in improving all aspects of soil quality (structure, water relations, chemical fertility and biodiversity) because it provides energy and substrates for microbial metabolism, and promotes biological diversity (Loveland and Webb 2003) [30]. Thus, total and labile SOC pools (e.g., microbial biomass and enzyme activities) are important indices for assessing soil quality (Jin *et al*. 2009; Naresh *et al*., 2015) [22, 41]. Moreover, the labile fractions are very sensitive to changes in soil biological quality during the process of restoration (Pajares *et al*. 2009) [45].

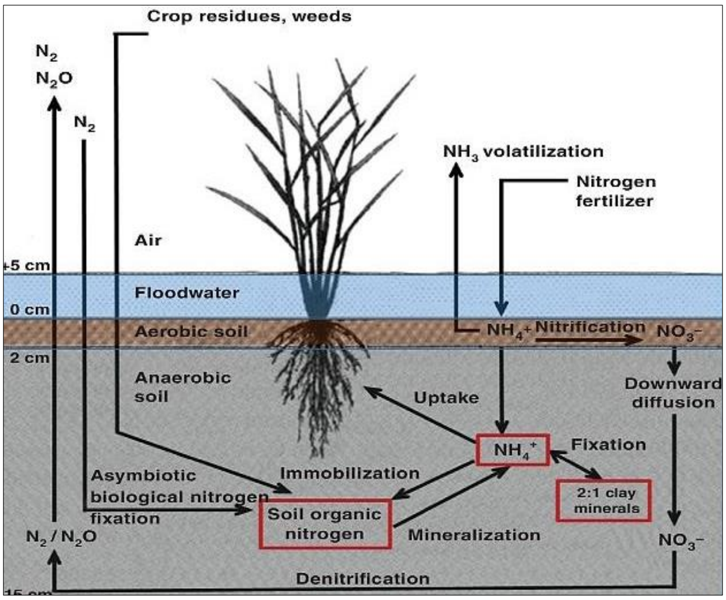
Nutrient release and uptake by plants is facilitated by soil microbial activity and decomposition of crop residues. Decomposition of crop residues under CSA practices further enhance C mineralization and make nutrients available to plants (Datta *et al*., 2019) [65]. Therefore, soil biological properties, carbon mineralization and simultaneously nutrient release and their uptake by crop at different wheat growth stages are strongly related.

The relationship between grain yield and crop biomass accumulation can help in accomplishing improvements in yield through better agronomic management practices and plant breeding (Malhi *et al*., 2006) [63]. Grain yield usually increases with simultaneous increase in total dry biomass and nutrient uptake under optimum growing conditions (Malhi *et al*., 2006) [63]. Distribution patterns of biomass accumulation within plant, its amount, dynamics and nutrient uptake differ with crop growth stages and are influenced by crop cultivars and climatic conditions (Gawronska and Nalborczyk, 1989) [64]. Therefore it is required to determine the total nutrient availability and the temporal pattern of their uptake at different crop growth stages for synchronization of nutrient supply with crop nutrient demand to optimize fertilizer recommendations (Malhi *et al*., 2006) [63].

Tradeoffs of puddling on soil biological properties

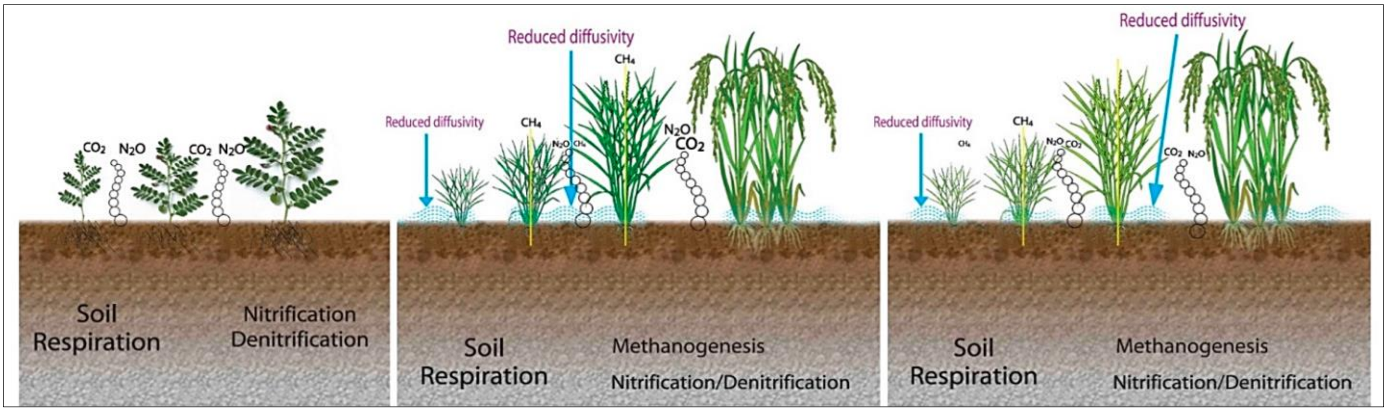
Gunapala and Scow, (1998) [17] attributed the increased MBC and MBN to increased microbial activity and availability of substrates under favorable temperature prevailing in puddled soil for transplanted rice (Gajri and Majumdar, 2002) [11]. When it is conventional puddled transplanting of rice with residue removal, the different scenarios were recorded by many researchers in rice-based cropping systems. Jat *et al*. (2020) [20] also found that climate smart agriculture (CSA) practices after five years, conventional puddling of rice followed by tillage for wheat (conventional scenario) had lower MBC, MBN, dehydrogenase activity (DHA), alkaline phosphatase activity (APA) and β-glucosidase over CSA based rice-wheat cropping. For example, conventional puddling of rice and full tillage for wheat had around 42% lower MBC, 79% lower MBN, 58% lower APA and 14% lower DHA at 0−15 cm depth than CSA based scenarios. These lower MBC, MBN and enzyme activities in puddled soils might be attributed to unfavorable soil temperature and soil moisture prevailing under conventional scenario. Disturbance of soil by puddled transplanting of rice had higher microbial biomass C (MBC) in soil than MBC in soils under non-puddled rice.

Alam, (2018) [1] also found that soil heterotrophic respiration and nitrification processes mainly take place in aerobic condition to facilitate the emission of CO_2 and N_2O, while methanogenesis and denitrification are dominant under anaerobic condition, discharging CH_4 mainly and insignificant amount of N_2O to the atmosphere. In rice fields, average CH_4 emission was 106 mg m^{-2} d^{-1} for continuous irrigation, 56 mg m^{-2} d^{-1} when the field was drained in the middle of the cropping cycle, 13 mg m^{-2} d^{-1} when the field was drained three times and 151 mg m^{-2} d^{-1} for a late continuous irrigation.



