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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
Director
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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.

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

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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.*, 1995; Solberg *et al.*, 1997; Campbell *et al.*, 1998; Dormaar and Carefoot, 1998; Duiker and Lal, 2000; Lal, 2004) and continues at decreasing rates until SOC stocks reach a new equilibrium (IPCC, 2007). Therefore, in the short term an exponential relationship between application and accumulation of SOM can be expected, until a saturation point, mainly determined by soil texture and by the chemical composition of SOM, is reached (Jacinthe *et al.*, 2002; Six *et al.* 2002a). In the long term, more important than agronomic management is the ratio of the current SOC level to the steady-state level. Soil carbon sink capacity 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 (Johnson *et al.*, 1995; Freibauer *et al.*, 2004; Smith, 2004). This means that the SOC sequestration rate is potentially greatest in soils that have lost the most carbon relative to their steady state, and that when SOC is already close to a maximum steady-state level SOC gains under a management enhancement are lower. For example, when land has been recently converted from grassland or forest to cropland, SOC levels are more likely to decline under whatever management regime because the system is still moving towards a new steady-state.

2.2 CONSERVATION AGRICULTURE FOR CARBON STORAGE IN CROPLAND

FAO uses the following definition of CA (Seguy, 2009) “a resource-saving agricultural production system that aims to achieve production intensification and high yields while enhancing the natural resource base through compliance with three interrelated principles, along with other good production practices of plant nutrition and pest management. These are: minimum mechanical soil disturbance with direct seeding; permanent soil organic cover with crop residues[9] and/or cover crops to the extent allowed by water availability; and species diversification through varied crop associations and/or rotations (involving annual and/or perennial crops including trees)”.

> Conservation Agriculture is a production system based on three principles: minimum mechanical soil disturbance, permanent soil organic cover, varied crop rotations.

The reason for these three criteria is that the CA fundament, similar to that of most stable natural ecosystems, is the permanent and total protection of the soil through species diversity. In order to keep a protective layer of vegetation on the soil surface, soil should not be mechanically disturbed other than for the purpose of placing seed or fertilizer. Ideally 100 percent of the surface should be kept covered, but in some cases the surface covered on the sowing row can be as low as 3 - 10 percent, depending on the equipment used and

[9] **Crop residues** = Crop residues include any biomass left in the field after the principal economic components of the crop have been harvested.

the quantity and quality of crop residues available. From the perspective of SOC accumulation in CA systems, a well-designed crop rotation guarantees the permanent presence of abundant, undisturbed (above- and below-ground) biomass to foster the build-up of new SOC (Stagnari *et al.*, 2009). At the same time, carbon losses by decomposition are reduced by SOC inclusion within soil aggregates, as enhanced by the low soil disturbance (de Moraes Sà *et al.*, 2001).

The following is a description of the main purposes for the three above-mentioned CA pillars:

i) Producing abundant above- and below-ground biomass to protect the soil. The physical protection of the soil from weather is particularly relevant during the dry season. It reduces soil and nutrient erosion (hence improves soil productivity), water evaporation, temperature fluctuations, surface sealing and crusting (Tebrügge and During, 1999). Moreover, including crops that have strong roots helps break compaction horizons and keeps them open. Finally, due to their adhesion properties, organic materials, such as bacterial waste products, organic gels, fungal hyphae, worm secretions and casts, contribute to soil aggregate formation and stability (FAO, 2005b). Aggregate preservation is important in general, and particularly in lateritic soils with high iron and aluminium, as aggregates provide the necessary structural protection to soil carbon. When aggregates become disrupted, the microbiota (mostly bacteria and fungi) start consuming the youngest carbon pool and along with it the major (i.e. temporary and transient) binding agents are lost, causing the soil to be dispersed. When macropores are disrupted the remaining recalcitrant carbon bonds with soil cations and so creates cohesion forces that cause soil compaction (Verhulst *et al.*, 2010).

ii) Balancing the C/N ratio over the crop rotation by rotating between cereals (high in carbon) and legumes (high in nitrogen). This means that the cropping pattern should provide enough nitrogen along with structural carbohydrates (e.g. lignin) in order for nitrogen from decaying surface residues to be released slowly and serve as a source for the following crop (Huggins *et al.*, 1998; Gregorich *et al.*, 2001; Gál *et al.*, 2007). A high concentration of slowly decomposable crop residues alone will decrease the rate of decomposition and cause temporary soil nitrogen immobilisation, whereas residues with a low carbon - nitrogen (C/N) ratio (such as legumes) alone improve nitrogen availability but are decomposed too quickly to guarantee the necessary soil protection.

iii) Keep "soil biological infrastructure"[10] active. The vertical structuring of the living component of a soil, the soil food web, is complex and has different compositions of flora and fauna in different ecosystems. Agricultural systems should be adopted that preserve all complex biological networks and interactions among roots, fungi, other microflora, micro- and macrofauna, and accommodate an exponential increase of carbon accumulation in the soil. As soon as soil carbon accumulation reduces, the crop sequence should be replaced by a new, more intensive one to increase the return of fresh organic matter in time and space. In CA systems intensive crop rotations[11] are an essential component to provide abundant, varied organic matter (i.e. nutrients, and hence substrate, rich in carbohydrates and nitrogen) to keep soil biota active, foster diversity of their genera and species, and enhance their functional roles.

iv) Control weeds, pests and diseases. A diversified rotation of complementary plants is a relevant phytosanitary strategy. In general, the greater the number and the higher the diversity of crops and genera involved in a rotation, the higher the biodiversity and the greater the potential for biological control of pathogens, insect pests and weeds, through cutting the build-up of inocula or populations (Vilela *et al.*, 2004). In addition, crop residues that remain on the soil surface produce a protective layer of mulch that acts as a barrier for weed emergence. Furthermore, some cover crops may also be introduced that have allelopathic effect on weeds (Séguy

[10] **Soil biota** = Soil is a complex habitat for diverse biota and predator-prey relationships. Soil organisms, spending all or a portion of their life cycles within the soil or on its immediate surface (including surface litter and decaying logs), make up the diversity of life in the soil and are responsible, to a varying degree depending on the system, for performing a range of processes important for soil health and fertility in soils of both natural ecosystems and agricultural systems. A brief description (FAO 2005b) of organisms that are commonly found in the soil, based on the FAO soil bulletin 80, follows. Microorganisms include algae, bacteria, cyanobacteria, fungi, yeasts, myxomycetes, actinomycetes. These are able to decompose and transform organic matter into nutrients that are assimilated by plants. Their populations are very sensitive to depth and are highly disrupted by mechanical soil disturbance. Likewise, various members of the microfauna (such as collembola, mites, nematodes and protozoa) generally live in the soil water films and feed on microflora, plant roots, other microfauna and sometimes larger organisms, and are therefore important to release nutrients immobilized by soil microorganisms. Mesofauna includes mainly microarthropods feeding on organic materials, microflora, microfauna and other invertebrates. Macrofauna species are visible to the naked eye and include vertebrates and invertebrates (such as snails, earthworms, soil arthropods) that feed in or upon the soil, the surface litter and their components. In both natural and agricultural systems, soil macrofauna are important regulators of decomposition, nutrient cycling, soil organic matter dynamics and pathways of water movement as a consequence of their feeding and burrowing activities, such that leaf litter and other materials become buried, eventually migrating slowly to the base of the A horizon (the definition is given along with that of O horizons).

[11] **Intensive crop rotation** = Crop rotation characterized by high species density in space and in time that produce high amounts of crop residues, and maintain the soil surface permanently covered to "close the window" between the wet and the dry season.

et al., 1999) and specific pests can best be controlled by intercropping species that act as physical barriers, that attract antagonists or that exude suppressant or repellent chemicals.

Additional complementary CA functions come free of additional costs (apart from the opportunity cost of the crop residues). A brief overview of these follows:

v) Economic sustainability. Crop diversification is a criterion recommended for economic stability and sustainability. A direct correlation between the amount of crop residue and the yield of the following crop was shown by Séguy and Bouzinac (2002), although for good soil and crop management, a varied crop succession should be integrated with fertilizer application to return to the soil the nutrients removed by the harvested crop products.

vi) Soil nutrients. The organic matter accumulation-mineralization cycle is the functional engine of CA, as it helps to restore and maintain soil fertility and to reduce soil erosion. Organic matter causes the active fraction of SOM and binding agents to increase. As a result, aggregation (which offers structural protection from oxidization to less stable SOM) and stability of soil structure[12] both increase (Hernanz *et al.*, 2002). When the organic matter is degraded and enters the stable pool (<53 μ), the large negative charge developed by the humus (which is highly recalcitrant with respect to biodegradation) increases and so does the cation exchange capacity. For these reasons soil aggregate size distribution can be used as a synthetic indicator of the potential of a cropping system to rebuild soil quality (Tran Quoc H. *et al.*, 2008a).

vii) Soil moisture. Generally, soil protected by a superficial layer of organic matter improves the capture and the use of rainfall through increased water absorption and infiltration and decreased evaporation from the soil surface. This leads to reduced runoff and soil erosion and higher soil moisture throughout the season compared to disturbed soils left unprotected (Kronen, 1994; Duiker and Lal, 2000; Post and Kwon, 2000; Knowles and Singh, 2003; Baker, 2007; Bationo *et al.*, 2007). This is due to three separate processes. First, SOM plays a major role in absorbing water at low moisture potentials. Second, soil protection through organic matter and the higher presence of large water-stable soil aggregates enhances resistance against water and wind erosion (Puget *et al.*, 1995; Balabane *et al.*, 2005). Third, water infiltration rate is a function of the initial water content and of soil porosity. Porosity and its distribution down the profile in turn depend on soil texture and structure, aggregate stability, SOM content and therefore on the type, shape and size of soil structural units;

[12] **Soil structure** = Arrangement of primary soil particles into secondary units (i.e. peds), which in turn are characterized on the basis of size, shape and grade. The arrangement of solids and voids existing at a given time determines structural form, the ability to retain this arrangement under different stresses determines structural stability, and the capacity of the soil to recover structure or stability after a stress is removed is called resiliency (Kay, 1990).

the presence of channels created by roots, meso- and macrofauna also play a role. In low clay soils, organic matter is the main stabilizer of soil aggregates and pores as neither silt nor sand have cohesive (i.e. plastic) properties.

viii) Substrate for soil functional biodiversity. Absorption and accumulation of carbon is favoured by ecosystems with high biodiversity. And the enhancement of the rotation complexity (i.e. changing from monoculture and crop-fallow to continuous rotation cropping, or increasing the number of crops of different families in a rotation system) results in higher SOC sequestration rates (Rasmussen *et al.*, 1980; Duiker and Lal, 1999; Clapp *et al.*, 2000; West and Post, 2002; Corbeels *et al.* 2006). Roots play a crucial role in the soil ecosystem by providing the substrate for energy to the edaphon of different soil strata and so boost soil biodiversity (increase in number and type of soil biota). Inputs from (deep) rooting systems are ideal for taking carbon deep into the soil, where it is less susceptible to oxidation, and can generally maintain soil carbon levels even in warm or semi-arid regions. Decomposition of old rooting systems adds organic matter at depth, while active roots produce exudates and, notably in the case of legumes, favourable mycorrhizal associations which promote a larger microbial population in the rhizosphere and facilitate the binding of aggregates (Rillig and Mummey, 2006).

ix) More SOM chemical effects. These include metal complexing, buffering capacity, and adsorption of xenobiotics[13]. Further specific functions are also related to the type of cover crops used. For instance, some cover crops (such as those of the genera *Brachiaria*, *Cassia*, *Stylosanthes*) help to reduce the acidity of ferralitic soils, others (such as common millet - *Panicum miliaceum*) recycle potassium, yet others can be specifically used to control invasive weeds (e.g. some species of *Sorghum* help control *Cyperus rotundus*) or to detoxify soil polluted by xenobiotics. Species may have multifunctional roles: *Crotalaria retusa*, for instance, is a nitrogen fixing legume, controls weeds and, since it is non-edible for cattle, can be used by farmers who cannot protect their fields from grazing during the dry season (Séguy, 2003). The long term experiments of Franzluebbers (2008) also show that corresponding to changes in surface SOM, extractable potassium, phosphorus, iron, manganese, copper, zinc are also greatest in cropping systems with minimum soil disturbance, contributing to enhanced soil fertility and maintenance of yield.

x) Off-site functions. Most important is the reduction of GHG emissions and that of sediment load in water bodies (Bassi, 2000) relative to disturbed and unprotected soils, especially in regions with steep slopes in combination with high rainfall intensities where soils are prone to produce surface runoff.

