Soil Carbon Sequestration Through Conservation Tillage and Residue Management

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Abstract

To mitigate the changing climate due to the increase concentration of greenhouse gases (GHG) in the atmosphere, studies on carbon (C) sequestration potential of different agricultural management practices are receiving worldwide attention. Conservation agriculture (CA) is highly recommended for its high C sequestration capacity and the productive use of crop residues that are otherwise burnt and pollute the environment. The adoption of CA offers preservation of soil moisture by leaving at least 30% of the soil surface covered with crop stubble/leaf litters, thereby decreasing wind and water erosion. The amount of residue cover left on the field depends on the type of operation, availability of implements and the fragility of the residue. Under CA, if 1 ft of residue is left on the field, an additional amount of 1.6–2.0 t/ha of crop residue is being added in to the field

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compared to farmers' practice that improves soil aggregation, infiltration, organic C status and enhanced biological properties. The C sequestration in CA is accomplished through the addition of carbon through residues, protection of soil organic carbon in soil aggregates under minimum soil disturbance and addition of soil organic carbon (SOC) to deeper soil layer due to the inclusion of legumes in the cropping system. In fact, practising CA can potentially sequester C at rates of 300–600 kg C/ha/year depending on the type of soil and climatic conditions. In addition, CA practices are widely adopted to increase soil productivity, revert soil degradation, improve C sequestration and also increase input use efficiency and crop yields. Therefore, location-specific CA must be developed and advocated. The challenges and bottlenecks in disseminating CA in a large scale must be addressed and overcome by further studies with policy initiatives and interventions.

Keywords

Conservation agriculture · Conservation tillage · Crop residue management · Soil health · Carbon sequestration

14.1 Introduction

Conventional practices comprising repeated intensive tillage operations, residue burning and high- or low-input farming resulted in the decline in crop productivity and deterioration of soil health (Verhulst et al. 2010). It also affects the soil's physical properties, hampers biological degradation and results in stagnancy of crop yields despite increased use of improved varieties, pesticide and fertilizer. These conventional modes of agriculture through intensive farming practices were successful in achieving the goals of production in the short run but simultaneously led to the degradation of the natural resources in the long run (Somasundaram et al. 2020a, b). The growing concerns for sustainable agriculture have been seen as a positive response to the limits of both low-input traditional agriculture and intensive modern agriculture relying on high levels of inputs for crop production. Sustainable agriculture depends on the practices that help to maintain ecological equilibrium and favour natural regenerative processes (Lal 2015), such as nitrogen fixation, nutrient cycling, soil regeneration and protection of natural enemies of pest and diseases as well as the targeted use of inputs (Oliver and Gregory 2015). Agricultural systems relying on sustainability approaches not only support high productivity but also preserve biodiversity and safeguard the environment. Thus, conservation agriculture has come up as a new paradigm to achieve the goal of sustained agricultural production (Abrol and Sanger 2006; Hobbs 2007; Somasundaram et al. 2020b). It is a major step towards the transition to sustainable agriculture. Conservation agriculture (CA), which has its roots in the universal principles of providing permanent soil cover (through crop residues, cover crops and agroforestry), minimum soil disturbance and crop rotations are now considered as the principal route to sustainable agriculture: a way to achieve the goals of higher productivity while protecting natural resources and environment. Rainfed (semi-arid and arid) regions are categorized by highly variable and unpredictable rainfall, structurally unstable soils and low crop productivity. Many research results demonstrated that no/minimum/reduced tillage system without crop residues left on the soil surface can pose a serious threat to soil health as it enhances greater runoff and soil erosion. It indicates that no tillage alone in the absence of soil cover is unlikely to become a favoured practice. Therefore, the minimum soil disturbances in the form of no tillage or minimum tillage coupled with maximum soil cover (at least 30% crop residue cover) and diversified cropping system not only helps to check runoff and soil erosion but also improves soil aggregation and infiltration and enhances carbon sequestration in the long run.

Carbon sequestration is defined as the process of transfer and secure storage of atmospheric CO_2 into other long-lived global pools including oceanic, pedologic, biotic and geological strata to reduce the net rate of increase in the atmospheric CO_2. Carbon sequestration may be a natural- or anthropogenic-driven process. The objective of an anthropogenic-driven process is to balance global C budget such that future economic growth is based on a ‘C-neutral’ strategy of no net gain in atmospheric C pool. A considerable part of the depleted SOC pool can be restored through the conversion of marginal lands into restorative land uses; adoption of conservation tillage with cover crops; crop residue mulch; nutrient recycling; use of compost and efficient use of inputs in agriculture, i.e., nutrient, water and energy. Besides mitigation of climate change, soil carbon sequestration is a win-win situation as it helps in build-up of soil fertility, improves soil quality, improves agronomic productivity, protects soil from compaction and nurtures soil biodiversity.

