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*Review article*

# Conservation Agriculture Effects on Soil Greenhouse Gas Fluxes: An Overview

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**Abstract:** Conservation Agriculture (CA) alters soil properties and microbial processes compared to conventional agriculture. These changes can affect soil-atmosphere greenhouse gas (GHG) fluxes. In this overview, we summarized the results of global literature and the gaps in measuring and understanding of GHG fluxes in CA systems and conventional agriculture. Some studies compared soil carbon sequestration and soil respiration in conservation agriculture and no-tillage system with conventional agriculture and the results were not consistent in all experiments. Interactions between CA pillars and soil factors such as soil moisture, temperature, texture can determine the rate of respiration rate and soil-atmosphere $CO_2$ fluxes. The majority of studies reported larger $N_2O$ emissions in no-tillage treatment compared with conventional tillage while some other studies reported no difference between no-tillage and conventional tillage systems. In the majority of CA studies, there is lack of required information which is necessary to understand the mechanisms and processes that affect soil GHG fluxes. Determining factors like climate, amount of plant residues, soil type, crop types included in crop rotation and cover crops and duration of the study are not considered. Static chamber method was used for measuring soil-atmosphere GHG fluxes in the majority of studies. Spatial and temporal changes in GHG flux rates are high and missing part of highly episodic events by using static chamber method may result over- or under-estimation in flux balance calculation. Applying standard techniques for measuring continuous fluxes can help to calculating accurate GHG balance.

**Key words**: Conservation Agriculture, Soil Greenhouse Gas (GHG) fluxes, Soil Tillage

## 1. Introduction:

Agricultural lands are one of the major anthropogenic sources of greenhouse gases emissions and contribute about 13% of global emissions [1]. Agricultural practices may affect agroecosystems and offer a way to mitigate greenhouse gases emission. Agricultural soils are a net source or sink for greenhouse gases depending on the status of soil physical, chemical, and biological properties. Changes in these variables control microbial process which controls C sequestration in soils and GHG fluxes. Carbon sequestration in agricultural lands is considered to be the most important of GHG abatement strategies and the global mitigation potential estimated to be almost 1400Mt $CO_2$ eq [2].

Conservation Agriculture was introduced to control wind and water erosion [3] and due to providing multiple ecosystem services in agroecosystems, agricultural lands under CA practices in the world is growing [4]. CA is a system of agricultural practices that include minimum soil disturbance, permanent organic soil cover, and crop rotation. CA has several ecosystem services such as climate change mitigation as related to greenhouse gases (GHG) emission, C sequestration and regulation of water and nutrients through modification of several soil properties (chemical, physical and biological). CA practices foster the buildup of new soil organic carbon by protecting soil surface via plant residues or cover crops [5]. Further, $CO_2$ emissions have been shown to be reduced by the inclusion of soil organic carbon in soil aggregates [6]. Regarding $N_2O$ emission, many agricultural practices such as tillage, legume cropping, crop residues and manure or mineral N fertilizers may contribute to the emission rate.

In many past research papers and reviews, ecosystem services of CA including GHG fluxes have been investigated. The majority of these studies focused on the effects of reduced or no-tillage systems and effects of plant residues and crop rotation are ignored. Moreover, understanding the processes of GHG fluxes in agroecosystems with CA practices is arduous due to site-specific context, management, soil type, and climate. For instance, $CO_2$ emission is often lower in no-till than in conventional till [7] but an increase in no-till has also been reported compared to conventional tillage [8]. Some studies reported that tillage can increase emission of $N_2O$ [9, 10] but some reported decrease in $N_2O$ emission compared to no-till treatment [11, 12]

In this paper, we summarize CA effects on soil GHG fluxes and bring to light gaps and questions needed to provide a framework for the potential competence of CA practices in GHG mitigation. This review is based on global literature about CA practices effects on smallholder farming systems and experiments set upped to compare conventional agriculture with CA. We discuss CA effects on $CO_2$, $N_2O$, and $CH_4$ fluxes separately to link CA effects on microbial processes that control these GHG fluxes.