[13] **Xenobiotic** = Chemical compound which is found in a living organism but which is foreign to it.

CHAPTER 3

Evidence that CA promotes soil carbon accumulation

Many of the factors determining the soil carbon budget[14] are influenced by land management practices. Therefore verifiable estimates on the effect of different management systems on carbon accumulation in agricultural soils are needed. In section 3.1, the relevant literature has been reviewed to identify the most frequent situations in which alleged CA systems are associated with negative SOC accumulation rates. Section 3.2 deals with SOC accumulation in deeper soil layers. In section 3.3, global and regional data are discussed. In section 3.4, the lessons learned on the effect of different management systems on SOC and on the methodology for their evaluation are presented.

3.1 WHERE CA PRINCIPLES AND METHODS ARE NOT FOLLOWED

A survey of the literature indicates that when carbon loss or no carbon sequestration are associated with non-traditional farming practices, they are most frequently a result of: i) soil disturbance, ii) monocropping, iii) specific crop rotations, iv) poor management of crop residues, or v) soil sampling extended deeper than 30 cm.

A point by point analysis of these topics follows with the aim of correcting confusion with terminology in the literature.

> In the literature, no carbon accumulates in agricultural soils where CA principles are not followed.

3.1.1 Soil disturbance

No-till (NT)[15] and minimum tillage (MT)[16] production systems are often used in literature as synonyms for CA, and the results achieved under NT and MT are often ascribed to CA. In reality, CA is a broader concept that requires compliance with the simultaneous application of three criteria. Two of them (diversified crop rotations and associations, and permanent soil cover) are discussed later (in sections 3.1.2, 3.1.3 and 3.1.4); the third one

[14] **Carbon budget** = Carbon input versus output at a given time.

[15] **No-till** = Agricultural systems where soil-disturbing activities are limited only to those necessary to plant seeds, and place nutrients. Crops are planted directly into a seedbed that has not been tilled since the previous seedbed.

[16] **Minimum tillage** = Agricultural systems based on the minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions; the tillage reduction can be in intensity of tillage, depth of tillage or time involved (number of machinery passes for all tillage operations).

involves minimum mechanical soil disturbance continuously maintained over time. One reason behind this important pillar is that SOC accumulation is a reversible process and any short-term disturbance, in a system which aims to improve carbon status as a long-term management tool, will not achieve significant improvement in SOC accrual (Jarecki and Lal, 2003; Al-Kaisi, 2008). Formation of stable microaggregates within macroaggregates is inhibited under TA, and the periodic cultivation of NT soils undermines biotic and abiotic processes (Six *et al.*, 1998). Grandy *et al.* (2006) indicated that with even a single tillage event, sequestered soil carbon and years of soil restoration may be lost, and that the damage to the soil life was usually greater than the loss of soil carbon. In general, in tilled soils the mixing of the litter favours bacteria (hence quick degradation processes), while the higher presence of fungi in NT systems (Beare *et al.*, 1992; Beare *et al.*, 1993; Frey *et al.*, 1999; Guggenberger *et al.*, 1999; Drijber *et al.*, 2000) is responsible for a build-up of soil carbon in the form of polymers of melanin and chitin which are relatively stable and resistant to degradation (Stahl *et al.* 1999; Bailey *et al.* 2002). Beyond its effect on the oxidative breakdown of SOM through mineralization, tillage has a direct effect on CO_2 exchange between the soil surface and the atmosphere. The mouldboard plough disturbs the greatest soil volume and produces the maximum CO_2 flux, while NT causes the least amount of CO_2 loss, with the amount of CO_2 loss being directly correlated to the disturbed soil volume (Reicosky and Lindstrom, 1993, 1995; Reicosky, 1997, 1998). In addition, ploughing is a very energy-intensive process that uses energy derived from fuels: on average TA uses up to 80 percent more energy than CA (more details are given in section 4.1). Studies have also identified tillage-induced soil erosion[17] as the major cause of the severe soil carbon loss and soil translocation

Where CA principles and methods are not followed:

- **SOIL DISTURBANCE**

  SOC accumulation is a reversible process: with even a single tillage event, sequestered soil carbon and years of soil restoration may be lost.

  Formation of stable microaggregates within macroaggregates is inhibited under TA.

  In TA soils the mixing of the litter favours bacteria, hence promotes rapid degradation processes.

  The plough disturbs the highest soil volume, produces the maximum CO_2 flux and uses the most energy, NT the least.

  Tillage-induced soil erosion is the major cause of severe soil carbon loss on upper slope locations of upland landscapes.

[17] **Tillage erosion** = Net downslope translocation of soil by tillage implements, exposing subsoil at the crest while burying soil at the bottom.

on convex upper slope positions of cultivated, upland landscapes (Lobb *et al.*, 1995; Lobb and Lindstrom, 1999; Reicosky *et al.*, 2005).

3.1.2 Monocropping

Some authors found negative SOC storage rates under repeated monocropping in NT systems (Carter and Kunelius, 1986; Angers *et al.*, 1997; Wanniarachchi *et al.*, 1999, VandenBygaart *et al.*, 2003). However, based on the CA definition, monoculture is in itself a reason for exclusion from CA systems, and the negative SOC storage rates should be related to the cropping pattern and not to either the CA system nor to the soil depth sampled. As stated previously, changing from monocropping to a multicrop rotation results in a positive influence on SOC concentration. Several studies comparing SOC concentration under multiple cropping with monocropping systems support this theory (Havlin *et al.*, 1990; Entry *et al.*, 1996; Mitchell *et al.*, 1996; Robinson *et al.*, 1996; Robinson *et al.*, 1996; Buyanovsky and Wagner, 1998; Gregorich *et al.*, 2001; Lopez-Fando and Pardo, 2001).

Soil type and climatic conditions are further important determinants and variables that can strongly influence the effects of the cropping pattern on SOC, as shown by the experiments on continuous barley[18] reported in the paper of VandenBygaart *et al.* (2003). After conversion to NT, Angers *et al.* (1997) found negative SOC rates in Humic Gleysols (with clay, clay-loam, silt-loam texture) sampled at depths greater than 30 cm; while the experiments of Nyborg *et al.* (1995) done in other study areas (i.e. on sand loam Melanic Brunisols, loam Gray Luvisol and loam Black Chernozem) showed positive carbon sequestration rates and net carbon differences of CA relative to TA. In the first study area, Gleysols in combination with a mean annual precipitation of 891 mm and mean annual temperatures of approximately 1°C were not very favourable for any agricultural activities, even less so for monoculture. For their lower mean annual precipitation (547 mm) and comparable mean annual temperatures (2°C), the other study areas seem to be more suitable as croplands and explain the better results achieved.

> ***Where CA principles and methods are not followed:***
>
> - MONOCROPPING IN NT SYSTEMS
>
>   Monoculture is in itself a reason for exclusion from CA systems.
>
>   Changing monocropping to a multicrop rotation results in positive influence on SOC concentration.

[18] **Barley** = *Hordeum vulgare*

3.1.3 Crop rotations and cover crops that do not allow a positive N balance

Different rotations have different potential to promote and support carbon sequestration. In general terms, carbon accumulates in the soil when the nitrogen balance of the crop rotation is positive, i.e. when the input from nitrogen fixation or fertiliser is higher than the nitrogen exported with harvested produce plus the amount lost by leaching or in gaseous forms (Sidiras and Pavan, 1985; Bayer and Mielniczuck, 1997; Boddey, 1997; Alves *et al.*, 2002, 2003, 2006; Sisti *et al.*, 2004; Bayer and Bertol, 1999; de Maria *et al.*, 1999; Amado *et al.*, 1999, 2001; Bayer *et al.*, 2000a, b).

Some authors reported negative SOC accumulation rates under CA mainly associated with specific rotations, i.e. with fallow-, barley-, soybean-[19] based rotations.

Fallow-based rotations should not be associated with the concept of CA, and negative rates for SOC accumulation are most likely to reflect high mineralization rates favoured in tilled and bare soils, a theory supported by the higher SOC content achieved under NT after the enhancement of the cropping intensity from fallow (Black and Tanaka, 1997; VandenBygaart *et al.*, 2003; Hernanz *et al.*, 2009; López-Bellido *et al.*, 2010).

A barley - wheat - soybean rotation does not seem to allow SOC accumulation (Angers *et al.*, 1997). One reason for this is that barley, as a versatile species, is often cultivated where growing conditions (e.g. climate and soil fertility) are most difficult and less favourable for cereal crops of major commercial importance and hence also for SOC accumulation. More details are given below, where soybean rotations are considered.

Further negative SOC accumulation rates under CA were found in experiments with maize - wheat - soybean (Yang and Kay, 2001; VandenBygaart *et al.*, 2002). Concerns about these conclusions relate firstly to the fact that the experiments are based on too few soil profiles sampled (i.e. one in the case of the research of VandenBygaart) and seem therefore not to be representative. Secondly, no reference is made of the previous land use, which is very relevant information, as mentioned in section 2.2 at point viii. Finally and most importantly, including soybean in the rotation does not seem to be sufficient to enhance SOC accumulation: most of the fixed nitrogen is exported with the grain (Sisti *et al.*, 2004) and, while its residues may improve nitrogen availability, they decompose very quickly, returning too little biomass to the soil to get significant SOC accumulation as compared to other legumes. For instance, all the enhancements in crop rotation complexity analysed in the survey of West and Post (2002) resulted in a mean carbon sequestration rate of 0.2 t of carbon ha^{-1} y^{-1}, with the exception of a change from continuous maize to maize - soybean rotations which resulted in 0.15 t of carbon ha^{-1} y^{-1} sequestered. When soybean is the only legume in the rotation, carbon

[19] **Soybean** = *Glycine max*

stocks under CA are comparable to those under TA (Machado and Silva, 2001; Freixo *et al.*, 2002), but when a green-manure crop with high annual above-ground biomass production is included to keep the nitrogen balance of the crop rotation positive, carbon stocks are significantly greater. For example, Diekow *et al.* (2005) tested the effects of different CA-based crop rotations and different levels of nitrogen fertilizer (N-fertilizer) over 17 years in an Acrisol in southern Brazil. The experiment started after conversion from grassland to TA-cropland and when carbon and nitrogen stocks had decreased under that management system. With the conversion to CA and the establishment of cereal-based cropping systems (i.e. fallow - oat[20] and fallow - maize) without N-fertilizer, additional carbon and nitrogen losses occurred. When N-fertilization was applied in the cereal-based rotations in the CA systems, the carbon and nitrogen stocks remained steady with time. However, the conversion to CA and the establishment of legume-based crop rotations (i.e. lablab[21] - maize and pigeon pea[22] - maize) restored the original carbon and nitrogen stocks of native grassland in its natural state in the 0 - 17.5 cm layer, and even surpassed it when the N-fertilizer was applied. Larger relative changes in the 0 - 2.5 cm depth were observed, where the carbon stock was on average 42 percent higher in legume treatments than in grassland soil.