14.2 Large-Scale On-Farm Residue Burning

Food grain production of the country has reached a record high of 292 million tons during 2019–2020 due to favourable weather conditions and other factors of productivity. Overall, India produces about 600 million tons (Mt) of crop residues annually, of which about 34% (204 Mt) of gross are estimated as surplus. In the Indo-Gangetic Plains, about 95 million tons of rice residues are produced which is about 39% of the total crop residues generated (Sidhu et al. 2015). Rice-wheat cropping system in north-west (NW) states produces about 34 million tons of rice residues of which Punjab alone contributes about 65%. The mechanized harvesting and threshing of rice using combine harvesters is a common practice in NW India. In the process, residues are left behind the combine harvesters in a narrow strip (windrow) in the field. Disposal or utilization of the leftover residue in the short span of 10–20 days for timely sowing of wheat crop is a challenging and difficult task (NAAS 2017). Acute shortage of labour in the peak season resulting in high cost of residue removal/cleaning from the field and increasing use of combines for crop harvest have forced farmers to adopt large-scale on-farm residue burning for timely seeding/planting of succeeding crops. In India, the highest amount of crop residue is burned in Uttar Pradesh (59.97 Mt), Punjab (50.75 Mt), Haryana (27.83 Mt) and

Fig. 14.1 Widespread residue burning in conventional farming practices (left), impediments during field operations

Maharashtra (46.45 Mt) followed by other states and the least in north-eastern part of India such as Mizoram (0.06 Mt) and Sikkim (0.15 Mt) (NPMCR 2014). Most of the crop residues are generated from cereal crops such as rice, wheat, maize and millets, contributing around 70% of the total crop residue generated in the country (NPMCR 2014).

Residue burning is a widespread practice in many parts especially in the rainfed region as it causes a lot of impediment during field operations (Fig. 14.1). It is a quick, labour-saving practice to remove residue that is viewed as a nuisance by farmers. However, residue burning has several adverse environmental and ecological impacts. The burning of dead plant material adds a considerable amount of CO_2 and particulate matter to the atmosphere and can reduce the return of the much needed C and other nutrients to the soil (Prasad et al. 1999). The lack of a soil surface cover may also enhance the loss of soil minerals through surface runoff/soil erosion. Crop residues returned to soil maintain organic matter (SOM) levels, and crop residues also provide substrates for soil microorganisms. As microbes decompose crop residues and soil OM, CO_2 is given off as a by-product of soil respiration. Therefore, it is reasonable to believe that accelerated residue decomposition might affect soil surface CO_2 fluxes.

Worldwide, many farmers resort to burning of field crop residue for a variety of real and perceived benefits, such as timeliness of field operations, reduced cost associated with residue management, increased crop yield and better control of weeds and diseases (Chen et al. 2005). However, it results in a considerable loss of organic C, N and other nutrients by volatilization as well as detrimental effect to soil microorganisms. In comparison to burning, residue retention increases soil carbon and nitrogen stocks, provides organic matter necessary for soil macro-aggregate formation (Six et al. 2000) and fosters cellulose-decomposing fungi and thereby enhances carbon cycling.

Crop residues in general serve a number of beneficial functions, including soil surface protection from erosion, water conservation and maintenance of soil organic matter (OM). Large amounts of residue in the soil surface have traditionally been viewed as a nuisance and have been associated with difficulties such as mechanical planting, poor crop stand establishment, decreased efficacy of herbicides, release of growth-inhibiting allelopathic compounds and, ultimately, yield reductions. Therefore, crop residues, particularly wheat residue, are commonly burned or ploughed followed by discing to prepare a seedbed for double-cropped soybean (Prasad et al. 1999) and rice residues are burnt in the Indo-Gangetic Plains (IGP) for the timely sowing of the succeeding wheat crop in rice-wheat cropping system (Sharma and Mishra 2001; Hobbs et al. 2008; Somasundaram et al. 2020a, b).

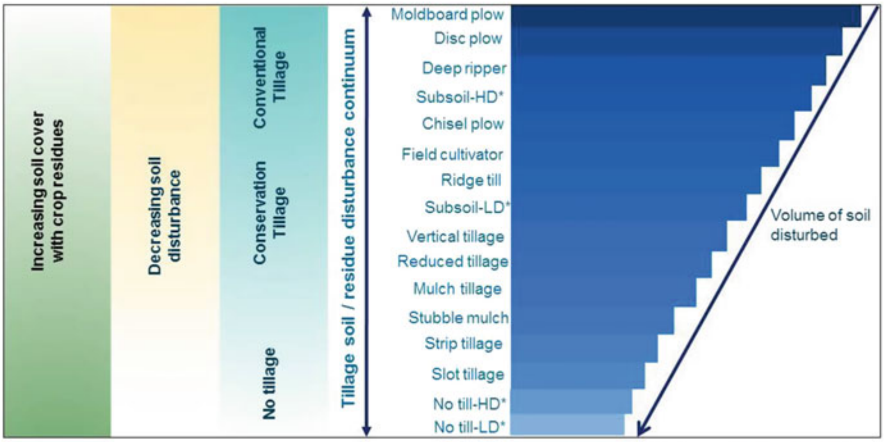
14.3 Conservation Tillage Versus Conservation Agriculture

Conservation tillage helps preserve soil moisture by leaving at least 30% of the soil surface covered with crop stubble/leaf litters, thereby decreasing wind and water erosion. The crop stubble layer reduces evaporation in the soil profile by one-half compared to bare soil. Conservation tillage can also reduce pollution caused by runoff and enrich the soil with organic matter. Conservation agriculture (CA) is a slower-evolving agricultural revolution that began at the same time as the Green Revolution and emerged as a new paradigm to achieve the goals of sustainable agricultural production. It is a major transition step towards sustainable agriculture. The concept of CA has emerged from reduced tillage. Concepts for reducing tillage operations and keeping soil covered came up, and the term *conservation tillage* was introduced to reflect such practices aimed at soil protection (FAO 2008; CTIC 1996; Friedrich et al. 2012; Reicosky 2015). Seeding machinery developments were allowed, in the 1940s, to seed directly without any soil tillage/soil disturbances. At the same time, theoretical concepts resembling today's CA principles were elaborated by Edward Faulkner in his book *Ploughman's Folly* (Faulkner 1945) and Masanobu Fukuoka with the *The One-Straw Revolution* (Fukuoka 1975). It wasn't until herbicides became readily available in the late 1950s and early 1960s that the era of conservation tillage could begin.

