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# Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture:

## *A literature review*

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# Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture:

## *A literature review*

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# FOREWORD

Soil organic matter plays a crucial role in maintaining soil health and its productivity potential. However, most of the world's agricultural soils have become depleted in organic matter and therefore soil health over the years, compared with their state under natural vegetation. This is because the dominant form of agriculture is based on tillage, which accelerates the decomposition of soil organic matter. At the same time, there has been a tendency for tillage agriculture to remove much or all of the crop residues, thus leaving the soil starved of substrate for soil organisms to maintain soil structure and exposed to soil erosion. This degradation process decreases soil's ability to hold water and nutrients, reduces rainfall infiltration and leads to increased soil compaction and loss of soil biodiversity. Such agricultural soils are not able to offer the best factor productivities for production inputs such as nutrient, water and labour, and are not able to harness environmental services such as clean water, carbon sequestration and control of erosion and pests. Thus, tillage-based production systems are considered generally unsustainable and it is important that our farming systems are transformed so the future production intensification can be achieved sustainably.

In addition to sustainable production intensification and enhancing factor productivity, there is a need to transform farming practices to sequester carbon so that climate change mitigation becomes an inherent property of future farming systems. Conservation Agriculture, a system avoiding or minimizing soil disturbance, combined with soil cover and crop diversification, is considered to be a sustainable production system that can also sequester carbon unlike tillage agriculture. However, there appears to be certain degree of uncertainty about the role of Conservation Agriculture in carbon sequestration and its role in reducing green house gas emissions.

This publication presents a meta analysis of global scientific literature with the aim to develop a clear understanding of the impacts and benefits of the two most common types of agriculture, traditional tillage agriculture and Conservation Agriculture with respect to their effects on soil carbon pools. The study conducted by the Plant production and Protection Division in collaboration with experts from several universities attempts to reduce the existing uncertainty about the impact of soil management practices on soil carbon pools and on carbon budget.

**Shivaji Pandey**
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# ABBREVIATIONS

| | |
|---|---|
| AGP | Plant Production and Protection Division of the Food and Agriculture Organization |
| CA | Conservation Agriculture |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| FAO | Food and Agriculture Organisation of the United Nations |
| GHG | Atmospheric greenhouse gas |
| IIASA | International Institute for Applied Systems Analysis |
| MLRA | major land resource area |
| MT | Minimum tillage |
| $N_2O$ | Nitrous oxide |
| NT | No-till |
| SOC | Soil organic carbon |
| SOM | Soil organic matter |
| TA | Tillage agriculture |

# SUMMARY

This study aims at developing a clear understanding of the impacts and benefits of the two most common types of agriculture, traditional tillage agriculture (TA) and Conservation Agriculture (CA), a no-till system, with respect to their effects on soil carbon pools. It is based on a meta analysis of scientific literature, attempting to reduce the existing uncertainty about the impact of soil management practices on soil carbon pools.

The results from literature review on carbon sequestration in TA are compared with CA, a broader agro-ecosystem management concept that requires compliance with three interrelated criteria, namely minimum or no mechanical soil disturbance, permanent organic soil cover, and diversified crop associations and rotations. The review shows that CA permits higher rates of carbon sequestration in the soil compared with TA. When no carbon sequestration or carbon loss is reported in agricultural systems, this is most frequently associated with any one or a combination of the following reasons: i) soil disturbance, ii) monocropping, iii) specific crop rotations, iv) poor management of crop residues, and v) soil sampling extended deeper than 30 cm.

Most of the world's agricultural soils have become depleted in organic matter and soil health over the years under TA, compared with their state under natural vegetation. This degradation process has proved to be reversible and the main ways to increase soil organic matter content and improve soil health seem to be: i) keeping the disturbance impact and interactions between mechanical implements and soil to an absolute minimum, ii) using effective crop rotations and associations, and iii) leaving crop residues as carbon source on the soil surface. The implementation of these practices can help restore a degraded agro-ecosystem to a sustainable and productive state. However, soil organic carbon (SOC) sequestration is generally non-linear over time and the effectiveness of conversion of a farming system from TA to CA depends on a number of variables: for example, soil carbon sink strength increases most rapidly soon after a carbon-enhancing change in land management has been implemented, and reduces with time as the stable SOC stock approaches a new equilibrium which in agricultural soils in Europe for example can take approximately 100 years after a carbon-enhancing land use change has been introduced. Even though some authors report significant increase in microbial activity soon after transition to CA, fuller advantages of CA in terms of soil health and its productive capacity can usually be observed only in the medium- to longer-term, when CA practices and soil biological processes become well established within the farming system.

