OPEN ACCESS
Freely Available Online

JOURNAL OF AGRONOMY RESEARCH
ISSN NO: 2639-3166

Research Article
DOI: 10.14302/issn.2639-3166.jar-21-3822

Ecological Significance of Residues Retention for Sustainability of Agriculture in the Semi-arid Tropics

Raj Gupta[1], DK Benbi[2,*], IP Abrol[1]

[1]Centre for Advancement of Sustainable Agriculture, National Agriculture Science Centre Complex, New Delhi, 110012, India

[2]Punjab Agricultural University, Ludhiana 141004, India

Abstract

In South Asia, land degradation is primarily a monsoon mediated phenomenon restricted to 2-3 rainy months. The overall strategy for land degradation neutrality should (i) favour actions that keep soils covered with residues and (ii) plant kharif (rainy season) crop before the onset of monsoons to provide soil cover. Retention of anchored residues provides surface cover, increases microbial activity, carbon sequestration, and availability of nutrients. Surface retained residues reduce root zone salinization, detoxify phytotoxic monomeric Al in acidic soils and enhance the potential for use of brackish ground water in crop production. Residues covers save irrigation water and overcome the ill effects of poor agronomic and water management practices. Early direct dry seeding in surface retained residues has the potential of making kharif season planting independent of the onset of monsoon rains in South Asia and helps reduce acreages of Kharif and Rabi fallow lands. For improving carbon content in Indian soils, perhaps the most important priority is to devise tillage and crop residue management approaches that promote *in situ* rain water storage and its use for growing more crops. The paper summarises how crop residues fuel and drive soil functions and related ecosystem services and plant growth.

Corresponding author: DK Benbi, Punjab Agricultural University, Ludhiana 141004, India, E-mail: dkbenbi@yahoo.com

Citation: Raj Gupta, DK Benbi, IP Abrol (2021) Ecological Significance of Residues Retention for Sustainability of Agriculture in the Semi-arid Tropics . Journal of Agronomy Research - 3(4):9-30. https://doi.org/10.14302/issn.2639-3166.jar-21-3822

Keywords: Aggregate stability, carbon sequestration, conservation agriculture, Crop residue, carbon sequestration, conservation agriculture, soil erosion, land degradation neutrality, straw burning, soil C pools, soil erosion

Received: Apr 23, 2021 **Accepted:** Jun 03, 2021 **Published:** Jun 07, 2021

Editor: Prem Narain, Professor and independent researcher 29278 Glen Oaks Blvd. W. Farmington Hills, MI 48334-2932 USA

Introduction

Summer monsoons are a unique climatological distinction of the arid and the semi-arid tropics (SAT), occupying nearly 80% of the total land surface of India. This region receives rainfall in the range from 300-1400 mm annually. Summer southwest monsoons are characterised by a short intense rainy season (June – September) that meets the water requirements of different sectors of the national economy including the rain-fed and irrigated agriculture. Northeast monsoons in winter control the climate from November to February. Despite extensive canal network, Indian agriculture remains highly dependent on monsoon rains. Livestock, in water scarce dry areas, invariably face fodder shortages during the summer season. Partly, the problem of fodder shortage is due to sharp focus of the plant breeders on increasing the harvest index (ratio of grain yield to total biological yield) of cereal crops, without substantive gains in straw/ residue production. Furthermore, development of combine harvesters and adoption of thrashing equipment has replaced hand-harvesting, which poses difficulties in straw collection for livestock feeding. These developments have significantly reduced the availability of crop residues for livestock feeding and soil mulching as well.

On-farm residue management has both direct and indirect consequences on carbon sequestration process which impact crop productivity and influence climate moderation. Chlorophyll mediated photosynthetic fixation of carbon (C) in organic form in plant residues, fuel soil life and serve as drivers of soil functions for delivery of ecosystem services. This has expanded the rationale role of crop residues in enhancing productivity through improved soil health and eco-functionality, sustainability and climate change mitigation. These roles make it important that we clearly understand the processes associated with residue management.

Farmers generally leave crop residues either in the field or plow them into the soils. Some farmers burn crop residues when the turn-around time is short for planting of next season crops. Burning crop residues has a serious environmental implication via air pollution and soil heating. Farmers having cattle, remove crop residues for livestock feeding and return the farm yard manure (FYM) and farm waste back to replenish soil fertility. Over the past few decades, this organic linkage has been seriously disrupted due to widespread mechanization of farming operations and reduced dependence of agriculture on livestock for draft power. Soil organic carbon (SOC) drives the soil ecosystem functions and global warming through soil organic matter decomposition and sequestration rates. A better understanding of practices that build SOC would help in implementing appropriate strategies that address the challenges related to food security, environmental degradation, climate change and ecological functioning of the soils. Fertiliser practices relevant to achieving the 4-R objectives [1] are important for enhancing productivity, and SOC sequestration and fertilizer response ratio of foodgrain production that has been declining since 1960s. We are conscious of the fact that the 4-R practices can vary regionally depending on the cropping systems, soil types, climate and socio-economic situations of the farmers. Organic manures directly add embodied C and indirectly through enhancing the crop growth vis-a-vis crop residue inputs, thereby making organic materials more efficient at increasing SOC storage than mineral fertilizer [2-5]. In this paper, we revisit a range of crop residue management issues and the ecological significance of retaining them in subtropical situations as the way forward for achieving our goals of agricultural sustainability, food security and land degradation neutrality.

Land Degradation by Erosion: A Summer Monsoon Phenomenon in the SAT

SAT region has a wide range of soils and agro-climatic conditions which provided the basis for co-evolution of different crop production and land use systems in South Asia. The region spread over 642 million hectares, has 218 Mha of crop lands and is home to around 1.6 billion people [6]. In the SAT region, soil organic matter (SOM) is considered to play an important role in the development of stable soil structure, infiltration of rain water, its storage and regulating the release and uptake of nutrients and water by plants. Rainfall generally increases as we move from west to the easterly direction. High variability in the amount, intensity and distribution of monsoon rainfall events (spatial and temporal variations) is one of the main causes of agricultural uncertainty in South Asia. Our inability to manage spatial and temporal rainfall variations, related with onset and withdrawal of monsoon rains, results in a crisis of shorts and uncertainty of good crop harvests in rainfed dry lands, low lands, black soils and the hilly regions. The main crisis of subtropical agriculture in the Indian sub-continent is rooted in unimodal / bimodal nature of the rains wherein more than 85% is received through southwest monsoon in the summer season. During peak summers, surface soil layers attain temperatures upto 50°C. Hot summers desiccate and sterilise the soils and burn SOM. Pre-monsoon rains in summer deep ploughed bare fields promote slaking and break-down of soil aggregates facilitating erosion of fertile top soil with runoff water. Thus, in the SAT region, land degradation by erosion is largely a monsoon phenomenon spread over a period of 2-3 months (June- August) involving the loss of some or all of the following: soil sediments, soil productivity, vegetation cover, biomass, biodiversity, ecosystem services, and environmental resilience. An engineering bias for creating blue water has also encouraged widespread run-off, soil erosion and land degradation [7]. Reversing processes that contribute to land degradation are central to water availability, soil health, adaptation to climate change and food security.

Thus, the SAT agriculture faces a twin challenge namely: (i) dissipate raindrop impact causing soil erosion by creating a residue cover, and (ii) develop a planting strategy for the kharif crops before the onset of the monsoon rains such as to provide soils a crop cover and to make an efficient use of *in situ* green water supplies and reduce annual water deficits.

Monsoon rainfall anomalies are known to have a significant impact on overall kharif production [8]. Negative impact of deficit rainfall has remained almost the same over time. Deficit rainfall impacts total food production more than the surplus rainfall [9]. However, response of excessive summer monsoon rain anomaly on food grains production declined post 1980s [10]. Therefore, an important aim of this article is also to evaluate whether Indian agriculture can be insulated against land degradation through recurrent annual rainfall anomalies by using appropriate conservation agricultural practices and adoption of residue management strategies [7]. Roles of crop residues have been discussed in some details in the ensuing sections.

Residue Availability in India

There is considerable uncertainty in the estimates of crop residue availability in India. National Plan for Management of Crop Residues report of the Ministry of Agriculture, Government of India [11] has indicated production of about 500 million tonnes (MT) of crop residues, annually. Recently, TIFAC-IARI [12] has published an elaborate survey on the availability of surplus residues of 11 major crops (rice, wheat, maize, sugarcane, cotton, gram, pigeon pea, groundnut, mustard, soybean and castor) grown in about 137 Mha. Four crops viz. rice, wheat, cotton and soybean occupied 72% area. The listed eleven crops generate about 683 MT of total dry biomass in the three crop growing seasons, of which 59% is generated during kharif, 39% during rabi and the remaining about 2% during summer season. The amount of residue produced in India is about 18% of the total global production on an area of 1502 Mha [13]. The TIFAC-IARI [12] report brings out that the total annual surplus crop biomass is approximately 178 MT, constituting about 26% of the total dry biomass generated in the country (Table 1). Five states (UP, Punjab, Maharashtra, Gujarat and Haryana) contribute 62.5% to the total annual surplus biomass. The surplus contributions followed the order: Uttar Pradesh (17.7%) > Punjab (17.3%) > Maharashtra (14.2%) > Gujarat (7.6%) > Haryana (5.6%). Large surplus availability of the residues particularly in rice, wheat and sugarcane is closely linked to crop production amounts and the number of residue fires [14]. Development and availability of new seed-cum-fertilizer drills/ planters, shredders, spreaders attached to combine harvesters, and promotion of direct dry seeding no-till conservation agriculture practices have opened up new avenues for preventing farm fires in favour of on-farm management of crop residues.