## 2. Carbon Sequestration and Carbon Dioxide Emission

### 2.1 Tillage

Soil respiration and carbon dioxide ($CO_2$) emission can decrease soil C stock. Soil disturbance increases soil C loss by altering soil respiration rate and $CO_2$ emission. Some studies have shown that minimum soil disturbance (reduced-tillage or no-tillage) elevated soil C compared with conventional tillage [13-16]. This improvement was often restrained to the top layer. At deeper soil layers (> 10 cm) soil C level might be equal or less than conventional tillage [13]. [15] compared soil C in 100 studies in USA and Canada and some from Brazil, Mexico, Spain, Switzerland, Australia, and China. In 54 cases soil C was higher in no-tillage system and in 39 cases there was no difference between conventional tillage and no-tillage treatments. In 7 studies soil C stock was lower in no-tillage system. The potential of CA for C sequestration and low $CO_2$ emission depends on multiple factors such as cropping system, soil texture, foregoing C concentration, management duration and climate [17].

In addition, soil C stock it is better to be reported in equivalent soil mass (ESM) basis rather than on fixed depth layer and it abates overestimation in C stock calculation with higher bulk density in CA treatment (Table.1).

| **Depth (cm)** | **Tillage treatment** | | | **No-tillage treatment** | | |
|---|---|---|---|---|---|---|
| | Bulk density (g cm$^{-3}$) | Soil C concentration (g kg$^{-1}$) | Cumulative C mass (Mg ha$^{-1}$) | Bulk density (g cm$^{-3}$) | Soil C concentration (g kg$^{-1}$) | Cumulative C mass (Mg ha$^{-1}$) |
| **5** | 1.34 | 6.3 | 4.4 | 1.29 | 12.9 | 8.4 |
| **10** | 1.33 | 6.3 | 8.9 | 1.45 | 7.9 | 14.5 |
| **20** | 1.33 | 5.9 | 17 | 1.44 | 5.4 | 22.8 |
| **30** | 1.32 | 6.1 | 25.4 | 1.47 | 4.3 | 29.4 |
| **40** | 1.33 | 5.7 | 33.8 | 1.42 | 3.6 | 34.8 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **ESM C** | | | 27.4 | | | 29.4 |

*Table 1: bulk density, soil C concentration and cumulative soil C in different depth layers in tillage and no-tillage treatments (Plaza-Bonilla et al., 2010), and the equivalent soil mass C (ESM C)*

In the majority of studies, soil C stock is reported based on fixed soil depth layer and soil bulk density is not included in the calculation. The result of studies using fixed depth rather than ESM is that reports of changes in soil C stocks are confounded by management-induced changes in bulk density rather than out- right changes in stock [17].

### 2.2 Crop Rotation

Potter *et. al.*,[18] evaluated no-tillage effects with four crop rotations (continuous wheat, continuous sorghum, wheat/fallow and wheat/fallow/sorghum/fallow) in a study and concluded that no-till management with continuous crops stored more C in soils in southern Great Plains in the USA. Fallow limited carbon accumulation.

Crop rotation can affect soil C sequestration by increasing biomass production and C diversifying rooting pattern. In many studies crop rotation with tillage in confounded and make it complicated to understand effects of crop rotation alone. West and Post [19] found that crop rotations stored more C than monoculture in no-tillage treatment, though there were exceptions with corn-soybean rotations with less soil C than monoculture maize.

Franzluebbers *et. al.*, [20] found that 65% to 98% of the variation in $CO_2$ flux could be accounted by crop rotation, tillage and season by altering soil temperature and moisture. While temperature increases soil $CO_2$ efflux, the effect on net ecosystem C balance depends on any effect on primary productivity. Crop rotation effects on soil C stock are linked with produced above- and below-ground biomass [19].