The study discusses the effectiveness of using average rates of soil carbon content for estimating sequestration at the global level. In reality, there are different carbon pools in the soil undergoing transformation from the undecomposed form to decomposing unstable form to decomposed stable form. The carbon sequestration potential of any soil, for the carbon pool considered, depends on the vegetation it supports (which influences the amount and chemical composition of organic matter being added), soil moisture availability, soil mineralogical composition and texture, depth, porosity and temperature. Therefore, when addressing carbon sequestration, rates should always be referred to specific carbon pools, as each carbon category has highly different turnover rates.

Another aspect of CA in relation to carbon budgets are the reduced power and energy requirements as a result of not tilling the soil. This translates into less fuel consumption, lower working time and slower depreciation rates of equipment per unit area per unit of output, all leading to emission reductions from the various farm operations as well as from the machinery manufacturing processes. In addition, crop residues left in the field return the carbon fixed in the crops by photosynthesis to the soil and the resulting improvement in soil health and fertility leads, over time, to reduced fertilizer use, and $CO_2$ emissions. Other relevant green house gas (GHG) emissions from agriculture, namely methane and nitrous oxides can also be reduced within a CA environment with some complementary practices.

This paper concludes that terrestrial sequestration of carbon can efficiently be achieved by changing the management of agricultural lands from high soil disturbance practices to low disturbance and by adopting effective nitrogen management practices so that the nitrogen balance remains positive. CA allows agro-ecosystems to store more $CO_2$, emit less and all in all improve ecosystem functioning and services, such as the control of rainfall runoff and soil erosion, carbon sequestration including below the plough layer and, when a mulch cover is adopted, increase in water infiltration. The combined environmental benefits of CA at the farm and landscape level can contribute to global environmental conservation and also provide a low-cost option to help offset emissions of the main GHGs. With CA fewer and/or smaller tractors can be used and fewer passes over the field are needed , which also result in lower fuel and repair costs. However, fuller productivity, economic and environmental advantages of CA can usually be seen only in the medium- to longer-term when CA practices and new soil conditions are well established.

These important lessons learnt from around the world regarding the high potential for carbon sequestration with CA systems and the associated opportunity for carbon trading and reduction in GHGs emissions should be taken into consideration in any climate change mitigation strategy for the future.

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CHAPTER 1
# Introduction

Concerns about rising atmospheric carbon dioxide ($CO_2$) levels coupled with climate change mitigation efforts have focused considerable interest in recent years on the world's soil carbon. The world's soils are estimated to have a high sink potential for carbon sequestration, not only in terms of their large potential carbon content, but also because soil organic carbon is particularly responsive to modification through agricultural land use. Conversion of natural ecosystems to cropland acts as a driver of climate change in two main ways. Firstly, agricultural activities directly produce and release about 10-12 percent of the atmospheric greenhouse gases (GHGs), such as $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$) (Smith *et al.*, 2007). Secondly, the conversion process alters the soil's physical, chemical and biological properties and so has an impact on the biological resilience of the agro-ecosystems (Oades, 1984; Elliot, 1986; Potter *et al.*, 1998). When soils in a natural state are converted to agricultural land, there is an important loss of soil organic carbon (SOC) mainly in form of $CO_2$ (VandenBygaart *et al.*, 2003). Furthermore, agricultural expansion is a major driver of biodiversity loss, which in turn threatens agricultural sustainability.

However, when assessing agricultural sustainability, both environmental impacts and yields should be considered. Global agricultural production will need to increase by 70 percent (and by practically 100 percent in developing countries) to meet the needs of an estimated world population of approximately 9.2 billion in 2050 (FAO, 2006a), but the environmental impact of changing land use to agriculture varies significantly under different management systems. Much of the traditional agriculture practised in industrialised as well as in developing countries is based on mechanical soil tillage[1*] (referred to in this paper as tillage agriculture (TA)[2]). In general the major purposes given

* See the Glossary of definitions of the terms used in this paper, given at the end of the book.

1 **Mechanical soil tillage** = Any mouldboard and/or disc ploughing, chiselling, disking; mechanical intervention to structure the soil in a different way

2 **Tillage agriculture (TA)** = Agricultural systems based on mechanical soil tillage, embracing all soil operations using implements such as a mouldboard plough, disk plough, chisel plough, rotary tiller, subsoiler, ridgers or bed-formers, and other farm tools or mechanical implements for seedbed preparation that aim at creating soil and environmental conditions for seed germination, seedling establishment and crop growth. These types of tillage systems often involve multiple operations and are often referred to as "conventional" or "traditional" tillage systems.
Minimum tillage is often used to refer to any system that has few tillage requirements. It should however also be regarded as a tillage-based form of agriculture, as it is commonly defined as 'the minimum soil manipulation necessary for crop production under the existing soil and climatic conditions" (Kassam *et al.*, 2009).

