Chapter

Soil Carbon Restoration through Conservation Agriculture

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Abstract

Poor soil fertility and soil degradation induced by persistent conventional farming with repeated tillage and removal or in situ burning of crop residue are major limitations to food security and environmental sustainability. However, degraded agricultural lands with depleted soil organic carbon (SOC) stocks are capable of soil carbon restoration through improved management practices like aggregation, humification and deep placement of C that can increase SOC sequestration. According to FAO, conservation agriculture (CA) is arrived as a solution to restore SOC with three pillars of minimum soil disturbance, permanent organic soil cover and diversified crop rotations. A significant increase in SOC levels under zero tillage (ZT) over conventional tillage (CT) was found; returning more crop residues to the soil is associated with an increase in SOC concentration that further increased by crop diversification. However, the incorporation of high-value trees with CA treated as a working model for C storage. Thus, conservation agriculture is an operational approach to restore SOC that aggrades soil, reduce environmental footprints and make agricultural systems more resilient to climate change.

Keywords: conservation agriculture, crop residues, soil carbon restoration, zero tillage

1. Introduction

Continuous increasing global population with a high demand for food is putting pressure on agricultural sector forces to replace traditional agricultural practices with advanced technologies. As a result, the sustainability of crop production systems based on soil quality gets affected by the nature of the farming system being implemented like prolonged cultivation of agricultural lands including tillage and inversion combined with the removal of crop residues accelerate the decomposition of soil organic matter and causes 20–67% soil C loss [1] leads to soil degradation and diminished the physical, chemical and biological properties of the soil [2]. Consequently, the depletion of carbon from soil elevates the atmospheric concentration of carbon dioxide (CO_2) from 316 to 400 ppm and global temperature by 0.12°C per decade [3]. It is found that a loss of soil organic carbon (SOC) of 42 and 59% due to changes in land-use pattern from forest to crop and from pasture to crop respectively [4]. On the other hand, agricultural activities directly produce about 10–12% of the atmospheric greenhouse gases (GHGs), such as CO_2, methane (CH_4), nitrous oxide (N_2O) [5]. However, world soils constitute the third-largest carbon (C) pool after oceanic and geologic pools.

Thus, the twin crisis of food insecurity and climate change can be addressed through the restoration of the soil carbon achieved through the implementation of recommended management practices on agricultural soils [6]. Understanding the dynamics of SOC in relation to land use and management strategies is of foremost importance to identify pathways of C sequestration in soils. It is necessary to build up soil carbon contents by increasing carbon inputs or decreasing decomposition of organic matter in the soil for sustainable agricultural productivity and a stable environment. Several management practices are recognized to improve soil organic carbon (SOC) contents in croplands, such as organic amendments, cover crops, diversified crop rotations, biochar, agroforestry, or conservation agriculture (CA) to address sequestration of carbon (C) in agroecosystems, especially in agricultural soils [7, 8]. Among them, CA is increasingly promoted as an alternative to tackle soil degradation resulting from agricultural practices that deplete soil fertility, aiming at higher crop productivity as short term benefit [9]. In practice, CA includes three basic principles of minimal soil disturbance, permanent soil cover through mulch or crop residues, and crop rotations. Rehabilitation of degraded soils to restore biomass productivity, in order to secure the various functions of CA, depend on above and belowground plant biomass may sometimes be aided with the adoption of agroforestry as management of forest plantations with the agricultural crop can enhance SOC stock through C sequestration [10]. Presently CA is being practiced in about 180 million hectares (Mha) area all over the world [11] of which 1.5 Mh area covered under CA in India [12] mainly in Indo-Gangetic plains (IGP) with rice-wheat (RW) cropping system. This chapter explores new initiatives taken for restoring C content in soil to mitigate climate change, improve soil health and maintain sustainable productivities with the help of CA practices.

2. Soil organic matter (SOM) in relation to SOC

Soil organic matter is the complex organic substances consisting of organic residues, humic substances, microbial bodies that undergo decomposition at various stages. It influences plant growth and yield by improving soil structure and acts as a reservoir of plant nutrients containing 2.5 Eg carbon (1Eg = 10^{18} g) (**Table 1**). The formation of the clay-humus complex increases the buffering capacity of the soil and forms stable complexes with some metals to make them available for plant uptake. Soil carbon is mainly present as organic matter or humus varies from 1% (coarse-textured soil) to 3.5% (grassland). But Indian soil is deficient in SOC due to prevalence of the tropical, sub-tropical, arid and semi-arid climatic condition, persistence tillage practice, non-judicious use of agrochemicals, removal of crop residue from land etc. The SOM can be divided into different pools based on the time needed for full decomposition and the derived turnover time of the products in the soil:

1. Active pools: turnover in months or a few years,

2. Passive pools: turnover in up to thousands of years.

SOM contains about 58% of soil carbon which can be classified according to its physical and chemical stability as:

1. **Fast pool** (labile or active pool): After the addition of fresh organic carbon to the soil, faster decomposition in a few days that get lost in 1–2 years.

	Reservoir	Estimates of the C pool (10^{18}g)
1.	Sedimentary rocks	60,000
2.	Oceans	38
3.	Fossil fuels	5
4.	Terrestrial biosphere	0.6
5.	Soils (1 m)	2.5
6.	Atmosphere	0.8

Source: [13, 14].

Table 1.
Estimates of global carbon reservoirs.

2. **Intermediate pool:** Comprises organic carbon that is partially stabilized on mineral surfaces and/or protected within aggregates, with turnover times in the range 10–100 years.

3. **Slow pool** (stable): Highly stabilized SOC, enters a period of very slow turnover of 100 to >1000 years.