There are limited studies investigated soil C input by plants biomass production (especially root biomass), to better explain crop rotation effects. Boddey *et. al.*, [21] showed that legume intercrops in the rotation increased soil C stock in no-tillage treatment was the response of higher production and residues inputs. They concluded that low mineral N in no-tillage treatment led to slower decomposition rate and $CO_2$ efflux, higher roots: shoots ratios and belowground C input.

### 2.3 Residue Retention

Plant residues effects on soil carbon and $CO_2$ emission are inconsistent. Johnson *et. al.*, [22] showed that crop residues removal did not alter $CO_2$ emissions compared with crop residues retained treatment. In some other studies, soil $CO_2$ emission was decreased. A USDA project in five states in the USA indicated that corn stover removal decreased soil total $CO_2$ emissions by 4%, relative to no removal [23].

Retention of crop residues is needed for increasing soil stock and it is affected mostly by the quality than quality of plant residues. Paul *et. al.*, [24] found that limited amount of residues have little or no effects on soil C stock. Moreover, the quality of plant residues is determined by the C: N ratio and it may affect soil C storage and dynamic. Plant residues with high C:N ratio reduce available N in soils and it may lead to lower crop production and materials with low C:N ratio as in case of legume residues increase available N and possibly microbial processes such as soil respiration and consequently $CO_2$ emission [25].

### 2.4 Interaction of Tillage, Crop Rotation, and Plant Residues

It is important to study interactions between CA pillars (minimum soil disturbance, crop rotation, and organic soil cover) to understand processes that are involved in soil GHG fluxes in agroecosystems. For instance, in CA systems no-tillage may not increase soil C stock when there are limited crop residues. Adequate crop residues are essential for increasing soil C stock. Dendooven *et. al.*, [26] concluded that soil tillage had no significant effect on $CO_2$ emission independent of crop residue management. Crop residual removal significantly reduced soil respiration rate and $CO_2$ fluxes. Residue management improved soil C stock and created C substrate for soil microorganisms and removing it reduced soil $CO_2$ emission. Interactions between crop residuals and other soil factors such as soil moisture, temperature, texture can determine the rate of respiration rate and soil-atmosphere $CO_2$ fluxes. However, these network of multiple interactions that alter soil C stock makes it difficult to identify a clear and fixed guideline for CA practices in agricultural fields.

Models can be used to simulate interactions between CA components at different levels to evaluate the contribution of different practices in soil C storage. Several studies have simulated C sequestration and reported relatively small C stock improvement in soils under no-tillage system [27, 28]. Model simulations can be used in investigating on interactions among CA practices to figure out the primary factors affecting soil C sequestration in different agroecosystems. In model simulations, it should be noticed that the models are validated for the soil, climate and crop types to be able to reflect changes in soil C stock in the response of CA practices [17].

## 3. Nitrous Oxide Emission

Nitrous oxide ($N_2O$) is a long-lived GHG with 298 times higher global warming potential that of $CO_2$ and remains in the atmosphere 114 years. Denitrification and nitrification processes in soils produce N2O and emit into the atmosphere. Nitrification is the dominant process in aerobic condition while in anaerobic condition denitrification occurs chiefly. The contribution of these two pass ways to $N_2O$ emission depends on changes in soil air and water distribution in the soil profile.

### 3.1 Tillage

$N_2O$ emission response to no-tillage or minimum soil disturbance in CA systems compared to conventional tillage is not clear [29]. The majority of studies reported larger N2O emissions in no-tillage treatment compared with conventional tillage [9, 10, 30-32]. Some studies reported lower $N_2O$ emission under no-tillage or reduced tillage treatment [7, 10, 33], while some other studies reported no difference between no-tillage and conventional tillage systems [8, 34-37]. Six *et. al.*, [38] reported that $N_2O$ emissions in no-tillage treatment decrease with time. And this results is consistent with Rochette *et. al.*, [39] concluded that no-tillage treatment increased $N_2O$ emission only in poorly-aerated soils.