Effect of Burning of Crop Residues

Crop residue burning is not an isolated practice restricted to Indian subcontinent alone. In the crop harvest season, farm fires can be seen above the wheat fields of the Canadian Prairies and the US Great Plains, sugarcane fields of Latin America and rice fields in South Asia. Although a good portion of the crop residues, in India is used for domestic and industrial purposes yet

Table 1. Estimates of total and surplus crop residues in India (Adapted from [12])

Crop	Area (Mha)	Crop residue production (MT)	Surplus crop residue (MT)
Rice	44.36	225.49	43.85
Wheat	30.84	145.45	25.07
Cotton	12.16	66.58	29.74
Soybean	10.69	27.79	9.96
Sugarcane	5.04	119.17	41.56
Other crops	33.86	98.14	28.56
Total	137.00	682.60	178.70

about 92 MT are burned by the farmers across the country. The amount of residues burnt in India almost equals the residues jointly produced in its neighbourhood in Nepal, Bangladesh, and Sri Lanka etc. [15]. Burning is an inexpensive means of removing crop residues from fields prior to tillage or seedbed preparation but is beset by several adverse effects. It weakens the local capacity of the agroecosystem services, ranging from protection of soils against erosion to recycling of nitrogen (N). Crop residue burning is known to hasten the decline of SOM levels [16] and decrease soil polysaccharides with consequent reduction in the percentage of water-stable aggregates [17]. Heat from field burning of residues penetrates surface soils [18], which raises soil temperature upto 75°C in upper 2 inches [19,20]. Open field fires burn about 75% of the total residues and an equal amount of N is also oxidised. Residue burning significantly changes pore size distribution, reduces pore space volume and significantly decreases moisture storage and soil hydraulic conductivity [21]. Residues burning increases bulk density, reduces soil porosity and water intake of the soils thereby increasing their erodibility [22]. Thus, residue burning seems to reduce the permeability, increase compaction and susceptibility of the soil to water erosion [18]. It is commonly accepted that burning crop residues promotes soil water repellency, caused by hydrophobic, long-chained organic molecules released from decomposing or burning plant litter or by microorganisms [23]. The root zone and the leaf surfaces of living plants have also been acknowledged as possible sources of hydrophobic compounds. The view that heat during a fire markedly changes and intensifies water-repellency [24] is now widely accepted and it has been observed that fire could induce hydrophobicity in a previously hydrophilic soil. Debano [25] suggested that heating of any hydrophilic soil containing more than 2–3% organic matter would induce water repellency. Residue burning not only redistributes and concentrates hydrophobic substances in the soil, the heat during a fire is also thought to improve the bonding of these substances to soil particles [26] and make them chemically more hydrophobic by pyrolysis [27]. Given a limited supply of hydrophobic substances to coat soil particles, coarser particles are more susceptible to developing water repellency because of their smaller surface area per unit volume compared with soils of finer texture [28,29]. Debano [25] concluded that water repellency is most likely to develop in soils with less than 10% clay content, and it is now well established that the addition of dispersible clay can be very effective in reducing water repellency in sandy soil [30]. Song et al. [31] pointed out that accumulation of hydrophobic compounds, such as lignin and lipid components, not

only enhance water repellency but also provide a molecular mechanism for stabilization of organic C.

Besides impacting the soil processes and ecosystem services, residue burning causes substantial loss of embodied plant nutrients and atmospheric pollution due to emission of green house gases (GHGs). and toxic volatile organic compounds (VOCs). Straw carbon, nitrogen and sulphur are completely burnt whereas the other nutrients are partially lost in the particulate matter emitted to the environment. Burning of one tonne straw (dry mass) releases 1515, 92, 2.7, and 0.07 kg of CO_2, CO, CH_4, and N_2O, respectively [32]. Open field burning of rice and wheat straw in India in 2000 was estimated to result in gaseous emissions of 110 Gg CH_4, 2306 Gg CO, 2 Gg N_2O, and 84 Gg NO_X [33]. However, in the year 2016-17, open field burning of rice and wheat residues was estimated to result in C equivalent emissions of 7151 Gg C in the north Indian state of Punjab alone [34].

From the above discussion, it is apparent that residue burning not only impacts SOM but also influences rain water storage and erosion hazards of the runoff water during the monsoon season besides causing loss of environmental pollution.

Crop Residues and Nutrient Cycles

Although the amount of SOM in dryland SAT soils is typically less than 1%, but even at low contents, SOM serves as a major pool for essential plant nutrients and facilitates aggregation and structural stability of soils. In many dryland cropping systems, depending on the fertiliser additions, 50% or more of the N required by the crop comes from mineralization of SOM. The microbial action mediating the mineralization-immobilization turnover of organic matter produces SOM - a process which is regulated by tillage, crops and, residue management practices [35]. For improving C content in Indian soils, perhaps the most important priority is to devise tillage and crop residue management approaches and actions that promote soil health, improve soil C storage, *in situ* rain water storage and its use for growing more crops and provide surface cover to soils to prevent run-off rainwater mediated soil erosion during the monsoon season [7]. Therefore, under continental monsoonal climates, rainwater management has to be an important element of the strategy for enhancing productivity, resilience and reversal of land degradation.

Increasing acreages of no-till agriculture and large adoption of reduced till methods by farmers can be seen as reducing the area burned to remove residues, particularly for seeding winter crops. However, the mind-set of many farmers is proving a deterrent to adoption of shifting paradigms of conservation agriculture. Practicing zero tillage after burning crop residues, negates the many benefits of conservation agriculture and is no good a practice. Augmenting the farm advisory services can prove helpful in the matter. Residue retention generally increases the mineralizable C and N compared to when residues are burned. Continuous retention of high C/N ratio cereal residues increase the microbial activity resulting in improved availability of nutrients.

Several studies have indicated that residue management systems have a significant impact on the levels of C and N in soils and hence on the crop production. Rice-wheat, a dominant cropping system of the Indian subcontinent, has a turn-around time of 50-60 days for rice and 35-40 days for wheat crop. Some farmers grow a green manure (GM) crop before rice and incorporate it to improve N availability. The practice of dry seeding of *Sesbania* with rice in which the GM crop is knocked down after 30-35 days with a herbicide molecule (2,4 D) is still in early adoption stages. Several studies have evaluated the effect of time of incorporation of rice/ wheat residues, starter-N application and combination of GM (*Sesbania cannabina*) on decomposition rates of crop residues [36-39]. Rice residue incorporation after 10 to 40 days had no effect on wheat yields. Rice yields increased (0.18–0.39 Mg ha^{-1}) when wheat residue was incorporated with GM. Starter N applied at residue incorporation did not influence wheat yields but decreased N recovery efficiency. Rice straw is a poor source of N when used alone, but its combination with fertilizer (applied as urea) resulted in agronomic efficiency just 15% lower than for the use of fertilizer nitrogen alone. This slight disadvantage was offset by several compensating factors: Rice straw provided greater residual benefit (i.e., it provided N over a longer time period) and with its high C:N ratio was a better source of organic C and was able to increase bacterial fixation of nitrogen. Recycling of rice straw may thus have a greater potential for reducing requirements for applications of inorganic nitrogen than the use of green manure. [40,41]. Besides improving plant N availability, the rice straw is an important source of potassium (K) as it has high concentration of this nutrient (> 2% K). Potassium is taken up in large amounts from the soil and a negative balance of −141 and −61 kg K_2O ha^{-1} has been reported for the intensive rice-wheat cropping systems in India [42]. Long-term addition of rice straw leads to improved K-fertility of soils and the effect is realized in various K-forms such as water soluble, exchangeable, NH_4OAc-extractable and lattice K [43]. Rice straw besides being source of K for the plants minimizes soil K depletion.

When residues are incorporated immediately before planting the next crop, the grain yields are lower than where residues are removed or burned. This is attributable to the slow decomposition rates of crop residues and resulting N immobilization [44]. Other potential problem of residue incorporation just before rice transplanting include accumulation of phenolic acids in soil and increased CH_4 emissions under flooded conditions [45,46]. However, early incorporation of wheat residues at shallow depth enables their aerobic decomposition, obviates problem of N immobilization, gas emission and facilitates degradation of phenols [47] and avoids any adverse effect on germination of young rice seedlings.

Evidently, incorporation of crop residue in the soil has a number of demonstrated benefits: it increases SOM content, nutrient availability, crop yield, and soil aggregate stability , and importantly, fuel soil's life.

Crop Residues help Management of Soil Acidity and Salinity

During decomposition of crop residues, soluble humic molecules and low molecular weight aliphatic organic acids are released from the residues and/or are synthesized by the decomposer microflora. These compounds detoxify the phytotoxic monomeric Al in soil solution, by blocking P adsorption sites on Al and Fe oxide surfaces and/or through precipitation of Al as insoluble hydroxy-Al compounds [48]. Thus organic residues could be used as a strategic tool to reduce the rates of lime and fertilizer P required for optimum crop production on acidic, P-fixing soils. Surface retained residues cut back evaporation and capillary rise thereby the salinization rates of root zone soil from the shallow and saline water tables. This improves crop growth and reduces the need for additional water for leaching of soluble salts out of the root zone [7]. Recently, it has been shown [49] that cyclic use of brackish water in salt tolerant growth stages of spice crops can significantly enhance C sequestration rates even in saline environments. Additional research is warranted to investigate the use of organic residues in the management of problem soils.