(a)

Fig 1a: Soil management in rice cultivation



(b)

Fig 1b: Soil processes responsible for greenhouse gas synthesis and emissions under the contrasting wetting and drying conditions in rice-based cropping systems

Main seasonal changes driven by paddy-upland rotation

Soil fertility must be maintained to sustain and improve long-term agricultural productivity, that is, crop yields. Comparison of soil under natural vegetation and adjoining cultivated topsoil has revealed that prolonged agricultural land use alters the magnitude, diversity, and spatial variability of a number of soil properties, primarily those related to fertility (Bueno and Ladha, 2009) [4]. Paddy-upland rotation fields are unique from other wetland or upland soils, because of the seasonal alternation of wetting and drying and the frequent alternation of anaerobic and aerobic conditions; the chemical speciation and biological effectiveness of soil nutrient elements vary with seasons (Figure 2). Under flooded conditions, the redox potential of paddy is low and, Fe^{3+}, Mn^{4+}, andare, respectively, reduced to, Fe^{2+}, Mn^{2+}, and S^{2-}. Thus, flooding also improves the availabilities of P, K, Si, Mo, Cu, and Co and reduces the availabilities of N, S, and Zn. By contrast, during the upland crop season, the redox potential is increased, thereby oxidizing the soil nutrient elements and changing the effectiveness of the abovementioned elements (Fan *et al*., 2008) [10]. Gupta *et al*. (2007) [16] argued that in most lowland rice soils, P availability initially increased on flooding and rice may meet its P requirement from the residual P applied to the receding wheat. Li *et al*. (2009) indicated that the efficiency of K fertilizer application is affected by various factors, and both rice and the subsequent crop remove enormous amounts of K, resulting in a significant negative K balance in soils regardless of whether K fertilizers are applied at recommended doses. Mn deficiency, which is common in the wheat of rice-wheat rotation systems in China and India leads to the decline in wheat yield. Except for the sporadic use of micronutrients of paddy-upland rotation the decrease in Mn availability in upland field is the main reason for the Mn deficiency (Liu *et al*., 1999) [26]. The change in soil moisture content also influences soil pH, thereby affecting the chemical equilibrium and consequently changing the form and effectiveness of soil nutrient elements (Morales *et al*., 2011) [40].

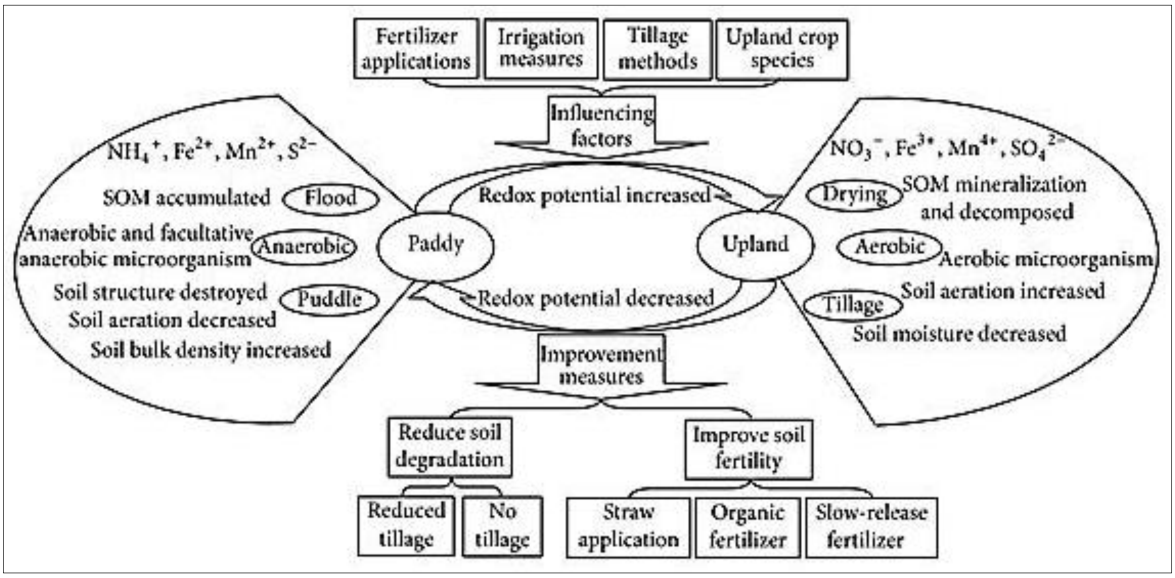


Fig 2: Characteristics of paddy-upland rotation and its improvement measures

Carbon (C) mineralization

Jat *et al*. (2020) [13] reported that carbon mineralization significantly varied at different growth stages of wheat (Fig. 3). At sowing, highest C mineralization was observed under partial climate smart agriculture (CSA) based rice-wheat-mungbean system (317 µg d^{-1} g^{-1} of dry soil) and full CSA based rice-wheat-mungbean system (276 µg d^{-1} g^{-1} of dry soil) at 13 days of the incubation and lowest was associated with conventional tillage (CT) based rice-wheat system (218 µg d^{-1} g^{-1} of dry soil). Similar trend was also observed at 23 day's interval. At 3 and 6 days interval full CSA based maize-wheat-mungbean system Sc4 and full CSA based rice-wheat-mungbean system recorded higher C mineralization, respectively than other scenarios. At CRI stage, as the time progresses irrespective of scenarios C mineralization increased and highest was observed under Sc4 (403 µg d^{-1} g^{-1} of dry soil) followed bypartial CSA based rice-wheat-mungbean system (393 µg d^{-1} g^{-1} of dry soil) after 23 days of incubation (Fig. 3). At tillering stage, interesting observation was recorded. Initially at 3 days interval, higher C mineralization was observed in all the scenarios but after 6 days interval significant decline was observed irrespective of scenarios except partial CSA based rice-wheat-mungbean system. After 23 days, highest C mineralization was observed in full CSA based maize-wheat-mungbean system (353 µg d^{-1} g^{-1} of dry soil). Irrespective of interval days significantly higher C mineralization was observed in panicle initiation stage than at sowing, CRI and tillering stage. Highest C mineralization was recorded in Sc3 (732 µg d^{-1} g^{-1} of dry soil) and partial CSA based rice-wheat-mungbean system (722 µg d^{-1} g^{-1} of dry soil) after 23 days of incubation. At harvest, CSA based scenarios showed significantly higher C mineralization after 3 days of the incubation experiment. In full CSA based rice-wheat-mungbean system and full CSA based maize-wheat-mungbean system after 13 days, there was decline in C mineralization and highest was associated with full CSA based maize-wheat-mungbean system (623 µg d^{-1} g^{-1} of dry soil) and partial CSA based rice-wheat-mungbean system (624 µg d^{-1} g^{-1} of dry soil) after 23 days of the experiment (Fig. 3).

