Journal of Pharmacognosy and Phytochemistry 2020; 9(5): 2488-2493

Journal of Pharmacognosy and Phytochemistry
Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
www.phytojournal.com
JPP 2020; 9(5): 2488-2493
Received: 12-07-2020
Accepted: 03-08-2020

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Soil carbon sequestration and greenhouse gas emission reductions under conservation agriculture: A review

Arvind Kumar, Vikas Sharma and Manoj Kumar

Abstract

Conservation agriculture sequesters maximum soil organic carbon near soil surface layer. Adoption of conservation agriculture with use of crop residues mulch, no till farming and efficient use of agricultural inputs help to conserve moisture, reduce soil erosion and enhance SOC sequestration. Rate and amount of SOC sequestration differ with soil types, depths and land use and varies from one region to another. The soil organic carbon (SOC) pool, a significant indicator of soil quality, has many direct and indirect effects on such quality. Increases in the SOC pool improve soil structure and tilth, counter soil erosion, raise water capacity and plant nutrient stores, provide energy for soil fauna, purify water, denature pollutants, improve the crop/crop residue ratio and mitigate the effects of climate. Conservation tillage systems (such as minimum and no-till) have been observed to contribute to the role of soil as a carbon sink. In India, agriculture contributes about 17 per cent of the country's total GHGs emission. An intensive agricultural practice during the post-green revolution era without caring for the environment has supposedly played a major role towards enhancement of the greenhouse gases. Due to increase in demand for food production the farmers have started growing more than one crop a year through repeated tillage operations using conventional agricultural practices. Increase in carbon emission is the major concern, which is well addressed in kyoto protocol. An article synthesizes the much-needed state-of-knowledge on the effects of conservation agriculture practices on SOC sequestration and greenhouse gas emission identifies potential research gap, and limitations in studying SOC dynamics.

Keywords: Greenhouse, agriculture, soil surface layer

Introduction

Concerns about rising atmospheric carbon dioxide (CO_2) levels coupled with climate change mitigation efforts have focused considerable interest in recent years on the world's soil carbon. According to the study, the impact of doubled carbon dioxide concentrations on crop water productivity and yield varies regionally. The principles of conservation agriculture are frequently assumed to increase soil organic carbon and crop yield under all circumstances. A new analysis confirms that this is not the case, and that the likelihood of increasing either soil organic carbon or crop yield is environmentally dependent. Results show that maize suffers yield losses with doubled carbon dioxide levels, due in large part to the plant's already greater efficiency at using carbon dioxide for photosynthesis compared with the other crops. Maize yields fall by 15 percent in areas that use irrigation and by 8 percent in areas that rely on rain. Even so, losses would be more severe without the carbon dioxide increase: yields would decrease 21 percent for irrigated maize and 26 percent for rainfed maize. The world's soils are estimated to have a high sink potential for carbon sequestration, not only in terms of their large potential carbon content, but also because soil organic carbon is particularly responsive to modification through agricultural land use. Conversion of natural ecosystems to cropland acts as a driver of climate change in two main ways. Firstly, agricultural activities directly produce and release about 10-12 percent of the atmospheric greenhouse gases (GHGs), such as CO_2, methane (CH_4), nitrous oxide (N_2O) (Six *et al.*, 2002) [18]. Secondly, the conversion process alters the soil's physical, chemical and biological properties and so has an impact on the biological resilience of the agro-ecosystems. When soils in a natural state are converted to agricultural land, there is an important loss of soil organic carbon (SOC) mainly in form of CO_2 (Vanden Bygaart *et al*., 2003) [20]. Furthermore, agricultural expansion is a major driver of biodiversity loss, which in turn threatens agricultural sustainability.

Providing enough food for the growing global population and stabilizing atmospheric greenhouse gas concentrations are the two greatest challenges that humanity faces this century. The two challenges are linked in that anthropogenic climate change is making it increasingly difficult to achieve yield increases required to feed humanity and depending on the type of farming systems employed, agricultural production can either make a positive or negative net contribution to atmospheric greenhouse gas concentration. It is therefore critical to the quality of human existence that farmers around the world use practices that can demonstrably increase yields while at the very least causing no further net contribution to climate change.

