The Pharma Innovation Journal 2023; SP-12(9): 1880-1885

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277-7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2023; SP-12(9): 1880-1885

www.thepharmajournal.com
Received: 03-07-2023
Accepted: 11-08-2023

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Effect of conservation agriculture on nitrogen and carbon dynamics for sustainability

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Abstract

Human attempts to increase food production have had a lasting impact on our environment. Prolonged reliance on traditional farming methods, particularly those involving extensive tilling and the removal or burning of crop residues, has exacerbated soil erosion and led to the gradual degradation of our soil resources. This situation has paved the way for the emergence of conservation agriculture (CA), a widely embraced set of management principles that promise more sustainable agricultural production. The importance of CA becomes even more pronounced as it plays a pivotal role in both adapting to and mitigating the adverse effects of climate change on agriculture and the environment. CA practices have demonstrated substantial effects on the dynamics and distribution of soil organic carbon (SOC) and nitrogen, in addition to enhancing and maintaining crop yields. Achieving a noticeable increase in SOC and achieving satisfactory productivity effects through CA requires an appropriate period for SOC accumulation. Consequently, the advantages of CA may not become apparent right away. So, long term experimental research can only provide us the accurate picture. Therefore it is necessary to discuss about the dynamics of nitrogen and carbon in long term CA based experiments.

Keywords: Conservation agriculture, carbon sequestration, nutrient dynamics, soil aggregates

Introduction

Industrial revolution started during the period of late 18th century leads to invention of many new technologies and machineries. This lead to mechanization of work in all sectors. The efficiency of the work got increased as machines did not get tired like humans. Looking into that mechanization of agriculture began after the advent of tractors during 1900s. People felt that this can revolutionize agriculture by transforming it into commercial farming from subsistence farming. The capitalist mindset looked at it in a way to commercialize agriculture and earn profit from it. They started tilling the soil to get higher output. Over tilling and overgrazing had a drastic negative impact on agriculture leading to degradation of the tillage. Excessive tilling eroded the top layer and lead to the Dust Bowl in the United States. Drought leads to lack of moisture in the top soil layer increasing the friability of the soil particles. As the soil particles did not have anything to hold on to, so with wind it started to blow which affected the visibility and caused health issues. It rendered large hectare of land unproductive. All these problems lead to the formation of new type of sustainable agriculture system i.e. Conventional Agriculture. It is the combination of ideas given by Mr. H.H. Bennet who is the father of soil conservation and Mr. Edward H. Faulkner who is the father of no-tillage.

Conservation Agriculture

If we look into conservation agriculture is basically a sustainable farming system defined as“a concept for resource saving agricultural crop production, which is based on enhancing natural and biological processes above and below ground” (FAO). It is a resource saving technology based on three principles:

1. Minimal soil disturbances enabled through no-till/reduced tillage
2. Maximum soil cover/residues
3. Diversified crop sequences/rotations (spatial and temporal crop sequencing)

Minimal soil disturbances: The importance of this principle is that it focuses on reducing the traffic in agriculture land. Due to inversion of soil, especially by primary tillage the soil aggregates break exposing the soil organic matter, which gets oxidized resulting in decreasing of soil fertility and increasing carbon footprint of agriculture by increasing GHGs. This will decrease land productivity in due course of time. The benefits of this principle are:

- Reduced water and wind erosion
- Reduction of fuel, time and labor costs
- Increasing Water infiltration and conserving soil moisture
- Decreasing the amount of fertilizer per hectare