3. Global carbon cycle

Soil carbon stocks consist of soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC). Soils contain carbon in both organic and inorganic forms, i.e., oxidized carbon and non-oxidized carbon. The sum of the two forms of carbon is referred to as total carbon.

The global soil carbon, estimated to be 2500 Pg (1 Pg = 10^{15} g) which is nearly 3.3 times the atmospheric pool and 4.5 times the biotic pool size (760 Pg) [15] whereas, the total amount of SOC and SIC stored worldwide are estimated to be 1550 Pg C 950 Pg in the top 1 m of soils in a dynamic equilibrium of gains and losses (**Figure 1**). Pools of C in rocks are inert that changes over the millions of years of time while pools of C in the terrestrial biosphere, atmosphere, oceans constitute active pools that are vulnerable to anthropogenic activities. Exchange of C among these pools over a short and long period of time is known as the Global Carbon Cycle (GCC). The Global Carbon Cycle has been changing due to the increase in atmospheric C pool and decrease in biosphere and soil C pool consequently resulting in global warming. Conversion of natural to agricultural ecosystems cause 60% depletion of the SOC pool of temperate regions and 75% or more in cultivated soils of the tropics, further creates severe soil degradation when the output of C exceeds the input.

4. Salient causes of carbon loss from soil

Loss of C from the SOC pool occurs in the form of CO_2 and CH_4 while SIC fraction produces only CO_2. There are certain processes like mineralization; erosion and leaching responsible for the loss of C pool in disturbed soil [16]. Environmental factors like an increase in soil temperature mainly stimulate the rate of mineralization of the SOC pool while calciferous materials are subjected to certain climatic factors leading to the dissolution of carbonates and bicarbonates releases of CO_2 to the atmosphere. There are certain anthropogenic activities instigate the Soil C losses are discussed below:

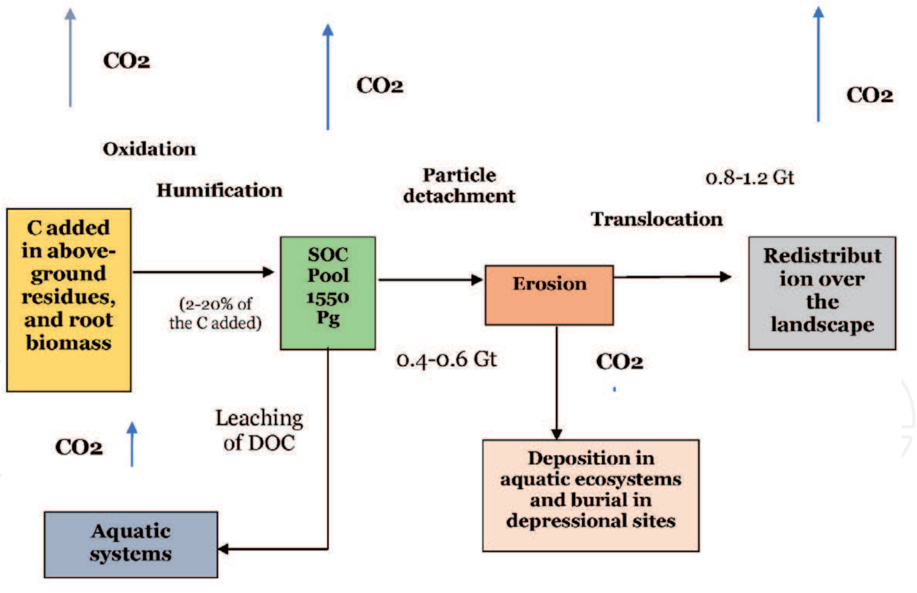

Figure 1.
Soil organic carbon dynamic equilibrium [6].

1. Deforestation
2. Soil erosion
3. Excessive plowing
4. Burning of crop residues
5. Summer fallow
6. Bare soil during the winter season
7. Monocropping
8. Weak elemental recycling
9. Nutrient depletion
10. Water deficiency
11. Low input subsistence farming and soil fertility mining
12. Intensive cropping and cultivating marginal soil

The depletion of the SOC leads to land degradation which decreases biomass productivity reduces the quantity of biomass returned to the soil. Among all factors responsible for soil degradation, accelerated soil erosion has the most severe impact on the SOC pool depletion. Moreover, soil degradation comprises of:

1. **Physical degradation:** reduction in aggregation, a decline in soil structure, crusting, compaction, reduction in water infiltration capacity and erosion.
2. **Chemical degradation:** nutrient depletion, a decline in pH and acidification, a build-up of salts in the root zone, imbalance and disruption in elemental cycles and

3. **Biological degradation:** reduction in activity and species diversity of soil fauna, a decline in biomass C and depletion of SOC pool.

However, the depleted SOC pool can be restored through conversion to appropriate land use, and adoption of recommended management practices (RMPs) e.g., mulch farming, reduced tillage, crop rotation, conservation agriculture (CA), integrated nutrient management (INM), integrated pest management (IPM), precision farming [17].

- **Aggregation:** Increase in stable micro-aggregates to protect against microbial activities through the formation of organo-mineral complexes encapsulates C.

- **Humification:** Formation of chemically recalcitrant humic compounds that improve the relative proportion of passive fraction of SOC by the presence of a higher proportion of high activity clays (HACs).

- **Translocation into the sub-soil:** Accumulation of SOC into the sub-soil through deep root placement discouraging the loss of C from a zone of disturbance by tillage and intercultural operations, and minimizing the risks of erosion.