Crop rotation is an important agro-ecosystem management practice to preserve and improve agricultural sustainability that can significantly contribute to SOC accrual. Examples of the quantities of residues achievable under different climates and common rotation systems, regardless of agricultural treatment, are provided in Annex 1. SOC quantities achievable in different climates under many common rotation systems are given in Annex 2. A review of the long-term impact on SOC content of different tillage systems under the same crop rotation schemes is given in Annex 3.

3.1.4 Crop residues removal and mixing

The availability of sufficient plant residue is often a limit to the amount of carbon accumulated in the soil. In some cases all above-ground production may be removed (harvested or used as livestock feed) or burned, leaving only the root biomass for incorporation into the SOM; in other cases above- and below-ground inputs are mechanically mixed (e.g. by disking or chiseling) into the soil. When this happens, residues decay more rapidly for three main reasons: first, for the direct contact with soil-borne decomposing organisms; second, for the generally favourable soil conditions for microbial decomposition in terms of moisture, nitrogen availability, temperature; and third, for the favourable conditions for microbial activity resulting from tillage in terms of aeration (Magdoff and Weil, 2004). It is interesting to observe

[20] **Oat** = *Avena sativa*
[21] **Lablab** = *Lablab purpureus* (L.) Sweet, *Dolichos lablab* L.
[22] **Pigeon pea** = *Cajanus cajan*

that the composition of the material incorporated into the soil affects the decay of the SOM present in the soil: mixing readily decomposable carbon (e.g. residues with low C/N ratio, or liquid manure) in the presence of stable SOM generally induces a priming effect[23] and increases CO_2 emissions; in contrast, the composition of crop residues not mixed into the soil does not affect the decay of the SOM present (Chadwick *et al.*, 1998; Flessa and Beese, 2000; Kuzyakov *et al.*, 2000; Chantigny *et al.*, 2001; Bol *et al.*, 2003; Fontaine *et al.*, 2004; Sisti *et al.*, 2004; Fontaine, 2007).

In a soil that is not tilled for many years, SOM decomposition in soil surface layers is reduced and causes the active fractions of SOM to increase (Franzluebbers *et al.*, 1995a, b; Stockfisch *et al.*, 1999; Tebrügge and During, 1999; Horáček *et al.*, 2001). There is a strong linkage between superficial SOM accumulation, the consequent carbon vertical stratification (Hernanz *et al.*, 2002; Moreno *et al.*, 2006), water infiltration, erosion resistance and the conservation of nutrients. Consequently in NT soils the degree of SOC stratification (i.e. the stratification ratio) can be used as an indicator of soil quality. Another indicator to assess the influence of management on functional processes in soils (such as decomposition and nutrient cycling) is soil enzyme activity (Dick, 1994; Karlen *et al.* 1994; Bandick and Dick 1999; Dilly *et al.*, 2003). Soil enzymes catalyze the innumerable reactions necessary for the life processes of microorganisms in soils, decomposition of organic residues, cycling of nutrients. Bandick and Dick's experiments (1999) on the effects of field management on soil enzymes (i.e. amidase, amylsulfatase, deaminase, fluorescein diacetate hydrolase, invertase, cellulase and urease) showed that their activities were generally higher in cropping systems where cover crops or organic residues were added. In particular, deaminase was not a good indicator

Where CA principles and methods are not followed:

- REMOVAL OF CROP RESIDUES
  Export of soil organic matter and loss of carbon from the system
- MIXING OF CROP RESIDUES
  Residues mixed into the soil decay more rapidly.

  Mixing readily decomposable carbon in the presence of stable SOM induces a priming effect; the composition of crop residues not mixed does not affect the decay of the native SOM.

In a soil not tilled for many years the SOM active fractions increases.
Soil enzyme activity is higher in cropping systems with cover crops and/or organic residue cover.

[23] **Priming effect** = Mobilization by microbial decomposition of stable SOC stimulated by the addition of substrates with readily available energy.

of soil quality, while ß-glucosidase proved to better reflect soil management effects. Kandeler *et al.* (1999) found that in the top 10 cm of the soil enzyme activities significantly increased only two years after transition to CA as compared to TA, and after four years nitrogen mineralization in the 20 to 30-cm soil layer was significantly higher under TA. Also the work of Balota *et al.* (2004) on soil enzyme activity in southern Brazil provided evidence on CA's role in fostering microbial activity. Under CA, in the 0 - 5 cm soil layer amylase increased by up to 68 percent, cellulase by 90 percent, amylsulfatase by 219 percent, acid phosphatase by 46 percent and alkaline phosphatase by 61 percent. Further analyses in Uzbekistan demonstrated higher protease activity under CA as compared to soils with no residues (Nurbekov, 2008). In conclusion, agricultural systems that rely on permanent organic soil cover and NT to maintain crop residues on the surface layer lead to superficial SOC accumulation, and offer potential benefits in controlling some of the negative environmental effects traditionally associated with agro-ecosystems.

3.2 RHIZODEPOSITS AND SOC ACCUMULATION IN DEEPER SOIL LAYERS

There is little consensus in the literature with respect to SOC accumulation under CA relative to TA in deeper soil layers. Some authors recorded lower carbon concentrations under TA compared with CA below the plough layer. For example, Centurion and Demattê (1985) and Corazza *et al.* (1999), working in the tropical central savannah region of Brazil, found that soil carbon stocks in the surface layer were higher under CA than under TA, but when sampling was extended to 100 cm, the lower carbon content below the plough layer under CA cancelled out all differences between the two management systems. However, it should be observed that the soil at the site was affected by calcium deficiency, which had not been corrected before the experiment started, and, while this problem is less severe under TA, under CA it might have affected rooting depth and could have reduced carbon accumulation below 30 cm. Another example for lower SOC accumulation under CA is given by Baker *et al.* (2007): the authors cite the five experiments reviewed by VandenBygaart *et al.* (2003) where the profile was sampled to a depth greater than 30 cm and a majority of the trials (35/51, i.e. 69 percent) registered less SOC in the NT treatment relative to TA. As a general rule, the carbon concentration in deep soil layers is higher under TA vis-à-vis CA when the carbon-enriched top layer (through fertilization) is inverted and all labile carbon is transferred from the surface to deeper layers (Baker *et al.*, 2007). However, in this way the recalcitrant carbon from deeper layers becomes exposed to rapid oxidation and mineralization at the soil surface; this effect occurs even more rapidly when discs are used after ploughing to disaggregate the surface layer. In addition, SOC accumulation achieved with deeper fertilization ceases and regresses as soon as the external carbon input is interrupted. In the medium term, the amount of SOC that reaches deeper layers in natural ecosystems is smaller than that added as fertilizer in tilled systems, but if the CA system is sustained in the long run, the depth of the O horizon[24] will increase. Changing the soil composition under the ploughed layer needs time: although the superficial layer (0 - 5 cm) is the most responsive to land management changes, the 0 - 1.5 cm layer (i.e. the active zone) is dispersed and, after transitioning from TA to CA, it will take time for the aggregates to rebuild and for the soil to be restored.

An important process that explains the functioning of deep carbon accumulation in CA soils seems to be the translocation of soluble carbon compounds that originate from undisturbed surface residues through the formation of organo-mineral complexes with iron oxides (Eusterhues *et al.*, 2005; Wright *et al.*, 2007). In NT-managed soils, where deeper rooting is facilitated by old root channels and those opened by soil fauna, an alternative or additional explanation for deep carbon accumulation could be that roots, due to their chemical recalcitrance to decomposition, contribute twice the amount of soil carbon (i.e. particulate organic matter) than surface residues (Hussain *et al.*, 1999; Wilts *et al.*, 2004; Johnson *et al.* 2006).

Experiments on the CA potential for SOC accumulation through the whole soil profile are presented in Annex 4.

Mechanisms for deep carbon sequestration:

In the medium term, carbon concentration in deep soil layers is higher under TA when the carbon-enriched top layer is inverted.

- Recalcitrant carbon from deeper layers becomes exposed to rapid mineralization at the surface.
- SOC accumulated ceases and regresses as soon as the external carbon input is interrupted.

In the long run, in CA systems the depth of the o horizon increases.

- Soluble carbon compounds are translocated from surface residues.
- Roots, due to their chemical recalcitrance, contribute twice as much carbon as surface residues.

3.3 VARIABLES INFLUENCING SOIL CARBON ACCUMULATION: ANALYZING GLOBAL DATA

Various experiments have detected increased SOC and nitrogen levels under CA as compared to TA (Yang and Wander, 1999; Halvorson *et al.*, 2002; West and Marland, 2002; West and Post, 2002; Franzluebbers and Arshad, 1996; Wright *et al.*, 2007; Calegari *et al.*, 2008; Chen *et al.*, 2009). Some authors

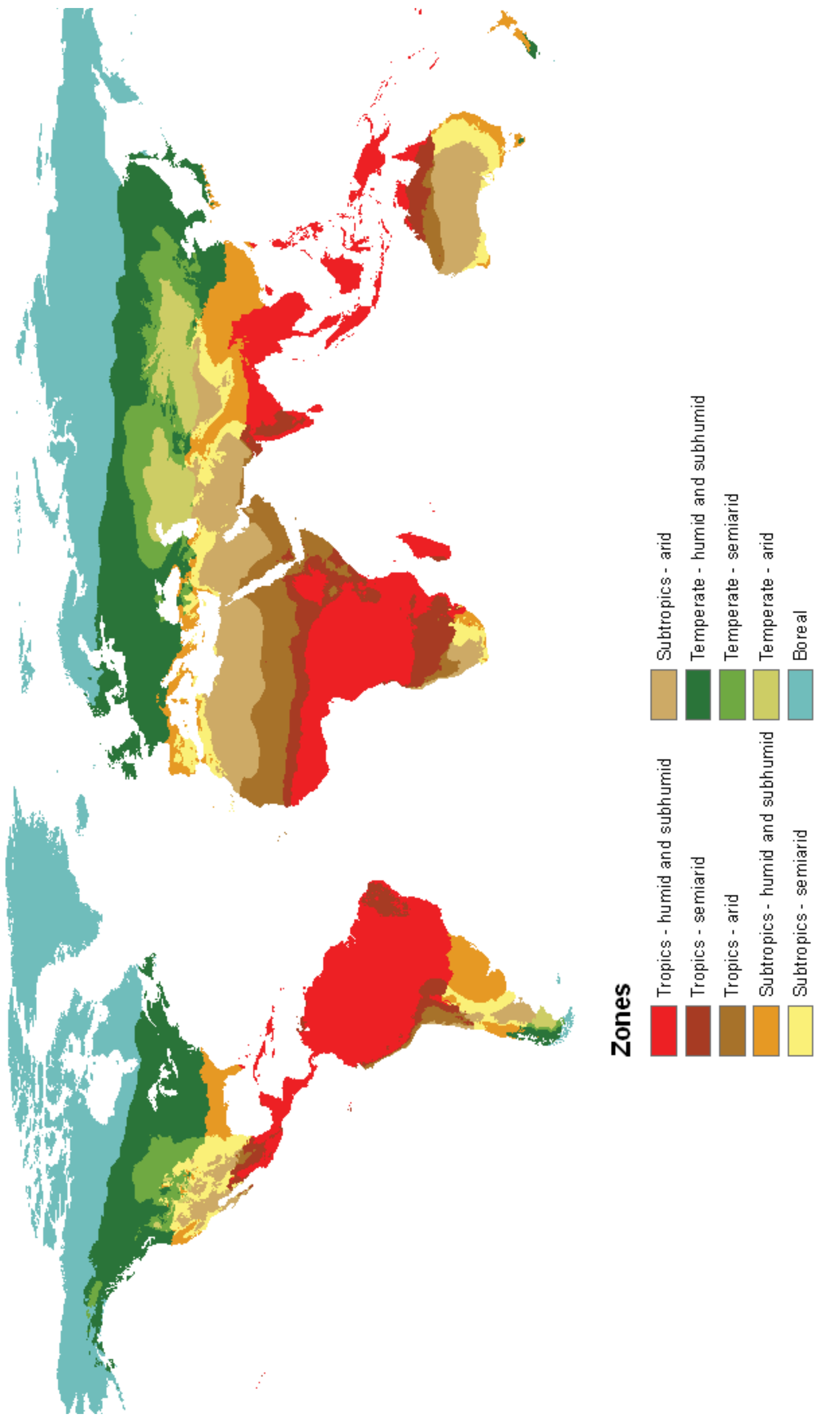
[24] **O horizon** = Soil layer with a high percentage of organic matter that is sometimes present covering the upper mineral horizon designated as A horizon. This latter is the horizon where organic material mixes with inorganic products of weathering.

also show that the conversion from TA to CA promotes SOC accumulation (Phillips *et al.*, 1993; Lee *et al.*, 1993; Kern and Johnson, 1993; Lal, 1997; Franzluebbers, 2005). Others, however, conclude that CA does not have a positive effect on carbon sequestration in agricultural soils (Baker *et al., 2007*; Blanco-Canqui and Lal, 2008).