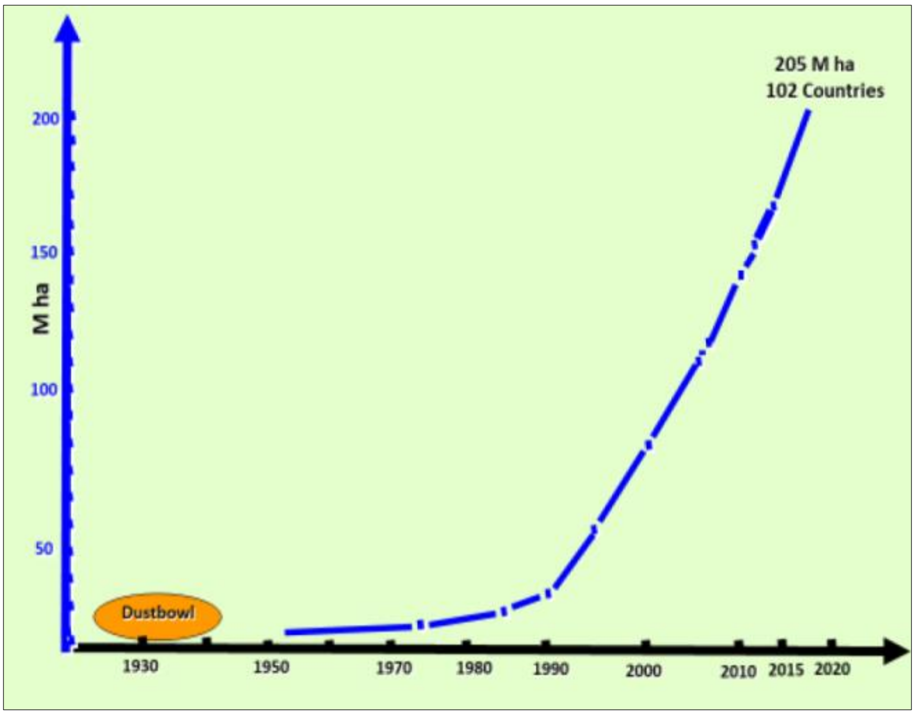
Maximum soil cover/residues: It says that minimum 30 per cent of the land must be covered with residues. As presently we are facing the issue of residue management and residue burning, so by going for residue retention on the field in this method we can solve the problem. It will also provide physical layer of protection for the top soil from wind and water erosion. It also acts as a source of food for the microbes which will enhance the soil biodiversity. The other benefits are:

- Recycling of nutrients
- Organic matter accumulation and C sequestration
- Suppressing weeds

Diversified crop sequences/rotations: This will break the cycle of pest, disease and weeds which is associated with monocropping. Moreover it will act as a contingent cropping planning during various weather vagaries by intercropping**.** Inclusion of legumes will enhance the nitrogen content of the soil as well. Other benefits include:

- Increase in water use efficiency
- Enhance the soil structure, diverse range of soil flora and fauna
- Reduction of pest populations and plant diseases
- Increase soil fertility and yield

Status of conservation agriculture in World and India



Source: Kassam *et al*., 2022 [9]

Fig 1: Status of Consevation agriculture in the world till 2022

Conservation agricultural practices are gaining increased attention worldwide (Fig 1). CA ispracticed globally on about 205 mha of area in about 102 countries. United States holds the largest area. Initially during 1930s occurrence of Dustbowl created awareness about ill effects of extensive tillage practices. Due to which the need of minimum tillage practice arised. This lead to increasing adaptation of No/Minimum tillage among farmers worldwide. Moreover, increasing oil prices and invention of suitable technologies lead to increasing popularity. In case of CA mechanization plays an important role. Traditional method of planting practices cannot be performed here. Presence of crop residues on the surface layer can hamper seed placement ang germination as well. Due to these reasons, we need specialized planter for sowing purpose like Happy seeder in India.

If we look into India's status, it has 1.5 mha under CA.CA was introduced in the country about two decades ago but it is still in infant stage with maximum concentration in Indo-Gangatic plain. Lack of availability of residues and farmer's interest are some of reasons for the less area. Especially in dryland areas where farmers use straw as fodder for cattles, it is difficult for the farmers to go for residue retention in field. Scattered lands and smaller land holding also create shindrance for adaptation of conservation agriculture. Still then, development of new machineries and new farming policies can pursade the farmers to uptake this farming system in India.