With the anthropogenic global farming (IPCC 2013) [7], land surface temperatures may be increasing more rapidly than over the ocean (Diffenbaugh and Field, 2013) [2]. The rapid rate of warming implies a major challenge for ecosystems to adjust with regards to land use and degradation and other biotic and abiotic stresses. Global food insecurity, already affecting about 1 billion people, may be exacerbated. The abrupt climate change (ACC) could disrupt the progress towards a hunger-free world. Prevalence of drought and other extreme events can exacerbate food insecurity in several global hotspots (e.g., Sub-Saharan Africa, and South Asia), including India.

Provision of food is a primary function and key ecosystem service (ES) of agriculture. There is growing recognition that agricultural systems are both dependent on ES that support production functions and a source of important agricultural and non-agricultural ES. Ecosystem services are categorized as provisioning, regulating, supporting, and cultural. The level of delivery of the different services is determined by a combination of ecosystem properties, including soils, vegetation, and climate and the resulting ecological processes (Fisher *et al*., 2009) [9]. Agricultural intensification aimed atincreasing production can affect ecosystem components and processes. Intensification can disrupt many of the regulating and supporting ES, including nutrient cycling, climate regulation, regulation of water quality and quantity, pollination services, and pest control. It can also alter the biological diversity underpinning many of these ES. While some agricultural practices can decrease ES delivery (tradeoffs) others can enhance or maintain ES (synergies). Increasing food production at the expense of ESs can undermine agroecosystem sustainability including crop production.

Fertilization of crops is needed to overcome deficiencies in nutrients supplied by soils, especially in those soils exhausted by years of soil erosion, intensive disturbance with tillage, and continuous harvest of products that remove large quantities of nutrients. Excessive fertilization can also occur when agronomic prescriptions exist without regard for economic and environmental consequences. Optimum N fertilizer application to maximize C offset should then be reduced to as low as 24 kg N ha^{-1}yr^{-1} to achieve soil organic C sequestration of only 0.07 Mg C ha^{-1}yr^{-1} (Franzluebbers, 2005) [4]. Soil health is an indispensable quality for agricultural sustainability, and conservation agriculture (CA) intends to achieve the latter for livelihood security through minimal soil disturbance and retention of crop residues as soil cover. Soil organic matter (SOM) and soil biochemical properties are the most widely accepted indicators of soil quality. SOM is involved in the enhancement of soil quality by improving soil structure, nutrient storage and biological activity. Improved management of agricultural lands such as adoption of improved residue management practices, and lessened tillage intensity can result in greater carbon sequestration in soils Nieder and Benbi (2008) [15].

Conservation agriculture and ecosystem services

Conservation agriculture is being promoted widely in many areas of Sub Saharan Africa and elsewhere in the tropics to recuperate degraded soils. Whilst CA has been successfully introduced in high input and high yielding smallholder systems in the rice-wheat region of South Asia, the low input, low productivity systems characteristic of much of Sub Saharan Africa requires attention. Although there are still in sufficient long term CA experiments and on-farm studies in Sub Saharan Africa. It is clear that the biggest obstacle to improving soils and other ES is the lack of residues produced due to low productivity. Increases in topsoil C, as observed for the majority of CA studies from temperate regions, are critical for recuperating soils and the numerous ES associated with it. Even in cases where increased topsoil C has been found in experimental fields in Sub Saharan Africa. All three CA practices are currently not part of the traditional practices in Sub Saharan Africa making their adoption challenging. While RT or NT may be accepted due to lower labor requirements, the frequent weeding required throughout the cropping season with NT may negate those effects.