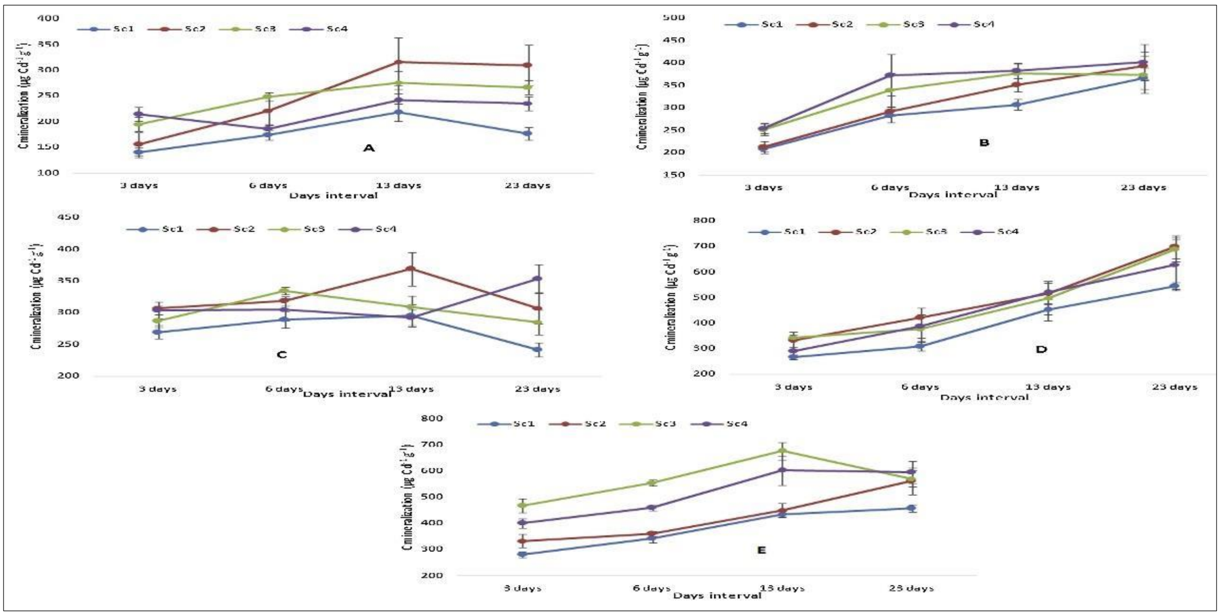


Fig 3: Variation in mean mineralizable carbon at different growth stages of wheat A) Sowing B) Crown root initiation C) Tillering D) Panicle initiation E) Harvest

Choudhury *et al*. (2014) [5] observed that DSR combined with zerotillage in wheat along with residue retention (T_6) had the highest capability to hold the organic carbonin urface ($11.57 gkg^{-1}$ soil aggregates) with the highest stratification ratio of SOC (1.5). Moreover, it could show the highest carbon preservation capacity (CPC) of coarse macro and meso-aggregates. A considerable proportion of the total SOC was found to be captured by the macro-aggregates (>2-0.25mm) under both surface (67.1%) and sub-surface layers (66.7%) leaving rest amount in micro-aggregates and 'silt + clay' sized particles. Sepat *et al*. (2014) [49] also found that Zero tillage increased the microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) by15.0and18.3%, respectively, over CT. Plot sunder zero tillage—raised bed (ZT-B) recorded highest soil MBC, while in the case of MBN, ZT-B remained comparable with zero tillage—flat bed (ZT-F) and conventional tillage— raised bed (CT-B). Plots under conventional tillage— flat bed (CT-F) recorded 17.4 and 19.4% lower values of MBC and MBN, respectively over ZT-B plots. Crop residue application recorded 41.0and 39.8% higher MBC and MBN, respectively than no residue plots. Venkanna *et al*. (2014) [66] also found that the SOC stocks ranges from 22.68 to 94.83 Mg ha^{-1} with a mean of 52.84 Mg ha^{-1} in Alfisols, 34.37 to 73.67 Mg ha^{-1} with a mean of 51.26 in Inceptisols and 27.80 to 74.20 Mg ha^{-1} with a mean of 49.33 Mg ha^{-1} in case of Vertisols and associated soils. The SIC ranges from 4.14 to 25.54 Mg ha^{-1} with a mean of 12.39 Mg ha^{-1} in Alfisols, 7.23 to 34.17 Mg ha^{-1} with a mean of 17.47 Mg ha^{-1} in Inceptisols and 9.08 to 71.78 Mg ha^{-1} with a mean of 22.93 Mg ha^{-1} in Vertisols and Vertic intergrade. In most of the cases, surface SOC is greater than deeper layers, whereas the reverse trend is observed for SIC in most of the cases. Total carbon stock ranges from 30.81 to 116.42 Mg ha^{-1} (mean 65.24 Mg ha^{-1}) in Alfisols, 43.12 to 107.20 Mg ha^{-1} (mean 68.73 Mg ha^{-1}) in Inceptisols and 39.39 to 145.98 Mg ha^{-1} (mean 72.26 Mg ha^{-1}) in Vertisols and associated soils. Ratio of organic to total carbon stock is maximum in Alfisols followed by Inceptisols and Vertisols.

Jat *et al*. (2018) [19] also found that Highest OC was observed under Sc4 (7.7 g kg^{-1}) followed by Sc3 (7.5 g kg^{-1}). Conventional farmers practice (Sc1) showed lowest OC (4.5 g kg^{-1}) at 0-15 cm soil depth. Highest OC (4.9 g kg^{-1}) at 15-30 cm soil depth was observed under Sc2 compared to others. Compared to other scenarios, OC was 23-27% higher in Sc 2 at 15-30 cm depth. Samal *et al*., (2017) [47] reported that full CA recorded significantly higher TOC stock (47.71 ± 2.46 Mg C ha^{-1} soil) as compared to other scenarios in the total depth of soil studied. On the contrary, S_4 (diversified cropping system with high cropping intensity) showed significantly lower C stock (39.33 ± 2.40 Mg C ha^{-1}) than all other scenarios. On an average, TOC stock in different scenarios follows the order: S3 (47.71 ± 2.46) > S_2 (43.91 ± 0.84) > S1 (41.65 ± 0.13) > S_4 (39.33 ± 2.40 Mg C ha^{-1} soil). Maximum accumulation of SOC (19.41 ± 1.84 Mg C ha^{-1}) in top depth of soil was observed under S_3 followed by S_4 (16.56 ± 1.71 Mg C ha^{-1}), S2 (16.53 ± 0.78 Mg C ha^{-1}) and S_1 (16.22 ± 0.60 Mg C ha^{-1}) and SOC accumulation reduced in lower depths. In 10-20 cm depth significantly low SOC was observed in S_4 (12.61 ± 0.10 Mg C ha^{-1}) and statistically at par values of SOC were obtained in rest scenarios (S_1-S_3). In 20-30 cm soil depth significantly greater SOC accumulation was recorded in S2 (12.82 ± 1.10 Mg C ha^{-1}) and S3 (13.10 ± 0.21 Mg C ha^{-1}) in comparison to S1 (10.36 ± 1.07 Mg C ha^{-1}) and S4 (10.16 ± 0.80 Mg C ha^{-1}). Sapkota *et al*. (2017) [48] revealed that the effects on SOC stock were significant at 0-0.05 and 0.05-0.15 m soil depths only. At 0-0.05 m, ZTDSR-ZTW+R and PBDSR-PBW+R, on an average, had significantly higher SOC stocks, that is 2.4 t/ha more than CTR-CTW. ZTDSR-ZTW, ZTDSR-ZTW+R and PBDSR-PBW+R had a similar improvement in total SOC at 0.05-0.15 m, which was significantly higher (by about 2.0 t/ha) than for CTR-CTW. All the treatments had similar SOC stocks at 0.15-0.3 m and 0.3-0.6 m soil depths. Calculations for the whole 0-0.6 m depth showed that ZTDSR-ZTW+R and PBDSR-PBW+R contained 5.6 t and 3.9 t/ha more SOC than CTR-CTW, respectively. Naresh *et al*. (2018) [42] showed that, soil organic carbon buildup was affected significantly by tillage and residue level in upper depth of 0-15 cm but not in lower depth of 15-30 cm. Higher SOC content of 19.44 g kg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots.