Importance of Conservation Agriculture for sustainable food production

Scenario of present method of agriculture shows us that it is not a sustainable farming system. The decling factor productivity due to deterioration of soil health owing to less soil organic matter is the main reason. Moreover changing climate has adversely challenged agriculture sectors, unpredicted rainfall and longer dry spell periods are affecting farmer's hard work. Soil pollution due to increasing use of chemicals id affecting the biotic life present in it. So we need to find solution to these problems as agriculture is the major source of food on the planet.

Conservation agriculture comes as answer to the most suitable method of farming the present context. Along with the solutions to the above problems in the changing climate it can sequester the atmospheric carbon and solve two of our biggest problem i.e. reducing GHGs from the atmosphere and enhance soil health thereby increasing food production. For this we need to understand carbon and nitrogen dynamics in conservation agriculture systems.

Carbon and nitrogen dynamics

Nutrient dynamics refers to the movement of nutrients from the atmosphere to soil and back again to atmosphere. In agricultural context we look deeper into different forms of the elements in soil. So it is defined as "Processes that determine the state or form in which nutrients occur in soils". It is two parts:

a) **Transformation:** It is mainly performed by the soil microbes. It is further divided into:
- Mineralization: Changing of nutrients from unavailable form to available form
- ii)Immobilization: changing of nutrients from available to unavailable form

b) **Nutrient uptake:** It refers to uptake of nutrients by the plants from the roots.

Nutrient dynamics will help us to understand how the nutrient flows and its balances to enhance soil health, productivity and environment sustainability.

Soil organic carbon and its importance

Carbon which is present in soil organic matter is called as soil organic carbon. It constitutes about 58% by weight of soil organic matter. Organic carbon is mainly present in the top soil (2500 Pg C). SOC plays vital component of productive agriculture. It recognized as a tool to mitigate climate change. It is an important tool to enhance soil health which will in turn enhance soil fertility. It will also amplify the soil physical structure which will increase water holding capacity of soil, aeration, hydraulic conductivity etc. enhancement of soil organic carbon in soil will also affect soil microbial population which will increase the nutrient supplying capacity of the soil.

Soil erosion is one of the major factors of SOC loss as top soil holds major carbon. Losing top soil leads to los fertile soil as well organic carbon. Enrichment of soil with SOCby adoption of conservation-effective measures (i.e., CA on cropland) can avoid the emission of 1.1 Pg C year^{-1} caused by erosion-induced mineralization of SOC (Lal 2003) [11]. The adoption of CA is more relevant in achieving the aspirational goal of "4 per mille," set at COP21 (Conference of the parties to the United Nations Framework Convention on Climate Change in Paris) as a compensation for the global emissions of GHG by anthropogenic sources.

Nitrogen dynamics and its importance

It is the primary macronutrient and it is required in largest amount compared to all other macronutrients. Plant uptake in two ionic forms - NH_4^+ and NO_3^-. Sources of nitrogen to plants are fertilizer and atmospheric N fixed by nitrogen fixing bacteria. It is mainly require for the vegetative growth and development and delay in maturity. It is the major component of chlorophyll, amino acids, protein and enzymes which drives various metabolic activities.

Nitrogen within the soil is intricately linked to carbon within soil organic matter (SOM). Various factors that impact the cycles of carbon and nitrogen in the soil are influenced by agronomic practices. Conservation agriculture (CA) practices regulate these cycles, resembling the stability of natural ecosystems by maintaining conditions of minimal soil disturbance, permanent organic soil cover, and species diversity. In this context, CA optimizes the productive conversion of carbon and nitrogen in an agroecosystem, reducing undesirable gaseous losses of both carbon and nitrogen.