14.4 Definitions of Conservation Tillage and Conservation Agriculture

Baker et al. (2002) defined conservation tillage as 'Conservation tillage is the collective umbrella term commonly given to no-tillage, direct-drilling, minimum-tillage and/or ridge-tillage, to denote that the specific practice has a conservation goal of some nature. Usually, the retention of 30% surface cover by residues characterizes the lower limit of classification for conservation-tillage, but other conservation objectives for the practice include conservation of time, fuel, earthworms, soil water, soil structure and nutrients. Thus residue levels alone do not adequately describe all conservation tillage practices'.

Conservation tillage comprises a wide-ranging set of management practices with an aim to leave some crop residue on the soil's surface to enhance infiltration of water and decrease soil erosion. The several practices termed as 'conservation tillage' have led to terminological confusion. Reicosky (2015) articulates that



*HD= High Disturbance; LD=Low Disturbance

Gradients of the colour depicts the intensities/frequencies of the variables/factors

Fig. 14.2 Schematic depiction of different tillage and planting systems. (Adopted and redrawn from Reicosky 2015)

conservation tillage is frequently confused with no-till or options of CT used in vague terms like minimum tillage, mulch tillage, ridge tillage, strip tillage and reduced tillage, where planting is achieved on specially prepared surfaces with various amounts of crop residue cover (Hobbs 2007; Dumanski and Peiretti 2013; Derpsch et al. 2014; Reicosky 2015). For better understanding, different tillage practices and planting system are presented in Fig. 14.2.

'Conservation agriculture (CA) aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. CA system often referred to as resource efficient or resource effective agriculture' (*FAO*, http://www.fao.org/ag/ca/). This includes the sustainable agricultural production need that all humankind obviously wishes to achieve.

Now it is clear that CA does not just mean not tilling the soil and then doing everything else the same. It is a holistic system with interactions among households, crops and livestock since rotations and residues have many uses within households; the result is a sustainable agriculture system that meets the needs of the farmers (Sayre and Hobbs 2004) (Table 14.1).

Somasundaram et al. (2020b)

Table 14.1 Comparison of conventional farming verses conservation agriculture

Particulars	Conventional agriculture	Conservation agriculture	Rationale
Tillage practices	• Farmers follow intensive inversion tillage practices for improving soil structure/tilth of soil and also to control weeds. • Soil tillage operation usually done through rotavators, chisels, moulboard plough, rippers, discs, etc.	• Direct planting/drilling of seeds without prior inversion of the soil • Planting of seeds by making holes using handheld device or mechanized tools • Use of no-till seeder, strip-till drill, turbo happy seeder (THS) of different variants	• Continuous intensive tillage practices destroy soil structure in the long-term and result in a declining fertility and organic matter levels in soil • CA reduces SOC loss and improves overall soil health
Crop residue management	• Farmers remove or burn residue or mix them into the soil with plough or hoe/tillage implements	• Crop residues are left on the field helps in protecting soil from erosion/degradation • Planting of cover crops	• Crop residue improves soil physical (soil structure, stability, moderation of hydrothermal regimes), biological and chemical properties
Cropping system/ cover crops	• Use of monocropping	• Diversified cropping systems/ rotation • Crop rotation or intercropping of different crops with contrasting rooting pattern • Use of cover crops	• Helps in maintaining soil fertility/health • Breaks pest and disease cycles • Cover crop protects soil from erosion and limit weed growth

14.5 Conservation Agriculture: The Most Promising Alternate Agriculture

Conservation agriculture (CA) technologies involve minimum soil disturbance, maximum soil cover through crop residues or cover crops, and crop rotations for reverting soil degradation and achieving higher productivity and also considered as a sustainable system (Abrol and Sanger 2006; Hobbs 2007) (Fig. 14.3). CA has emerged as an alternative to residue burning, where residue is managed in situ, thereby improving soil organic carbon and sustaining soil health. In comparison to burning, residue retention through conservation agriculture CA increases soil carbon and nitrogen stocks and provides organic matter necessary for the improvement of water availability and nutrient cycling.

The major benefits of CA include (1) reduced costs due to savings in fuel and labour; (2) timely planting of kharif and rabi season crops resulting higher yields;

Fig. 14.3 Crop establishment under residue in CA

(3) saving of irrigation water up to 15–20% and (4) avoidance of the burning of residue, by managing residue in situ helps in nutrient recycling and carbon sequestration in the soil. Though CA technologies have spread extensively in the USA, Brazil, Argentina and Australia covering about 156 M ha (FAO 2015) and 180 M ha (Kassam et al. 2019), the adoption in India is very slow (< 5 m ha) due to poor-availability CA machineries and location-specific technologies particularly for weed management.