Responses of soil organic carbon to straw return

Straw returning can improve soil structure, increase the organic matter content of the soil, and provide a good environment for the growth and reproduction of microorganisms, as well as sufficient carbon and nitrogen sources and energy, which improves the species, abundance, and activity of soil microorganisms

(Lou *et al*., 2011) [29]. Bacteria account for 70%-90% of all soil microorganisms and are the most active factor in soil, playing an important role in the decomposition of cellulose in straw (Xu *et al*., 2010) [67];

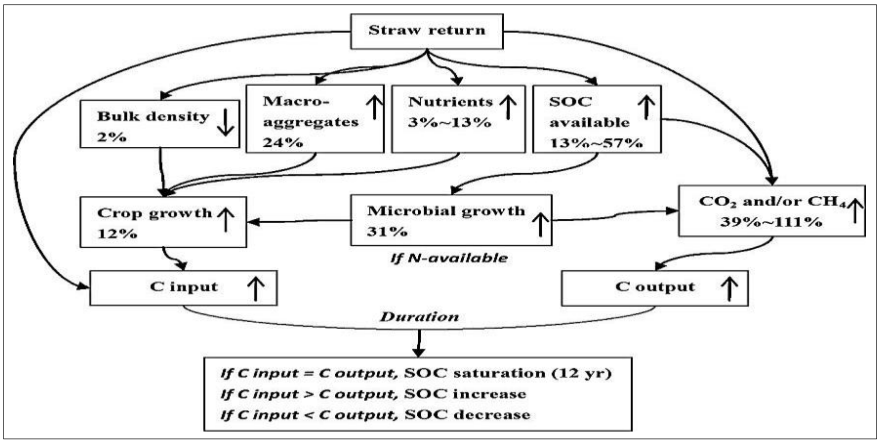


Fig 4: Mechanism for the responses of soil C dynamics to straw return in agro-ecosystems

Dai *et al*. (2020) [6] reported that the WSOC contents were higher in NPKS2 than in NPK in the 0-5, 5-10, and 10-20 cm soil layers and in CK in all soil layers (Fig. 5a). The HWSOC, EOC, and POC contents were higher in NPKS2 than in NPK and CK in all soil layers (Fig. 5b, c, and e). HWSOC comprised 2.83 to 4.25%, EOC from 17.34 to 33.81%, and POC from 21.49 to 38.26% of total SOC. The MBC contents were higher in NPKS2 than in NPK in the 0-5, 5-10, and 10-20 cm soil layers and in CK in all soil layers (Fig. 5d). Similarly, the LFOC contents were higher in NPKS2 than in NPK in the 10-20 and 20-30 cm soil layers and in CK in all soil layers (Fig. 5f).

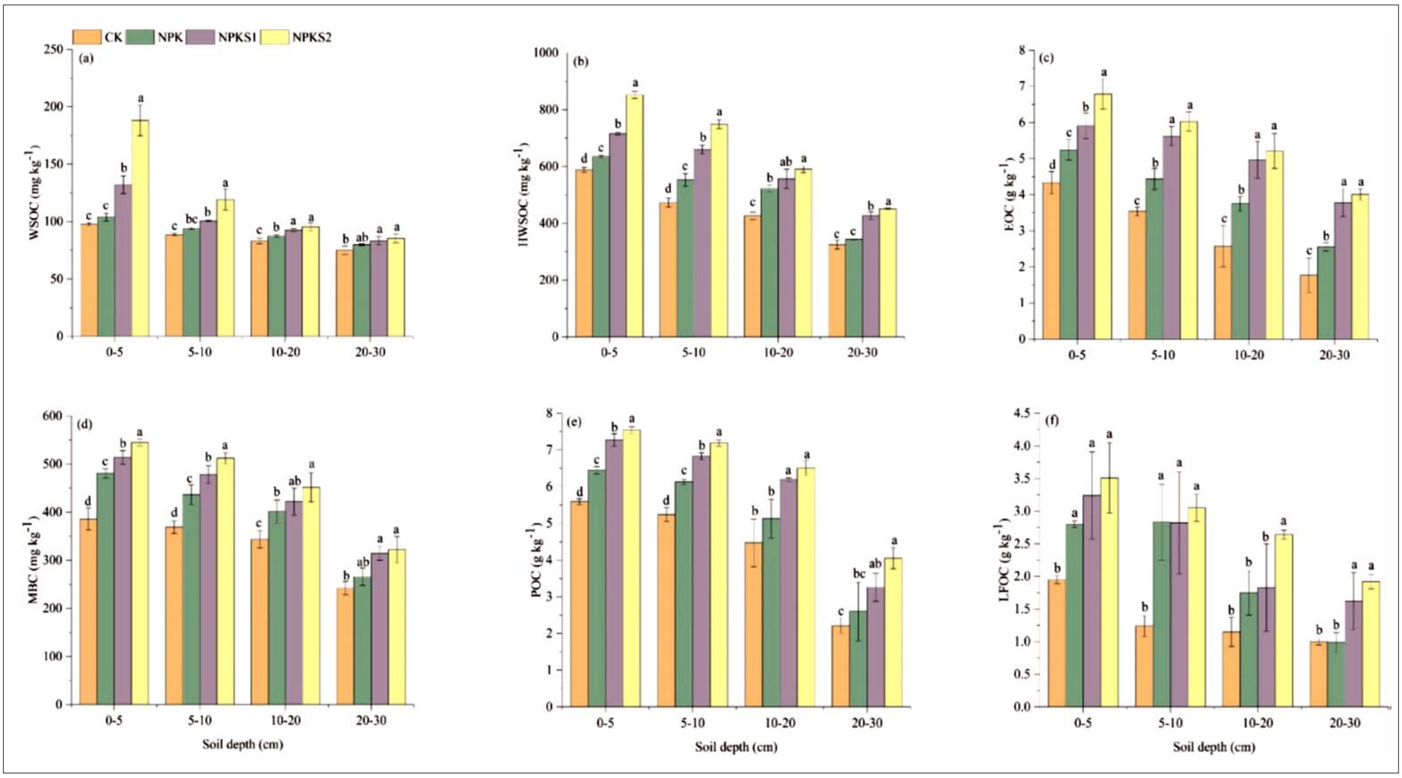


Fig 5: The effects of straw incorporation on labile organic C fractions (WSOC, water soluble organic C; HWSOC, hot-water soluble organic C; EOC, easily oxidizable C; MBC, microbial biomass C; POC, particulate organic C; LFOC, light fraction organic C) in the soil layers of 0-5, 5-10, 10-20, and 20-30 cm

Zhu *et al*. (2014) [62] also found that the different treatments significantly affected the contents of soil TOC and labile organic C fractions, where PD generally had the highest contents of TOC, DOC, MBC and EOC at the three soil depths. Crop straw return treatments (PR, PW, PD, RR, RW, RD) had consistently higher amount of TOC and labile organic C fractions at the three soil depths than without crop straw return treatments (PN, RN). Moreover, PN had significantly lower TOC, DOC, MBC and EOC at 0-7 cm and 7- 14 cm, and RN had the lowest TOC and MBC at 14-21 cm compared to other treatments (Fig. 6).