The significance of CA becomes even more crucial when addressing and mitigating the adverse impacts of climate change on agriculture and the environment (Trenberth 2011) [26]. The accumulation of soil organic carbon is the primary advantage of CA, enhancing soil sustainability. This increase in SOC has positive impact on nitrogen as well as other biological, chemical and physical properties. This will also help in mitigating climate change by carbon and nitrogen sequestrations. This has two major positive impacts, firstly, it will reduce greenhouse gases in the atmosphere and secondly, holding carbon and nitrogen in soil will enhance agriculture production. It takes time for Conservation Agriculture (CA) to accumulate enough Soil Organic Carbon (SOC) and show significant improvements in productivity, which means that the advantages of CA may not become immediately evident (Chivenge *et al*. 2007) [3]. Enhanced soil quality and improved nutrient cycling contribute to greater crop resilience and adaptability to regional climate variations, particularly by enhancing crop efficiency in coping with severe drought conditions in certain regions (Hobbs and Govaerts 2010) [5]. CA proves especially advantageous in areas where soil moisture and organic matter are limiting factors (Thierfelder and Wall 2009) [24].

Carbon and nitrogen stock and sequestration

Soil the third largest pool of carbon and holds more carbon than the combination of both atmosphere and vegetation. Locking the carbon in soil as carbon stock will enhance soil health and will cut off green house gas emission from agriculture. Nitrous oxide is one of the major GHG with global warming potential of about 300 times more that carbon dioxide, therefore holding it in soil is highly important for the planet.

No tillage has highly positive impact on increasing carbon stock. Liu *et al*. (2013) [12] recorded that after 17 years, the SOC stock increased from initial quantity of 45.1 Mg C ha^{-1} to 52 Mg C ha^{-1} in case of CA, while in conventional agriculture there was an increase of 46.3 Mg C ha^{-1} from the initial quantity of 45.4 Mg C ha^{-1}. Continuous addition or residues along with no tillage has enhanced the carbon stock. Similar results are also observed with nitrogen, long-term effects (22 years) of no-till with residue retention enhanced total soil N and its fractions in a dry-land winter wheat cropping system. More soil N accumulated for the whole soil profile (0 to 60 cm) in the no tillage (3.38 Mg ha^{-1}) treatment relative to the conventional tillage (3.17 Mg ha^{-1}) treatment (Zhang *et al*., 2016) [28]. Silva *et al*. (2019) [22] conducted an experiment on the emissions of CO_2 resulting from soil cultivation and management practices in agricultural production systems and found that on the first day after tillage, CO_2 emission was 87% higher in the plot under conventional tillage (3.86 μmolm^{-2} s^{-1}) than reduced tillage (2.06 μmolm^{-2} s^{-1}) and 147% higher than in the plot under no tillage (1.56 μmolm^{-2} s^{-1}). This figures enables us to understand that CA can reduce carbon foot print of agriculture.

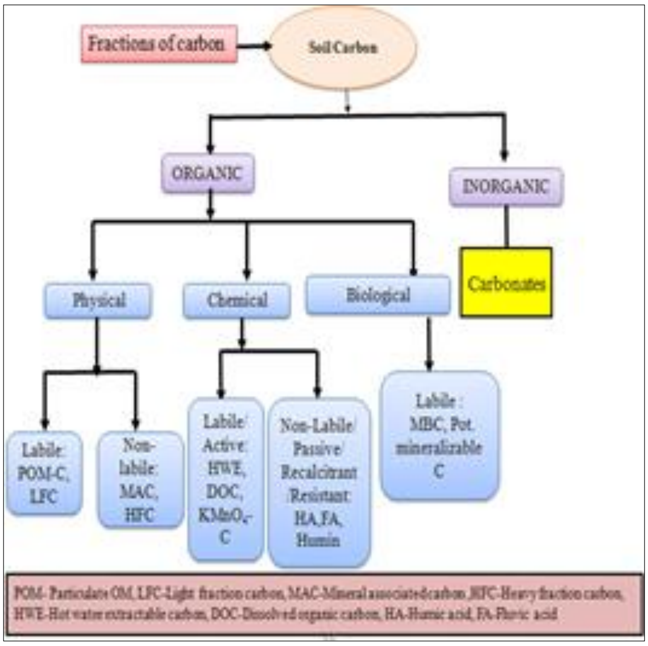
Soil sequestration is another way to enhance soil carbon and nitrogen. It refers to storing the atmospheric carbon dioxide in the soil for longer period through plants. Prasad *et al*. (2016) [20] reported that among tillage systems, the rate of C sequestration in minimum tillage was 186 kg C ha^{-1} yr^{-1} as compared to 62 kg C ha^{-1} yr^{-1} in conventional tillage. As we discussed above the negative impact of nitrous oxide, Beare *et al*. (1994) [2] reported that in case of no tillage due to the presence of higher amount of macro-aggregates, they are holding large quantities of nitrous oxide in them by physical barrier. This shows us the importance of conservation farming from ecosystem point of view.