The key challenges relate to the development, standardization and adoption of farm machinery for seeding amidst crop residues with minimum soil disturbance; development of crop harvesting and management systems with residues maintained on the soil surface; and development and continuous improvement of site-specific crop, soil, irrigation, nutrients weed and pest management strategies that will optimize the benefits of the new systems.

Minimum and zero-till technologies for wheat have been demonstrated to be beneficial in terms of economics, irrigation water saving and timeliness of sowing in comparison to conventional tillage. However, there are problems with direct drilling of wheat into combine harvested rice/maize fields as loose straw clogs in the seed drill furrow openers (Fig. 14.4), seed metering drive wheel traction is poor due to the presence of loose straw and the depth of seed placement is nonuniform due to frequent lifting of the implement under heavy residue conditions.

These constraints have been resolved by the innovative latest version of the Turbo Happy Seeder (THS) (Fig. 14.5), which is recognized as a significant technological innovation *for* in situ residue management. For efficient sowing of wheat using Turbo Happy Seeder, the loose rice residue needs to be uniformly spread across the field, but the traditional combine harvesters put the loose residues in a narrow swath. Manual spreading of residues is a cumbersome, uneconomical, inefficient and laborious process, compounded by the acute shortage of labour. Therefore, a straw management system (SMS) named Super-SMS has been developed and commercialized by the Punjab Agricultural University, Ludhiana, to equip the combine harvesters with mechanized straw spreaders, which helps in uniformly spreading the rice residue as a part of the process of harvesting rice. Harvesting of

Fig. 14.4 Clogging of loose straw in seed drill

Fig. 14.5 Wheat sowing using Turbo Happy Seeder under residue retention

rice by Super-SMS-fitted combine harvesters allows concurrent sowing of wheat, which saves time, energy and one irrigation by utilizing the residual moisture of rice fields. Most importantly, it dispenses the compulsions for crop residue burning. This combination facilitated easy operation of the Turbo Happy Seeder with about 20–25% increase in its capacity and less wear and tear of cutting flails (NAAS 2017).

14.6 Crop Residue Management

The amount of residue cover left on the field is greatly affected by the type of operation and the implements that have been used. Each implement's design, adjustments, and depth of soil disturbance, and to a lesser extent, its speed and the condition of the residue, will have an effect on the percentage of both fragile and

Fig. 14.6 Crop residue retention in CA plots

non-fragile residue remaining on the soil surface. Other factors that affect residue cover are the type of residue, chopping versus leaving residue unchopped, carryover of residue, degree of grazing after harvest, type of field operations, soil moisture and weather conditions, and timing of field operations. The effect of each of these factors varies considerably. The fragility of the residue is important and will determine the amount of residue that will remain on the soil surface as it interacts with other factors. Valzano et al. (2005) defined the three crop residue management practices, namely residue retention, residue incorporation and residue burning. Residue retention involves leaving stubbles on the soil surface, treated or untreated (Fig. 14.6). The untreated stubble is considered standard harvesting by cutting high or low with no modification of the stubble levels. The treated stubble is considered to have levels reduced by cutting low or by windrowing, baling or removal (chaff carts). This method of stubble management protects the soil surface from wind and water erosion, while retaining carbon at the soil surface. Another option may be in situ or ex situ composting of residues and their application to field. Under residue incorporation method, residues are incorporated to the soil during field preparation. Under residue burning, farmers resort to burning of residues in the field, which damages both the environment and soil biodiversity.

14.7 Residue Addition Under CA

It is estimated that additional amount of about 1.6 t/ha of crop residue is being added in to the field compared to farmers practice, if 1-ft-height residue is left on the field under no-tillage (NT)/reduced tillage (RT). Conservation agricultural practice (CA) added about 1.6 t/ha wheat residues (0.65 t/ha C) to a vertisol compared to 0.7 t/ha (0.30 t/ha C) in farmers' practices, suggesting the addition of C in the soil through CA. Similarly, about 2.6 t/ha residue was added under maize-gram system (Somasundaram et al. 2013, unpublished data) (Table 14.2).

Table 14.2 Residue addition under conservation agriculture practices

	Addition of residue (air-dry weight kg/ha)	
Stubble retention	Soybean-wheat	Maize-gram
Farmers' practice (10–15 cm)	676	1500
Reduced tillage/no-tillage (1 ft)	2283	4100
Difference (CA − farmer's practices)	2283 − 676 = 1607	4100 − 1500 = ~2600

14.8 Conservation Agriculture and Soil Carbon Sequestration

Conservation agricultural systems have been successfully developed for many different regions of the world. These systems, however, have not been widely adopted by farmers for political, social and cultural reasons.

Through greater adoption of conservation agricultural systems, there is enormous potential to sequester soil organic carbon, which would:

1. Help mitigate greenhouse gas emissions contributing to global warming.
2. Improve soil health and productivity and avoid further environmental damage from the unsustainable use of inversion tillage systems, which threaten water quality, reduce soil biodiversity and erode soil around the world.