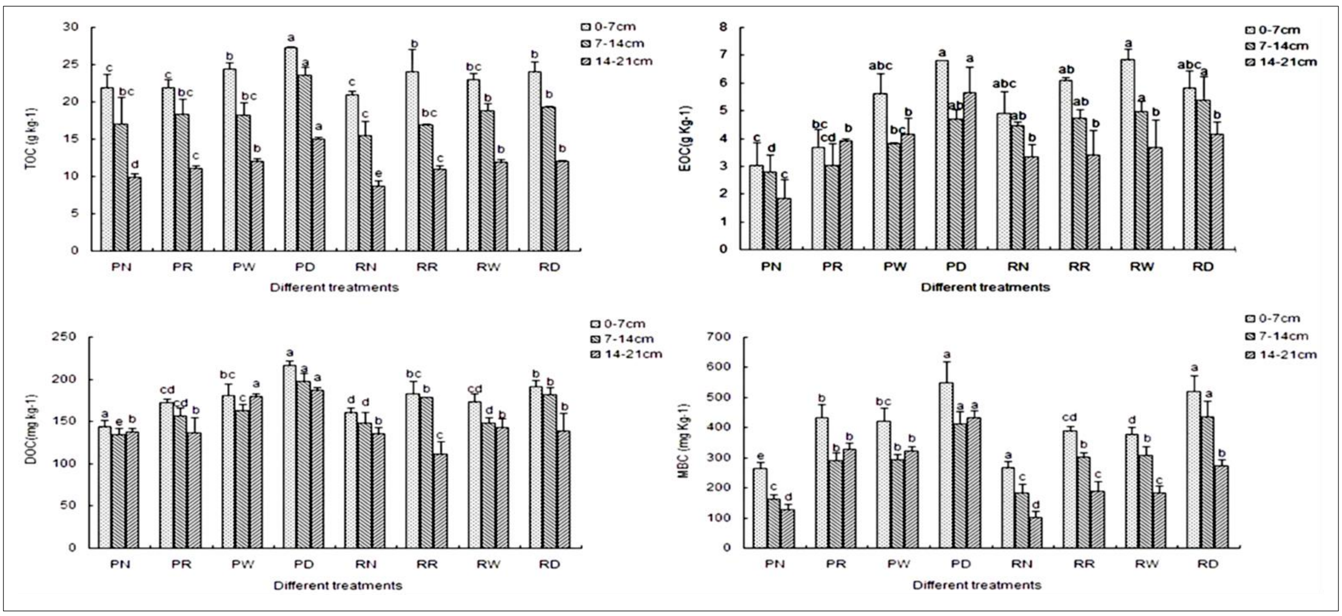


Fig 6: Effects of different treatments on soil TOC, EOC, DOC and MBC contents at three depths

Ma *et al*. (2020) observed that cumulative mineralization showed a decreasing trend as soil depth increased, and the straw returning mode significantly affected cumulative mineralization in the upper 20 cm soil layer compared with the 20-50 cm layer (Fig.7). Cumulative mineralization was higher for WR-MR than for WR and NSR by 5.0% and 38.8%, respectively, in the 0-5 cm soil layer, by 15.9% and 46.0%, respectively, in the 5-10 cm soil layer, and by 32.7% and 21.9%, respectively, in the 10-20 cm soil layer.

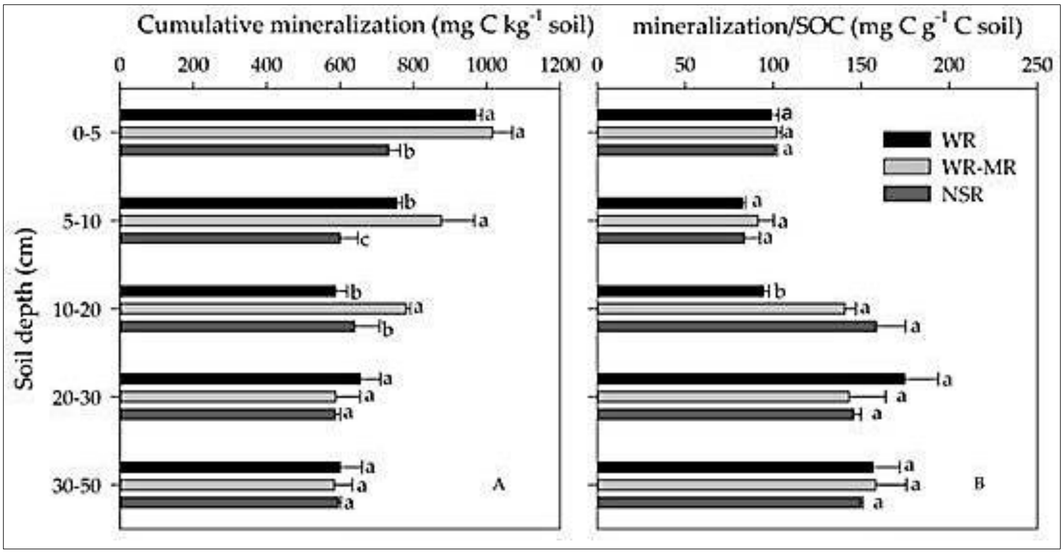
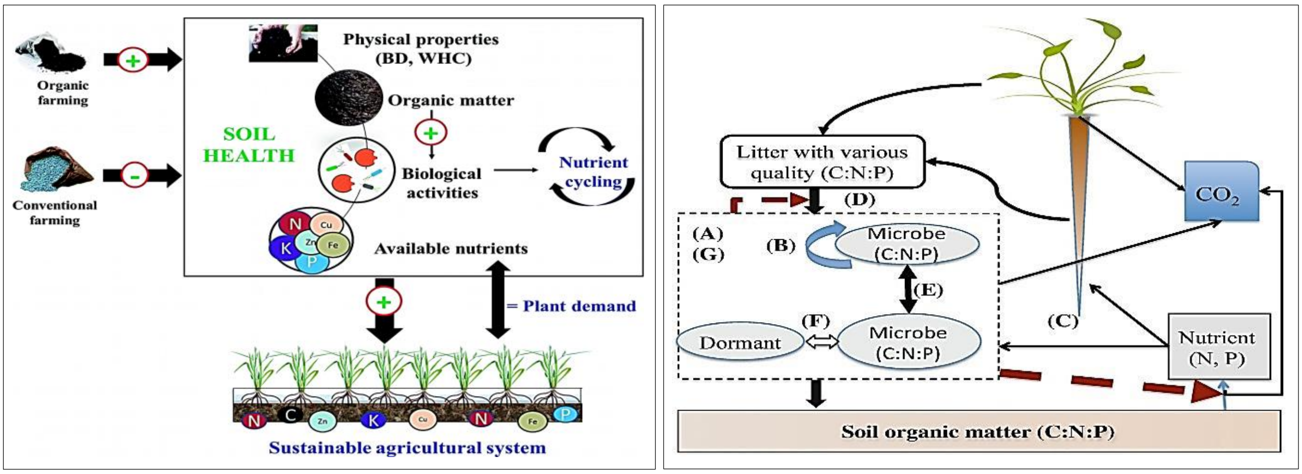


Fig 7: Effects of straw return modes on cumulative mineralization (A) and SOC/mineralization (B). NSR, no straw returning; WR, only wheat straw returning; WR-MR, both wheat and maize straw returning

Ghosh *et al*. (2018) [14] observed that the plots with 50% NPK+ 50% FYM had significantly higher SOC content followed by 50% NPK + 50% GM in topsoil. Significantly lower bulk SOC was found with control plots in topsoil. Significantly higher (+35 and 38%) SOC with 50% NPK +50% FYM compared to control in both soil layers, respectively. Similar trend of bulk SOC was observed in the 5-15 cm soil layer. This increase was found due to significantly increased C input with organic amendments coupled with mineral fertilization. Build-up of organic carbon is more in surface layer than in lower depth because of more addition of roots and plant biomass in surface layers and lack of nutrient and biological activity in deeper layers, which ultimately constrain the rooting depth.