- **Formation of secondary carbonates:** Soil inorganic carbon (SIC) sequestration mainly prevalent in arid and semi-arid land-use systems through the formation of secondary carbonates [18] and leaching of carbonates into the groundwater in irrigated soils [19].

5. Soil carbon sequestration

The Paris Agreement at the 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC), all set an agenda for reducing global warming below 2°C and limiting the temperature increase to 1.5°C by lowering GHG emissions to encourage climate resilience through diverse pathways without compromising food production. But, under the current scenario, GHG emissions by anthropogenic activities could increase 55 Gt CO_2 equivalents in 2030 [20] and to achieve the objective of COP21, anthropogenic emissions need to hit the highest point within the next 10 years subsequently decline the trends towards net GHG removal by the end of the century. The "4 per 1000" initiative was launched as a part of the Lima-Paris Action Agenda promotes SOC sequestration to improve food security and mitigate climate change. According to this initiative, anthropogenic GHG emissions should be counter-balanced by a yearly increase of global soil carbon stocks in the top 40 cm of soils by 0.4% considerably. Moreover, agricultural activities and land-use change may enhance GHGs emissions like 25% of the CO_2, 50% of the CH_4, and 70% of the N_2O that perhaps compensate by SOC sequestration [21]. To achieve this target, improved management practices should be adopted for C sequestration in agricultural, forest and wetland land along with rehabilitation of degraded soils. Various institutions of more than 170 countries initiated a highly ambitious goal with the collaboration between scientists, educator and farmers, policymakers to implement suitable practices for increasing SOC stocks. In addition to that, 103 countries have set mitigation and adaptation targets related to agricultural practices, and about 129 countries developed goals related to forests and degraded land [22]. This initiative creates a global enthusiastic target to increase 0.4% SOC stock per year in all land uses, including forests. Generally, an optimistic point of view was reported from 20 countries in a survey on SOC stock estimates with their feasibility to achieve the 4 per 1000 target [23]. Water resources are appreciably important in SOC sequestration to adapt and mitigate climate change to fulfill SDGs as a demand for water increased by the intensification of agroecosystems [24] which further become successful after following proper nutrient management strategies, especially N, along with soil and water [25]. Soil C sequestration is the process of transfer of atmospheric CO_2 into SOM as C held in recalcitrant forms is less susceptible to losses by decomposition. To deal with CO_2, SOC sequestration involves three basic steps:

1. Removal of CO_2 from the atmosphere via plant photosynthesis;

2. Transfer of carbon from CO_2 to plant biomass; and

3. Transfer of carbon from plant biomass (crop residues) to the soil where it is stored in the form of SOC, i.e., labile pool with highest turnover rate.

Thus, SOC sequestration should be done in such a way that captured atmospheric CO_2 can retain C in the slow SOC pool. But, it is a fact that the stable pool has little potential for carbon sequestration due to its resistance to change by management practices [26]. In the short term, it is important to manage the easily decomposable SOM by enhancing the cropping intensity that has the major impact on microorganisms, humic complex production, which ultimately sequesters C. For the medium and long term, C sequestration can be achieved through the placing of recalcitrant C to the deeper layer which is resistant to rapid mineralization. It can be done by creating a positive C budget as the rate of SOC sequestration varies from 100 to 1000 kg C ha^{-1} $year^{-1}$. However, the rate of SOC change is greater in the tropics, thus leading to a shorter time for SOC equilibrium to be attained in tropical regions. The SOC sequestration is affected by many factors including C input, crop rotation, tillage management, climate condition, fertilization, and soil texture (**Figure 2**). Carbon sequestration is soil can be done by following four major processes:

1. Decreasing the level of soil disturbance to enhance the physical protection of soil carbon in aggregates.

2. Increasing the agricultural inputs (e.g., organics) to soils.

3. Improving soil microbial diversity and abundance.

4. Maintaining continuous living plant cover on soils year-round.

Successful carbon sequestration is achieved when C storage through soil conservation practices exceeds their losses [28] by transforming atmospheric CO_2 into biomass through photosynthesis, and incorporation of biomass into the soil to enrich humus. Carbon sequestration is possible through a range of processes, occurring naturally in plants and soils but soil contains approximately three times more C than the amount stored in living plants [29]. However, the C inputs from various sources like trees, shrubs, and vegetation in the form of litterfall, roots, and rhizodeposition contribute towards enhancing SOC stocks, mostly within woody components. Thus, SOC stocks can be increased by practicing agroforestry in adjacent to the cultivation of agricultural lands [7]. Agroforestry with two main segments of agroforestry systems: belowground and aboveground is potent enough

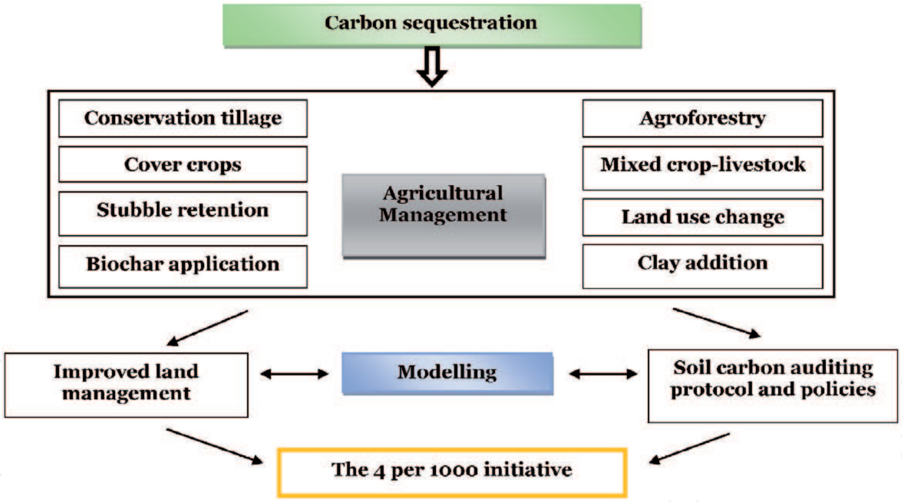

Figure 2.
Impact of improved management practices on SOC dynamics [27].