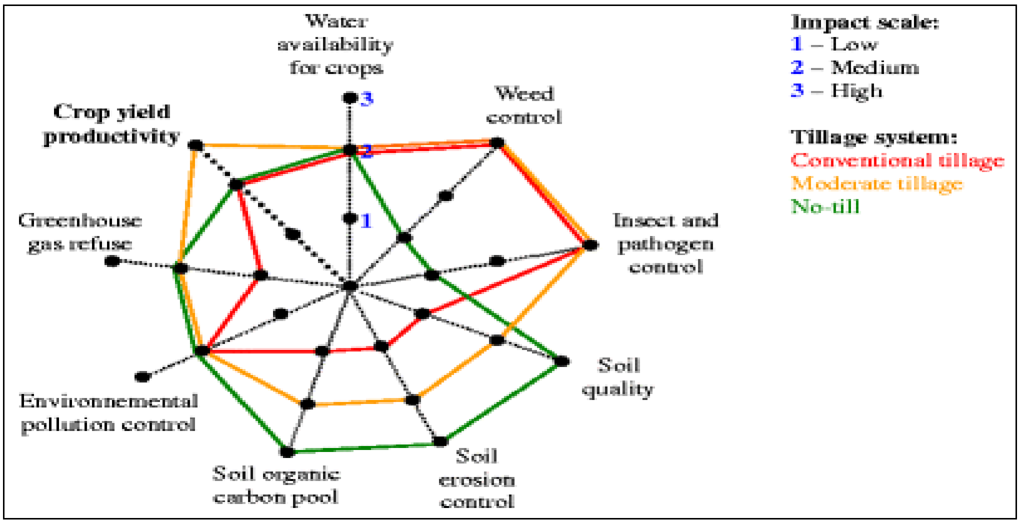

Fig 1.

Residue retention will be difficult to achieve in areas with substantial livestock without increasing the amounts available and perhaps providing incentives. Acceptance of crop rotations may be limited in areas of chronic food insecurity and staple crop production until functioning markets are established. All these limitations point to nuanced approach to

CA or the promotion of the different CA practices in Sub Saharan Africa. A sequence of interventions, as suggested by Lahmar *et al*. (2012) [22], may be more appropriate. The first step is to increase crop production through nutrient management, followed by soil and water management practices that improve soil quality and water retention, and then gradually the introduction of CA practices if and where appropriate to the soil, climate and socioeconomic conditions. These steps must be based on evidence that the practice or suite of practices result in increased ESs without compromising increased yields.

Bulk density and total porosity

Bulk density of the soil top layer (the top 30 cm) is usually lower in PT soils than in continuous no-till, reflecting the rapture effect of tillage near the surface. The implement used in PT system makes soil more compact and after repeated tilling, the hardpan is usually formed underneath the plow layer. This in turn can affect the movement of air, water and inhibits root growth. Hardpan has a high bulk density with a few macro-pores for roots to grow through and tend to reduce macro-aggregates.

Soil structure and aggregation

In conservation agriculture, soil is protected by permanent residue cover and this protects the soil from the impact of the rain drop, water and wind erosion (Six *et al*., 2000) [17]. In PT there is no protection of soil by the soil cover which increases chances of further destruction. Plow tillage is one of the major drivers of soil destruction through physical breakdown of the soil structure as compared to reduced tillage. As a result, soil becomes susceptible to soil erosion due to dis-integration of soil aggregates. Although plow tillage results in better structural distribution than reduced tillage and no-till, the components of the soil structure in PT are very weak to resist water slacking resulting in structural deterioration.

Soil organic carbon (SOC) and their fractions

Soil organic carbon (SOC) has been widely reported (Naresh *et al*., 2016) [14] as a primary factor that indicates soil quality because of its effect on soil key quality parameters. Under no-till CA, the amount of SOC generally increases compared with PT (Verhulst *et al*., 2010) [21]. The top layer of the soil is important because it is where most of the cropping and soil management practices take place. Therefore, soil management practices are amongst the most important factors influencing changes in SOC. This increase in SOC is more pronounced in the top soil. Moreover, residue retention on soil surface has also been shown to increase the amount of SOC concentration. In a long term study (11 years) conducted by Dikgwatlhe *et al*. (2014), it was found that zero-tillage with residue retention resulted in an increase of SOC in the 0–10 cm soil layer compared to rotary tillage with residues incorporated and PT with residue retention and removed.