Soil biological properties of rice-wheat rotation

Soil microorganisms are involved in various biochemical processes and are vital in maintaining soil fertility and plant yields. The diversity of rhizosphere microorganisms is beneficial to soil health, and the trophic interactions within the rhizosphere affect the aboveground community of plants (Marais *et al*., 2012) [36]. Different plants have different soil microbial com-munities, and crop rotation provides greater concentration and diversity of organic materials, both of which may lead to greater diversity of microbial communities. Several studies have reported a positive effect of crop rotation on the abundance of beneficial micro-organisms. Cropping systems could markedly affect the composition, abundance, diversity, and activity of soil bacterial communities; evidence shows an association between crop type and microbial community composition. For instance, *Bradyrhizobium* sp And *Herbaspirillum* sp colonize the interior of rice roots when grown in rotation with a legume crop, which may promote rice growth and productivity (Yanni *et al*., 1997) [59].



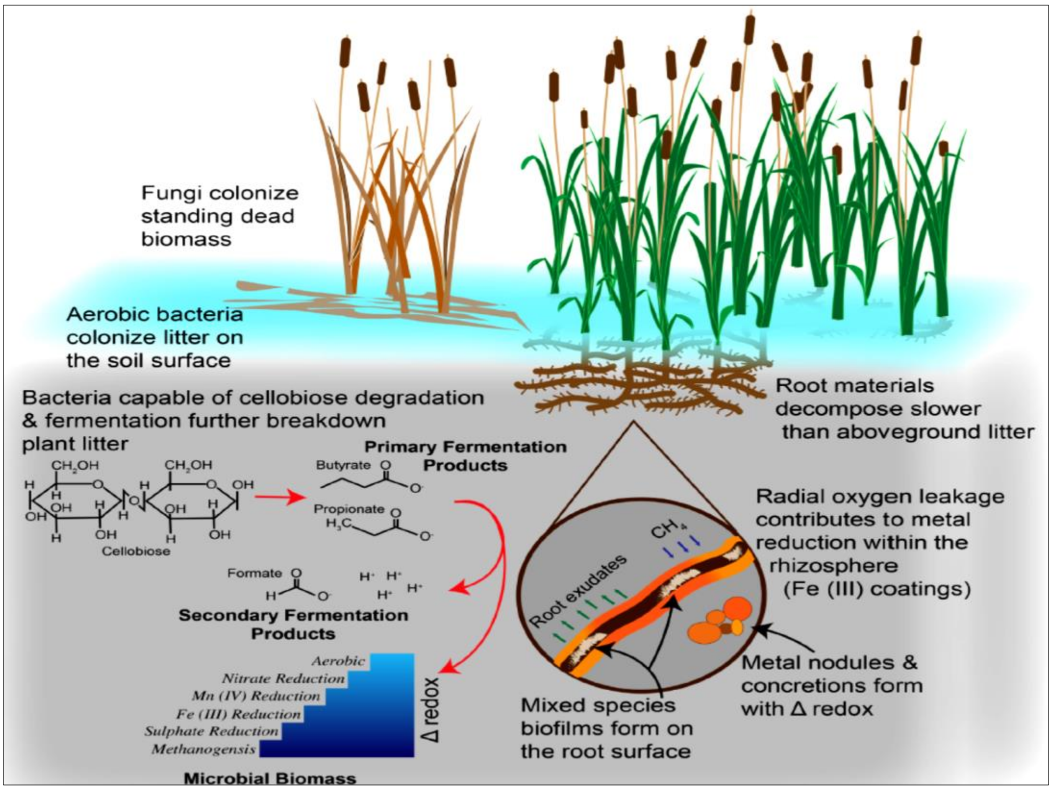


Fig 8: Beginning with above- and below- ground plant inputs, the figure illustrates the various transformations of C mediated by the wetland microbial community. The left side of figure shows how plant materials, such as cellobiose, are processed by the anaerobic microbial community into primary and secondary fermentation products that can be used by microorganisms as alternative electron acceptors. The insert illustrates processes within the rhizosphere, particularly those linked to metal cycling, which may be a key C storage mechanism

Bhattacharya *et al*. (2013) [68] reported that tillage-induced changes in POMC were distinguish able only in the 0- to 5- cm soil layer; the differences were insignificant in the 5- to15- cmsoillayer. Plots under ZT had about 14% higher POM C than CT plots (3.61 g kg^{-1} bulk soil) in the surface soil layer. Mandal *et al*. (2013) [33] reported that averaged across fertilization and manure treatments, MBC varied significantly with soil depth, with mean values of 239, 189 and 127 mg kg^{-1} at 0-7.5, 7.5-15 and 15-30 cm depths respectively. Surface soil had higher MBC than deeper soil layers, due primarily to the addition of leftover CRs and root biomass to the topsoil. When averaged across soil depths, the MBC content under the different treatments was in the order: NPK+GR +FYM> NPK+FYM=NPK+GR>NPK+SPM>NPK+CR>PKZnS>NPK Zn=control. Incorporation of CR slows mineralization processes; hence, microbes take longer to decompose the residue and use the released nutrients. Conversely, incorporation of GR, with a narrow C: N ratio, hastened mineralization by enhancing microbial activity in the soil.

Zhu *et al*. (2014) [62] also found that soil TOC and labile organic C fractions contents were significantly affected by straw returns, and were higher under straw return treatments than non-straw return at three depths. At 0-7 cm depth, soil MBC was significantly higher under plowing tillage than rotary tillage, but EOC was just opposite. Rotary tillage had significantly higher soil TOC than plowing tillage at 7-14 cm depth. However, at 14-21 cm depth, TOC, DOC and MBC were significantly higher under plowing tillage than might be that rotary tillage and plowing tillage mixed crop straw into the deeper soil layer, making SOM well distributed at different depths Consequently, under short-term condition, rice and wheat straw both return in rice-wheat rotation system could increase SOC content and improve soil quality.

Tripathi *et al*. (2014) [53] observed that the significant positive correlations were observed between TOC and organic C fractions (POC and SMBC), illustrating a close relationship between TOC and POC and TOC and SMBC and that SOC is a major determinant of POC and SMBC. The microbial biomass carbon includes living microbial bodies (bacteria, fungi, soil fauna and algae) (Divya *et al*., 2014) [69]; it is more sensitive to soil disturbance than TOC. The proportion of SMBC to TOC is evaluation of carbon availability indexes for agriculture soil, whichisusually 0.5-4.6%.