Adoption of CA practices improves soil carbon sequestration due to the addition of carbon through residues, protection of soil organic carbon in soil aggregates under minimum soil disturbance and addition of soil organic carbon to deeper soil layer due to inclusion of legumes in the cropping system. Further, crop residues retained on the soil surface under conservation agriculture (Fig. 14.6) serve a number of beneficial functions, including soil surface protection from erosion, enhancing infiltration and cutting runoff rate, decreasing surface evaporation losses of water, moderating soil temperature and providing substrate for the activity of soil microorganisms, and a source of SOC. Long-term implementation of conservation agricultural practices also increases the organic matter levels in the soil. Lower soil temperatures and increased soil moisture contributes to slower rates of organic matter oxidation. An increase in organic matter is normally observed within the surface soil (0–10 cm) which helps in better soil aggregation. Carbon turnover rate slows down when soil aggregation increases and soil organic carbon (SOC) is protected within stable aggregates (53–250μm).

The impact of conservation tillage and crop residues combination has shown the remarkable potential in C sequestration in comparison to conservation tillage alone. Conservation agriculture, based on the use of crop residue mulch and no-till farming can sequester more SOC through conserving water, reducing soil erosion, improving soil structure, enhancing SOC concentration and reducing the rate of enrichment of atmospheric CO_2 (Lal 2004). Doraiswamy et al. (2007) found that ridge tillage in combination with fertilizer and crop residue is very effective in SOC sequestration through erosion control. Ghimire et al. (2008) reported that SOC sequestration could be increased with minimum tillage and surface application of crop residue, and SOC sequestration was highest in top 0–5 cm soil depth irrespective of the tillage and crop residue management practices. Suman et al. (2009) reported that changes in residue management and incorporation of organic manures may help in carbon sequestration by restoring soil organic carbon (SOC).

Ghimire et al. (2008) reported that soil (0–50 cm depth) retained 8.24 kg C/m^3 under no-tillage practice, which was significantly higher than 7.86 kg C/m^3 from conventional tillage treatment. Crop residue treatment in no-tillage soils sequestered significantly higher amount of SOC than any other treatments in the top 15 cm soil depths. Thus, it was revealed that SOC sequestration could be increased with minimum tillage and surface application of crop residue. Crop residue served as a source of carbon for these soils especially in the upper soil depths. No-tillage practice minimizes the exposure of SOC from oxidation, ensuring higher SOC sequestration in surface soils of no-tillage with crop residue application.

Minimum tillage practices, including no-till (NT) and reduced tillage (RT), have received attention due to their ability to both reduce soil erosion and increase C sequestration in the agricultural surface soils (Cole et al. 1997) by increasing aggregate stability. Alvarez (2005) reviewed the effect of nitrogen and no-tillage on soil organic carbon (SOC) from 137 sites and concluded that nitrogen fertilizer increased SOC but only when crop residue were retained. Furthermore, nitrogen fertilizer used in tropics resulted in no SOC sequestration, while, in the temperate regions, there was a trend towards an increasing SOC sequestration. In contrast to CA, conventional cultivation generally results in the loss of soil C and nitrogen. However, CA has proven its potential of converting many soils from sources to sinks of atmospheric C, sequestering carbon in soil as organic matter. In general, soil carbon sequestration during the first decade of adoption of the best conservation agricultural practices is 1.8 t C/ha/year. On 5 billion ha of agricultural land, this could represent one-third of the current annual global emission of CO_2 from the burning of fossil fuels (FAO 2008). Lal et al. (1998) estimated that the widespread adoption of conservation tillage on some 400 M ha of crop land by the year 2020 may lead to total C sequestration of 1500–4900 Mg.

A study conducted at IISS, Bhopal, also reveals the effect of tillage systems on SOC was found to be significant only at the surface layer (0–5 cm) and higher SOC value was observed under no-tillage (NT) and reduced tillage (RT) compared to conventional tillage (CT) after 3 years of crop cycles (Fig. 14.7). Further, reduction in tillage operations coupled with residue retention helps in maintaining the soil organic carbon (Somasundaram et al. 2018). Similarly, Bhattacharyya et al. (2012) reported that reduction in tillage intensity led to a significantly larger SOC accumulation in the surface soil layer (0–5 cm), but not in the 5–15-cm soil layer after 6 years of cropping in a sandy-clay-loam soil (Typic Haplaquept) near Almora, India. The year-round NT management practice was very effective for SOC sequestration in a rainfed lentil-finger millet rotation system (net gain in SOC storage was about 0.37 Mg/ha/year in the 0–15-cm soil layer).

Of late, worldwide conservation agriculture (CA)/no-till (NT) farming is considered as a practicable approach to increase or maintain SOC and also improve soil