This section gives an overview of the most important measures that should be taken into account when setting up experiments and elaborating data in order to correctly assess the SOC accumulation potentials of different management systems, and aims at disproving conceptual flaws.

Prudence should be used when trying to summarize global features, as it is the case for instance for West and Post (2002) and the Conservation Agriculture Carbon Offset Consultation held in the USA in 2008. The first, comparing data from 276 paired treatments worldwide, estimate that a change from TA to CA can on average sequester SOC at a maximum rate of 0.57 t of carbon ha^{-1} y^{-1}. The soil carbon sequestration rate reported by the Conservation Agriculture Carbon Offset Consultation is 1.8 t ha^{-1} y^{-1} in the first ten years of adoption of CA. The carbon sequestration potential of any soil, for the carbon pools considered, depends on many variables. Therefore, when addressing carbon sequestration, rates should always refer to specific carbon pools, as each carbon category has a very different turnover rate. For instance, carbon accumulated in the first ten years is young and highly oxidizable. In addition, in order to assess the effects of management practices on soils, it is necessary to have some reference base for the same soil types under the same climatic conditions. Undisturbed soils under natural vegetation should be used as a benchmark and compared to soils disturbed by human activities. Furthermore, data analysis should be carried out, at the most, at the level of agro-ecological zones. As anticipated in section 2.1, the rate of conversion of the carbon content in crop residues into SOM is strongly related to the climate, and rates achieved under different climatic conditions are not directly comparable and should not be aggregated. Therefore, for instance, soil carbon stocks achieved in the subtropics, where mild climate and regular rainfall allow cropping throughout the year, cannot be compared with those relating to continental and sub-continental temperate areas. The potential rate of carbon sequestration will have to be calculated based on the agro-ecological zone, as done for example by West and Marland (2002) and Calegari *et al.* (2008) for CA and by de Moraes Sà and Séguy (2008) for TA. The first authors, analyzing 76 long-term experiments in the USA, reported a potential rate of carbon sequestration of 0.34 t of carbon $ha^{-1}y^{-1}$; the second based on experiments of 19 years to report a rate of 1.24 t of carbon $ha^{-1}y^{-1}$ for southern Brazil. While under TA, 100 percent of the organic matter from crop residues and, in the cases described in section 3.1.4, also part of the carbon stored in the soil is lost as CO_2.

FIGURE 1
Map of Thermal Climates and Moisture Regimes



Some considerations on CA performance in different climatic and moisture regimes (Figure 1) are given in the next sections: tropical and subtropical humid and subhumid zones are commented on in section 3.3.1; tropical and subtropical semi-arid zones in section 3.3.2; and temperate zones in section 3.3.3. The classification adopted here is based on the thermal-climatic zones according to the Global Agro-Ecological Zones (IIASA/FAO, 2010). These have been modified as follows: i) tropical lowlands and highlands have been merged into the tropics class; ii) temperate oceanic, sub-continental and continental zones have been merged into the temperate class; iii) subtropics with low rainfall have been reallocated under subtropics with either summer or winter rainfall. Each climatic zone has then been divided into three moisture regimes: the humid and subhumid one is characterised by values of aridity index above 0.50 (FAO, 2009b), the semiarid regime is characterised by values of aridity index from 0.50 through 0.20 and the arid regime presents aridity index values below 0.20.

3.3.1 Subhumid and humid tropical and subtropical zones

Most common tropical and subtropical soils have a mixed mineralogy. With respect to less weathered soils (e.g. soils dominated by 2:1 clays), they are characterized by: i) the capacity to form aggregates more independently from organic matter inputs, and ii) by the higher aggregate stability at a certain carbon content. Such capacities of soils with high content in mineral particles with variable charges are the results of the coexistence of negative and positive charges at prevailing field pH. This allows mineral-mineral binding, in addition to organic matter functioning as a binding agent between 2:1 and 1:1 clays (Elustondo *et al.*, 1990). Despite these characteristics, tropical and subtropical soils suffer from low nutrient retention capacity due to the faster turnover of SOM and organic compounds. In fact, edaphon activity is most vigorous under the high moisture and temperature regimes, and needs to be supported with adequate "feed" (substrate) to keep the ratio of the carbon stored to the GHGs released as high as possible (Scopel *et al.*, 2004; Séguy *et al.*, 2006). In addition, 1:1 clays, that are often dominant in tropical and subtropical soils, offer low protective capacity to SOM.

In order to alleviate the problem of low nutrient retention capacity, agronomic systems should be adopted that increase the protection of carbon and nitrogen from rapid mineralization. In their review, Six *et al.* (2002b) compared CA with TA providing evidence that SOM turnover was slower in CA than in TA soils. More specifically, macroaggregates in CA soils contained on average 1.7 times more microaggregates and 3-times more intra-microaggregate carbon than macroaggregates in TA soils. This means that lower soil disturbance, higher faunal and microbial, particularly fungal, biomass (Doran *et al.*, 1980; Doran *et al.*, 1987; Parmelee *et al.*, 1990) and binding agents in CA systems are efficient tools to protect carbon from microbial activity.

Further major limitations to agricultural production in the subtropics with summer rainfall are steep slopes and, particularly in dissected topographies, low organic matter content. In such areas, several studies testify that the permanent protection of soil is an important measure for erosion control which also reduces the risk of pollution of surface waters with sediment, pesticides and nutrients.

For the reasons stated in section 2.2 at point i, to reach environmental and economic sustainability in humid and subhumid tropical and subtropical areas, profitable cropping systems with high adaptation capacity in adverse environments and with high biomass should be developed to keep the soil covered during the dry season and to maintain aggregate stability, favouring plant growth and carbon sequestration (de Moraes Sà *et al.*, 2008). Such cropping systems may combine a cash crop during the summer season with intercrops to take advantage of available soil moisture (Hobbs, 2007). Due to their representativeness of an economically relevant area at severe risk of soil degradation, two experiments of Tran Quoc *et al.* (2008a, b) have been chosen and commented on here. In Sayaboury province, the major site for maize production in Lao PDR, land preparation is mainly based on ploughing, even on slopes of 45 percent, and the main crop under rainfed conditions is monocropped maize. After five years, the authors showed that conversion from maize monoculture with heavy mechanized tillage to a CA-based rotational sequence of maize - rice[25] and maize - *Brachiaria ruziziensis* led to 50 percent higher maize yields. In addition, climate-induced yield fluctuations, typical of monocrop systems, were evened out and soil physical, chemical and biological characteristics were rapidly improved. Total water-stable aggregates were greater under CA conditions due to an increase in large aggregates (from 2 to 8 mm) at each depth. In contrast, the TA system showed a decrease in large aggregates and an increase in medium and small water-stable aggregates (from 0.250 mm to 1 mm). The CA system also showed higher values for soil water-holding capacity (on average 152 mm in the first 30 cm) relative to TA (131 mm) and to the natural ecosystem (137 mm).

3.3.2 Tropical and subtropical semi-arid zones

Water scarcity and soils susceptible to erosion and degradation are the ecological constraints to rainfed production in drylands[26] (TAC, 1994).

The first is often worsened by unsustainable land use practices (Hassan and Dregne, 1997). In semiarid areas crop residues are often used as a source of animal feed (Stewart and Robinson, 1997) and in areas where soil moisture conservation and the maintenance of soil fertility rely on fallow, as in West Asia and in North Africa, on average less than one crop a year is grown on

[25] **Rice** = *Oryza sativa*

[26] **Drylands** = Areas characterized by lack of water, which constrains their two major interlinked services of primary production and nutrient cycling (FAO, 2005a).

rainfed land. Soil tillage and inversion are typically done before the beginning of the rainy season to create short-term macroporosity, which is deemed to be necessary to absorb rain water. However, in the long term, mechanical soil disturbance destabilizes aggregates and hence reduces water infiltration (Sequi, 1989). And, in soils dominated by unstable aggregates, rains have the tendency to disrupt aggregates thus causing pore occlusion, soil crusting and surface runoff. Soil cover combined with reduced mechanical soil disturbance tends to make dryland soils more suitable for agriculture as compared to TA practices, especially where the soil temperature is above the optimum for plant growth. First, affecting soil colour and albedo, surface residues left undisturbed reduce soil temperature. Further, on average the mulch layer helps the soil-crop system reduce losses down the profile as described at point vii in section 2.2. For these reasons, in drylands crop management systems should be introduced that guarantee a high accumulation of organic matter (Thiombiano and Meshack, 2009; Silici, 2010). Thierfelder and Wall (2009) studied the effect of CA techniques on soil moisture relations in drylands: on a fine textured soil in Zimbabwe and on a sandy soil in Zambia. In Zimbabwe, the CA treatments had a 49 percent and 45 percent greater infiltration rate than TA in the first 60 cm; in Zambia the same treatment had 57 percent and 87 percent greater soil infiltration rate than the TA control treatment in both seasons.

Degraded soils are characterised by low fertility, associated with low levels of organic matter and nitrogen: total SOC in the upper 100 cm of dryland soils amounts to about 40 t ha^{-1} (Batjes, 1999). Soil degradation and erosion are particularly insidious processes because they are not readily apparent to farmers until their effects are severe and often irreversible by traditional means (Cleaver and Schreiber, 1994). In the absence of excessive human disturbance, dryland vegetation has good resilience, often recovering rapidly from droughts; but when continuous cropping is practised over the years, soil disturbance and failure to return above-ground plant residues and other required inputs leads to a further reduction in SOC. As general rules, keeping a sufficient amount of live and dead biomass *in situ* helps to decrease erosion (Tiessen and Cuevas, 1994); and increasing dryland cropping intensity is one of the ways to offset agricultural emissions (Lal *et al.*, 1998b). However, as previously explained, the effectiveness of such practices in increasing the carbon input to the soil is influenced by soil management. Examples of the effect of different management practices and residue retention on SOC sequestration in dryland areas follow. The database that Pieri (1995) collected from trials on highly sandy soils in semi-arid regions of Africa showed that TA led to annual average losses of about 5 percent of the organic matter in the upper 15 cm of soil. Long-term experiments of Melero *et al.* (2009) on a sandy clay loam Entisol and on a clay Vertisol in dryland CA- and TA-based farming systems (in semi-arid south-west Spain) showed the effectiveness of CA in enhancing soil carbon and biological status: contents of labile fractions of the total organic carbon, microbial biomass carbon, enzymatic activities (i.e. ß-glucosidase and o-diphenol oxidase activity) in the Entisol and in the Vertisol were higher in CA than in TA trials. Ryan (1997) reported that even in the sandy soils in the north of the Syrian Arab Republic modest increases in SOC with NT were possible. Ringius (2002) reported that in western Nigeria CA increased soil carbon by 4.3 t ha^{-1} y^{-1}. Some experiments also show that reducing mechanical tillage alone is enough to positively affect crop yields. Among these experiments, two are cited here: the one of Rockström *et al.* (2009) in semi-arid and dry sub-humid east and south Africa, and the simulations of Farage *et al.* (2007) with CENTURY 4.0 and RothC-26.3 models to investigate the effects on soil carbon stocks of the conversion from TA to NT in dryland farming systems in Nigeria, Sudan and Argentina.