Soil structure has a direct relation with bulk density, soil C stock, and aggregate formation. All these factors are influenced by soil disturbance and tillage. Soil aggregate formation in no-tillage system due to higher soil organic input is higher than conventional agricultural systems [40-42]. Nitrification is the main source of $N_2O$ emission when water filled pore space (WFPS) is below 40% while the contribution of denitrification in $N_2O$ emission increases above 65-70% WFPS [43, 44].

Soils with higher soil moisture content and higher C input under CA practices increases $N_2O$ emissions [45-47].However, The impact of tillage on $N_2O$ emission depends on temperature, soil moisture, soil chemical and physical characteristics and duration of no-tillage treatment [31].

### 3.2 Crop Rotation

Crop rotation can alter $N_2O$ emission by changing soil $NO_3$ availability originated from soil organic matters decompositions [48]. The quantity and quality of crop residues can alter $N_2O$ emissions. Legume residues contain low C : N ratio and can result in higher $N_2O$ emissions [49]. On the other hand, crop residues with high C : N ratio may result in N immobilization and consequently low $N_2O$ emission. However, $N_2O$ emission in CA systems depends on crop rotation and the quality and quantity of crop residues [17].

Wang *et. al.*, [33] reported substantially higher $N_2O$ emission than those observed in cereal cropping systems in semiarid region in Australia. They concluded that factors might contribute to higher emission from these croplands may include higher clay and soil organic C content, higher precipitation, temperature, and generally occurrence of wet and warm summer.

### 3.3 Residue Retention

Crop residue retention in CA systems lead to higher soil organic matter on the soil surface. High soil moisture and anaerobic conditions associated with high content of soluble carbon. Consequently, easily decomposable organic matter can boost denitrification and $N_2O$ emissions [43].

Effects of CA practices on soil $N_2O$ fluxes is controversial. There are 3 main reasons for observing inconsistent results in studies investigated CA pillars effects on $N_2O$ emissions. a) the majority of studies measures short-term (single season or one year) soil $N_2O$ fluxes, b) high temporal and spatial variation in soil $N_2O$ emissions, and c) methodological problems in field measurements. For example, sampling intervals vary from several days to one month in different studies. Estimating annual emission can be over-estimated about 200% if the sampling interval is about one month due to missing considerable episodic events [50]. However, complete seasonal or annual patterns of emissions should be captured in static chamber based methods [17].

## 4. Methane Emission

Methane ($CH_4$) is another GHG with 25 times higher global warming potential than $CO_2$ over a 100 year time and its lifetime in the atmosphere is 12 years. The main terrestrial source for $CH_4$ emission is methanogenic archaea which exist in soils with high soil moisture content such as lowlands, wetlands and rice fields [51]. Methanotrophic bacteria live in upland soils like agricultural fields and have the ability to utilize $CH_4$ as their energy source [52].

### 4.1 Tillage

Tillage in agricultural practices reduced the $CH_4$ oxidation capacity of methanotrophic bacteria by six to eight times as compared to natural undisturbed soils [53]. The destruction of an aerobic micro-sites within the soil structure and the removal of the organic layer that develops at the top of the uncultivated soils may be responsible for the reduction of CH4 uptake rates in cultivated soils [54]. Some studies focused on tillage effects on the activity of methanotrophic bacteria in agricultural fields. For example, Maxfield *et. al.*, [55] suggested that tillage can reduce significantly methanotrophic biomass and activity.

### 4.2 Crop Rotation

Different kinds of crops can have distinct CH4 balances. Hütsch *et. al.*, [56] observed that intact soil cores from a continuous maize plot showed lower CH4 oxidizing activity than samples from a continuous rye plot. Crops with low C:N ratio has the potential to decrease $CH_4$ oxidation in soils by altering soil Ammonium ($NH_4$) or Nitrate ($NO_3$) concentrations. $NH_4$ inhibition in methanotrophic activity in the field was first reported by [57]. Physical similarities between CH4 and NH3 permit both compounds to compete for methane monooxygenase enzyme (MMO) [58].