Effect of Residues Retention on the Soil Surface

Residues control erosion primarily by two modes of action: reducing wind speeds below the threshold level for soil particle movement, and intercepting falling raindrops, preventing them from detaching soil particles. In addition, presence of residues reduces surface runoff of soil particles by increasing the water infiltration rates. Relatively low amounts of residues can be effective in enhancing infiltration but more are necessary to reduce evaporation losses. Crop residues retard heat loss from the soil during winter and hinder soil warming during summer. The extent of thermal insulation afforded by the residues depends on the amount, thickness and orientation of residues. Residue orientation can range from standing stubble to residue randomly lying prostrate on the soil surface. Standing stubble dissipates wind energy at the soil surface and thus minimizes the effectiveness of heat and water vapor transfer by convection from the soil to atmosphere. Stubbles are important in trapping snow and also influencing the interception of solar radiation; taller stubble generally traps more incident radiation and thus reduces the proportion that is reflected from the residue surface. Residues reduce both evaporation and runoff.

Effect of Surface Residues on Loss of Soil Moisture and Water Requirement

Straws are known as good absorbers of water, averaging 2-3 kg of water per kg of straw; shredding further enhances this capacity to 3-3.8 kg per kg of crop residue [41]. Snow trapping by surface residues also significantly enhances soil water storage, with a more pronounced effect as stubble height increases. Retention of crop residues on soil surface has mulching effects of reducing soil water evaporation and moderating soil temperature besides suppressing weeds. Surface residues are reported to reduce soil water evaporation in wheat by 35 percent, thus helping save irrigation water. An analysis of published results on the effects of tillage and crop establishment methods in maize-wheat-mungean sequence [50] revealed that compared with the conventionally tilled system, surface retention of residues in zero tillage and raised bed systems saved 400-600 mm water annually in the cropping sequence (Fig. 1).

Savings in irrigation water were because repeated irrigation cycles keep the surface soil moist longer and in the first stage of drying. When soil surface is wet (after the rainfall or irrigation event) and is in first stage of drying, the benefits from surface residues in reducing evaporation are greatest. Evidently, the presence of surface residue cover reduces energy input for evaporation and vapour exchange with atmosphere [51]. After formation of a dry soil surface layer, conductivity to the surface limits water loss and hence the benefits of residues may be little or decrease during the dry season. It has been suggested that during periods of extended dryness, evaporation losses from a residue covered surface can actually exceed that from a bare surface. This is because first-stage drying under the covered surface takes longer time to form a dry layer than under bare surface conditions. Thus, in irrigated agriculture with repeated cycles of watering, surface residues can result in a large saving of stored soil moisture from losses due to evaporation. Use of crop residues as surface mulch in spring and summer crops regulates hydrothermal regime through reduction in soil water evaporation and moderation of soil temperature. Mulching is reported to reduce seasonal evaporation loss by 15 cm in maize and 20 cm in sugarcane [52] besides increasing crop yields.

In a field experiment conducted on a deep black soil, effect of surface residues and tillage and crop establishment (TCE) methods on plant stand and yield of rice was studied in tilled and permanent zero-till conditions under rainfed and irrigated conditions [53]. They observed that surface mulching and zero tillage and TCE methods significantly improved the plant stand of rice crop under rainfed conditions. Rice plant stand in presence of residues under rainfed conditions was generally similar to one observed under irrigated condition without residue covers. Provision of irrigation water masked the ill effects of poor agronomy (no residue cover, excessive deep tillage) and a few supplemental irrigations to rainfed rice crop significantly improved its productivity (Fig. 2). These results point out that the early direct dry seeding in surface retained residues has the potential of making Indian agriculture (kharif season planting) independent of monsoon rains and thus helps prevent rainy season fallows and reduce the acreage of fallow lands in the Vertisols. Thus dry seeding is the single most desirable agronomic practice for harnessing the potential of early rains during hot summers and provides the soil surface covers against erosion during the rainy season

Carbon Sequestration and Adaptation to Climate Change

Soils in the semiarid tropics generally have SOM in the range of 0.5 to 3%, and typically less than 1% [35]. Even at low SOM contents, it significantly influences aggregation and structural stability of soils. Globally, soils have been considered a large C sink but Indian researchers have long lived with a notion that C status of Indian soils cannot be enhanced under tropical climates. Recently, it has been indicated that even though soils are almost essential for us to survive climate change, they are unlikely to help remediate this change [54]. Therefore, it would appear that the current emphasis on C sequestration as the primary goal of mitigating climate change is somewhat misplaced and an 'inverted' priority. This is because what were considered as secondary benefits (improved rainwater storage, reduced soil erosion, and producing more food) must be viewed as primary objectives of research and development towards better farming. Several studies in recent years have examined the potential of Indian soils to sequester C [55-57] and have reported that 'better-bet' soil and crop management practices can mitigate more than half of the total GHG emissions in India [58-60]. Generally, farmers adopt different practices to increase SOC stocks such as (i) integrated use of inorganic fertilizers and organic manure [3,61];

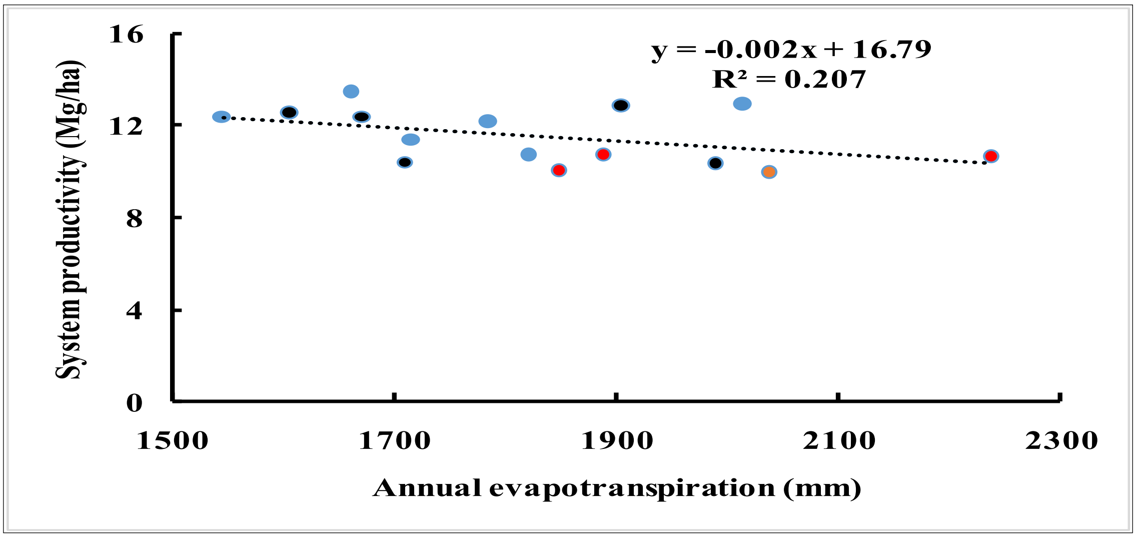

Figure 1. Effect of change in annual evapotranspiration on total productivity of maize-wheat-mungbean cropping system practiced with three tillage and crop establishment methods. Red dots refer to conventional tillage, blue dots to zero tillage and black dots to raised beds

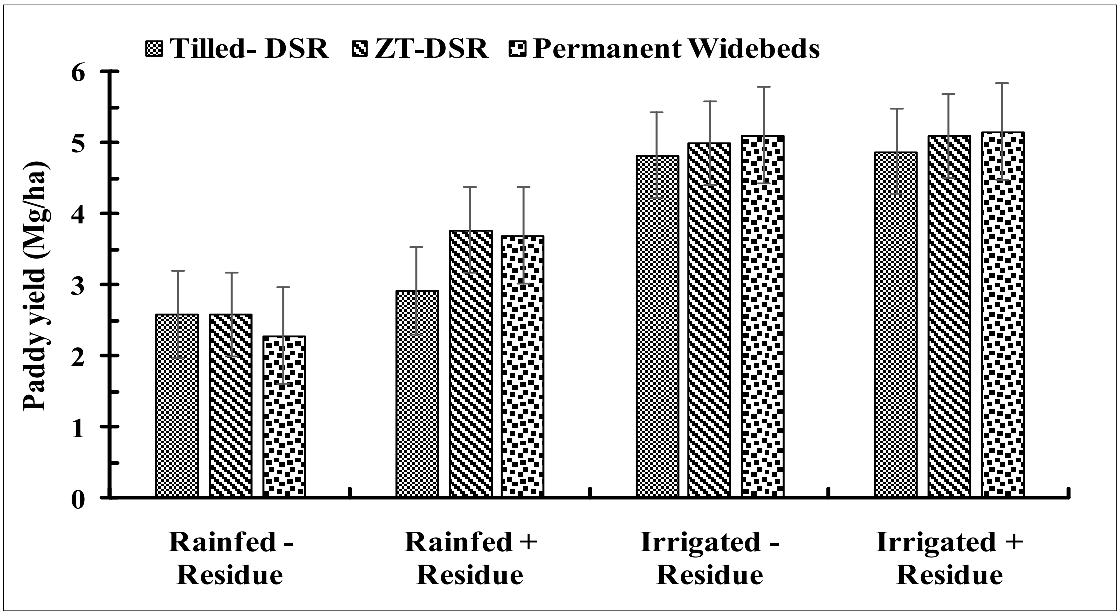

Figure 2. Effect of tillage and crop establishment methods, residue mulch and irrigation provisions (+/-) on productivity of a direct dry seeded rice crop on Jabalpur deep black soil (Adapted from Gupta et al., 2019)

(ii) application of green manure, cover crops and compost; (iii) addition of anchored and trashed plant residues with reduced or zero tillage [62,63]; or (iv) introduction of black C or biochar to the soil [38,64,65]. Results of long-term experiments conducted for more than 4 decades on Mollisol, Inceptisol, Alfisol and Oxisol in India have shown that use of organics together with balanced application of fertiliser nutrients, improve SOC, moisture retention and infiltration rates [5,66,67].