The potential to accumulate carbon in semi-arid regions is large because dryland soils are far from saturation, these regions extend over vast surface areas (more than ½ of the earth's land area is dryland) (FAO, 2004) and tillage reduction seems to be the most effective strategy for carbon accumulation and crop yield enhancement in hot, dry environments (Batjes and Sombroek, 1997; Buschiazzo *et al.*, 2001). However the effectiveness of the agricultural management system depends on many factors. Some of these are modifiable, such as choosing the right equipment (Choudhary and Baker, 1994) and, where livestock is a key component of the farming system, managing grazing of crop residues to permit soil cover and carbon accumulation. Soil texture, on the contrary, is not changeable and determines the degree of organic matter protection. In coarse-textured soils, which usually offer limited protection to organic matter, the organic matter accumulation rate is expected to be lower (Zingore *et al.* 2005; Chivenge *et al.* 2006). In highly depleted soils, carbon sequestration has the highest potential, but it is a slower process to start, because the soil microbial population that drives the SOC and nutrient cycles requires specific nutrient ratios which take time to achieve (Stevenson, 1986).

3.3.3 Temperate zones

Unlike tropical soils, temperate soils can only rely on biological mechanisms to stabilize carbon. This means that organic matter is the primary binding agent for soil aggregates and that in initial macroaggregate formation low organic matter inputs and losses cannot be compensated for by other factors (Six *et al.*, 2002b).

In moist temperate areas, soil erosion and degradation risks are often underestimated because their symptoms, such as pollution of air and water, are measured off-farm and remain unseen by farmers. They feel therefore little incentive to change management practices for environmental reasons. Farmers tend to consider environmental issues where these are easy to observe, i.e. mostly only in farms in vulnerable habitats (Evans, 1996). In many cases where the erosion occurs, it is hardly noticeable and its effects on yield reduction are small, unless SOC falls below 1 percent (Holland, 2004; Delgado *et al.*, 2011). In these circumstances farmers are unlikely to be aware of the problem and to take action. Adoption of environmental measures should then be promoted to compensate for non-evident environmental risks and to protect the already scarcely efficient carbon sequestration process of colder climates. In fact, in temperate areas, lower mineralization rates translate into slower transformation of organic matter into SOM.

The comparative analysis between CA and TA systems done by Six *et al.* (2002b) for temperate soils evidenced that the mean residence time of carbon was on average 1.5 times longer in CA than in TA.

Long-term measurements of carbon sequestration in agricultural soils in USA (Dick *et al.*, 1998; Lyon, 1998), Germany (Tebrügge and During, 1999) and Russia (Kolchugina *et al.*, 1995) showed that ploughing can decrease SOC content by 10 - 30 percent in 20 years as compared to NT. In Canadian Prairies that are degraded due to wind erosion, a switch to NT farming in the late 80s led to the disappearance of dust storms. In similar areas where CA has minimal levels of adoption, such as Ukraine and Kazakhstan, degradation problems continue because of intensive tillage.

CA seems to have the potential to achieve sequestration rates of 0.25 to 1 t of carbon ha^{-1} y^{-1} in humid temperate areas (Lal, 2008b), and in drier temperate areas to increase the productivity from rainfall and therefore to reduce the risk of crop failure (FAO, 2006b; Derpsch and Friedrich, 2009; López-Bellido *et al.*, 2010).

3.4 INFLUENCE OF SOIL AND CROP MANAGEMENT SYSTEMS ON SOC - LESSONS LEARNT

When assessing the effect of different management systems on SOC, care should be taken that the only variable in the experiment is the management system. Three experiments are considered here as examples of conceptual flaws that should be avoided.

Example 1. The study by Blanco-Canqui and Lal (2008) specifically aimed at assessing: i) changes in SOC within the topsoil due to conversion to NT farming; and ii) the depth distribution (0 - 60 cm) of SOC in NT soils compared with TA and natural vegetation (i.e. forest soils). Based on experiments in paired fields under NT and TA at 11 sites (referred to as a major land resource area, i.e. MLRA), in the eastern USA, the authors concluded that NT is beneficial to water and soil conservation, but does not help store more SOC than intensive tillage. According to the authors, the only significant difference with TA may be that SOC under NT soils is more stable. To enhance SOC sequestration above that achieved with TA they advise manure application, return or occasional burial of crop residues, use of cover crops, complex crop rotations and high biomass producing crops. The first remark on this study regards the fact that some features of CA and of NT are all indistinctly and erroneously attributed to NT systems. For instance, the authors claim that NT is an important technology for improving soil processes, controlling erosion and conserving water resources. On the contrary, NT alone is not sufficient to achieve water and soil conservation, and much less to consistently promote SOC accumulation. What the authors suggest as improved NT practices for SOC accumulation enhancement coincides with the definition of the CA technology, with, of course, the exception of their recommendation to plough and bury crop residues. CA systems should be regarded as intensive, despite the underlying idea in the paper that intensive farming systems are synonymous with TA. For these reasons, it would have been advisable that the authors compared TA with CA systems rather than with NT ones. The other reason why the results achieved under NT and TA in this experiment are not comparable is that paired fields, although next to each other, and with similar soil and slope conditions, had different cropping systems. For instance, NT maize silage was compared with TA continuous tobacco[27] with wheat and rye cover crop. The effect of crop rotations is crucial and cannot be neglected. In this regard it should also be noted that, as discussed in sections 3.1.2 and 3.1.3, neither the eight maize - soybean (- legume/vegetables) rotations analysed in this experiment nor the two continuous silage maize rotations allow positive SOC accumulation. The only cropping system included in the study that had the potential to sequester SOC (i.e. maize - soybean with rye cover crop) returned 50 percent greater SOC concentration on a mass basis in CA compared with that in TA soils. All this being considered, the generally negative conclusion on NT carbon accumulation potential by Blanco-Canqui and Lal is not surprising. Other authors have also commented on this study. Franzluebbers (2009) observed that Blanco-Canqui and Lal themselves "pointed out the difficulties in interpreting the results of the farm-survey approach undertaken, especially regarding the difference in cropping history of each field site, difference in current crop management system since enrolled in a particular tillage system, difference in type of tillage implements, difference in fertilizer use, and difference in crop residue returned ... [but] the greater concern was the sampling approach, which should have tempered the strength of conclusions. Only one field was sampled within a MLRA, and therefore, conventional statistical analysis should not have been used to assess the effects of management within a MLRA. A more appropriate choice of analysis should have been to use the 11 MLRA sampling locations as replicates for the three management systems. Because multiple fields of a management system within a MLRA were not sampled, then the only valid comparison was of management systems across MLRAs. How management affects SOC within a MLRA (> 1 million ha) should not have been based on three cores within a single field." "Reasonable conclusions from the study of Blanco and

[27] **Tobacco** = *Nicotiana tabacum*

Lal (2008) should have been limited to: i) SOC storage was greater under NT than under TA only in the surface 10 cm on farmers' fields in the eastern Corn Belt and ii) greater random variation with increasing soil depth limited the possibility to declare differences in SOC and nitrogen storage between tillage systems."

Example 2. Luo *et al.* (2010) carried out a meta-analysis on global data from 69 paired experiments to assess the response of SOC under TA and NT and concluded that the latter treatment is not beneficial to increase the total SOC. Seven of the total experiments reviewed by the authors are reported as NT, but they should have more correctly been referred to as CA systems. These are the experiment of Christopher *et al.* (2009) in the Midwestern of the USA on maize - soybean - wheat, the experiment of Machado *et al.* (2003) in Brazil, those of de Moraes Sá *et al.* (2001), de Moraes Sá and Lal (2009) and of Sisti *et al.* (2004) in Brazil. All Brazilian experiments show some form of benefits on SOC through CA, the others do not.

Example 3. Govaerts *et al.* (2009) reviewed 78 papers to analyse the potential impact of CA on carbon sequestration: in 40 cases the soil carbon stock was higher in NT as compared to TA, in 31 cases there was no significant difference, and in seven it was lower. Beyond the general consideration that no mention on residue retention is made, lower SOC under NT is associated with a sorghum monocrop, a soybean monocrop, a maize monocrop, wheat - fallow, wheat - rye and maize - soybean systems, which have all already been discussed as not being conducive to increase SOC.

CHAPTER 4

Is the carbon budget for CA systems higher than for TA systems?

Many of the agronomic practices and methods often recommended to increase carbon accumulation in soils contain hidden carbon costs in terms of ancillary GHG emissions.

The aim of this chapter is to quantify the carbon footprint of the variables that constitute the CA and TA production cycles.

4.1 MECHANICAL EQUIPMENT

In CA systems, the use of machinery is characterized by lower farm power requirements and reduced number of passes across the field relative to TA systems. This translates into lower rates of soil carbon oxidation, smaller tractors and longer tractor life, reduced working time, hence slower depreciation rates of equipment and less fuel consumption per unit area per unit of output (Frye, 1984; FAO, 2001). Table 1 summarizes the relative carbon cost within the production systems analysed based on relevant literature from different authors (Smith *et al.*, 1998; Tebrügge, 2000; FAO, 2001, 2008, 2009a).

TABLE 1
Carbon costs of the variables that intervene in the CA and the TA systems

Variables	Cost of the variable under CA as compared to TA
fuel consumption per unit area per unit output	35 - 80% less
number of passes	50 - 54% less
size of machinery	50% lower power requirement
depreciation rate of machinery	2 - 3 times lower (i.e. 2 - 3 times longer lifetime)

Among the carbon costs attributable to the use of machinery, the CO_2 efflux from the soil induced by different treatments should be included. Reicosky's measurements (1997) of CO_2 released in different treatments reveal that carbon losses from soil induced by mouldboard ploughing are highest and that losses occurring after sod seeding are lowest. All measurements are given in Table 2 as a percentage of carbon content in the crop residues.

TABLE 2

Percentage of carbon in the crop residues released from the soil after different treatments (Reicosky, 1997).

Tillage practice	Percentage of carbon in the crop residues released as CO_2
mouldboard plough	134
mouldboard plough and disc harrow	70
disc harrow	58
chisel plough	54
sod seeding	27

4.2 FERTILIZATION

On soils that have already experienced significant losses of organic matter as a result of tillage, fertilization is often assumed to increase the rate of SOC accumulation. But little is to be found in the literature that provides appropriate estimates of the net carbon sequestration ascribable to the fertilization of agricultural soils. Studies show that fertilizers do not usually generate a net sink for carbon, as their production and application come with a higher carbon cost (Jenkinson, 1990; Paustian *et al.*, 1992; Varvel, 1994; Ismail *et al.* 1994; Gregorich *et al.*, 1996; Drinkwater *et al.*, 1998; Halvorson *et al.*, 1999; Schlesinger, 2000). Even when N-fertilizers are considered, the direct linear relationship that most often occurs between long-term nitrogen additions and SOC accumulation (Rasmussen and Rohde, 1988) is usually insufficient to balance the emissions associated with the industrial production, transport and application of the fertilizer (Jenkinson, 1990; Paustian *et al.*, 1992; Varvel, 1994; Ismail *et al.*, 1994; Gregorich *et al.*, 1996; Potter *et al.*, 1997; Drinkwater *et al.*, 1998; Halvorson *et al.*, 1999). The need for carbon-expensive N-fertilizers could be reduced over time where strategies that allow lower nutrient losses by leaching are implemented. In fact nitrate leaching from agricultural lands is largely determined by the nitrate content of the soil just before the rainy season starts: between 79 and 98 percent of this does not originate from unused fertiliser applied earlier in the year, but is formed by mineralization of organic nitrogen in the post-harvest season when temperatures are high (Macdonald *et al.*, 1989).