Sources	Mi C $year^{-1}$
Water land restoration	20
Restoration of degraded land	50
Agroforestry	600
Forest management	250
Grazing management	375
Rice management	20
Cropland management	150
Source: [30].	

Table 2.
Potential of carbon sequestration by 2040.

in increasing sequestration of carbon in agricultural lands where the aboveground component is described as stem and leaves of herbaceous plants and trees while the belowground component contains roots and microorganisms associated with roots [30]. Although, in the belowground segments carbon is more stabilized due to interactions between soil particles with root biomass [31] and slow decomposition rate is observed over above-ground biomass [32]. **Table 2** indicates that agroforestry has the greatest capability for carbon sequestration among various other sources.

6. Mechanism of carbon sequestration through carbon stabilization

The carbon stabilization process of C sequestration starts with the formation of unstable macroaggregates, subsequently stabilization and the contemporary formation of microaggregates within macroaggregates, finally conclude with the breakdown of macroaggregates with the liberation of the microaggregates. Young macroaggregates offer physical protection to C and N from microbial enzymes but need to be further stabilized. Microaggregates within macroaggregates are occluded intra-aggregate particulate organic carbon (iPOM C) in soil microaggregates which may responsible for long-term soil C sequestration in agricultural soils as these are relatively stable and secluded habitats for microorganisms.

Carbon sequestration depends on turnover time and physical, chemical protection against microorganisms which further influenced by the quality and physical location of SOC fractions in the soil system (**Table 3**). In most soils, young and unstable macroaggregates are formed with the help of biological factors like growing roots, fungal, bacterial and faunal activity by mixing fresh organic matter with exudates and soil particles. When partially decomposed intra-macroaggregate organic matter encapsulated with clay minerals and microbial products, microaggregates are formed, which lead to long-term carbon stabilization in macroaggregates by protection from mineralization. Further, with time the macroaggregates lose labile binding agents and release minerals, highly recalcitrant SOM and microaggregates released may again be occluded within new macroaggregates. It is evident that physical disturbances like tillage disrupt macroaggregates exposing coarse iPOM C to microbial attack and preventing its incorporation into microaggregates as fine iPOM C. While, this slower turnover rate of microaggregates within macroaggregates in zero tillage allows greater protection of coarse POM. The organic C in the soil is mainly stabilized through the following mechanisms:

6.1 Physical protection

The C sequestration in soils through physical protection is mainly done by aggregation [33] formed by clumps of soil particles adhered with by clay, fine roots, and glue-like substances generated by microbes decomposing organic matter, such as glomalin produced by arbuscular mycorrhizal fungi [34, 35]. As these aggregates form, small particles of C, like partially decayed plant residues, are captured in the center of the aggregates which are physically protected from microbial attack as they cannot penetrate the center of these stable aggregates where oxygen and water are low, discourage microbial metabolism [36]. Roots, fungal hyphae and less degraded organic materials stabilize macroaggregates and their oxidation of C is dependent on management practices [37]. On the other hand, highly decomposed organic components stabilize more C in microaggregates, facilitated by its high surface area and polyvalent cation bridging, as the oxidation of C in these aggregates is least [38]. It is evident that the turnover time of C is higher in microaggregates (412 years) than C in macroaggregates (140 years) [39] due to higher the level of physical protection of organic matter across the aggregate-size classes, depending upon the amount and type of clay in soil [40]. These stable aggregate can protect SOC for very long but can be degraded by tillage exposing soil carbon to microbial attack [41].

Types of organic matter	Location	Turnover time, Year	Category
Microbial biomass	Pores, particle/aggregate surface	0.1–0.5	Libile
Litter	Soil surface, pores	1–5	Rapid
Light fraction	Voids, aggregate surface	5–15	Moderate
Particulate	Voids, bio pores	5–20	Moderate
Humus	Inter-microaggregate	20–50	Slow
Humus	Adsorbed on intra-microaggregate	50–3000	Passive

Source: [42].

Table 3.
Turnover time of soil organic carbon depending on the quality and physical location within the soil.

6.2 Chemical stabilization

Apart from the physical protection of SOC through aggregate formation, C compounds can be chemically protected from decomposition. Chemical stabilization of SOM is controlled by the quantity and type of clay minerals, amorphous minerals, exchangeable cations, and the chemical composition of SOM. The surfaces of clay particles are strongly negatively charged. Soil microbial community produces some by-products having strong positive charges forming strong bonds with negatively charged clay particles, effectively protecting the molecules from microbial attack [33]. The protection of soil organic matter is enhanced by silt and clay content [43] due to the sorptive capacity provided by the larger surface area of minerals [44] which further depends on clay mineralogy [40]. Several studies find that 2:1 clay minerals generally have a greater ability to stabilize SOM than 1:1 clays [45] of which vermiculite and smectite are probably more efficient for the absorption of SOM due to higher specific surface areas compared to illite [45, 46]. While amorphous iron (Fe) and aluminum (Al) oxides present in acid soils have higher potential to stabilize SOM than clay minerals [47]. Carbon stabilization in saline soils is done through a higher concentration of exchangeable Ca which increases the bridging of organic ions with clay minerals [48].