Geographically, distribution of SOC is very heterogeneous and strongly dependent on soil type, land use and climatic conditions. Black soils contain a mollic horizon having high quality humus down to a depth of 60-80 cm. This high quality humus is the result of high base saturation, stable aggregate structure, SOC losses and intense biological mixing [68]. These soils are, however, very sensitive to degradation due to erosion, crusting, nutrient mining and therefore, need to be managed carefully. Improvement in water content, swiftly changes the bulk density and macro-porosity of fine textured black soils. Above field capacity, changes in soil water content impacts low-tension oxygen diffusion processes more than the water content itself [69]. We have observed that low oxygen in wet black soils adversely affects seed germination during rainy season even on the ridges. Surface retention of residues in the presence / absence of a crop stand bring about a significant change in cracking behaviour of deep black soils. Deep wide cracks a common phenomenon of deep vertisols disappear after few seasons by surface mulching of crop residues. Disappearance of cracking behaviour in presence of crop residues, greatly improves the irrigation efficiency and water use in black soils.

Above discussion, presumably suggests that oxygen diffusion rate in black soils could possibly be a better parameter than moisture content *per se* in computing SOM decomposition rates. Influence of surface residues on cracking behaviour of black soils, likely affects the moisture, temperature and aeration regimes and hence the organic C decomposition rates and C storage potential of these soils. Therefore, Q_{10} concept needs some additional research. Dry lands have large potential to sequester SOC but C storage in drylands is affected and limited by a number of bioclimatic elements including availability of the organics for recycling.

Decomposition of Crop Residues

Organic matter levels in soils are determined by a number of interacting factors including bio-climate, soil type, tillage and crop establishment methods (TCE), cropping systems and methods of returning residues to the soils (incorporation, surface retention/ removal), and the types of residues added to the soils (straws, green manure, farm yard manures or composts). Extent of erosion hazards also influence SOM levels and transformations. Carbon sequestration and stabilization regulate SOC levels and have important implications on soil productivity and the potential of using soils to enhance soil C storage and mitigating predicted climate changes [70]. In the decomposition of crop residues, factors such as water, temperature and the biochemical composition govern microbial activity responsible for decomposition and accumulation of SOM. In general, low temperature and high moisture favour increases in SOM and vice versa, implying thereby that semiarid regions have high SOM decomposition rates. Microbes can function over a wide temperature range but exhibit optimum growth and activity in 20-30^{o} C range at field capacity moisture contents. As soils dry out, bacterial activity decreases but fungi can still act on the residues even at low soil water contents [71]. At constant temperature and moisture conditions, the residue composition influences the rate and extent of its decomposition. Crop residues with a high C/N ratio (e.g., wheat) decay at a slower rate than residues with a low C/N ratio (e.g., corn). The decomposition rates of relatively labile substrates have been related to C/N ratio and that of more recalcitrant organic residues to lignin content or lignin-to-N ratios [39,72]. Microbes produce SOM through decomposition of organic residues and release CO_2 through heterotrophic respiration. They also utilise SOM and humus carbon as energy source. Lignaceous rice and wheat residues of high C/N ratio (80-120:1) induce a high microbial demand for nitrogen and if not met by straw, may immobilise native soil N or fertiliser N. The effect of temperature on decomposition rates of organic matter is often described using a variety of models including the van't Hoff, Arrehenius, Lloyd and Taylor, and Gaussian [73]. A comparison of various models has revealed that for field situations, these models differed greatly in predicting response to temperature [74]. In several publications, effects of factors such as residue composition (C:N ratio), soil moisture and temperature variations, residue orientation (anchored and flat placements) and mineral matrix (surface area) on organic matter decomposition rates have been considered [37,39,63,75].

There are ample evidences to show that SOC stocks are strongly influenced by residue management and a soil's ability to protect (or stabilise) carbon [41,76,77]. Charged mineral surface facilitate formation of organo-mineral complexes that protect organic molecules both physically and chemically from microbial decomposition [78-80]. The amount and type of soil clay greatly influence the quantity of C stabilized; the soils with higher clay content, particularly with higher exchange capacities retain greater amount of residue C [81]. For instance, montmorillonite clay resulted in greater C stabilization particularly in the later stages of decomposition whereas kaolinite did not influence C stabilization in soil [81]. Clays besides increasing microbial biomass and activity improve C use efficiency by reducing C loss as CO_2 thus leading to greater C stabilization in soil. For reasons of charge density, SOC in New Zealand was poorly correlated with clay content but well-correlated with the apparent specific surface area of the mineral matrix of the soils [82,83]. The estimates of specific surface area based on measurements of water adsorption of soils and fluctuations of water contents seemingly provide a simple and cost effective method of working out the SOM decomposition rates. Using field capacity soil moisture variations with time, decomposition rates of SOM could be adequately defined by Mohammed et al. [37]. Since SOM itself can also adsorb soil water, Kirschbaum et al. [84] estimated the soil carbon-based contribution to water adsorption to reach unconfounded estimates of mineral specific surface area in arriving at the realistic decomposition rates of SOM.

Anchored standing crop residues decompose slowly in the arid and semi-arid regions via photo-oxidation of organic matter [85]. In photo-oxidation, lignin plays a key role in regulating plant litter decomposition [86], humic substance formation [87,88] and production of dissolved organic matter (DOM) [89]. Photo-oxidation reduces the molecular size of lignin or DOM [90], which potentially increases the biodegradability of DOM [91]. In the initial stages (1-2 weeks), residue decomposition was related to crop residue organic N, C/N ratio, size of water soluble organic C pool and intermediately available C pool [92]. Photo-degradation exercises a dominant control on decomposition of above-ground residues in a manner that can possibly short-circuit the carbon cycle [85]. This implies that a substantial fraction of plant biomass carbon may be lost directly to the atmosphere without cycling through SOM pools. Photo-oxidation of the anchored crop residue in rainfed dry lands could play a significant role in organic matter degradation. Above-surface residue (anchored) decay very slowly than those lying prostrate on the surface [63]. Studies have shown that soils high in SOM retain more moisture, especially when residues are retained on the soil surface as compared to when they are incorporated. Placement methods of residues have a significant influence on the decomposition rates. Incorporated residues generally decompose faster than those retained / placed on the soil surface. Reinertsen et al. [92] reported that indigenous microflora, which colonise the cereal straws provide adequate inoculums to facilitate decomposition. Thus the slow decomposition rates of residue placed on the surface is mainly due to prevailing suboptimal temperature and moisture regimes

Effect of Residue Burning on C Pools, Soil Properties and Nutrient Availability

The burned C is primarily biochemically stable and unlikely to play a significant role in C cycle. So the labile C and the mineral associated C (recalcitrant) remains. Its amount should be proportional to surface area of mineral and the C inputs after decomposition of the labile C. Sowing of zero till wheat in surface residues is a better alternative strategy to avoid residue burning, improving crop productivity, increasing C-sequestration, and enhancing the sustainability and soil quality in rice-wheat system. Residue returned to the soil besides enlarging SOC pool, impacts its quality in terms of persistence, turnover rates and functionality. Crop residues and organic amendments improve SOC pool directly through addition of embodied C and indirectly via greater crop mediated C input resulting from enhanced crop yield [93]. The quality of SOC is generally characterized by separating into various physical (based on size, density, protection or accessibility), chemical (extractability or oxidizability) and biological (microbial activity, kinetically defined) pools [4,94-96]. The separated pools with different turnover times considered labile/ active, non-labile/ stable and recalcitrant/passive are associated with specific stabilization mechanism (Table 2). Recent works have suggested that C accrual and persistence in soil can be better described if SOM is broadly separated into particulate organic (POM) and mineral-associated organic matter (MinOM) pools [3,97,98] with further sub-divisions into coarse POM and fine POM. The POM represents more labile pool and MinOM, because of mineral association, a stable pool of SOC [3] though both the fractions are subject to occlusion within macroaggregates that slows decomposition [94,99,100]. Long-term SOM stabilization is thought to be through (i) physical protection by micro-aggregates, (ii) chemical protection by binding with oxyhydrates [101] and inter-molecular interactions with organic or inorganic substances [102], and (iii) molecular recalcitrance promoted stabilization of hydrophobic particulate organic matter contributing to C sequestration in paddy soils [103].

Surface retained residues or buried in soil undergo fragmentation and degradation, adds to coarse POM pool, which decomposes progressively to more resistant finer particle sizes with the narrowing of the C/N ratio [3,97,104]. A number of studies have reported the accrual of added organic C as POM-C in soil. The light fraction POM responds to residue application to greatest extent followed by sand-sized heavy fraction and silt and clay sized MinOM-C [3]. Surface residues are known to improve aggregate stability and formation of macro-aggregates, which provide protection to the associated organic C fractions from decomposition thus increasing their residence time [105,106]. The effect is enhanced with no-till which promotes aggregate stability and the formation of recalcitrant SOM fractions within micro- and macro-aggregates [107]. The improved aggregate stability results from increased microbial activity due to metabolism of carbohydrates and the interaction of plant phenolic acids released during decomposition of residue structural components [108] and the less oxidative biochemical environment of no-till soils [109]. Therefore, conservation agriculture results in higher C accrual and persistence in soil.

Do Soil have Infinite Capacity to hold SOC?