> The quantity of nitrate leached is a function of the mineralization of organic N in post-harvest.

One strategy for reducing nutrient leaching is the use of catch crops. Another is the adoption of management practices that favour soil biota: not only do they favour the fast recycling of nutrients (Van Kessel *et al.*, 1994; Drinkwater *et al.*, 1998; Lafond *et al.*, 2008), but they also help to immobilize most residual nitrogen (along with organic carbon) in the soil (Amado and Costa, 2004). However, most important are management practices that favour high residue levels, which act as physical buffers. Finally, according to several authors part of the N-fertilizer could be replaced by legume nitrogen. For example, the experiments of Christopher and Lal (2007) in the more southerly regions of the USA showed significant nitrogen inputs (in the range from 0.04 to 0.27 t of nitrogen ha^{-1}) from species of vetch[28], clover, pea[29] and white lupin[30], which translate into considerably higher yields for the main crop (Franzluebbers, 2007). The work of Boddey *et al.* (2009b) in southern Brazil showed that the integration of winter leguminous green-manures (e.g. lupins and hairy vetch[31]) into the rotations as the crop before maize[32] can substitute relevant quantities of N-fertilizer. In a study in the Brazilian state do Rio Grande do Sul, Giacomini *et al.* (2004) found that maize preceded by vetch under CA management yielded a mean of 6.0 t of grain ha^{-1} y^{-1} over three consecutive years, compared with 4.3 t ha^{-1} y^{-1} when preceded by oat or 3.7 t ha^{-1} y^{-1} when preceded by spontaneous vegetation (a natural fallow). The yield of maize following a combination of oat (max 30 percent) and vetch (min 70 percent) was 70 percent higher that of the maize with 0.18 t ha^{-1} y^{-1} of nitrogen applied as urea following natural fallow. Another study performed under CA management in the same state by Lovato *et al.* (2004) showed that, when 0.14 t ha^{-1} y^{-1} nitrogen was applied to the maize following oat in the rotation, biomass production increased by 92 percent over the treatment without nitrogen; and that the same level of nitrogen fertilization in a vetch-maize system increased biomass production by only 38 percent. This indicates that the legume winter cover crop already supplies most of the nitrogen required by the maize. Despite this evidence, the main obstacles to planting a nitrogen-fixing legume before the cereal crop that requires the nitrogen are the reluctance by most conventional farmers to integrate cover crops with no direct financial return into their cropping schemes and the lack of time in the agricultural season. In temperate climates the growing season is indeed often limited by low temperatures. These impediments may be overcome by introducing intercropping systems that maintain year-round soil cover. Neither do low temperatures seem to be as serious a problem as is often believed. Drinkwater *et al.* (2000) reported that hairy vetch planted at the Rodale Institute in Pennsylvania in late August after winter wheat[33] was able to accumulate between 0.14 and 0.22 t of nitrogen ha^{-1} in the period until early May the next year when maize was planted.

In conclusion, if CA practices were extensively adopted, a number of positive externalities would be achieved and GHG emissions, nutrient losses by leaching, contamination of ground water reserves, the need to add readily decomposable carbon (e.g. liquid manure) would be reduced.

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[28] **Vetch** = *Vicia spp.*
[29] **Pea** = *Pisum sativum*
[30] **White lupin** = *Lupinus albus* L.
[31] **Hairy vetch** = *Vicia villosa* L.
[32] **Maize** = *Zea mays*
[33] **Winter wheat** = *Triticum aestivum* L.

4.3 GHG DYNAMICS

If the full impact of a change in land management on carbon dynamics is to be evaluated, fluxes of the main GHGs that may alter the CO_2-mitigation potential of soil management practices must be considered. In the next sections the two GHGs CH_4 and N_2O are considered and special attention is given to the activities responsible for major emissions. CH_4 and N_2O have a similar but greater greenhouse effects than CO_2: CH_4 has an approximately 20 times higher global warming potential[34] than CO_2, while N_2O is approximately 310 times more potent than CO_2 (Pisante *et al.*, 2010). For a more complete accounting of potential carbon credits associated with the management of agriculture soils, direct and indirect costs should also be estimated for the production and distribution of pesticides and herbicides. However, since pest and weed management systems must be locally devised and can be variable, any broad estimate of their carbon costs would be of little use and is not addressed in this study. In many cases vegetation from cover crops can be crushed with a knife roller and the residues maintained to cover the soil until planting the next crop (Derpsch, 2002). On the other hand, for residues with high nitrogen content (low C/N) that decompose very quickly, desiccant herbicides may be needed to control vegetation before the winter crop. Further analyses in this area are needed.

4.3.1 Methane emissions

CH_4 flux from soil to atmosphere is the net result of two bacterial processes that are strongly influenced by land use, land management and the type of soil: CH_4 production in strictly anoxic micro-environments (methanogenesis) and CH_4 consumption and oxidation in aerobic micro-environments by CH_4-oxidizing bacteria (methanotrophs).

Comparative data between CA and TA for CH_4 uptake are lacking and only data from temperate soils were found: Cochran *et al.*, 1997; Hutsch 1998; Kessavalou *et al.*, 1998b; Ball *et al.*, 1999; Robertson *et al.*, 2000. Six *et al.* (2002b) summarized these data and reported an on average 0.00042 ± 0.0001 t C-CH_4·ha^{-1} y^{-1} greater CH_4 uptake under CA, which they attributed to the higher pore continuity and presence of ecological niches for methanotrophic bacteria in CA compared with TA (Hutsch 2001).

Flooded rice fields represent globally one of the main sources of CH_4 (GEIA, 1993) because: i) drainage at the end of the growing season causes the CH_4 formed during continuous flooding to be released; ii) the aerenchymal system of the rice plants transport CH_4 from soil to the atmosphere; and iii) paddy rice accounts for some 160 million ha worldwide, i.e. some

[34] **Global Warming Potential** = Index developed by IPCC to quantify the ability of a gas to trap the infrared radiation (i.e. heat) relative to the ability of the same amount of the CO_2 reference gas to trap heat in a given time horizon. The global warming potential of any gas depends on its radiative forcing and on its lifetime (IPCC, 2007).

75 percent of the global rice volume (Maclean *et al.*, 2002). For these reasons, rice production systems are given special attention here below.

Rice farmers tend to keep their fields continuously submerged to control weeds, although long-term experiments suggest that continuous puddling[35] for rice destroys soil physical properties and affects both the puddled rice yield and the following crop negatively (FAO, TECA web resource). Water conservation in the paddy is guaranteed by bund construction to prevent run-off and by puddling to create a soil stratum resistant to percolation. New technologies to reduce the use of water and GHG emissions in rice cultivation are now available. One is the Systems of Rice Intensification (SRI), an approach that allows intensification by optimisation of external inputs (i.e. water and seed) relative to the conventional rice production system (Uphoff *et al.*, 2009; Uphoff and Kassam, 2010; Kassam *et al.*¸ 2011; http://sri.ciifad.cornell.edu/index.html) through compliance with the following: i) moist (but well drained and aerated) soil conditions; ii) transplanting rice seedlings at a very young age; iii) wider spacing of plants; iv) use of organic matter (i.e. compost made from any available biomass and manure if available) and chemical inputs; and v) frequent weeding. Another approach is interrupting the flooding: conventional irrigated rice systems with high yielding modern rice cultivars in soils with alternate wetting or drying (AWD) and with high external inputs can achieve medium to high yields (Stoop *et al.,* 2009; Bouman *et al.*, 2005; Yang *et al.*, 2005). However, only timely flooded rice or rainfed lowland rice in flooded fields with periods of non-submergence can help to save water and reduce CH_4 emissions, but seem to have the potential to increase the release of N_2O. Given that irrigated aerobic rice and SRI do not require anaerobic conditions, it would appear that both practices can combine well with CA (Friedrich *et al.*, 2009). Systematic research is required to evaluate and adapt such methods for CA, so that soil puddling can be avoided, transplanting-based systems converted to direct seeding, and weed incidence still kept under control with integrated management practices. This would noticeably reduce the total growing period (Friedrich and Gustafson, 2007) and make further labour, fuel and water saving possible. In addition this approach would not only reduce the CH_4, but also the N_2O emissions (Salas, 2010).

4.3.2 Nitrous oxide emissions

Agriculture, through mineral nitrogen fertilization and its effect on soil structural quality and water content, influences the terrestrial nitrogen cycle and is the main source of N_2O emissions worldwide (Ball *et al.*, 1999). This gas is mainly produced by nitrification under microaerophilic[36] soil conditions

[35] **Puddling** = Intensive mixing of soil under wet conditions for rice to create a hard pan, level the soil and remove the soil structure; it can be done by the combination of tractor wheels or animal hooves with tillage implements such as ploughs, rotary cultivators or harrows.

[36] **Microaerophilic conditions** = Aerobic environment with lower levels of oxygen than are present in the atmosphere.

(at values for water-filled pore space from 20 to 80 percent) and through denitrification under anaerobic soil conditions. The latter process is the most important. The main factor controlling the speed of both processes is substrate availability: ammonia in the case of nitrification and oxidized nitrogen forms (nitrates and nitrites) in the case of denitrification processes. Nitrification is also favoured at high temperatures and is inhibited at acid pH values.

The main reasons why some authors find that enhancing SOC stock through a shift from TA to CA may also exacerbate emission of N_2O are anoxic environments within the soil in CA systems, substrate availability for microbial degradation (i.e. carbon and nitrogen from crop residues) and tight coupled carbon and nitrogen cycles (Aulakh *et al.*, 1984b; Sexstone *et al.*, 1985; Mosier *et al.*, 1991; Vinther, 1992; Hojberg *et al.*, 1994; Mackenzie *et al.*, 1998; Robertson, *et al.*, 2000; Six *et al.*, 2004).

As for CH_4, the nitrogen pathway in flooded rice fields requires specific mention. In continuously submerged fields, nitrogen is chiefly available as ammonium and is mainly lost through NH_3 volatilization (Vlek and Craswell, 1981). Soils allowed to become (temporarily) aerobic will enhance nitrification and if the nitrate is not taken up, it is subject to losses by denitrification (Reddy and Patrick, 1976; Eriksen *et al.*, 1985; Sahrawat and Keeney, 1986). Rice production systems recommended for the reduction of CH_4 emissions are also advisable in these circumstances. In any case, soil compaction is to be avoided by all means, if necessary through controlled traffic systems which keep traffic and any danger of compaction out of the cropping area.

Beyond rice production, asphyctic soil conditions and hence enhanced N_2O emissions for humid and compacted soils would be possible during the transition phase from TA to NT, if structural and drainage problems were not addressed and corrected before or during conversion and if inappropriate cropping systems were put in place. When soils are too heavy and poorly drained, drainage systems should be implemented; when present, plough pans should be broken; cover crops with robust and deep rooting systems should be chosen; varied rotations should be adopted to encourage functional diversity of rhizosphere bacteria populations and favour nitrogen-fixing ones.