Fractions of carbon and nitrogen

In soil, carbon and nitrogen remain in various different forms (Fig 2 & 3) depending on the decomposition rate. Soil biota plays the most important role here by converting the labile form to non labile form and immobilizing the certain carbon and nitrogen in the cycle and vice-versa. Conservation agriculture practice like, permanent beds with 20 per cent residue retention of wheat, 50 per cent residue retention of maize and retention of green gram residue increased the SOC mainly due to the active SOC pools, permanganate oxidizable-C(1.70 g kg^{-1}), hot water extractable-C (0.32 g kg^{-1}) and soil microbial biomass C (310 mg kg^{-1}) compared to conventional tillage with complete residue removal (0.58, 0.23 g kg^{-1} and 183 mg kg^{-1},respectively) (Tigga *et al*., 2020) [25]. In various different cropping systems no tillage recorded greater hot-water extractable organic C (HWEO-C) stocks of 61%, 55% and 53%, and permanganate oxidizable C (POX-C) stocks of 23%, 21% and 32% were attributed to NT than those in CT soils under Rice based, Soybean based and Cassava based cropping system, respectively, at 0–5 cm soil layer. The reason is that due to residue retention combined with conservation tillage enhances microbial activity. Without physical disruption the carbon and nitrogen does not come in contact with atmospheric air which prevents oxidation enabling higher soil carbon and nitrogen according to Hok *et al*. (2013) [6]. Similar to the above conclusions, Karlen *et al*. (2013) [8], Sharifi *et al*. (2008) [21], Malhi *et al*. (2018) [14] and Badagliacca *et al*. (2021) [1] were some of the authors who reported the occurrence of higher carbon fractions in conservation agriculture compared to conventional agriculture.

Yield from conservation agriculture is affected by time period of land conversion from conventional to conservation agriculture system. It takes certain time period to provide higher yield as recorded by Pergo *et al*. (2019) [18]. In their experiment it was found that long term experiment of conservation agriculture provide higher yield that conventional systems, compared to medium and short term experiments. Although carbon fractions were higher in all the time line of CA compared to conventional agriculture. Increasing SOC not only depends on management factors, it is also affected by climatic factors. Especially in tropical regions, due to higher temperatures the decomposition occurs at a faster rate due to higher microbial respiration resulting in declining organic carbon, even with adoption of conservation agriculture as recorded by Pinheiro *et al*. (2015) [19].

Zero tillage also has positive impact on different fractions of nitrogen owing to microbial activity and residue retention. In one experiment by Kumar *et al*. (2021) [10] the zero tillage system, when applied to maize-chickpea cropping, demonstrated its superiority in terms of all nitrogen fractions, contributing to improved yield, nitrogen uptake, physico-chemical soil properties, and soil fertility levels. Notably, organic nitrogen forms, particularly total hydrolysable and amino acid nitrogen, exhibited robust positive relationships with available nitrogen. In summary, organic nitrogen comprised a significant portion of soil nitrogen and played a pivotal role in both soil nitrogen cycling and crop production. Beyond its conversion into mineral nitrogen for plant uptake, organic nitrogen also supplied certain organic components that could be directly absorbed by plants. Inclusion of legumes in crop rotation along with conservation tillage has further positive impact on soil health and crop yield (Mamata *et al*., 2023) [15]. Crop diversification also enhances light and heavy carbon fractions along with higher soil carbon and nitrogen (Maiga *et al*., 2019) [13]. Crop diversification enhances microbial activity which hastens the process of residue decomposition leading to higher fraction of carbon and nitrogen.