6.3 Biochemical stabilization

Biochemical stabilization of SOM is the function of structural bond strengths, the regular degree of occurrence of structural units and the degree of aromaticity [49] which are related to the inherent chemical composition of residues [33]. Non-hydrolyzable forms of C are considered as chemically stable structures, such as lipids, waxes, insoluble polyesters, and microbial-synthesized macromolecules because of their high aliphatic nature whereas, lignin being an aromatic compound is more resistant to decomposition [50]. So, aliphatic and aromatic C compounds present in soil constitute stable or passive pools [51].

7. Conservation agriculture to restore soil carbon

Conservation agriculture was introduced as a concept of the resource-efficient agricultural crop production system based on integrated management of agroecosystems combined with input use efficiency [52]. Conservation agriculture is a broader concept than conservation tillage, where more than 30% of the soil surface cover with crop residues is practiced. As per FAO definition, CA is to achieve acceptable profits, high and sustained production levels and conserve the environment based on three basic principles: (1) minimum or no mechanical soil disturbance; (2) permanent soil cover (consisting of a growing crop or a dead mulch of crop residues); and (3) diversified crop rotations. Recently, 4th basic principle was proposed by [53] i.e., improving soil fertility by integrated nutrient management (INM) to transform biomass carbon into soil organic matter for healthy crop management. Development of cereal straw retention or incorporation technique significantly reduced the problem of crop residue burning in South Asia which is a major contributor to environmental pollution [54]. Presently CA is being practiced in about 180 million hectares (Mha) area all over the world in which tropical and temperate regions cover 85.3 Mha and 95.12 Mha areas respectively (**Table 4**). These CA principles are applicable to a wide range of crop production systems from low-yielding, dry, rain-fed conditions to high-yielding, irrigated conditions following site-specific management practices to deal with various crop development

Climate	Region	The area under CA (Mha)	% of the world
Tropics/Sub-tropics	South America	69.9	38.7
	Asia	13.9	7.7
	Africa	1.51	0.8
	Sub-total	85.3	47.2
Temperate	North America	63.2	35.0
	Russia/Ukraine	5.70	3.2
	Europe	3.56	2.0
	Australia/New Zealand	22.70	12.6
	Sub-total	95.16	52.8
	Grand Total	180.46	100.0

Source: [11].

Table 4.
Global cropland area under conservation agriculture in 2015–2016.

factors such as pest and weed control tactics, nutrient management strategies, rotation crops, etc. However, laser land leveling is one of the few mechanical prerequisites in intensively cultivated irrigated agriculture and improves the input use efficiencies.

1. **Minimal soil disturbance:** The first objective is the application of zero tillage or reduced tillage seeding systems without disturbing more than 20–25% of the soil surface. It could maintain optimum proportions of gaseous exchange in the rooting-zone, reduces C losses as atmospheric CO_2 moderate organic matter oxidation, porosity for water movement and limits the weed seeds germination.

2. **Permanent soil cover:** The second objective is the retention of sufficient residue on the soil surface to protect the soil from erosive agents, water run-off and evaporation to improve water productivity and to enhance soil physical, chemical and biological properties associated with long term sustainable productivity by augmenting biomass C.

3. **Diversified crop rotations**: The objective is to employ economically viable, diversified crop rotations (preferentially leguminous plants) to help deep placement of SOC through the root network of different crops. It also moderates the outbreak of weed, disease, and pest problems; enhance soil biodiversity; take advantage of biological nitrogen fixation (BNF). Apart from these soil enhancing properties, crop diversification reduces labour requirement and provide farmers with new economic opportunities that can necessitate risk reductions in crop cultivation (**Table 5**).

Proper CA can create a positive ecosystem carbon budget and improve agronomic productivity. Bulk density and tillage practices are the two main factors governing TC content when comparing SOC under different management scenario [55].

	Conventional agriculture	Conservation agriculture
1.	Cultivating the land, using science and technology to dominate nature	Least interference with natural processes
2.	Excessive mechanical tillage and soil erosion	No-till or drastically reduced tillage
3.	Residue burning or removal (bare surface)	Permanent surface retention of residues
4.	Free-wheeling of farm machinery increased soil compaction	Controlled traffic, compaction in a tramline, no compaction in crop area
5.	Mono cropping, less efficient rotations	Diversified and more efficient rotations
6.	Poor adaptation to stresses, yield losses greater under stress conditions	More resilience to stresses, yield losses are less under stress conditions
7.	Heavy reliance on manual labour, the uncertainty of operations	Mechanized operations, ensure timeliness of operations
8.	Productivity gains in long-run are in declining order	Productivity gains in long-run are in incremental order
9.	Water infiltration is low	Water movement is high

Source: [56].

Table 5.
Some distinguishing features of conventional and conservation agriculture systems.

1. **Bulk density**: With the adoption of zero tillage (ZT), bulk density may be increased than conventional tillage (CT). The apparent mass of SOC in ZT could increase as more mass of soil should be taken from ZT soil over conventionally tilled soil if surface soil samples are taken at the same depth.

2. **Tillage practices**: Carbon content of surface soils have higher under ZT than CT while a higher SOC content in the deeper layers of CT plots where the residue is incorporated through tillage.