To achieve emission reductions, improved nitrogen management and well established and sensibly planned CA systems are indispensable, but not sufficient. In fact CA minimises the mineralisation process and the physical loosening typical of disturbed soils, but it does not eliminate physical compaction caused by the passing of heavy machinery and therefore it should always be combined with controlled traffic[37] (Tullberg, 2008). In addition, microaggregates in CA soils offer a more oxygen-limited environment than in TA soils. This explains the higher carbon and nitrogen protection from mineralization of CA, but also why some authors found higher denitrification

[37] **Controlled traffic** = Restriction of all heavy wheel traffic to permanent traffic lanes.

rates in CA than in TA soils. Six *et al.* (2002b) calculated the differences in annual N_2O fluxes between CA and TA based on fourteen comparative experiments in temperate agroecosystems (Burford *et al.*, 1981; Aulakh *et al.*, 1984a; Aulakh *et al.*, 1984b; Linn *et al.*, 1984; Germon *et al.*, 1985; Arah *et al.*, 1991; MacKenzie *et al.*, 1997; Palma *et al.*, 1997; Kessavalou *et al.*, 1998a; Kessavalou *et al.*, 1998b; Mackenzie *et al.*, 1998; Ball *et al.*, 1999; Lemke *et al.*, 1999; Robertson *et al.*, 2000) and in tropical soils (Angers *et al.*, 1997) that reported higher denitrification rates for the CA management system. The authors of the review concluded that in CA systems the N_2O flux was 0.00291 ± 0.00078 t N-N_2O ha^{-1} y^{-1} times (corresponding to 1.418 ± 0.382 t C-equivalents ha^{-1} y^{-1}) higher than under TA, and nullified the beneficial effect of higher CH_4-uptake and carbon sequestration of CA in terms of GHG balance. The authors also pointed out that more research is needed to investigate how the difference in N_2O-fluxes between CA and TA varies in time and the interactive effects of tillage, fertilizer application methodology and crop rotation.

CHAPTER 5
Concluding comments

This paper reviews the impact of the components of major agricultural systems on soil carbon dynamics. It demonstrates the correlation between CO_2 loss and tillage intensity and concludes that a shift from TA to CA, along with effective nitrogen management, provides an effective option to help offset emissions of the main GHGs (CO_2, CH_4, N_2O). In time such a shift also promotes carbon sequestration in the soil profile, including below the ploughed layer (Lal *et al.*, 1998c; Lal, 2002), and helps to restore a degraded agro-ecosystem to a sustainable one. However, the effectiveness of the conversion to CA with respect to SOC sequestration depends on many variables, and the full advantages of CA can usually be seen only in the medium- to longer-term when CA practices are well established, even though some authors, such as Kandeler *et al.* (1999) or Tran Quoc *et al.* (2008a, b), report significant increases in microbial activity soon after transition to CA. To provide an idea of the time scale, Smith *et al.* (1997) report that the period for European soils to reach a new steady state after a carbon-enhancing land-use change is between 50 and 100 years. In highly depleted soils, carbon sequestration has the highest potential, but it is a slower process to initiate because the soil microbial population that drives the SOC and nutrient cycles requires specific nutrient ratios (Stevenson, 1986).

Despite the beneficial environmental impact of CA, the main incentives for farmers to shift to it are related to productivity and economics rather than environmental sustainability, i.e. improving farms' competitiveness and cutting some of the most relevant production costs thereby increasing profit margins (Hengxin *et al.*, 2008). With CA fewer or smaller tractors can be used and fewer field passes are required, which result in lower investment, fuel and repair costs. Over time CA systems require less carbon-expensive N-fertilizer for the same output.

Why then do the majority of farmers still use the plough or other tillage implements? The review of the evidence shows that where TA is deeply rooted in the cultural background, lack of knowledge about CA systems and their management make it particularly difficult for farmers to produce crops without ploughing. CA is much more than simply seeding into sod and is more difficult to implement than TA. Most farmers would be able to mechanically incorporate chemical nutrients into the soil, bury weed seeds, and recreate a temporary soil structure on a seasonal basis as a precarious environment favourable for crop growth. Fewer farmers would know how to set up a crop rotation aimed at producing adequate biomass by crop successions, providing soil nutrients, reducing weed growth in time, diminishing pest incidence and producing competitive yields. Experience is also required to choose the right implements (especially NT planters) for specific on-farm conditions. A special CA case requiring additional techniques and management is the combination of livestock and crop production (Baker and Ritchie, 2007). Extractive management by overstocking or overgrazing is the most common cause of soil quality deterioration. Appropriate CA systems allow continuous cropping (for food or feed production) without damage to soil structure. However, for a pasture phase to help produce adequate biomass to build up SOC and achieve profitability, as suggested by Husson *et al.* (2009), ideally management should be aimed at keeping the pasture with full ground cover and always in the productive phase. The carrying capacity[38], rotational grazing, rest periods, length of outdoor grazing time vs. indoor housing should be well adjusted. When necessary, fertilizers and amendments should be added to compensate when priority is given to feeding of livestock with crop residues and translates in the inadequate replacement of nutrients. In time this leads to soil degradation and reduced carrying capacity. In the case of pastures which produce poor feed in terms of quality and quantity. A new level of productivity can be achieved with high-yielding short-rotation forage species (to be re-established once or twice per year) chosen for the specific requirements of the animals and of the local climate (Landers, 2007).

The shift to CA has been achieved where: i) farmers have been informed of the system and convinced of its benefits by experience; ii) training and technical support to early adopters have been provided; and iii) adequate support policies (e.g. funding through carbon sequestration contracts with farmers) have been implemented. With regard to policy support, according to the European Conservation Agriculture Federation, in Europe, where CA does not exceed 1 percent of the agricultural cropland, things have slowly begun to change because since 2004 the Common Agricultural Policy has been promoting sustainable agriculture systems for food safety and environmental sustainability. However it does not link environmental services to specific production systems. For credits for SOC preservation and accumulation to become a structural part of the solution to mitigate climate change, the societal value of soil carbon sequestered and of less GHG emissions should be based on all ecosystem services, and short-term and long-term increases in SOC pool would need to be commoditized and traded based on both on-site and off-site societal benefits (Lal, 2008a). Crop residue management should also be valued and subsidies considered. Some crop residues may be an additional source of income, and farmers may find it more convenient in the short-term to sell

[38] **Carrying capacity** = Number of heads of livestock that can be supported per unit of land area. Also known as maximum stocking rate.

them and pay higher costs in the medium- to long-term. Subsidies should be introduced to compensate for short-term economic losses and encourage the uptake of sustainable agronomic management systems. An example of a carbon offset scheme for agricultural land use has been in operation in Alberta, Canada (Goddard *et al.*, 2009). The province of Alberta, which has a strong agriculture-based economy and also the highest GHG emissions in the country (due to oil and gas production), first adopted a climate change action plan in 2002. Since 2007 this includes the implementation of a NT-based crop production system protocol on agricultural lands as an opportunity for direct and indirect reductions of GHG emissions through carbon offset trading with industry (Goddard *et al.,* 2009).

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 and sustainable crop production strategy for the future.

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Annexes

ANNEX 1

Quantities of residues achievable in different climates under common rotation systems, regardless of the agricultural practice

CROP ROTATION	CLIMATE	LOCATION	ORGANIC MATTER PRODUCED	AUTHOR
pigeon pea	semi-arid tropics	India	3 t ha^{-1} of dry leaf	Abdurahman *et al.* (1998)
cowpea			0.14 t ha^{-1} of dry leaf	
velvetbean[1]-based systems	Tropics	America central	35 - 50 t^{-1} ha^{-1} y^{-1} of biomass	FAO (2001)
soybean	semi-arid temperate	Canada		Reicosky (1997)
maize			twice the amount of soybean residue	

[1] **Velvetbean** = *Mucuna pruriens*

ANNEX 2

SOC quantities achievable in different climates under most common rotation systems (adapted from Jarecki and Lal, 2003)

CROP ROTATIONS with and without cover crop or green manure	CLIMATE	LOCATION	SOIL type	SOC INCREASE relative to the same rotation without cover crop or green manure [t^{-1} ha^{-1} y^{-1}]	AUTHOR
millet - wheat - green manure - sesbania[1]	Tropics	India	Sand loam	0.20	Chander *et al.* (1997)
millet - wheat - fallow					
wheat - barley - green manure	humid and subhumid temperate	Sweden	Sandy clay loam	0.35	Paustian *et al.* (1992)
wheat - barley					
cotton[2] - rye[3]	humid and subhumid subtropics	USA, Alabama	Sand loam	5.413	Nyakatawa *et al.* (2001)
cotton - fallow					
hairy vetch in tomato - maize				0.90	
tomato - maize					
tomato - eggplant[4] - rye	humid and subhumid subtropics	USA, Georgia	Sand loam	0.63	Sainju *et al.* (2002)
tomato - eggplant					
tomato - eggplant - hairy vetch				0.51	
tomato - eggplant					
tomato - eggplant - clover[5]				0.50	
tomato - eggplant					

[1] **Sesbania** = *Sesbania sesban*
[2] **Cotton** = *Gossypium* spp.
[3] **Rye** = *Secale cereale* L.
[4] **Eggplant** = *Solanum melogena*
[5] **Clover** = *Trifolium spp.*

(cont.)

CROP ROTATIONS with and without cover crop or green manure	**CLIMATE**	**LOCATION**	**SOIL type**	**SOC INCREASE relative to the same rotation without cover crop or green manure [t^{-1} ha^{-1} y^{-1}]**	**AUTHOR**
alfalfa[6]	humid and subhumid temperate	USA, Ohio	Silty clay loam	0.48	Lal *et al.* (1998a)
maize monocrop					
Kentucky bluegrass[7]				-0.04	
maize monocrop					
fescue[8]				2.12	
maize monocrop					
bromegrass[9]				2.08	
maize monocrop					
maize - rye	humid and subhumid temperate	USA, Washington state	Silty loam	0.53	Kuo *et al.* (1997)
maize					
maize - Austrian winter pea[10]				0.16	
maize					
maize - ryegrass				0.32	
maize					
maize - vetch				0.11	
maize					
maize - rapeseed[11]				-0.11	
maize					

[6] **Alfalfa** = *Medicago sativa*
[7] **Kentucky bluegrass** = *Poa pratensis*
[8] **Fescue** = *Festuca arundinacea*
[9] **Bromegrass** = *Bromus inermis.*
[10] **Austrian winter pea** = *Lathyrus hirsutus* L.
[11] **Rapeseed** = *Brassica napus*

ANNEX 3

Experimental results on the long-term impact on SOC content / carbon (C) inputs of different tillage systems under the same crop rotation schemes

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	soybean vs.	Subtropical	India, central					22% of the annual gross C input	Kundu *et al.*(2001)
	wheat							32% of the annual gross C input	
	black lentil - fallow vs.	Semiarid	Canada					1.4 - 1.8 t ha^{-1} of C	Curtin *et al.* (2000)
	wheat							2 - 3 times the amount of C annually achieved with the black lentil - fallow rotation	
	maize - oat - clover		USA, Illinois				Comparison of different crop rotations with the adjacent natural grassland	SOC content decreased by 29% in 64 years	Al-Kaisi (2008)
	maize - oat - clover with manure, lime and rock phosphate							SOC content increased by 4% in 64 years	
	maize - oat							SOC content decreased by 33% in 64 years	
	maize - oat with manure, lime and rock phosphate							SOC content decreased by 24% in 64 years	
	continuous maize							SOC content decreased by 45.6% in 64 years	
	continuous maize with manure, lime and rock phosphate							SOC content decreased by 35% in 64 years	

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
4 years of pasture	soybean - sunflower vs.	Temperate - humid	Argentina, Balcarce	loamy	complex of Typic Argiudoll and Petrocalcic Paleudoll soils	TA	11 years experiment (from 1984 to 1995)	Higher C sequestration achieved with this rotation. Beneficial effect of N-fertilizer on SOC sequestration.	Studdert and Echeverría (2000)
	continuous soybean								
	wheat - soybean vs.							Higher C sequestration achieved with this rotation.	
	continuous soybean								
	soybean - maize vs.							Higher C sequestration achieved with this rotation.	
	continuous soybean								
	maize - sunflower vs.							Lower C sequestration achieved with this rotation. Beneficial effect of N-fertilizer on SOC sequestration.	
	continuous maize								
	maize - soybean vs.							Lower C sequestration achieved with this rotation. Beneficial effect of N-fertilizer on SOC sequestration.	
	continuous soybean								
	wheat - sunflower vs.							Higher C sequestration achieved with this rotation. N-fertilizer application beneficial.	