Several early studies had assumed that soils have a finite capacity to store C even with the better-bet practices. This capacity often referred as maximum C stabilization capacity [82,110] is a function of rate and duration over which C sequestration continues. Most published studies have predicted C sequestration potential of different soils assuming a time span of about 25-50 years [111,112]. The Intergovernmental Panel on Climate Change [113] suggested 20-yr period for estimating the C sequestration rates following a change in management practices. An analysis of global data from 67 long-term experiments indicated that C sequestration rates with no-till (NT) could peak in 5 to 10 years with SOC reaching a new equilibrium in 15 to 20 years [114]. In a subsequent analysis, C sequestration rates for cropland management have been predicted to peak at about 10 years and continue at lower rates over another 40 years [115]. However, it has been argued that sequestration duration does not indicate soil C sequestration potential rather it reflects only the time to attain new steady state when C input equals C output with a given management. The soils could still sequester more C after adopting additional management changes till maximum soil C sequestration capacity, or soil C saturation, is reached [115]. Although the formation of mineral associated C may have an upper limit as determined by the quantity of fine silt and clay particles, but the accumulation of particulate organic C (POC) apparently has no saturation limit [76,98]. On the contrary, some researchers have suggested that C sequestration potential of soils cannot be predicted because C storage takes place not only through clay-organic complexes but also through organic-organic complexes.

From the foregoing discussions, it would appear that most soils are far from the saturation threshold. Management practices that protect existing C stocks and bring additional C inputs can significantly maximize the C sequestration potential. When this threshold is

Table 2. Soil organic carbon (SOC) pools, their composition and estimated turnover times.

Pool	Composition	Turnover time
Classification based on size		
Particulate organic matter (POM-C)	Relatively undecomposed light weight plant fragments; plant derived molecules or structural C compounds of low N content; ; size 53-2000 μm; unprotected; may be entrapped inside macro-aggregates; C/N 10-40; further divisions included coarse (size 250-200 μm) and fine (53-250 μm) POM-C;	<10 years to decades
Occluded POM (iPOM-C) in micro-aggregates	Occluded in soil micro-aggregates undergone some degree of decomposition; inaccessible to microorganisms; persists in soil through inherent biochemical recalcitrance and physical protection in aggregates thus presents a mechanism for long-term soil C sequestration in agricultural soils	1000-3000 years
Mineral associated organic matter C (MinOM-C)	Comprises predominantly microbial-derived compounds richer in N, size < 53 or <20 μm; higher natural abundance ^{13}C; protected from decomposition through association with soil minerals, sorption to mineral surfaces and physical protection in micro-aggregates. C/N 8-13	Decades to centuries
Classification based on biological stability		
Labile/active	Surface and buried plant residue, root exudates; particulate organic matter; microbial biomass; soluble carbohydrates	Days to years
Non-labile or stable	Well decomposed organic material associated with soil particles (humus)	Years to decades
Recalcitrant or passive	Charcoal or charred materials resulting from burning of organic matter	Decades to millennia

reached, SOC sequestration comes to an end and soils stops being a net carbon sink and become a net carbon source. For this reason, SOC sequestration is a reversible process [116]. Degraded soils having minimum SOC, are the ones that have the largest potential to gain C with appropriate management practices [117,118]. Sub-soils have large potential to sequester C because of a large SOC saturation deficit. In context of climate change it is interesting to know whether SOC stocks will continue to change in line with changing C input rates, or the SOC changes will be constrained by limits of C that a soil can stabilise and protect.

Residue Management for Land Degradation Neutrality

In India, a vast majority of the land holdings are with marginal and small farmers, located in the dryland / rainfed areas. These farm lands have low productivity owing to high decomposition rates of SOM and low water availability. While summer monsoon rains are the life-line for Indian agriculture, runoff water mediated soil erosion at the same time results in loss of soil carbon, nutrients, moisture and contributes to reduced biomass production as well as restricting the farmers' choices for diversification (biodiversity). Loss of surface soil in monsoon rains by far is a major process of soil degradation in the Indian subcontinent. Reversing processes contributing to land degradation are central to water availability, soil health, adapting to climate change and food security. It also appears (Fig 3) that rain water management has to be a crucial element of any strategy that enhances gene diversity and sequesters more carbon to offset the climate change effects, builds resilience and reverses land degradation [8]. Thus the overall strategy for land degradation neutrality should favour actions that provide for keeping soil covered with residues and make kharif season planting independent of the onset of monsoons (e.g. Direct dry seeding in residues before pre-monsoon showers) for protecting soils against rain drop actions and promote *in-situ* rain water storage and use to enable farmers grow more crops and prevent run off and soil erosion.

Increasing the use efficiency of rainwater and/ or irrigation support increased crop production resulting in increased allocation of carbon to the soil through residues and root biomass returned to the soil. No-till together with residue retention on the surface reduces soil erosion to rates close to those found in natural ecosystems [119]. Thus, the no-till conservation agriculture water centric management practices help build carbon in soils.

The Way Forward on use of Chemical Fertilizers, Organics and Conservation Agriculture

Fertilizer application rates have a profound influence on SOC contents and the health of the soils. Results of a large number of field trials conducted under the aegis of Indian Council of Agricultural Research- AICRP Long Term Fertilizer Experiments (LTFE) and the Modern Agronomy Experiments in different agro-ecoregions of India have indicated that fertilizer use has been a primary driver of increasing crop yields. It has also been observed that recommended dose of NPK plus FYM or GM application maximized crop productivity and enhanced SOC stocks for sustaining ecological functions on most soils in the semi-arid and sub-humid situations. However, several critical questions concerning balanced and efficient use of fertilizers, plateauing yields and reluctance of farmers to retain crop residues in the field and use of FYM remain unanswered. We have endeavoured to draw attention and discuss some of the underlying issues impacting soil health, nutrient use efficiency and production system sustainability.

- How does the continuous use of chemical fertilizers and FYM impact the carbon dynamics in soils?
- How does use of organics assist achieve soils their optimal ecofunctionality that cannot be compensated with fertilizers alone?
- How should available organic resources be optimized considering the specifics of hot summer season and monsoon rains that make Indian soils extremely prone to soil degradation through soil erosion?

Finding appropriate answers to the above vexed issues appear fundamental to achieving the sustainability goals. Much of the fertilizer use and soil management research in India has focused on defining fertilizer use and management practices for improving

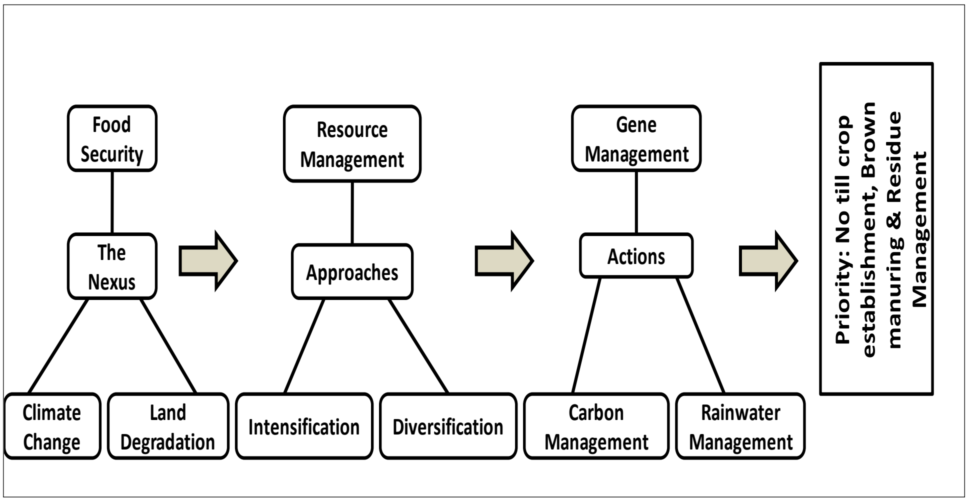

Figure 3. Priority actions for handling land degradation-food security-climate change nexus (Adapted from Abrol and Gupta, 2019)

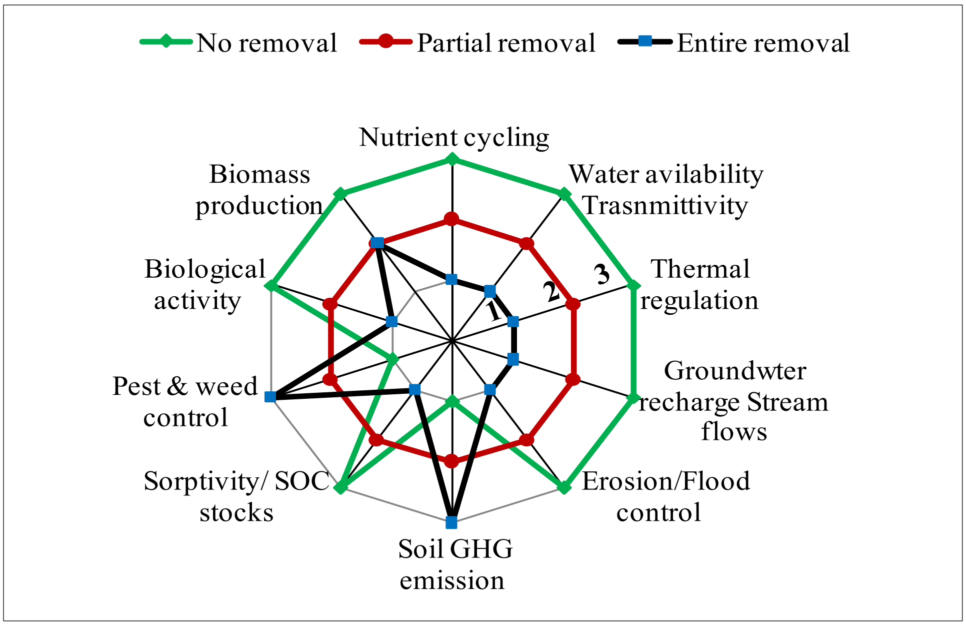

Figure 4. Impact of crop residue management on soil functions and plant growth (Adapted from Cherubin et al., 2017). The 1-3 impact scale denotes 1 - low, 2 – medium, and 3-high.

crop productivity and their use efficiency. Most studies have indicated that balanced fertilizer use (100% NPK) improve crop productivity with simultaneous build-up of SOC by 20-600 kg C ha^{-1} yr^{-1} across several sites in India [56]. Further, the SOC accumulation in plots receiving FYM is nearly twice (100-1200 kg C ha^{-1} yr^{-1}) of the plots receiving only chemical fertilizers. This implies that speeding up SOC build-up in Indian soils and improving use efficiency of the fertilizers would require simultaneous use of organics and chemical fertilizers. However, the range of SOC accrual values across India clearly show that C sequestration rate of "4 per thousand" [120,121] is quite difficult to achieve in Indian sub-continent with prevailing soil and crop management practices.