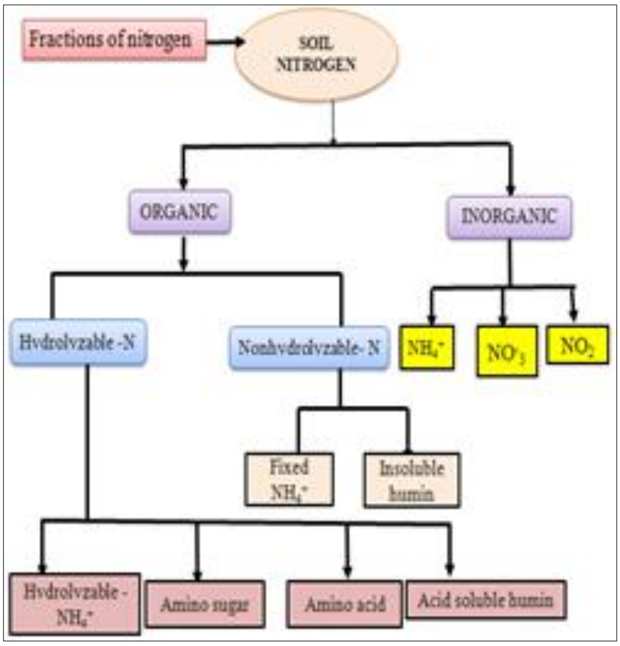


Fig 3: Fractions of nitrogen

Soil aggregated and associated Carbon and Nitrogen

Conventional tillage practices lead to the breakdown of soil aggregates, a highly undesirable action that significantly contributes to the destabilization of soil structure. Soils with stable aggregates possess greater potential for protecting carbon against both abiotic and biotic agents of degradation, in contrast to soils with weaker aggregates. These stable aggregates serve as a physical barrier around soil organic matter, effectively shielding it from oxidation. Additionally, various aggregate classes exhibit varying abilities to safeguard carbon, and tillage can influence the distribution of these aggregate fractions. But due to continuous disturbance of the soil due to tillage activities, the aggregates are broken exposing the organic matter. This leads to the oxidation and loss of carbon and nitrogen to the atmosphere. Among aggregates macro-aggregates (>0.25 µm) holds more importance as they are bigger in size so they hold larger carbon and nitrogen (Fig 4). But being bigger in size it is also highly susceptible for disintegration. Conservation tillage practice like using of chisel plough and rotary plough increased the pools of C (10–11%) and N (13–15%) associated with the macro-aggregate-sizefraction, while decreasing C (50–66%) and N (48–61%) associated with the micro-aggregate-size fraction (Kabiri *et al.*, 2015) [7]. Reduced tillage practices lead to protection of macro-aggregates where as destruction of macro aggregates lead to the formation of micro-aggregates. These microaggregates hold less carbon and nitrogen. As continuous tillage practices break the aggregates so this shows the increment of larger micro-aggregates (<0.25 µm). Sithole *et al*. (2019) [25] also concluded the same result after 13 years of tillage experiment. They found that large amount of carbon and nitrogen was associated with macro aggregates in no tillage practice whereas in conventional tillage carbon and nitrogen were associated with micro aggregates, which is highly prone to chemical oxidation. Therefore it can be concluded that stability of macro aggregates depends on tillage practices.