8. Influence of tillage practice on soil organic carbon

It is already discussed that soil disturbance stimulates the rate of decomposition of SOC and loss of C from soil to the atmosphere. Classic studies show that the disruption of soil aggregates in surface layers and decreases the amount of total SOC, mainly in macroaggregates occurs under conventionally tilled soil (**Figure 3**). Hence, by minimizing the disturbance through the adoption of reduced tillage (RT) practices, it is expected that such CO_2 emission from soil to the atmosphere can be reduced by combating global climate change scenario. Hence, RT is known to enhance SOC in the surface soil horizons over the CT mainly in tropical and sub-tropical regions over temperate one due to various reasons among which alterations of soil temperature and moisture regimes, erosion control are important. From a global database, it was found that a significant increase in SOC levels under ZT over CT whereas; it was statistically at par under conventional and RT. The average SOC sequestration rate (up to 30 cm depth) under ZT was 0.57 ± 0.13 Mg C ha^{-1} $year^{-1}$ [57]. However, the adoption of ZT practices enhances the physical protection of SOC where soil bulk density is relatively high because the volume of small macro-pores (15–150 μm) gets reduced which is important for microbial activity. Management practices are sensitive to climatic conditions as the largest change in SOC is observed under tropical moist

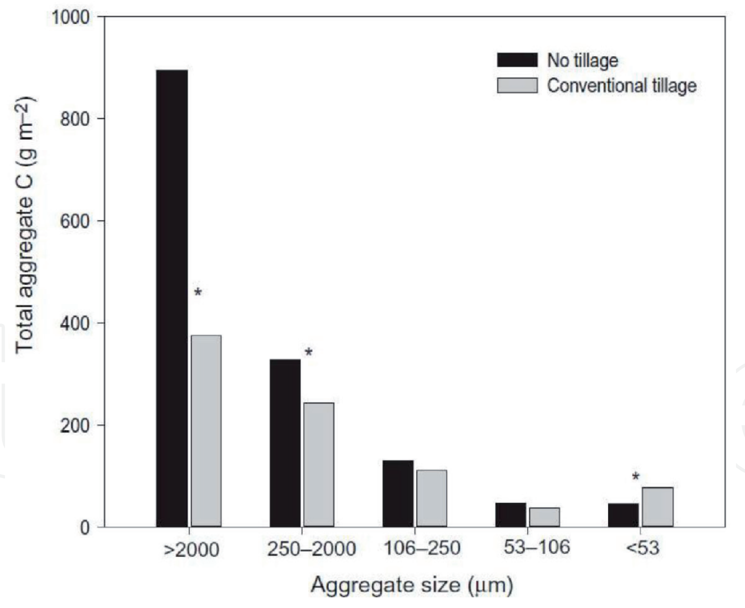

Figure 3.
Distribution of total aggregate C in no tillage and conventional tillage soils at 0–5 cm depth (indicates significant differences at P = 0.05 level) [60].*

environment followed by tropical dry, temperate moist and temperate dry [58]. Moreover, soil erosion and redistribution over a prolonged period can store SOC more under ZT practices when shifted from conventional ones [59].

Some distinguished factors affecting SOC content in soil are discussed here:

1. **Baseline C content:** Old weathered soils with less carbon content have more potential to sequester C compared to young C rich soils. So, eroded soils with less SOC have a higher potential to gain SOC when converted from CT to ZT.

2. **Porosity**: Lesser pore size can physically protect C within it to form microaggregates that are less susceptible to microbial decomposition.

3. **Climate:** Changes in SOC under different management practices are sensitive to the climate in the order of tropical moist > tropical dry > temperate moist > temperate dry.

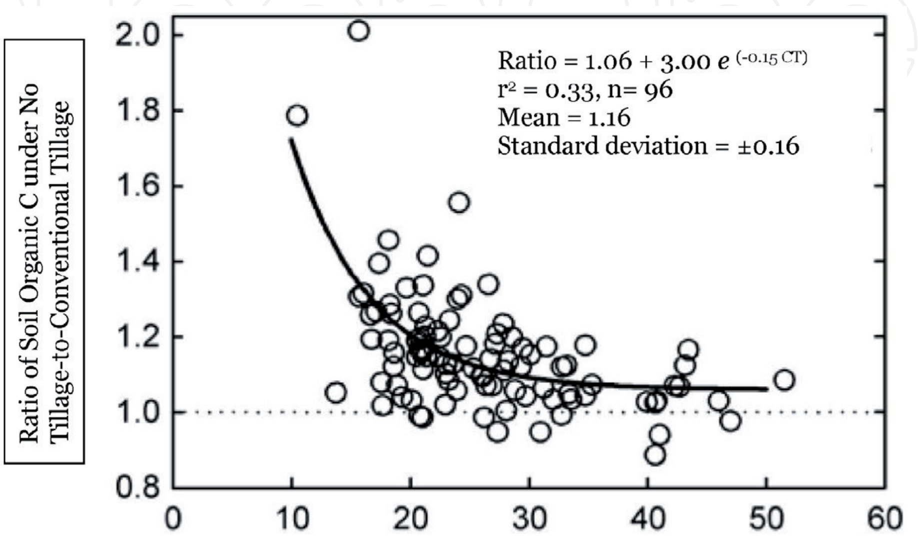

Figure 4.
The ratio of soil organic C under conservation tillage-to-conventional tillage as related to the initial soil organic C content under conventional tillage [61].

4. **Landscape position:** Landscape positions that had a low SOC stock in the past due to past erosion generally show gains in SOC.

The impact of ZT on soil organic C sequestration may be greater in degraded soils than in fertile soils which can be observed in **Figure 4** where the ratio of soil organic C with conservation tillage-to-conventional tillage was logarithmically greater in soils with lower SOC than in soils with higher SOC.