Some studies did not show any effect N application on CH4 oxidation even after several years [59].These results suggest either that the methanotrophic bacteria in these soil are tolerant to excess NH4 , or other soil properties like N immobilization and pH protect them. Gulledge *et. al.*, [60] hypothesized that the inhibition pattern could have resulted from immobilization or nitrification that initially buffered the CH4 oxidizers from exposure to NH4.

### 4.3 Residue Retention

Many studies investigated effects of plant residues on soil surface on soil moisture [61, 62]. CH4 transport in soils occurs in the gas phase exclusively. Soil moisture controls air diffusion into the soil and thus regulates the uptake rate of atmospheric CH4 in soils. The optimal range of water content depends on landuse. For grassy soils maximum CH4 oxidation occurred in a range from 18 to 33% of moisture content and for forest soils optimal soil moisture was between 30 and 51% [63].

With increasing soil organic matter, bulk density decreases while pore volume increases and soil granules form. This can alter the CH4 transform to the methanotrophs for oxidation [63].

Some studies investigated on soil structure to understand lower CH4 uptake in pastures than forest soils [64-66]. Soil aggregates are a key factor in soil structure and functioning, affecting water, air, heat and nutrient availability, the size and numbers of pores, water movement and soil greenhouse gas exchange [67]. Plant residue retention facilitates soil aggregate formation. Higher organic carbon input increase aggregate formation by increasing binding agent like humified organic matter, microbial and plant-derived polysaccharides, fungal hyphae and roots [68].

## 5. Conclusion

Many studies have indicated that CA pillars can increase soil C stock considerably [17, 69]. On the other hands, there are studies that showed no significant improvement in soil C sequestration in soils under CA practices [70]. Understanding the impacts of CA practices on soil C requires an integrated approach to articulate crop production to organic C input into the soil, decomposition rate, microbial activity and biomass and soil C formation. In addition, in future investigations on soil C stock determining factors like climate, amount of plant residues, soil type, crop types included in crop rotation and cover crops and duration of the study should be considered. In the majority of CA studies, there is lack of required information which is necessary to understand the mechanisms and processes affect soil C storage.

Amount of plant residues as soil organic cover in CA is a key factor in estimating the amount of C storage. Produced residues and management practices should be correlated with crop productivity to facilitate simulations in detailed process models. The amount of crop residues needed to improve soil C storage depends on different factors such as crop type, crop productivity and the balance between C input and soil organic decomposition rate. Soil C models should be used more with detailed information about amount of crop residues, management practices, and climate data to illustrate complex interactions and the importance of different factors.

Sampling depth is an important factor in reporting soil C stock. IPCC reference depth is 30 cm [71] and in some studies, the sampling depth is deeper than 30 cm, even up to 100 cm [13, 21]. Soil C reporting in a fixed depth basis leads to inaccurate results when soil bulk density differs due to different management systems for the same depth interval. Today there is a general agreement in reporting soil C stock on an equivalent soil mass (ESM) basis rather than fixed soil depth but many of studies do not use it because of methodological difficulties [17].

In the majority of studies, static chamber method was used for measuring soil-atmosphere GHG fluxes. Sampling frequency varies (from several days to one month) in different studies. Spatial and temporal changes in GHG flux rate is high and missing part of highly episodic events may result over- or under-estimation in flux balance calculation.

Regarding measuring $CH_4$, it is difficult to constrain $CH_4$ balance by using static chamber technique because of emissions tend to be episodic and they are often mediated by ebullition, which is–on a short time scale–a discontinuous process [72]. Applying standard techniques for measuring continuous fluxes and separately count the occurrence of ebullition events can help to calculate accurate $CH_4$ balance.

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