Liu *et al*. (2013) [27] showed that SMBC may provide a more sensitive appraisal and an indication of the effects of tillage and residue management practices on TOC concentrations. Ma *et al*. (2016) reported that the differences in SMBC were limited to the surface layers (0-5 and 5-10 cm) in the PRB treatment. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%,10.3%, 27.7%, 10% and 9% at 0-5, 5-10,10-20, 20-40,40-60 and 60-90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment. Malviya, (2014) [32] also indicated that irrespective of soil depth the SMBC contents were significantly higher under RT over CT.

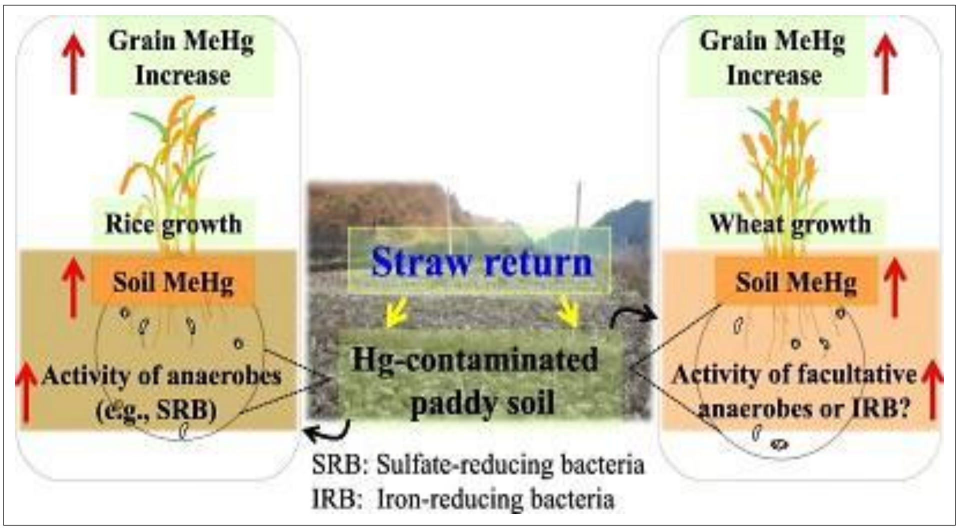


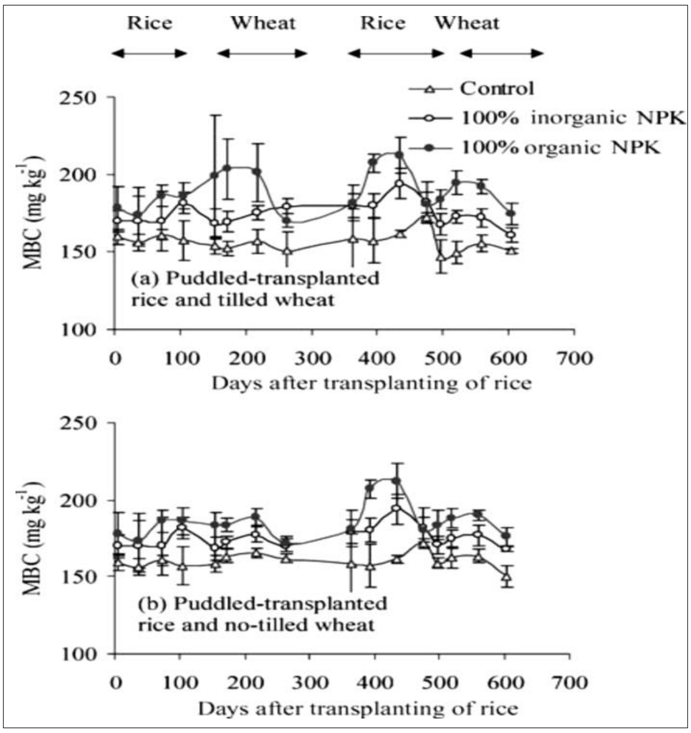
Fig 9: Comparison of methylmercury accumulation in wheat and rice grown in straw-amended paddy soil [Wang *et al*. (2019) [55]]

Mangalassery *et al*. (2014) [34] observed that zero tilled soils contained significantly more microbial biomass carbon than tilled soils. The meanmicrobial biomass carbon under zero tilled soil was 517.0mgkg-1 soil compared with418.7 mgkg^{-1} soil in tilled soils. Microbial biomass carbon was significantly higher in the 0-10 cm layer (517 mg kg^{-1} soil) than the 10-20 cm layer (419 mg kg^{-1} soil) under zero tillage and conventional tillage. Moreover, tillage and soil depth significantly influenced soil microbial biomass nitrogen. Zero tilled soils contained higher microbial biomass nitrogen (91.1 mg kg^{-1} soil) than tilled soil (70.0mg kg^{-1} soil). Surface layers (0-10 cm) maintained more microbial biomass nitrogen than sub surface layers (10-20 cm) under both zero tilled soils and tilled soils. Mc Gonigle and Turner (2017) [35] concluded that the MBC in crop land increased from 210 µg g^{-1} at 15g kg^{-1} SOC toonly 530µgg^{-1} at 45g kg^{-1} SOC. In contrast, MBC in grass land increased from 440µgg^{-1} at 15g kg^{-1} SOC to 1190µgg^{-1} at 45g kg^{-1}, there after increasing further to1800µgg^{-1} at 65g kg^{-1} SOC. The slope of increase of MBC in response to increasing SOC was 2.5-fold higher in grassland at 27.2(µg g^{-1})/ (g kg^{-1}) compared to 10.7 (µgg^{-1})/ (gkg^{-1}) for cropland.

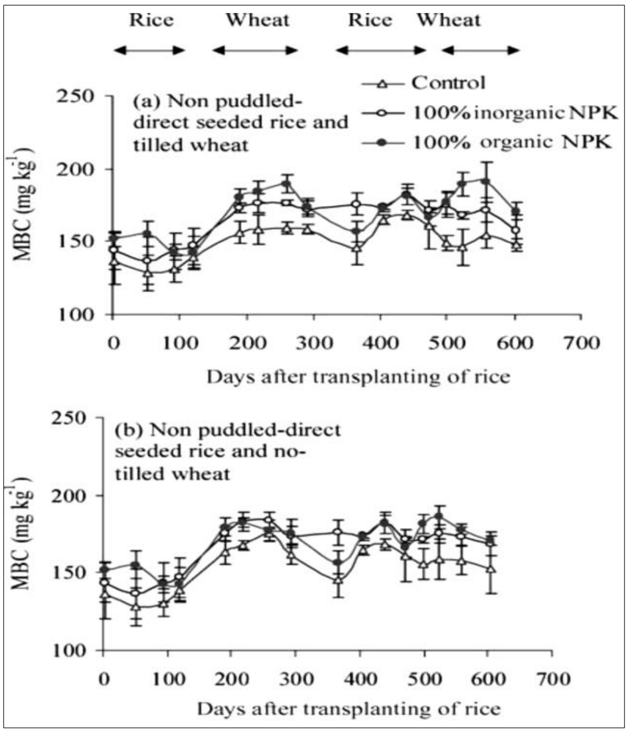
Naresh *et al*. (2015) [41] reported that the profile SOC stock differed significantly among treatments The highest SOC stock of 72.2Mg C ha^{-1} was observed in F_6 with T_6 followed by that of 64Mg C ha^{-1} in F_4 with T_2> that in F_3 with T_4 (57.9Mg C ha^{-1}) >F_5 with T_1 (38.4Mg C ha^{-1})= F_7 with T5 (35.8 Mg C ha^{-1}), and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_6 with T_6 treatment (56.3Mg Cha^{-1}) followed by F_4 with T_2 (51.4Mg C ha^{-1}) and F_3 with T_1 (48.4Mg Cha^{-1}). Wang *et al*. (2019) [55] revealed that fresh straw-derived organic matter enhances MeHg net production in soil through an overall increase in the activity of sulfate-reducing bacteria (SRB), particularly under anoxic conditions. Our study clearly demonstrated that straw amendment enhanced MeHg accumulation in wheat and rice grains and highlighted that straw return in Hg-contaminated soils may increase the health risk of MeHg exposure to local residents via crop consumption (Fig 9).