for mouldboard and/or disc ploughing in temperate areas are to loosen and prepare the soil for sowing, accelerate soil warming during spring and to control weeds. In humid regions, particularly in the tropics, where many soils are heavily leached and acidic often with high exchangeable $Al^{3+}$, tillage can serve the additional purpose of incorporating lime as an amendment. Tillage agriculture is considered to speed up the loss of soil organic matter (SOM) by increasing its mineralization and through soil loss by erosion. As in a vicious circle, the reduction of SOM, which is the substrate for soil life, interrupts the biological soil structuring processes carried out by the soil edaphon[3] , which in turn creates the need for more mechanical tillage leading to further soil degradation. In addition, tillage is a highly energy-consuming process which uses large amounts of fossil fuel per hectare (ha) in mechanised systems. In calculating the total $CO_2$ emissions from tillage operations, tractor engine $CO_2$ emissions should be added to those that originate from the oxidative breakdown of SOM through mechanical tillage.

As opposed to tillage-based systems, other agricultural production approaches, such as Conservation Agriculture[4] (CA), exist which are win-win strategies to both sequester carbon in the soil and achieve production intensification with competitive yields while enhancing the natural resource base.

The present review focuses on SOC sequestration and in particular it attempts to quantify the carbon footprint of the variables that intervene in CA and TA production cycles. The review was conducted to: i) develop a clear understanding of the impact and performance of CA relative to TA with respect to carbon sequestration; and ii) examine if in this respect there are any misleading arguments at present in the scientific literature with a view to highlighting the evidence that exposes their flaws. The document draws primarily on scientific papers published in leading peer-reviewed journals and the knowledge of the working group on CA in the Plant Production

[3] **Edaphon** = Soil microorganisms and fauna.

[4] **Conservation Agriculture (CA)** = Conservation Agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. CA is characterized by three linked principles, namely:

i. Continuous minimum mechanical soil disturbance refers to low disturbance no-tillage and direct seeding. The disturbed area must be less than 15 cm wide or less than 25 percent of the cropped area (whichever is lower). There should be no periodic tillage that disturbs a greater area than the aforementioned limits. Strip tillage is allowed if the disturbed area is less than the set limits.

ii. Permanent organic soil cover. Three categories are distinguished: 30-60 percent, >60-90 percent and >90 percent ground cover, measured immediately after the direct seeding operation. Area with less than 30 percent cover is not considered as CA.

iii. Diversification of crop species grown in sequences and/or associations. Rotation/association should involve at least 3 different crops. It aims at enhancing natural biological processes above and below the ground.

and Protection Division (AGP) of the Food and Agriculture Organization (FAO). A meta-analysis of the relevant literature has been undertaken and the cropping systems and research protocols followed by the researchers have been examined to explain any discrepancies in their findings.

# CHAPTER 2
# Definitions

Semantics is the main cause for confusion within the international literature with regard to carbon sequestration under different management systems. This chapter provides a brief description of SOC pools (section 2.1) and a rigorous definition of what should be considered as CA (section 2.2).

## 2.1 THE PATHWAY OF CARBON FROM CROP RESIDUES INTO SOIL ORGANIC MATTER AND SOIL ORGANIC CARBON

The term soil organic matter (SOM) is used to describe the organic constituents in the soil: tissues from dead plants and animals, materials less than 2 mm in size and soil organisms in various stages of decomposition. Undecomposed materials on the surface of the soil (such as litter, crop residues, shoot and root residues) are usually more than 2 mm in size and are not considered to be part of the SOM. SOM is generally richer in lignin, poorer in carbohydrates, oxygen and hydrogen vis-à-vis organic matter because the mineralization[5] process frees oxygen and preferentially degrades polysaccharides, so that the concentration of recalcitrant (or stable) compounds increases.

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. Inorganic carbon is present as various minerals and salts from weathered bedrock. Soil organic carbon (SOC) is the carbon occurring in the SOM: on average it constitutes about 58 percent of SOM mass.

The carbon stabilization process goes through the initial formation of unstable macroaggregates, to their subsequent stabilization and the contemporary formation of microaggregates within the macroaggregates. The final stage of the aggregate transformation cycle is the break down of macroaggregates with the liberation of the microaggregates. In most soils, young and unstable macroaggregates are formed by biological processes: growing roots, fungal, bacterial and faunal activity have a primary role in enmeshing fresh organic matter with exudates and soil particles. Only in soils dominated by oxides and 1:1 clays, which hold positive and negative charges at prevailing pH values, the primary binding agent for soil aggregates are mineral-mineral electrostatic forces that create physicochemical macroaggregates[6].

5 **Mineralization of organic matter** = Biological oxidation to carbon dioxide and water with liberation of the mineral nutrients.

6 **Physicochemical aggregates** = Macroaggregates held together by mineral electrostatic interactions.