Besides, balanced and integrated nutrient management, CA practices are reported to increase SOC accumulation and persistence. Published evidence suggests that C accumulation in soils from temperate region is nearly at double the rates than generally reported for subtropical soils. Generally, farmers apply tillage for incorporation of crop residues. Initially the practice destroys soil aggregates but subsequent litter decomposition can promote formation of water stable aggregates. Fresh litter C inputs provide readily bioavailable nutrients and energy for soil microbes to grow and exert a priming effect on decomposition of native SOC and play a significant role in governing the long-term dynamics of SOC. No-till (NT) cropping systems with residue retention usually favour increased macro-aggregate formation, from stable micro-aggregates facilitated by sequestered C, relative to conventional tillage [122]. Therefore, conjunctive use of organics with chemical fertilizers under CA is an effective and important soil C and yield response management strategy for sustainability of agriculture in the subtropical regions. On the contrary, crop residue burning and harvest for bioenergy production will likely lead to SOC depletions over time with implications for CO_2 and N_2O emissions from soils [123,124], reduce plant nutrient supplies, adversely impact the biota that regulate some key soil functions. Therefore, crop residue harvest/burning has multiple influences on soil properties, water storage, biological activity and soil resistance to structural degradation [125]. Impacts of crop residue management on soil functions and plant growth has been summarized diagrammatically in figure 4. It shows that crop residues have multiple roles, and different strategies affect the soil ecofunctions and ecosystem system services differently. Cherubin et al. [126] graded the soil functions and plant growth for 3 crop residue removal / harvest rates (high, moderate and low) on a 1-3 impact scale (1 - low, 2 – medium, 3-high).

This diagram allows an impact assessment associated with any residue management strategy. In Indian context, most of our soils are highly prone to summer monsoon rains mediated soil degradation each year during the kharif season. This is because agronomic fatigue does not allow crop planting before the onset of monsoon rains and reluctance of the farmers to keep soil surface covered with residues. Therefore better bet management strategies must include no-till, provide surface cover to soils via crop residues or plant cover established through direct dry seeding before the onset of monsoons, and use FYM during the rabi season to perk up the depleted carbon stocks. Apparently in figure 4, greater importance has been attached to large biomass production through efficient use of repeated cycles of green water supplies received through continental monsoons and the role surface residues play in cutting back the unproductive loss of water through evaporation.

Acknowledgements

One of the authors (RG) gratefully acknowledges the financial support received from the Indian National Science Academy, New Delhi for conduct of this study.

Declaration of Interest

The authors declare no conflict of interest

Data Availability

All data are included within the paper

References

1. Gupta R, Benbi DK, Abrol IP (2021) Indian agriculture needs a strategic shift for improving fertilizer response and overcome sluggish food grain production. Current Science. (in Press).

2. Li T, Zhang Y, Bei S, Li X, Reinsch S, Zhang H, Zhang J. (2020) Contrasting impacts of manure and inorganic fertilizer applications for nine years on soil organic carbon and its labile fractions in bulk soil and soil aggregates. Catena 194, 104739.
3. Benbi DK, Toor AS, Kumar S. (2012) Management of organic amendments in rice-wheat cropping system determines the pool where carbon is sequestered. Plant & Soil 360, 145–162. doi 10.1007/s11104-012-1226-3.
4. Benbi DK, Brar K, Toor AS, Sharma S. (2015) Sensitivity of labile soil organic carbon pools to long-term fertilizer, straw and manure management in rice-wheat system. Pedosphere 25, 534–535.
5. Nambiar KKM, Abrol IP. (1989). Long term fertilizer experiment in Indian overview. Fertilizer News 34 (4), 11-34.
6. Lal R. (2004) The potential of carbon sequestration in soils of South Asia. Conserving soil and water for society: Sharing solutions. Paper No. 134 doi.org/10.1016/j.catena.2020.104739 .
7. Gupta R, Tyagi NK, Abrol I. (2020) Rainwater management and Indian agriculture: A call for a shift in focus from blue to green water. Agricultural Research. doi.org/10.1007/s40003-020-000467-2
8. Abrol I, Gupta R. (2019) Climate Change-Land Degradation-Food Security Nexus: Addressing India's Challenge. Journal of Agronomy Research 2 (2), 17-35. doi:10.14302/issn.2639-3166.jar-19-3015.
9. Hari S, Khare P, Subramanian A. (2018) Climate change and Indian agriculture. Idea for India for more evidence- based policy. www.ideasforindia.in/topics/agriculture/climate-change-and-indian-agriculture.html. Accessed 17 Feb 2020
10. Gadgil S. (2012) Seasonal prediction of the Indian summer monsoon: science and applications to Indian agriculture. In: ECMWF seminar on seasonal prediction, 3–7 Sept. 2012, pp 104–130.
11. MOA (2014) National Policy for Management of Crop Residues (NPMCR), Ministry of Agriculture, Dept. of Agric. & Cooperation, Govt of India. 9p. http://agricoop.nic.in/sites/default/files/ NPMCR1. pdf
12. TIFAC- IARI Joint Report (2018) Estimation of surplus crop residues in India for biofuel production. Technology Information, Forecasting & Assessment Council (TIFAC), Department of Science & Technology (DST), Govt. of India, New Delhi. 221p.
13. Lal R. (2005) World crop residues production and implications of its use as a biofuel. Environment International 31: 575– 584
14. Jethva H, Torres O, Field RD, Lyapustin A., Gautam R, Kayetha V. (2019) Connecting crop productivity, residue fires, and air quality over Northern India. Scientific Reports 9, 16594. https://doi.org/10.1038/s41598-019-52799-x
15. Sarkar S, Skalicky M, Hossain A, Brestic M., Saha S, Garai S, Ray K, Brahmachari K. (2020) Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability 12: 9808; doi:10.3390/su12239808 .
16. Wagner DF. (1974) Effects of burning crop residues. North Dakota State Univ., Fargo, Coop. Ext. Serv. Circ. S-F 590. 5 pp
17. Dormaar JF, Pittman UJ, Spratt ED. (1979) Burning crop residues: Effect on selected soil characteristics and long-term wheat yields. Canadian Journal of Soil Science 59, 79-86.
18. Biederbeck VO, Campbell CA, Bowren KE, Schnitzer M, McIver RN. (1980). Effect of burning cereal straw on soil properties and grain yields in Saskatchewan. Soil Science Society of America Journal 44,103-111. doi.org/10.2136/sssaj1980.03615995004400010022x .
19. Jagnow G, Graff O. (1974) Boden biologische untersuchungsergebnisse zur beur teilung des einflusses der strohverbrennung auf die bodenmikroflora und auf die boden fruchtbarkeit. Ber. Landwirtsch. 52, 678-681
20. Mickovski M. (1967) Influence of burnt straw on the microflora of the soil. God. Zb.Zemjod.-Sumar. Fak. Univ., Skopje, Zemjod. 20, 55-68.
21. Rifat A. (2016) Effects of crop residue burning on soil physical and hydrological properties in semi-arid agricultural production systems. JAFAG 33(3), 223-235.