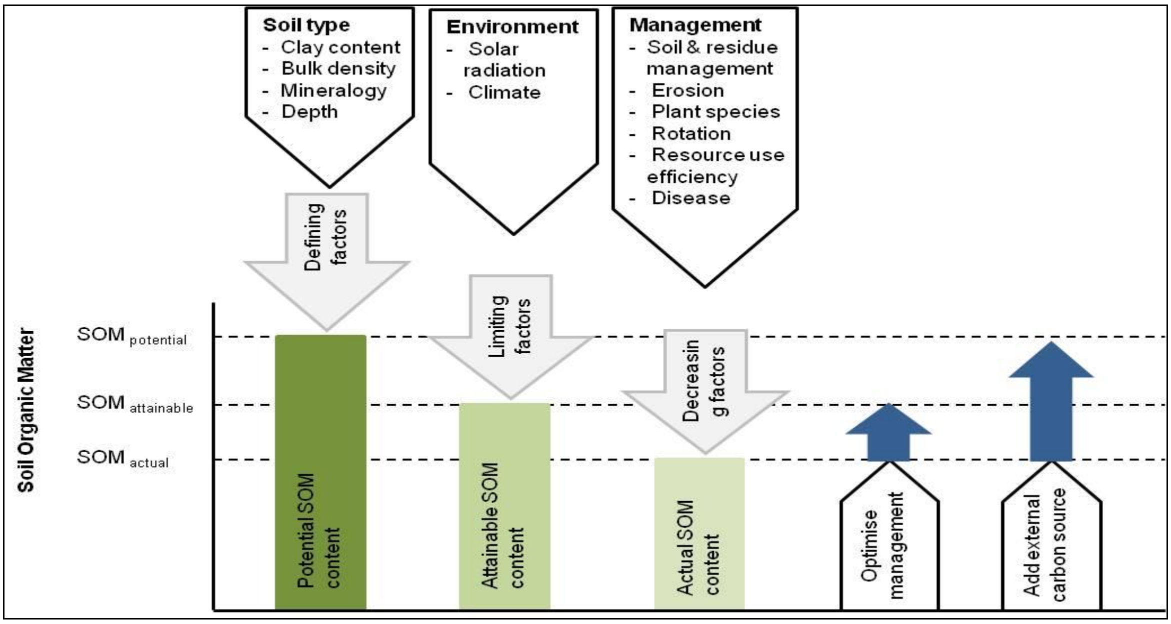

Fig 2.

Soil organic carbon based on physically defined fractions is increasingly used to interpret the dynamics of SOC in the soil (Six *et al*., 2000) [17]. Hermle *et al*. (2008) [5] distinguished three fractions in which C may be available. These are easily decomposable fraction (libile), material stabilized by physical-chemical mechanisms (intermediate) and the biochemically recalcitrant fraction (stable).

Macrofauna and Earthworms

Macrofauna are those organisms which have average body width greater than 2 mm. Plow. The impact has been more pronounced on larger organisms with less negative impact on species with high mobility and higher population growth potential (Decaëns and Jiménez, 2002) [1]. This group of organisms is divided into two, based on their function. These are litter transformers and ecosystem engineers. Litter transformers consist mostly of larger arthropods and soil mesofauna while ecosystem engineers on the other hand comprised mainly of termites and earthworms. Verhulst *et al*. (2010) [21] stated that ecosystem engineers have a large impact on influencing soil structure and aggregation as compared with litter transformers. In addition, ecosystem engineers ingest mixture of organic matter and mineral soil and are reported to be responsible for gradual introduction of dead organic material onto the soil.

Earthworms play a key role in formation of the soil structure. They remove organic material from the soil and incorporate them as a stable aggregate. They ingest the organic matter and incorporate them with inorganic material, pass the mixture through their gut and excrete it as a cast. This in turn assist in formation of stable macro aggregates (>250 mm), when allowed to dry and age, due to organic mucilage and/stable organo-mineral complexes and oriented clays left lined in the burrowing walls (Six *et al.*, 2004) [19]. The effect of earthworms on the soil structure is not only mediated by abundance but also by the functional diversity of their communities (Verhulst *et al*., 2010) [21]. Therefore, they vary in their ecological behaviour, thus, their effect on soil structure is different. Moreover, earthworms play a major role in the recycling of nutrients and formation of stable aggregates. In addition the stability of cast depends on the quality of ingested material (Six *et al*., 2004) [19].