Krishna *et al*. (2018) [23] reported that the total organic carbon (TOC) allocated into different pools in order of very labile > less labile > non labile >labile, constituting about 41.4, 20.6, 19.3 and 18.7%, respectively. In comparison with control, system receiving farmyard manure (FYM-10 Mg ha^{-1} season^{-1}) alone showed greater C build up (40.5%) followed by 100% NPK+FYM (120:60:40 kg N, P, K ha^{-1}+5Mg FYM ha-^{1} season^{-1}) 16.2%). In fact, a net depletion of carbon stock was observed with 50% NPK (-1.2 Mg ha^{-1}) and control (-1.8 Mg ha^{-1}) treatments. Only 28.9% of C applied through FYM was stabilized as SOC. A minimal input of 2.34 Mg C ha^{-1} y^{-1} is needed to maintain SOC level. The magnitude of carbon pools extracted under a gradient of oxidizing conditions was as follows: C_{VL}>C_{LL}> C_{NL}> C_L constituting about 41.4, 20.6, and 19.3 and 18.7%, respectively, of the TOC. However, the contribution of V_L, L and LL pools to SOC was 51.2, 23.1 and 25.5%, respectively. While active pool (C_{VL} + C_L) constituted about 60.1%, passive pool (C_{LL} + C_{NL}) represented 39.9% of the TOC. Among the treatments, 100% NPK+FYM (44.4%) maintained a proportionately higher amount of soil C in passive pools. With an increase in the dose of fertilization, on average, C allocation into passive pool was increased (33.0, 35.3, 40.7% and 39.3% of TOC under control, 50% NPK, 100% NPK and 150% NPK treatments, respectively).

Banerjee *et al*. (2006) [2] reported that two conditions of rice establishment, i.e., puddled and non-pudddled direct seeded, differed in terms of trends in MBC content in soil in the rice-wheat systems. In case of puddled, transplanted rice followed by either tilled or no tilled wheat, the MBC remained unchanged during the two years of the cropping period (Figures 10a). But in case of non-puddled, direct seeded rice followed by either tilled or no tilled wheat, there was increase in MBC (Figures 10b). In direct seeded rice-wheat system, though initially MBC was much lower than that of transplanted rice-wheat system, after two years of cropping MBC became on par. This suggested that puddling had initial advantage in terms of higher MBC and the non-puddled rice system had a lag phase up to 2 years to build up the microbial biomass.



(a)



(b)

Fig 10a: Microbial biomass carbon (MBC) content of soil in (a) puddled-transplanted rice and tilled wheat and (b) puddle-transplanted rice and no-tilled wheat

Fig 10b: Microbial biomass carbon (MBC) content of soil in (a) non-puddled direct seeded rice and tilled wheat and (b) non-puddled direct seeded rice and no-tilled wheat

Nutrient dynamics

Tillage, residue management and crop rotation can strongly affect the nutrient dynamics of any soil through their effect on mineralization and recycling of soil nutrients (Galantini *et al*., 2000) [12]. It is believed that long-term adoption of CA practices can lead to higher build up of nutrients into soil due to larger nutrient mineralization potential of soil as compared to CT(Duiker and Beegle 2006) [9]. The beneficial effect of CA in terms of higher nutrient availability partly may be due to crop residues retention over soil surface in comparison with incorporation of crop residues with CT and partly due to arresting their leaching losses by reducing decomposition of surface placed residues (Kushwaha *et al*., 2000) [24]. Govaerts *et al*. (2006) [15] also found that after long term adoption of CA (26 cropping seasons) in a input responsive well irrigated production system the N mineralization was higher in PB with residue retention than in CT with residues in corporation. Liebig *et al*. (2004) [25] 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.

During the decomposition of organic matter, in organic N can be immobilized (Zagaland Persson1994) [60], especially when organic material with a large CN ratio is added to the soil. Piegholdt *et al*. (2013) [46] also reported 15% higher total P content in the top soil (0-5 cm) of ZT plots as compared to CT due to larger P addition from decomposition of residues retained on the soil surface. Likewise, higher P levels in ZT than in CT were reported by other researchers (Duiker and Beegle, 2006) [9]. The higher values of available P under CA practices largely due to reduced mixing of the fertilizer P with the soil, leading to lower P-fixation. This is a benefit when P is a limiting nutrient, but may be a thre at when P is an environmental problem because of the possibility of soluble Plosses in runoff water. Yadav *et al*.(2016) [56] reported that after seven years of CA the highest amount of N, P and K (219.8, 24.9 and 203.1kg ha^{-1})in 0-15cm soil surface was recorded under PB planting while minimum amount of available N, P and K were observed under CT. There cycling of the higher amount crops residue of previous due to higher biomass yield in PB treatments lead to addition of more nutrients compared to CT. While, in case of CT the over/straw get in corporate in deep soil layer and which leads to rapid decomposition and might also lead to leaching of mineralized nutrients in much deeper soil layers which in turn reduces the available these nutrients in CT.

Conclusions

On system basis, ZT-DSR followed by ZTW+R resulted in the highest MBC, soil organic carbon and microbial quotients. The study revealed that soil quality indicators (microbial biomass carbon, microbial quotient) can be used to identify the most sustainable CA based practices in rice wheat system. Positively higher correlation coefficients of biomass carbon, soil organic carbon and microbial quotients under rice-wheat system are valuable indicators of improved soil quality under conservation practices. Maintaining soil quality at a desirable level is a very complicated and difficult task, because rice-wheat system fields are unique from other wetland or upland soils; they are associated with frequent cycling between wetting and drying under anaerobic and aerobic conditions; such rotations change the soil C and N cycles and make the chemical speciation and biological effectiveness of soil nutrient elements varied with seasons, increase the diversity of soil organisms, and make the change of soil physical properties more complicated. Therefore, fully understanding the characteristics of different rice-wheat system soil properties is necessary in maintaining soil quality and nutrient dynamics.

The NPKS2 treatment significantly increased total SOC contents, and labile organic C fractions (WSOC, HWSOC, EOC, MBC, POC, and LFOC), relative to CK in the top 30 cm soil. The CPMI was significantly higher in NPKS2 than in NPK and/or CK in the 0-5, 5-10, and 10-20 cm soil layers, indicating that it could contribute to more soil ecological benefits. SOC, soil labile organic C fractions, and CPMI correlated positively in the 0-5 and 5-10 cm soil layers. The sensitivities of labile organic C fractions varied with different treatments in the 0-5 cm soil layer.

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