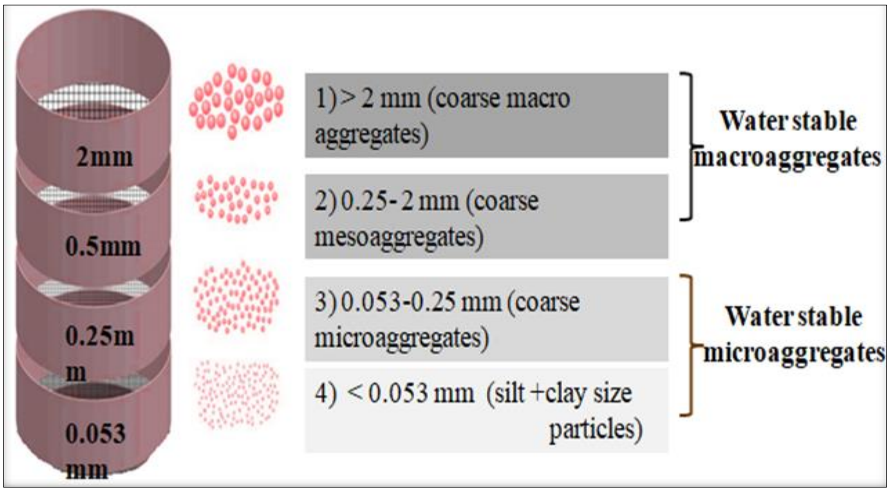


Fig 4: Different aggregate fractions

Stratification Ratio

It is defined as concentration of soil organic carbon or nitrogen in the surface divided by that deeper in the soil profile, (Franzluebbers, 2002) [4]. For a good quality soil it should be >2. This indicates higher soil organic carbon or nitrogen at the surface layer. As crop cultivation occurs at the surface layer (maximum root hairs at 0-25 cm), thus higher SOM at this layer will help in gaining higher production due to better soil health. Conservation tillage, characterized by reduced number of tillage operations and leaving crop residues on the soil surface, had stratification ratio of soil organic C (>2) and was significantly greater than under traditional tillage practices (<2) (Moreno *et al*., 2006) [17]. Xue *et al*. (2015) [27] recorded that stratification ratio (SR) in case of no tillage at 0-5:5-10cm depth of SOC, total nitrogen and C: N ratio (1.45, 1.38 and 0.96, respectively) is significantly higher than plough tillage with residue incorporation at similar depth (1.11, 1.05 and 0.95, respectively). The similar trend was also observed in SR at 0-5:10-20 depth as well. In the same line Moreno *et al*. (2006) [17] studied the effect of long-term conservation tillage (CT) and traditional tillage (TT) on the stratification ratio of soil organic carbon.

Conclusion and future aspects

Conservation agriculture emphasizes three fundamental principles: minimizing soil disturbance, maintaining organic soil cover, and diversifying crops. CA enhances both crop and soil productivity, making agriculture more resilient to climate variations and aiding in the mitigation of climate change's impact on agriculture. It enhances the physical, chemical, and biological properties of the soil, leading to improved water infiltration and retention, enhanced nutrient cycling, and increased gaseous exchange, ultimately resulting in better carbon storage.

CA has been adopted by over 40 countries, with significant uptake in select regions. There is substantial potential to enhance land productivity in water-limited conditions through CA adoption. However, it's important to note that short-term CA implementation may not fully achieve the long-term objective of substantial soil organic carbon accumulation. To comprehensively assess CA's overall impact on soil carbon storage, in-depth soil profile studies are necessary. Therefore, the significance of CA becomes even more pronounced when addressing and mitigating the adverse effects of climate change on agriculture and the environment. Conservation agriculture based results take longer time to show its results. Furthermore it is affected by location, duration, type of soil and residue and climatic factors. Sosite-specific conservation agriculture technologies needs to be developed and disseminated for improving crop productivity, soil health, carbon sequestration and enhancing input use efficiency. We need to understand the mechanism of carbon and nitrogen cycle to enhance its concentration in soil in an effective way. Comprehensive soil profile studies are needed to evaluate the overall effect of conservation agriculture on soil C and N storage in long term studies.

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