Soil microbial biomass (SMB)

Soil microbial biomass is a reflection of soil to store and recycle nutrients, such as C, N, P & S and SOM and has a high turnover rate relative to total SOM. The dominant factor controlling the availability of SMB is the rate of C input and also availability of N resources in the soil (Six *et al*., 2004) [19]. A uniform and continuous supply of C from organic crop residues serves as the energy source for microorganisms. Previous studies has shown that as the total organic C pool increased or decreases, as results of changes in C input in the soil, the microbial pool also increases or decreases (Franzluebbers *et al*., 1999) [3]. Microorganism's plays an important role in physical stabilization of soil aggregate and this was found to be linked to glomalin content which is an indication of degree of hyphal network development. These fungal hyphae form extended network in cultivated soil and are activated by contact with seedlings. In contrast to tillage system, in no-till conservation agriculture, the mycorrhizal system is more stable. Plow tillage promote the release and decomposition of previously protected SOM in the soil, initially increasing soil microbial biomass. The availability of nitrogen in the early stages of CA adoption usually decrease in the soil due to increase in microbial activity from surface residue decomposition and lack of incorporation in the soil and this is more pronounced in organic material with higher C/N ratios. The effect of tillage practice on SMB-C and N seems to be mainly confined in the surface layers with stronger stratification when tillage is reduced This can be attributed to higher level of C substrate available for microorganism growth, better soil physical condition and water retention under reduced tillage.

Conservation tillage and carbon sequestration

Several study compared soil organic carbon (SOC) in conservation and conventional tillage systems. The results from analysis suggest that switching from conventional cultivation to zero till would clearly reduce on-farm emissions. Vanden Bygaart *et al.* (2003) [20] found that reduced tillage increases the amount of carbon sequestered by an average of 320-150 kg C ha^{-1} in 35 studies of western Canada and that the removal of fallow enhanced soil carbon storage by 150-60 kg C ha^{-1} based on 19 Studies. West and Marland (2002) [23] reported that carbon emission from conventional tillage (CT), reduced tillage (RT) and no tillage (NT) were respectively 72.02, 45.27, 23.26 kg C ha^{-1} in case of corn cultivation and 67.45, 40.70, 23.26 kg C ha^{-1} for soybean cultivation based on annual fossil fuel consumption and CO_2 emission from agricultural machinery. Mosier *et al.* (2006) [12] reported that based on soil C sequestration, only NT soils were net sinks for GWP and economic viability and environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer.