22. Fasching RA. (2001) Burning –Effects on soil quality. Soil Quality Agronomy Technical Note No. 150.16 NRCS, USDA.
23. Doerr SH, Shakesby RA, Walsh RPD. (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth Science. Reviews 51, 33–65.
24. DeBano LF. (1981) Water repellent soils: a state-of-the-art United States Department of Agriculture, Forest Service, General Technical Report, PSW-46, Berkeley, California, 21 pp.
25. DeBano LF. (1991) The effects of fire on soil properties. United States Department of Agriculture, Forest Service, General Technical Report, INT-280, 151–156.
26. Savage SM (1974) Mechanism of fire-induced water repellency in soil. Soil Science Society of America Journal 38(4), 652-657. https://doi.org/10.2136/sssaj1974.03615995003800040033x
27. Giovannini G. (1994) The effect of fire on soil quality. In: Sala, M., Rubio, J.L. Eds. , Soil Erosion as a Consequence of Ž . Forest Fires. Geoforma Ediciones, Logrono, pp. 15–27.
28. Giovannini G, Lucchesi S. (1983) Effect of fire on hydrophobic and cementing substances of soil aggregates. Soil Science 136, 231–236.
29. Blackwell PS. (1993) Improving sustainable production from water repellent sands. Western Australia Journal of Agriculture 34, 160–167.
30. Cann M, Lewis D. (1994) The use of dispersible sodic clay to overcome water repellence in sandy soils in the South East of South Australia. Proceedings 2nd National Water Repellency Workshop, 1–5 August, Perth, Western Australia. pp. 49–57.
31. Song XY, Spaccini R, Pan G, Piccolo A. (2013) Stabilization by hydrophobic protection as a molecular mechanism for organic carbon sequestration in maize-amended rice paddy soils. Science of the Total Environment 458–460, 319–330. doi.org/10.1016/j.scitotenv.2013.04.052
32. Andreae MO, Merlet P. (2001) Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15, 955–966.
33. Gupta PK, Sahai S, Singh N, Dixit CK, Singh DP, et al. (2004) Residue burning in rice-wheat cropping system: Causes and implications. Current Science 87(12): 1713-1717.
34. Benbi DK, Kaur H, and Toor AS. (2019) Carbon footprint and sustainability of agriculture in Punjab. Research Bulletin, ICAR National Professor Chair, Punjab Agricultural University, Ludhiana.
35. Smith JL, Elliott LF. (1990) Tillage and residue management effects on soil organic matter dynamics in semiarid regions. Advances in Soil Science 13, 69-88.
36. Adachi K, Chaitep W, Senboku T. (1997) Promotive and inhibitory effects of rice straw and cellulose application on rice plant growth in pot and field experiments. Soil Science & Plant Nutrition 43, 369–386.
37. Mohammed AM, Nartey E, Naab JB, Adiku SGK. (2013) A simple model for predicting plant residue decomposition based upon their C/N ratio and soil moisture. African Journal of Agriculture Research 8 (19), 2153-2159. DOI: 1.5897/AJAR11.1342 .
38. Benbi DK, Yadav SK. (2015) Decomposition and carbon sequestration potential of different rice residue-derived by-products and farmyard manure in a sandy loam soil. Communications in Soil Science & Plant Analysis 46, 2201-2211
39. Benbi DK and Khosa MK (2014) Effect of temperature, moisture and chemical composition of organic substrates on C mineralization in soils. Communications in Soil Science & Plant Analysis 45: 2734-2753. https://doi.org/10.1080/00103624.2014.950423
40. Cassman KG, De Datta SK, Amarante ST, Liboon SP, Samson MI, et al. (1996) Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources for tropical lowland rice. Experimental Agriculture 32, 927-944.
41. Smil V. (1999) Crop Residues: Agriculture's Largest Harvest. BioScience 49(4), 299-308.

42. Tandon HLS, Sekhon GS. (1988) Potassium research and agricultural production in India. New Delhi: FDCO; p. 144.
43. Yadav SK, Benbi DK, Toor AS. (2019) Effect of long-term application of rice straw, farmyard manure and inorganic fertilizer on potassium dynamics in soil. Archives of Agronomy and Soil Science 65: 3, 374-384. doi: 10.1080/03650340.2018.1505040
44. Benbi DK, Manchanda JS, Gosal SK, Walia SS, Toor AS, et al. (2011) Soil health issues for sustaining agriculture in Punjab. Directorate of Research, Punjab Agricultural University, Ludhiana, 42p.
45. Wassmann R, Lantin RS, Neue HU, Buendia LV, Corton TM, Lu Y. (2000) Characteristics of methane emission from rice fields in Asia. p. 23–36. In R. Wassmann et al. (ed.) Methane emissions from major rice ecosystems in Asia. Kluwer Academic Publishers, Dordrecht.
46. Khosa M, Sidhu BS, Benbi DK (2010) Effect of organic materials and rice cultivars on methane emission from rice field. Journal of Environmental Biology 31, 281-285
47. Witt C, Cassman KG, Olk DC, Biker V, Liboon SP, et al. (2000) Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. Plant & Soil 225, 263–278.
48. Haynes RJ, Mokolobate MS. (2001) Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutrient Cycling in Agroecosystems 59, 47–63.
49. Chandel S, Datta A, Yadav RK, Dheri GS (2021) Does saline irrigation influence soil carbon pools and nutrient distribution in soil under seed spices? Journal of Soil Science & Plant Nutrition. https://doi.org.10.1007/s42729-021-00413-3 .
50. Parihar CM, Jat SL, Singh AK, Majumdar K, Jat ML, Saharawat YS. (2017) Bio-energy, water-use efficiency and economics of maize-wheat-mungbean system under precision-conservation agriculture in semi-arid agro-ecosystem. Energy 119, 245-256. doi.org/10.1016/j.energy.2016.12.068
51. Papendick RI, Parr JF, Meyer RE (1990) Managing crop residues to optimize crop/livestock production systems from dryland agriculture. Advances in Soil Science 13, 253-272.
52. Jalota SK, Arora VK. (2002) Model based assessment of water balance components under different cropping systems in north-west India. Agriculture Water Management 57, 75-87.
53. Gupta R, Kumar N, Singh SK, Sahoo RN, Abrol IP. (2019) Resource management domains of kharif and rabi season fallows in Central Plateau region of India: A strategy for accelerated agricultural development. Journal of Agronomy Research. DOI:10.14302/issn.2639-3166.jar-19-2590
54. Amundson R, Biardeau L. (2018) Soil carbon sequestration is an elusive climate mitigation tool. Opinion. Proceedings National Academy of Sciences 115(46), 11652-11656. www.pnas.org/cgi/doi/10.1073/pnas.1815901115
55. Bhattacharyya T, Pal DK, Chandran P, Ray SK, Mandal C, et al. (2008) Soil carbon storage capacity as a tool to prioritize areas for carbon sequestration. Current Science 95, 482-494.
56. Benbi DK. (2015) Enumeration of soil organic matter responses to land-use and management. 33rd Professor J.N. Mukherjee – ISSS Foundation Lecture. Journal of the Indian Society of Soil Science 63, S14-S25.
57. Singh P, Benbi DK. (2018) Nutrient management effects on organic carbon pools in a sandy loam soil under rice-wheat cropping, Archives of Agronomy and Soil Science 64, 1879-1891, DOI: 10.1080/03650340.2018.1465564.
58. Benbi DK (2018) Carbon footprint and agricultural sustainability nexus in an intensively cultivated region of Indo-Gangetic Plains. Science of Total Environment 44, 611–623.
59. Sapkota TB, Vetter SH, Jat ML, Sirohi S, Shirsath PB, et al. (2018) Cost-effective opportunities for climate change mitigation in Indian agriculture. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2018.11.2250048-9697

60. Ramesha T, Bolan NS, Kirkham MB, Wijesekara H, Kanchikerimath M., et al. (2019) Soil organic carbon dynamics: Impact of land use changes and management practices: A review. Advances in Agronomy. https://doi.org/10.1016/bs.agron.2019.02.001

61. Rasmussen PE, Rohde CR. (1988) Long-term tillage and nitrogen fertilization effects on organic nitrogen and carbon in a semiarid soil. Soil Science Society of America Journal 52(4), 1114-1117. https://doi.org/10.2136/sssaj1988.03615995005200040041x

62. Ismail L, Blevins RL, Frye WW. (1994) Long-term no-tillage effects on soil properties and continuous corn yields. Soil Science Society of America Journal 58, 193-198.

63. Ma L, Peterson GA, Ahuja LR, Sherrod L, Shaffer MJ, et al. (1999) Decomposition of surface crop residues in long-term studies of dryland agroecosystems. Agronomy Journal 91, 401-409.

64. Tryon EH. (1948) Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecological Monographs 18, 81-115.

65. Glaser B, Lehmann J, Zech W. (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Biology & Fertility of Soils. 35, 219–230. doi 10.1007/s00374-002-0466-4.

66. Benbi DK, Biswas CR, Bawa SS, Kumar K. (1998) Influence of farmyard manure, inorganic fertilizers and weed control practices on some soil physical properties in a long-term experiment. Soil Use and Management 14: 52-54. DOI: 10.1111/j.1475-2743.1998.tb00610.x

67. Pant PK, Ram S. (2018). Long-Term manuring and fertilization effects on soil physical properties after forty two cycles under rice-wheat system in North Indian mollisols. International Journal of Current Microbiological & Applied Science 7, 232-240.

68. Altermann M, Rinklebe J, Merbach I, Korschens M., Langer U, et al. (2005) Chernozem- Soil of the Year 2005. Journal of Plant Nutrition and Soil Science 168, 725-740.

69. Lin HS, Mc Innes KJ, Wilding LP, Hallmark CT. (1998) Macro porosity and initial soil moisture effects on infiltration rates in Vertisols and Vertic intergrades. Soil Science 163: 2-8.

70. Goh KM. (2004) Carbon sequestration and stabilization in soils: implications for soil productivity and climate change. Soil Science & Plant Nutrition 50(4), 467- 476.

71. Scott DE, Elliott LF, Papendick RI, Campbell GS. (1986) Low temperature or low water potential effects on the microbial decomposition of wheat residues. Soil Biology & Biochemistry 18, 577- 582.

72. Nisar S, Benbi, D.K. (2020) Stabilization of organic C in an Indo-Gangetic alluvial soil under long term manure and compost management in a rice–wheat system. Carbon Management. https://doi.org/10.1080/17583004.2020.1824483

73. Benbi DK and Nisar S. (2020) Developments in measurement and modelling of soil organic carbon In: Carbon Management in Tropical and Sub-Tropical Terrestrial Systems, Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-13-9628-1_23. DOI: 10.1007/978-981-13-9628-1_23

74. Benbi DK, Boparai AK, Brar K. (2014) Decomposition of particulate organic matter is more sensitive to temperature than the mineral associated organic matter. Soil Biology & Biochemistry 70: 183-192. DOI: 10.1016/j.soilbio.2013.12.032

75. Kirschbaum MUF, Moinet GYK, Hedley CB, Beare MH,. McNally SR. (2020) A conceptual model of carbon stabilisation based on patterns observed in different soils. Soil Biology & Biochemistry https://doi.org/10.1016/j.soilbio.2019.107683 .