Young macroaggregates offer physical protection to carbon and nitrogen from microbial enzymes, but need to be further stabilized. The processes for the formation of water stable aggregates[7] include ageing[8], wet-dry cycles (that cause closer rearrangements of soil particles) and growing roots (that exert pressure, remove water and produce exudates that have a role both as cementing agents and as substrate for further microbial activity). In soils characterized by a mixed mineralogy and in the absence of high organic matter inputs, physicochemical macroaggregates can be stabilized by root growth. During macroaggregate stabilization, partially decomposed intra-macroaggregate organic matter becomes encapsulated with minerals and microbial products forming microaggregates, which lead to long-term carbon stabilization by protection from mineralization. Over time, the macroaggregates tend to lose labile binding agents and break down to release minerals, highly recalcitrant SOM, and microaggregates. In time, these latter may be occluded again within new macroaggregates.

Based on SOM size, state of decomposition, chemical and physical properties, the following SOM pools can be distinguished:

i) The **labile pool**, also known as the **active pool**, is the least decomposed organic matter: smaller than 2 mm in size (the threshold for organic matter to be considered SOM) but larger than 0.25 mm (the minimum dimension for aggregates to be considered macroaggregates). As it mainly consists of young SOM (such as plant debris) only partially protected in macroaggregates (which are not stable by definition), it is characterized by a rapid turnover or transformation, and is sensitive to land and soil management and environmental conditions. Due to these characteristics, labile SOM pools play an important role in short-term carbon and nitrogen cycling in terrestrial ecosystems and can be used as a sensitive indicator of short- and medium-term changes in soil carbon in response to management practices (Chan, 1997; Whitbread *et al.*, 1998).

ii) **Particulate organic carbon** is the physical portion of SOM smaller than 0.25 mm in size and bigger than 0.053 mm (250 - 53 μ). It is a labile, insoluble intermediate in the SOM continuum from fresh organic materials to humified SOC, ranging from recently added plant and animal debris to partially decomposed organic material.

iii) The **stable pool**, also known as **recalcitrant SOM**, comprises particles of less than 0.053 mm (<53 μ) in size. It is the organic matter that has gone through the highest level of transformation, and is incorporated into aggregates, where its further decomposition is protected. It holds moisture

[7] **Water stable aggregates** = Aggregates that can resist air drying and quick submersion in water before sieving.

[8] **Ageing** = Deposition of polysaccharides and other organic cementing agents by microbial activity.

and, thanks to its negative charges that retain cations for plant use, it acts as a recalcitrant binding agent preventing nutrients and soil components being lost through leaching.

Part of the biomass returned to the soil is converted into carbon compounds with a long residence time (i.e. humus and related organo-mineral complexes). This fraction varies depending on the quantity and quality of the biomass. In an ecosystem at steady-state, production of plant residues will be balanced by the return of dead plant material to the soil: above-ground residues are left on the surface to decompose, or a portion may be transported or mixed into the soil by the activity of soil fauna, while roots and root exudates enter the soil directly. For example, in a native prairie in its natural state more than 23 percent of plant production is accumulated in the SOC (Batjes and Sombroek, 1997), whereas in agricultural systems the conversion rate of the plant residue into SOC varies from 15 to 26 percent (de Moraes Sà and Séguy, 2008). In the short term, it is the management of the easily decomposable SOM and the enhancement of cropping intensity that has the greatest impact on microorganisms, humic substance building, SOC protection and ultimately on carbon sequestration (Varvel, 1994; Potter *et al.*, 1997; Campbell *et al.*, 2001 a, b; Jarecki and Lal, 2003). The carbon fixed in vegetation through photosynthesis is potentially available as a net gain to the soil only when plant residues accumulate *in situ* and are incorporated in the soil through humification facilitated by macrofauna and microorganisms, as in CA systems. In contrast, when the separation of plant residues from the harvestable components and their transport from fields is done by the use of machines, the energy cost and $CO_2$ released by fossil fuel combustion would need to be calculated. Beyond agronomic management, the direction and rate of change in SOC content is also determined by the following factors:

i) the crop rotation pattern,
ii) the input rates of organic matter,
iii) the chemical composition of organic matter inputs,
iv) the soil type and texture (hence by the degree of protection or bonding of the stable carbon fraction within the soil),
v) the previous land use,
vi) the climatic conditions,
vii) the high variability of SOC values between the sampling locations in the same field (sometimes higher than the measured increase/decrease) which requires subsequent sampling to be repeated at the same spots over time to eliminate any factor of spatial variability (Campbell *et al.*, 1996a; Larney *et al.*, 1997; Paustian *et al.*, 1997; Balesdent *et al.*, 2000).

This means that the rate of increase in SOC stock after adoption of improved management practices follows a sigmoid curve: it attains a maximum level of sequestration rates in 5 - 20 years (Cole *et al.*, 1993; Nyborg *et al.*,