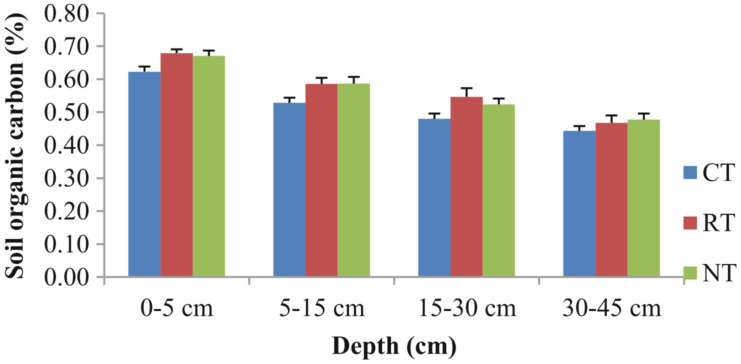


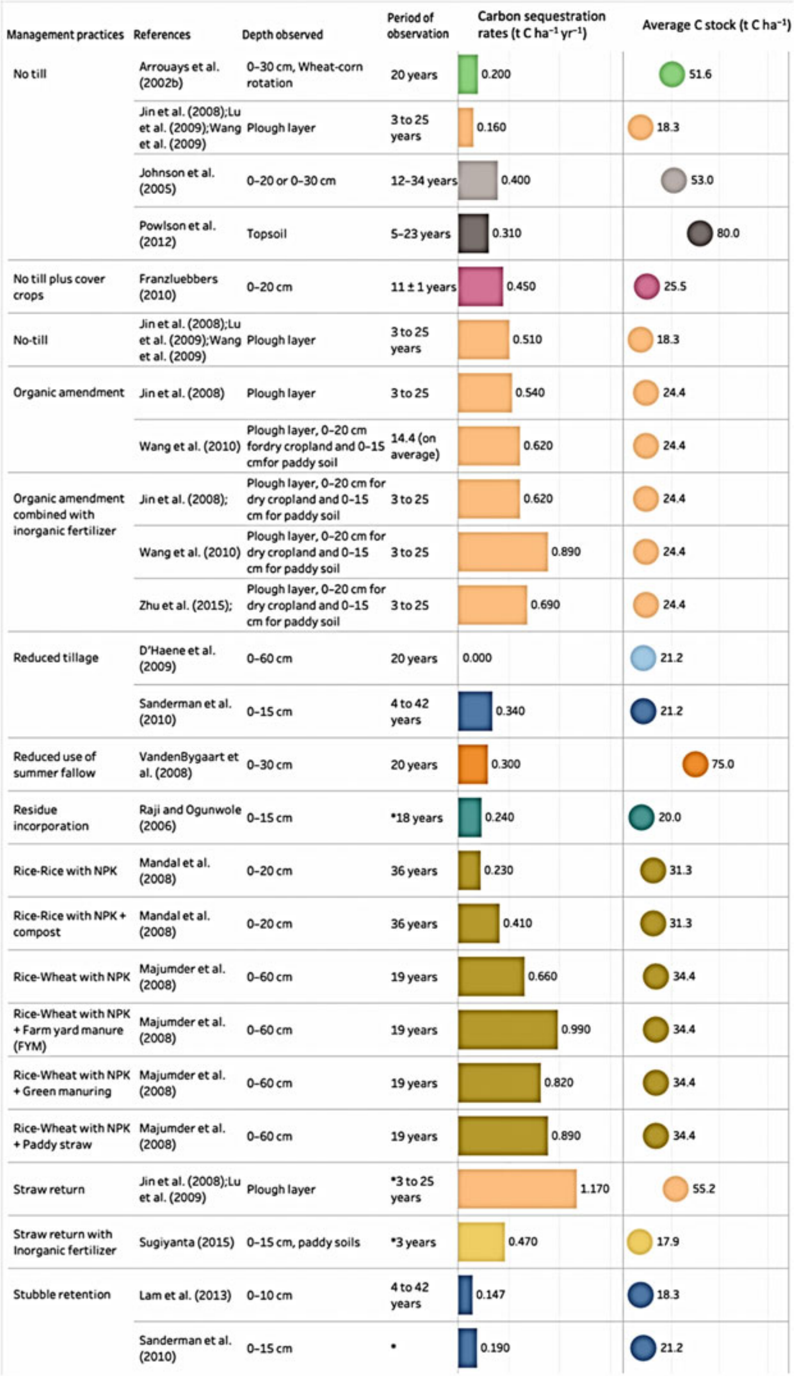
Fig. 14.7 Soil organic carbon (%) under different tillage systems after four crop cycles

aggregation (Powlson et al. 2011; West and Post 2002; Dalal et al. 2011; Palm et al. 2014). It has been estimated that practising NT can potentially sequester C at rates of 300–600 kg C/ha/year in the USA (Lal et al. 1998; West and Marland 2002). Franzluebbers (2005, 2010) reported that NT favoured SOC sequestration rates by approximately 400 kg C/ha/year than conventional tillage (CT). Similarly, Watson et al. (2000) reported that these rates are in the same range as the estimate of 200–400 kg C/ha/year conservation tillage practices for Australia, the USA and Canada. Anger and Ericksen-Hamel (2008) indicated that on an average, there was 4.9 Mg/ha more SOC under NT than CT. However, overall this difference in favour of NT increased significantly but weakly with the duration of the experiment. Dalal et al. (2011) reported that tillage effects were small on SOC and total nitrogen following 40 years of continuous no-tillage in Vertisols of Queensland region. The carbon (C) sequestration potential of different agricultural management practices is presented in Table 14.3.

There have been several meta-analyses and scientific literature reviews on the effects of NT versus CT on SOC in world soils (e.g., West and Post 2002; Alvarez 2005; Baker et al. 2007; Palm et al. 2014). Many of the earlier studies found NT to have significantly higher SOC than mouldboard plough and chisel plough systems when the soils were only sampled to 0.15- or 0.30-m depth (West and Post 2002; Baker et al. 2007). Baker et al. (2007) reported that conservation tillage was recorded to sequester C only to a depth of 30 cm or less. It was observed in few studies that conservation tillage has shown no consistent increase of SOC, where sampling extended beyond 30 cm or deeper. Moreover, many studies reported worldwide indicated higher concentrations near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage (Alvarez 2005; Baker et al. 2007; VandenBygaart 2016).