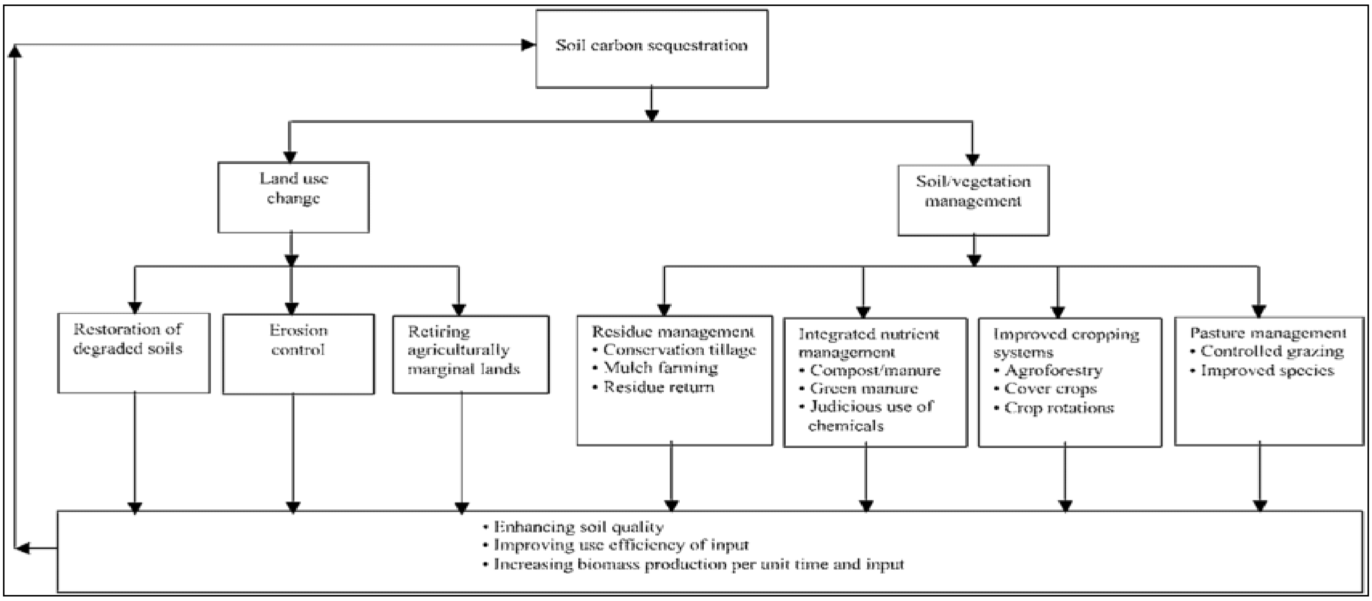

Fig 3.

Conservation Agriculture with Greenhouse Gas Emission

In this section we deal with the net emissions of N2O and CH4 from soils as a result of CA practices. It is also important to note that there can be considerable impacts of CA compared to conventional agriculture with changes in the intensity of mechanical tillage, less irrigation, and possibly less N fertilization and the associated reduced use of fossil fuels with CA. These effects are not considered in this paper. Jain *et al*., 2014 [10] estimates, on farm burning of 98.4 Mt of crop residues led to the emission of 8.57 Mt of CO, 141.15 Mt of CO_2, 0.037 Mt of SOx, 0.23 Mt of NOx, 0.12 Mt of NH_3 and 1.46 Mt NMVOC, 0.65 Mt of NMHC, 1.21 Mt of particulate matter for the year 2008–0. CO_2 accounted for 91.6% of the total emissions.

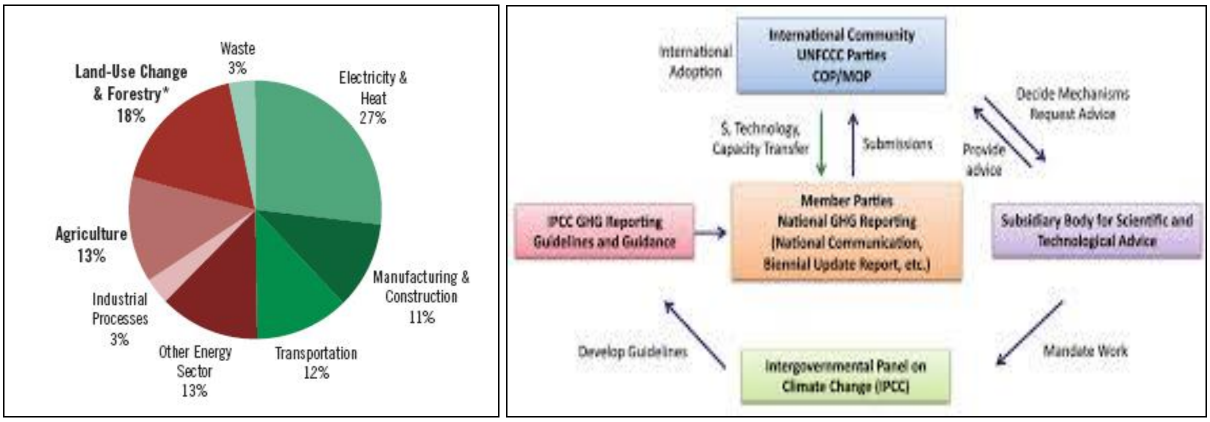

Fig 4.

Nitrous oxide and Methane

N_2O is a potent and long-lived GHG, having a global warming potential 298 times that of carbon dioxide (CO_2) and remaining in the atmosphere for up to 114 years. N_2O is produced in soils in the microbiological processes of nitrification and denitrification. Nitrification - the oxidation of ammonium to nitrate - occurs in aerobic conditions while denitrification, the reduction of nitrate (NO_3) to N_2O and N_2, takes place in anaerobic conditions. The retention of crop residues and higher soil C in surface soils with CA play major roles in these processes. Under anaerobic conditions associated with soil water saturation, high contents of soluble carbon or readily decomposable organic matter can significantly boost denitrification (Dalal *et al*., 2003) with the production of N_2O favored with high quality C inputs.