9. Influence of residue application on soil organic carbon

Crop residues retention in fields is a well-known management practice deals with several positive effects like improving better soil structure, water retention, and reducing erosion loss [62]. They are potential enough to improve the nutrient content of soils [63] and helping in SOC accumulation in soils due to increased crop rhizodeposition [64]. Nevertheless, returning straw up to 50 cm depth approximately increases 13% SOC concentration in bulk soil are studied from a global meta-analysis of 176 fields where labile pools contribute about 27–57% increase in SOC content in soils. A study suggested that crop residue removal is not recommended in SOC-poor tropical and temperate soils, while partial residue removal is commendable in organic C-rich temperate soils. The degree of SOC dynamics on residue application depends on many factors such as rate of addition, climate, soil texture, and quality of the substrate [65]. The SOC content is further influenced by the quality of crop residues [66] which is partly determined by its C:N ratio as crop straw with a low C:N ratio decomposes more rapidly [62]. For example, maize residues with higher C input and C:N ratio decompose slower than soybean residues contributing higher SOC content in the soil. Nowadays, burning of straw is commonly practiced, to manage stubble loads which continuously enhances nutrient loss, air pollution and reduces soil health. Moreover, it also causes a loss of SOC as evident by a field trial over a period of 19 years in south-eastern Australia where a loss of 1.75 Mg C ha^{-1} (0–10 cm layer) [67]. But, residue retention increases SOC content in soil mainly during the first two decades years than in the longer term [68]. By considering all the fluxes, straw incorporation can lead to improving C sink in upland soils and decreases fluxes of GHGs like CH_4 as a decrease in CH_4 emissions following maize straw incorporation [44]. Apart from that several studies showed that application supplementary nutrients (inorganic N, P, and S) enhance SOC storage by minimizing positive priming of SOC mineralization during incorporation of C-rich crop residues into the soil [69]. Management of crop residues (retention or incorporation) improves organic matter levels in soils. Returning more crop residues to the soil is associated with an increase in SOC concentration [70]. The rate of decomposition of crop residues depends not only on the amount retained but also on the composition of the residues and soil types. As lignin is resistant to rapid microbial decomposition, it can promote the formation of a complex structure, which often encrusts the cellulose-hemicellulose matrix and thus slows down the decomposition while the soluble fraction is decomposable in nature and helps in the decomposition of hemicellulose [71]. The SOC content was increased from 0.45% to 0.55% and from 0.29% to 0.35% with the residue mulch treatments at 0–15 cm and 15–30 cm, respectively [72]. A higher amount of SOC was observed in surface soil than subsurface soil due to surface retention of crop residue under CA over CT [73]. Moreover, a 100-year simulation study demonstrates the loss or gain of SOC stocks at various straw incorporations in wheat cropping in sandy loam soils are depicted in **Figure 5**.

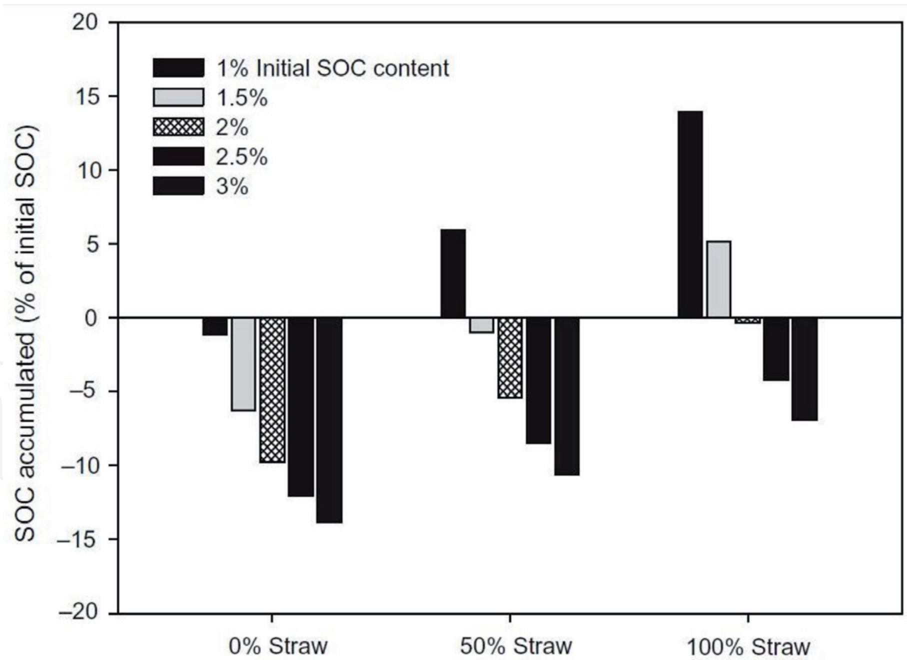

Figure 5.
Impact of residue incorporation on SOC storage at 0–3 m after 100 years continuous wheat cropping [74].