Analysis of the results from the long-term experiments demonstrated that a shift from conventional tillage (CT) to no-till (NT) could sequester 57 ± 14 g C/m^2/year (West and Post 2002). Carbon sequestration rates, with a change from CT to NT, can be expected to peak in 5–10 years with SOC reaching a new equilibrium in

Table 14.3 Carbon sequestration potential of different agricultural management practices (* depicts C stock estimated on regional estimates)



Management practices	References	Depth observed	Period of observation	Carbon sequestration rates (t C ha^{-1} yr^{-1})	Average C stock (t C ha^{-1})
No till	Arrouays et al. (2002b)	0–30 cm, Wheat-corn rotation	20 years	0.200	51.6
	Jin et al. (2008);Lu et al. (2009);Wang et al. (2009)	Plough layer	3 to 25 years	0.160	18.3
	Johnson et al. (2005)	0–20 or 0–30 cm	12–34 years	0.400	53.0
	Powlson et al. (2012)	Topsoil	5–23 years	0.310	80.0
No till plus cover crops	Franzluebbers (2010)	0–20 cm	11 ± 1 years	0.450	25.5
No-till	Jin et al. (2008);Lu et al. (2009);Wang et al. (2009)	Plough layer	3 to 25 years	0.510	18.3
Organic amendment	Jin et al. (2008)	Plough layer	3 to 25	0.540	24.4
	Wang et al. (2010)	Plough layer, 0–20 cm fordry cropland and 0–15 cmfor paddy soil	14.4 (on average)	0.620	24.4
Organic amendment combined with inorganic fertilizer	Jin et al. (2008);	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	3 to 25	0.620	24.4
	Wang et al. (2010)	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	3 to 25	0.890	24.4
	Zhu et al. (2015);	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	3 to 25	0.690	24.4
Reduced tillage	D'Haene et al. (2009)	0–60 cm	20 years	0.000	21.2
	Sanderman et al. (2010)	0–15 cm	4 to 42 years	0.340	21.2
Reduced use of summer fallow	VandenBygaart et al. (2008)	0–30 cm	20 years	0.300	75.0
Residue incorporation	Raji and Ogunwole (2006)	0–15 cm	*18 years	0.240	20.0
Rice-Rice with NPK	Mandal et al. (2008)	0–20 cm	36 years	0.230	31.3
Rice-Rice with NPK + compost	Mandal et al. (2008)	0–20 cm	36 years	0.410	31.3
Rice-Wheat with NPK	Majumder et al. (2008)	0–60 cm	19 years	0.660	34.4
Rice-Wheat with NPK + Farm yard manure (FYM)	Majumder et al. (2008)	0–60 cm	19 years	0.990	34.4
Rice-Wheat with NPK + Green manuring	Majumder et al. (2008)	0–60 cm	19 years	0.820	34.4
Rice-Wheat with NPK + Paddy straw	Majumder et al. (2008)	0–60 cm	19 years	0.890	34.4
Straw return	Jin et al. (2008);Lu et al. (2009)	Plough layer	*3 to 25 years	1.170	55.2
Straw return with Inorganic fertilizer	Sugiyanta (2015)	0–15 cm, paddy soils	*3 years	0.470	17.9
Stubble retention	Lam et al. (2013)	0–10 cm	4 to 42 years	0.147	18.3
	Sanderman et al. (2010)	0–15 cm	*	0.190	21.2

(continued)

Table 14.3 (continued)

Management practices	References	Depth observed	Period of observation	Carbon sequestration rates (t C ha^{-1} yr^{-1})	Average C stock (t C ha^{-1})
Compost addition	Lee et al. (2013)	0–30 cm paddy soils	42	0.240	40.5
	Wei et al. (2015a); Wei et al. (2015b)	0–15 cm	13–20	0.460	36.0
			13–21	1.000	36.0
Compost addition with inorganic fertilizer	Lee et al. (2013)	0–30 cm, paddy soils	42	0.390	40.5
Compost with inorganic fertilizer	Wei et al. (2015a);Wei et al. (2015b)	0–15 cm	20	1.200	74.8
Conservation tillage	Lam et al. (2013)	0–10 cm	4 to 40 years	0.150	18.3
	Metay et al. (2009)	0–25 cm	28 years	0.100	51.6
Conventional till to no-till	VandenBygaart et al. (2008)	0–30 cm	20 years	0.210	150.0
Conversion of annual cropping to crop+ley rotation Grassland	Dick et al. (1998)	0–30 cm	30 years	0.500	78.0
Conversion to ley farming	Powlson and Johnston (2015)	0–23 cm	30 years	0.200	80.0
Crop rotation	Arrouays et al. (2002a,b)	0–30 cm	20 years	0.160	51.6
	Sanderman et al. (2010)	0–15 cm	4 to 42 years	0.200	21.2
Crop rotation with perennial grasses	Savin et al. (2002)	Plough layer	5 years	0.110	64.6
Farm yard manure (@0.16 Mg C/ha/yr)	Buysse et al. (2013)	0–25 cm	20 years	0.450	50.0
Farm yard manure/crop residue	FAO (2004)	Topsoil	50 years	0.100	33.4
			51 years	0.300	33.4
Inorganic fertilizer	Minasny et al. (2012)	0–15 cm, paddy soils	8 years	0.320	27.3
	Pathak et al. (2011)	0–15 cm	6–32 years	0.160	13.3
Inorganic fertilizer + FYM	Pathak et al. (2011)	0–15 cm	6–32 years	0.330	13.3
Inorganic fertilizer with straw return	Minasny et al. (2012)	0–15 cm, paddy soils	40 years	0.520	17.9