76. Hassink J. (1997) The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant & Soil 191, 77–87. https://doi.org/10.1023/A:1004213929699

77. Six J, Conant RT, Paul EA. et al. (2002) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant & Soil 241, 155–176. doi.org/10.1023/A:1016125726789

78. Vogel C, Heister K, Buegger F, Tanuwidjaja I, Haug, S et al. (2015) Clay mineral composition modifies decomposition and sequestration of organic carbon and nitrogen in fine soil fractions. Biology & Fertility of Soils. https://DOI10.1007/s00374-014-0987-7
79. Kleber M, Karin E, Marco K, Christian M, Robert M, Peter N. (2015) Mineral–organic associations: formation, properties, and relevance in soil environments. Advances in Agronomy 130, 1-140. https://DOI10.1016/bs.agron.2014.10.005.
80. Dignac M-F, Derrien D, Barré P, Barot S, Cécillon L, et al. (2017) Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agronomy for Sustainable Development 37, 14. doi:10.1007/s13593-017-0421-2
81. Sørensen LH. (1972) Stabilization of newly formed amino acid metabolites in soil by clay minerals. Soil Science 114, 5-11
82. Beare MH, McNeill SJ, Curtin D, Parfitt RL, Jones HS, et al. (2014) Estimating the organic carbon stabilisation capacity and saturation deficit of soils: a New Zealand case study. Biogeochemistry 120, 71-87.
83. McNally SR, Beare MH, Curtin D, Meenken ED, Kelliher FM, et al. (2017) Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. Global Change Biology 23, 4544–4555.
84. Kirschbaum MUF, Giltrap DL, McNally SR, Liang LL, Hedley CB, et al. (2020) Estimating the mineral surface area of soils by measured water adsorption. Adjusting for the confounding effect of water adsorption by soil organic carbon. European Journal of Soil Science 71, 382-391. DOI: 10.1111/ejss.12892.
85. Austin AT, Lucía V. (2006) Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation. Nature 442, 555–558.
86. Melillo J M, Aber J D, Muratore J F. (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63, 621–626.
87. Ertel JR, Hedges JI. (1984) The lignin component of humic substances: Distribution among soil and sedimentary humic, fulvic, and base-insoluble fractions. Geochimica et Cosmochimica Acta 48(10), 2065-2074.
88. Kiem R, Kögel-Knabner I. (2003) Contribution of lignin and polysaccharides to the refractory carbon pool in C-depleted arable soils. Soil Biology & Biochemistry 35, 101-118.
89. Kalbitz K, Kaiser K, Bargholz J, Dardenne P. (2006) Lignin degradation controls the production of dissolved organic matter in decomposing foliar litter. European Journal of Soil Science 57, 504–516
90. Lou T, Xie H. (2006) Photochemical alteration of the molecular weight of dissolved organic matter. Chemosphere 65, 2333–2342.
91. Rosenstock B, Zwisler W, Simon M. (2005) Bacterial consumption of humic and non-humic low and high molecular weight DOM and the effect of solar irradiation on the turnover of labile DOM in the Southern Ocean. Microbial Ecology 50, 90–101.
92. Reinertsen SA, Elliott LF, Cochran VL, Campbell GS. (1984) Role of available carbon and nitrogen in determining the rate of wheat straw decomposition. Soil Biology & Biochemistry 16, 459-464.
93. Biswas CR, Benbi DK. (1996) Sustainable yield trends of irrigated maize and wheat in a long-term experiment on loamy sand in semi-arid India. Nutrient Cycling in Agroecosystems 46, 225-234.
94. Poeplau C, Don A, Six J, Kaiser M, Benbi DK, et al. (2018) Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils – A comprehensive method comparison. Soil Biology & Biochemistry 125: 10-26.
95. Nieder R, Benbi DK (2008) Carbon and Nitrogen in the Terrestrial Environment, Springer, Heidelberg and New York, 432p
96. von Lützow M, Kogel-Knabner I, Ekschmitt K, Flessa H, Guggenberger G, et al.(2007) SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. Soil Biology & Biochemistry 39, 2183–2207.

97. Lavallee JM, Soong JL, Cotrufo MF. (2020) Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Global Change Biology 26: 261-273. doi: 10.1111/GCB.14859

98. Cotrufo MF, Ranalli MG, Haddix ML, Six J, Lugato E. (2019) Soil carbon storage informed by particulate and mineral-associated organic matter. Nature Geoscience 12, 989–994.

99. Schrumpf M, Kaise K, Guggenberge G, Persso T, Koegel-Knabner I, et al. (2013) Storage and stability of organic carbon in soils as related to depth, occlusion within aggregates, and attachment to minerals. Biogeosciences 10, 1675–1691. https :// doi.org/10.5194/bg-10-1675-2013

100. Puget P, Chenu C, Balesdent J. (2000) Dynamics of soil organic matter associated with particle-size fractions of water-stable aggregates. European Journal of Soil Science 51, 595–605. https :// doi.org/10.1111/j.1365-2389.2000.00353.x

101. Zhou P, Song GH, Pan G, Li LQ, Zhang XH. (2009) Role of chemical protection by binding to oxyhydrates in SOC sequestration in three typical paddy soils under long-term agro-ecosystem experiments from South China. Geoderma 153, 52–60.

102. Sollins P, Homann P, Caldwell BA. (1996) Stabilization and destabilization of soil organic matter: mechanisms and controls. Geoderma 74, 63 -105.

103. Zhou P, Genxing Z, Genxing P, Riccardo P, Riccardo S. et al. (2010) Molecular changes in particulate organic matter (POM) in a typical Chinese paddy soil under different long-term fertilizer treatments. European Journal of Soil Science 61(2), 231-242. doi: 10.1111/j.1365-2389.2009.01223.x.

104. Bird M, Santrùková H, Lloyd J, Lawson E. (2002) The isotopic composition of soil organic carbon on a north-south transect in western Canada. European Journal of Soil Science 53, 393–403.

105. Benbi DK, Senapati N. (2010) Soil aggregation and carbon and nitrogen stabilization in relation to residue and manure application in rice–wheat systems in northwest India. Nutrient Cycling in Agroecosystems 87, 233–247. DOI 10.1007/s10705-009-9331-2

106. Sodhi GPS, Beri V, Benbi DK (2009) Soil aggregation and distribution of carbon and nitrogen in different fractions under long-term application of compost in rice-wheat system. Soil & Tillage Research 103, 412–418.

107. Paustian K, Six J, Elliott ET, Hunt HW. (2000) Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48, 147–163.

108. Martens DA. (2000) Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. Soil Biology & Biochemistry 32, 361-369

109. Doran JW. (1980) Soil microbial and biochemical changes associated with reduced tillage. Soil Science Society of America Journal 44, 765-771.

110. Stewart CE, Plant AF, Paustian K, Conant R, Six J. (2008) Soil carbon saturation: Linking concept and measurable carbon pools. Soil Science Society of America Journal 72, 379-392.

111. Batjes NH. (1999) Management options for reducing CO2-concentration in the atmosphere by increasing carbon sequestration in the soil, Report 410-200-031. Dutch National Research Programme on Global Air Pollution and Climate Change & Technical Paper 30, International Soil Reference and Information Centre, Wageningen

112. Paustian K, Cole CV, Sauerbeck DR, Sampson N. (1998) CO2 mitigation by agriculture: An overview. Climatic Change 40: 135–162.

113. Houghton JT, Meira Filho LG, Lim B, Tréanton K, Mamaty I, et al. (eds) (1997) Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, volumes 1–3. Hadley Centre Meteorological Office, United Kingdom.

114. West TO, Post WM. (2002) Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Science Society of America Journal 66, 1930–1946.

115. West TO, Six J. (2007) Considering the influence of sequestration duration and carbon saturation on

estimates of soil carbon capacity. Climatic Change 80, 25–41

116.Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. (2016) Climate-smart soils. Nature 532, 49–57. doi:10.1038/nature17174.

117.Gupta RK, Rao DLN. (1994) Potential of wastelands for sequestering carbon by reforestation. Current Science 66(5), 378-380.

118.Kane D. (2015) Carbon sequestration potential on agricultural lands: A review of current science and available practices. National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, LLC. http://sustainableagriculture.net/publications.

119.Duboc O, Zehetner F, Gerzabek MH. (2011) Recent Developments of no-till and organic farming in India: Is a combination of these approaches viable? Journal of Sustainable Agriculture 35, 576–612

120.Soussana J.-F, Lutfalla S, Ehrhardt F, Rosenstock T, Lamanna C, et al. (2017) Matching policy and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. Soil & Tillage Research 188, 2–14. https://doi.org/ 10.1016/ j.still.2017.12.002.

121.Lal R. (2018) Promoting "4 per thousand" and "adapting African agriculture" by south-south cooperation: Conservation agriculture and sustainable intensification. Soil & Tillage Research 188, 26–33. https://doi.org/10.1016/ j.still.2017.12.015.

122.Six J, Paustian K, Elliott ET, Combrink C. (2000) Soil structure and soil organic matter: I. Distribution of aggregate size classes and aggregate associated carbon. Soil Science Society of America Journal 64, 681-689.

123.Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K. (2004) The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Global Change Biology 10, 155–160, doi: 10.1111/j.1529-8817.2003.00730.xr2004.

124.Carvalho JLN, Hudiburg TW, Franco HCJ, DeLucia EH. (2017) Contribution of above- and below ground bioenergy crop residues to soil carbon. Global Change Biology Bioenergy. doi:10.1111/ gcbb.12411.

125.Stavi I, Bel G, Zaady E. (2016) Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems: a review. Agronomy for Sustainable Development 36, 1-12.

126.Cherubin MR, Dener MSO, Brigitte JF, Laisa GP, Izaias PL, et al. (2017) Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. Scientia Agricola 75(3), 255-272, DOI: http:// dx.doi.org/10.1590/1678-992X-2016-0459