10. Influence of crop rotation on soil organic carbon

Conservation agriculture can increase the possibility of crop intensification due to faster turnaround time between harvest and planting. Diversified crop rotation provides an opportunity to produce huge biomass C that influences SOC by changing the quantity and the quality of organic matter input than under monocropping. Conservation of moisture as practiced under CA can result in growing an extra cover crop right after harvest of the main crop that leads to higher SOC contents by increasing the input of plant residues and providing a vegetal cover during critical periods. In many annual cropping systems, the field is left free after crop harvest, thus lowers annual biomass production as C inputs to the soil, which unable to compensate the soil C losses throughout the year. On the contrary, the introduction of cover crops or periodic green fallows increases average annual biomass production leads to a net gain of carbon rather than a loss [75]. Crop diversification with legume crops can increase the complexity and diversity of C as they contain carbon compounds resistant to microbial metabolism, thus increasing C stabilization [76]. These strategies greatly increase the total amount of aboveground as well as belowground biomass entering agricultural systems by increasing the roots proliferation against annual cropping systems (mainly cereal crops) with a shallow rooting network. However, the increase in SOC concentration can be negated when the crop cover is incorporated in the soil. In general, it has been observed that enhancing the rotation complexity results in an increase in SOC but the magnitude is lower than that observed when shifting from conventional to zero tillage. It is still effective in retaining C and N in soil than a monoculture. The effect of crop rotation on SOC contents can be due to increased biomass input, because of the greater total production, or due to the changed quality of the residue input. For instance, legume-based systems contain greater amounts of aromatic C content maintaining ideal C:N ratios, thus productivity gets increased. The SOC was increased by 72% with a CA-based maize-wheat-mungbean system and 83% with the rice-wheat-mungbean system compared to conventional RW system [77]. Conservation agriculture significantly increased SOC content in both 0–15 cm and 15–30 cm depth compared with CT in the maize-based cropping system for % years [73] (**Table 6**).

Treatment	Soil organic carbon ($g\ kg^{-1}$)		Total soil organic C stock ($t\ ha^{-1}$)		Change in total SOC stock ($t\ ha^{-1}$)
	0–15 cm	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–30 cm**
ZT	6.23	5.23	14.8	13.4	7.72
CT	4.73	4.33	11.2	10.7	0.88

Source: [73].

Table 6.
Effect of long-term tillage on total soil organic carbon in the 0–15 cm and 15–30 cm layers in the maize-based cropping system.

11. Conservation agriculture with trees

It is the strategy of inclusion of trees in order to combine the best of CA leading to a working model under different social, economic, biophysical, institutional and policy conditions. This practice is aimed at improving the uptake of CA through the provision of fodder, fuel, construction materials, agricultural implements, biomass, nutrients, fencing, fruits, among other products and services. Agroforestry is a widely practiced system of agricultural production around the world to that can be grouped under silvoarable systems (alley cropping, parklands), silvopastoral systems (e.g., Dehesas, Montados), protective systems (windbreaks, shelterbelts, riparian buffers), multistorey systems (e.g., home-gardens), rotational woodlots, and shifting cultivation [78]. Besides providing agricultural crops, fodder, and firewood/timber, these systems sustain a number of environmental benefits and ecosystem services such as erosion control, water availability, increased diversity of species, improved esthetics of agricultural landscapes and improve soil fertility by SOC sequestration by C fixation in tree biomass as well as deposition of C-containing materials topsoils and subsoils, lower decomposition by recalcitrant litter, reduced soil disturbance, and improved physical protection of organic matter by aggregates [79]. Incorporation of nitrogen-fixing and high-value trees is important objectives besides three basic principles of CA since a complex interaction between C and N is found in soils. Nitrogen-fixing trees (especially *Gliricida*) together with maize increased 42% yield than non-fertilized fields and similar to fields receiving 92 kg N ha^{-1} derived from a field study conducted in Malawi and Zambia [80]. In a worldwide meta-analysis stated that 0.3–7.4 Mg ha^{-1} per year C is being sequestered under different systems [78] in which rates of sequestration are higher in tropical agroforestry systems than in temperate environments as this mechanism largely varies depending on the climate conditions, soil conditions, tree species and management practices [79]. So, land-use extensification is a hopeful strategy for SOC sequestration [17] as 0.3–1.9 Mg ha^{-1} of C gets sequestered per year due to conversion of arable land to forest/grassland [81] and the build-up of SOC stocks is primarily because of shifting from stable to labile SOC [82]. Moreover, the age of the system is also an important factor in improving the total soil C as it is evident that total C stock under 27-year-old pin oak stand (117 Mg ha^{-1}) is much lower than 69-year-old oak beech stand (227 Mg ha^{-1}) [83]. Establishment of bioenergy plantation crops can enhance SOC stock and offset fossil fuel combustion, besides; woody crops sequestered considerable organic C belowground primarily as large roots (79%) and to a lesser extent as fine roots (21%) [84]. Agroforestry land-use systems can also be managed by increasing the SOC reservoir in the soil by avoiding burning and minimizing soil disturbance/tillage practices and by erosion control.

12. Conclusion

Conservation agriculture minimizes C loss from the soil and helps in C restoration to manage agroecology with sustained productivity. Conservation agriculture is a holistic approach related to the cropping system that characterized the maximization of crop production in short term basis as well as potential long-term sustainability. Conservation tillage in association with suitable management practices in as depending upon climatic conditions enhances SOC content efficiently under tropical environment over temperate one. Diversified crop rotation provides an opportunity to produce huge biomass C that influences SOC than under monocropping. Moreover, straw incorporation can lead to improving C sink in upland soils and decreases fluxes of GHGs like CH_4. Crop diversification with legume crops can increase the complexity and diversity of C as they contain carbon compounds resistant to microbial metabolism, thus increasing C stabilization. Future studies need to cover the site-specific component of CA. Development of CA-based best resource management, efficient inputs with stress tolerance characters should be taken into consideration to mitigate the adverse effect of climate change. Thus, the key to enhancing soil quality and achieving food security lies in managing agricultural ecosystems using ecological principles which lead to the enhancement of SOC pool and sustainable management of soil and water resources. The increasing evidence points to the validity of conservation agriculture as a carbon storage practice and justifies further efforts in research and development. Concerning the potential of CA as a strategy for C sequestration, important research still needs to be done. To promote CA, appropriate policy, institutional support, advanced technologies, suitable economic incentives should be given to the farmers.

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