Country
Australia
Belgium
Canada
China
England
France
India
Indonesia
Nigeria
Russia
S. Korea
Taiwan
UK
USA
USA (southeast)

Modified from Minasny et al. (2017)

15–20 years. A meta-analysis of the published data showed that converting from conventional to no-tillage increased SOC storage in over 20 years by 23% in the tropical moist climates as compared to temperate dry climates (10%) (Ogle et al. 2005).

There are several evidences that suggest the existence of a C saturation level based on the physicochemical process that stabilizes or protects organic carbon in the soil. While many long-term field experiments exhibited a proportional relationship between C inputs and soil C content across treatments (Paustian et al. 1997), some experiments in high C soils show little or no increase in soil C with two- or threefold increases in C inputs (Campbell et al. 1991). Alvarez (2005) reported that the build-up of SOC under reduced tillage (RT) and no-tillage (NT) follows an S-shaped time-dependent process, which reached a steady state after 25–30 years. Similarly, Marland et al. (2003) reported that soil organic carbon will gradually approach a new steady state that depends on the new set of practices. Many researchers estimated the time period necessary to reach the new steady state range from 20–40 years (Marland et al. 2003) to 50–100 years (Sauerbeck 2001; Ingram and Fernandes 2001) (Fig. 14.8).

14.9 Conclusions

Overall, several practices termed as ‘conservation tillage’ have led to terminological confusion. Indeed, conservation tillage (CT) is frequently confused with no-till or options of CT used in vague terms such as minimum tillage, mulch tillage, ridge tillage, strip tillage and reduced tillage, where seeding/planting is accomplished on specially prepared surfaces with varying amounts of crop residue cover. However, conservation agriculture (CA) technologies involve minimum soil disturbance, maximum soil cover through crop residues or cover crops, and crop rotations for reverting soil degradation, achieving higher productivity and also considered as a sustainable system. These CA practices were considered a practicable approach to increase or maintain carbon sequestration in the soil. Sequestering carbon in the soil and biota is a win-win strategy as it can mitigate climate change and also improve soil and crop health. Worldwide, CA practices not only improve soil aggregation, infiltration and reduce soil erosion but also greatly influencing the nutrient availability/recycling in soils as compared to conventional farming practices. Therefore, simultaneous application of location-specific CA principles can increase soil productivity and avoid degradation of soil resource from the unsustainable use of inversion tillage systems, which threaten water quality, reduce soil biodiversity and erode soil at a greater extent. However, site-specific CA technologies should be developed and disseminated for improving crop productivity, soil health, carbon sequestration, and enhancing input use efficiency. The constraints in the way of large-scale adoption of CA practices should be overcome by systematic research and development efforts and policy initiatives. The CA technologies need to be promoted by providing incentives, technological know-how, required resources and policy support to the farmers.

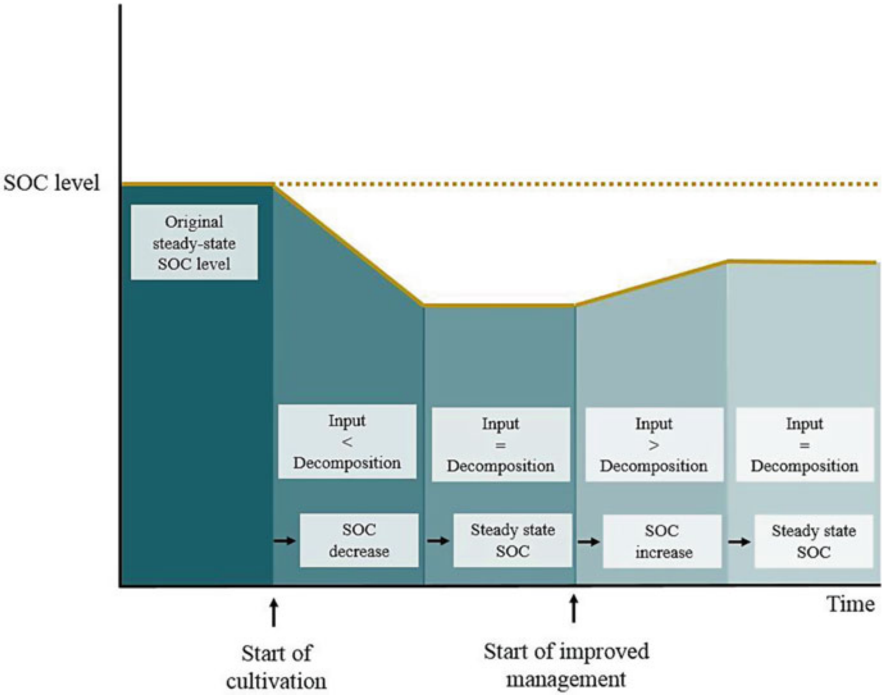


Fig. 14.8 SOC sequestration with time duration. (Source: Modified from Sauerbeck 2001)

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