Methane has a lifetime of 12 years and a global warming potential 25 times that of CO2 over a 100 year time horizon. Agricultural soils contribute to CH_4 emissions as a result of methanogenic processes in waterlogged conditions that are usually associated with rice production. Flooded rice production contributes 15% of total global CH_4 emissions (IPCC, 2010). In contrast to N_2O, CH_4 can be consumed (oxidized) by soil microorganisms and resulting in a CH_4 sink which is sensitive to both temperature and soil water content (Dalal *et al*., 2008) [8].

Conservation agriculture for soil carbon storage

Conservation agriculture was a movement that developed in the 1970s enabled by the development of herbicides for weed control. Of its three main principles—less tillage, more soil cover and improved rotations—the first two can directly affect the carbon dynamics of cropping soil. Since the first origins of agriculture, weed control prior to planting of crop seeds has been achieved by mechanically tilling the soil with hoes or ploughs to uproot weeds and give crops a competition-free environment to thrive. Conservation Agriculture is a production system based on three principles: minimum mechanical soil disturbance, permanent soil organic cover, varied crop rotations. It is resource-saving agricultural production system that aims to achieve production intensification and high yields while enhancing the natural resource base through compliance with three interrelated principles, along with other good production practices of plant nutrition and pest management. These are: minimum mechanical soil disturbance with direct seeding; permanent soil organic cover with crop residues9 and/or cover crops to the extent allowed by water availability; and species diversification through varied crop associations and/or rotations (involving annual and/or perennial crops including trees). From the perspective of SOC accumulation in CA systems, a well-designed crop rotation guarantees the permanent presence of abundant, undisturbed (above- and below-ground) biomass to foster the build-up of new SOC. At the same time, carbon losses by decomposition are reduced by SOC inclusion within soil aggregates, as enhanced by the low soil disturbance.

Conservation agriculture

Conservation agriculture is an approach of managing agro-ecosystem for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and environment (FAO, 2010). According to the definition, minimum soil disturbance refer to low disturbance, no tillage and direct seeding. The disturbed area must be less than 15 cm wide or less than 25% of the cropped area (Verhulst *et al*., 2010) [21]. In this practice, there should be no area disturbed (by tillage) greater than the set limit. The aim for permanent soil cover is to protect the soil from water and wind erosion; reduce water run-off and evaporation; to improve water productivity and to enhance soil properties associated with long term sustainable productivity The adoption of this management principle has been pushed further by ever increasing prices of production cost, scarcity of water, climate change and degradation of ecosystem services which force farmers to look for alternatives that can reduce cost while improving natural resource base and productivity (Kassam *et al*., 2009) [11].

Conventional tillage

It is defined as the tillage type that leaves less than 15% of the crop residues on the soil surface after planting the next crop. Conventional tillage, generally involves ploughing and intensive soil disturbance. This type of tillage has been recognized as the major driver of soil degradation through the depletion of soil organic matter and associated nutrients loss (Mutema *et al*., 2013) [13]. Plow tillage (PT) is primarily practiced by commercial farmers in Subtropical India with huge capital investments on mechanized machinery and inorganic inputs such as fertilizers and herbicides. In small holder famers, this type of agricultural practice is not prevalent due to low incomes, land limitation and limited access to implements. They usually use animal drawn moldboard plow, small tractors and hand hoe for soil tillage.

Conservational tillage

Conservation tillage (CT) is defined as any tillage practice that minimizes soil loss and water, which often require the presence of at least 30% of the crop residues throughout the year. Hobbs (2007) on the other hand, stated that CT is a collective umbrella term that is commonly given to no-tillage, direct drilling and minimum tillage and ridge tillage to denote that the specific practice has a conservation goal of some nature.

Constraint to adoption of conservation agriculture by farmers

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

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