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	continuous wheat								
	wheat - soybean vs.							Higher C sequestration achieved with this rotation. N-fertilizer application beneficial.	
	continuous soybean								
	continuous wheat vs.		Canada, west					SOC stored at a rate of 0.15 ± 0.6 t of carbon ha^{-1} y^{-1}	VandenBygaart *et al.*(2003)
	fallow							2.2 less t of carbon ha^{-1} stored	
	wheat grass[1] vs.							SOC stored at a rate of 0.35 ± 0.19 t of carbon ha^{-1} y^{-1}	
	fallow - wheat							2.3 less t of carbon ha^{-1} stored	
	flax[2] vs.							SOC stored at a rate of -0.15 ± 0.2 t of carbon ha^{-1} y^{-1}	
	wheat							2.4 less t of carbon ha^{-1} stored	
	hay - fallow - wheat							SOC stored at a rate of 0.22 ± 0.19 t of carbon ha^{-1} y^{-1}	
	lentil[3] or red clover[4] - wheat - wheat vs.							SOC stored at a rate of 0.15 ± 0.11 t of carbon ha^{-1} y^{-1}	
	fallow - wheat - wheat vs.							2.3 less t of carbon ha^{-1} stored	

[1] **Wheat grass** = *Agropyron cristatum or Agropyron trichophorum*
[2] **Flax** = *Linum usitatissimum*
[3] **Lentil** = *Lens culinaria*
[4] **Red clover** = *Trifolium pratense*

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	fallow - fall rye[5] - fall rye vs.							SOC stored at a rate of 0.1 ± 0.14 t of carbon ha^{-1} y^{-1}	
	fallow - wheat - wheat							2.3 less t of carbon ha^{-1} stored	
	straw retention vs.							SOC stored at a rate of 0.12 ± 0.9 t of carbon ha^{-1} y^{-1}	
	straw removal							1.3 less t of carbon ha^{-1} stored	
	alfalfa[6] or red clover - maize vs.							SOC stored at a rate of 0.44 ± 0.28 t of carbon ha^{-1} y^{-1}	
	continuous maize							14.4 ± 11.5 less t of carbon ha^{-1} stored	
	wheat -sunflower wheat - wheat		Spain, south		Vertisol	NT vs. TA	Comparison of 4 different rotations for TA and NT over more than 11 years.	Over 11 years, wheat - sunflower and wheat - wheat rotations accumulate greater above-ground C than other rotations for both tillage systems.	López-Bellido *et al.* (2010)
	wheat - faba bean							Over 20 years, wheat - wheat and wheat - faba bean[7] sequestered 1.1 t C ha^{-1} y^{-1} for NT and 0.7 t C ha^{-1} y^{-1} for TA. This increment is greater for the 30 - 90 cm depths.	
	wheat - fallow							The lowest above-ground residue C corresponds to wheat - fallow in both tillage systems.	

[5] **Fall rye** = *Lolium perenne*
[6] **Alfalfa** = *Medicago sativa*
[7] **Faba bean** = *Vicia faba*

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	maize - soybean					Strip Tillage[8] vs. TA	Comparison of two adjacent fields under the same rotations and two different agricultural systems over a 2-year period.	Both systems are small net sources of C. Strip Tillage does not achieve any C sequestration benefit. Problems related to net ecosystem exchange measurements: i) short-term data used; ii) measurements are subject to experimental difficulties; iii) empirical gap-filling of time periods when measurements were not taken is required.	Baker and Griffis (2005)
Cereal-fallow rotation	winter wheat - *Vicia sativa* - pea	Semiarid	Spain	Loam	Vertic Luvisol	NT vs. MT vs. TA	20 years experiment comparing 3 agricultural systems under the same rotation.	The steady state of SOC sequestration is reached after 11 years of starting the experiment in NT and 12 years in TA and MT: the average SOC is 14% higher in NT than in MT and TA, whereas no significant differences are encountered between MT and TA.	Hernanz *et al.* (2009)
	maize - oat - sorghum - soybean vs.		USA, Nebraska - Mead			TA	10 years experiment	Higher C sequestration achieved with this rotation. Beneficial effect of no N-fertilizer application relative to low, medium and high doses applied.	Varvel (1994)
	continuous maize								

[8] **Strip Tillage** = The concept of strip tillage, as described by Lal (1973), requires that the seedbed is divided into a seedling zone and a soil management zone. The seedling zone (5 to 10 cm wide) is mechanically tilled; the interrow zone is left undisturbed and protected by mulch.
Strip tillage can also be achieved by chiselling in the row zone to assist water infiltration and root proliferation in presence of hardpans.

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	maize - oat - sorghum - soybean vs.							Higher C sequestration achieved with this rotation. Beneficial effect of no N-fertilizer application relative to low, medium and high doses applied.	
	continuous soybean								
	maize - oat - sorghum - soybean vs.							Higher C sequestration achieved with this rotation. Positive effect of no N-fertilizer application relative to low, medium and high doses applied.	
	continuous sorghum								
	maize - soybean - sorghum - oat vs.							Higher C sequestration achieved with this rotation. Beneficial effect of no N-fertilizer application relative to low, medium and high doses applied.	
	continuous maize								
	maize - soybean - sorghum - oat vs.							Lower C sequestration achieved with this rotation. Beneficial effect of high doses of N-fertilizer applied relative to no, low and medium doses applied.	
	continuous soybean								

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	maize - soybean - sorghum - oat vs.							Lower C sequestration achieved with this rotation. Beneficial effect of high doses of N-fertilizer applied relative to no, low and medium doses applied.	
	continuous sorghum								
Fallow - wheat rotation	continuous wheat vs.		Canada, Saskatchewan			TA	15 years experiment	Higher C sequestration achieved with no fertilizer application relative to fertilizer application.	Campbell *et al.* (1991 a, 1997); Campbell 2001a)
	wheat - wheat - fallow								
Fallow - wheat rotation	continuous wheat vs.		Canada, Saskatchewan			TA	30 years experiment	Higher C sequestration achieved with no fertilizer application relative to fertilizer application.	Campbell *et al.*(1991b, 1997)
	wheat - fallow								
75 years of cereal - fallow rotation	wheat - fallow		Canada, Saskatchewan			NT vs. TA	15 years experiment	Higher C sequestration achieved with NT.	Campbell *et al.* (1996b)
Arable land	continuous wheat vs.		Canada, Alberta			TA	41 years experiment	C sequestration achieved with no manure application only.	Janzen *et al.* (1987, 1997)
	wheat - wheat - fallow								
	legume-based	Arid or semiarid						Better results achieved on SOC, although no numerical evidence is given.	Gregorich *et al.* (2001)
	continuous maize with fertilizer								

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	Avena strigosa - common vetch - maize - cow pea		Brazil, southern	clay loam		NT	9 years experiment	0.82 t^{-1} ha^{-1} y^{-1} higher SOC as the following rotation	Bayer *et al.* (2000b)
	Avena strigosa - maize								
	Avena strigosa - common vetch - maize - cow pea					TA		0.62 t^{-1} ha^{-1} y^{-1} higher SOC when under TA	
	Avena strigosa - maize								
	cotton - maize vs.		USA, Alabama - Auburn			TA	100 years experiment	Higher C sequestration achieved with this rotation.	Entry *et al.* (1996); Mitchell *et al.* (1996)
	continuous cotton								
	maize - wheat - clover vs.		USA, Missouri - Columbia			TA	100 years experiment	Higher C sequestration achieved with this rotation. N-fertilizer application beneficial.	Buyanovsky and Wagner (1998)
	continuous wheat								
	maize - maize - oat - grass vs.		USA, Iowa - Nashua			TA	12 years experiment	Higher C sequestration achieved with this rotation.	Robinson *et al.* (1996)
	continuous maize								
	maize - maize - oat - grass vs.		USA, Iowa - Kanawha				36 years experiment	Higher C sequestration achieved with this rotation.	
	continuous maize								
36 years of TA	maize - maize - oat - grass vs.		USA, Iowa - Sutherland				34 years experiment	Higher C sequestration achieved with this rotation.	
	continuous maize								
	maize - alfalafa - grass - grass vs.		USA, Iowa - Kanawha				36 years experiment	Higher C sequestration achieved with this rotation.	
	continuous maize								

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
36 years of TA	maize - alfalafa - grass - grass vs.		USA, Iowa - Sutherland				34 years experiment	Higher C sequestration achieved with this rotation.	
	continuous maize								
	maize - soybean vs.		USA, Iowa - Kanawha				36 years experiment	Lower C sequestration achieved with this rotation.	
	continuous maize								
36 years of TA	maize - soybean + N-fertilizer vs.		USA, Iowa - Sutherland				34 years experiment	Higher C sequestration achieved with this rotation.	
	continuous maize								
	sorghum - soybean		USA, Nebraska - Lincoln			NT vs. TA	10 years experiment	In 1 experiment out of 2, lower C sequestration achieved under NT relative to TA.	Dickey *et al.* (1994)
	wheat - fallow vs.		USA, North Dakota - Mandan			NT vs. TA	7 years experiment	Lower C sequestration achieved under NT and with increasing doses of N-fertilizer.	Black and Tanaka (1997)
	wheat - wheat - sunflower							Higher C sequestration achieved under NT and with increasing doses of N-fertilizer.	
6 years of grass meadow	maize - soybean vs.		USA, Ohio - Wooster			NT vs. TA	19 years experiment	Higher C sequestration achieved under NT.	Dick *et al.* (1997)
	maize - oat - grass vs.							Higher C sequestration achieved under NT.	

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	continuous maize		USA, Minnesota - Waseca			NT vs. TA	6 years experiment	Lower values for C sequestration under NT relative to TA.	Mielke *et al.* (1986)
	oat/vetch - maize/ cowpea					NT		33 t C sequestered ha^{-1} y^{-1} in 9 years	Ryan (1997)
	wheat - sunflower[9] - pea	Dryland	Spain, south-west	Sandy clay loam	Entisol	NT vs. TA	Effects of NT and TA on soil carbon fractions and biological properties are compared in two soils under the same rotation. Labile fractions of the total organic carbon are determined as active carbon and water soluble carbon, while biological status was evaluated using soil microbial biomass carbon and the following enzymatic activities: dehydrogenase, o-diphenol oxidase and b-glucosidase activity.	Active carbon content was the most sensitive and consistent indicator for assessing the impact of different soil managements on soil quality in the two soil types. The contents of active carbon, water soluble carbon, microbial biomass carbon, b-glucosidase activity and o-diphenol oxidase activity in sandy clay loam Entisol, and contents of total organic carbon, active carbon and dehydrogenase activity in clay Vertisol were higher in NT than in TA at the sample depth (0-5 cm).	Melero *et al.* (2009)
				Clay	Vertisol				
32 years (from 1951 to 1983) of TA intensive cropping system (with no set rotation and seldom under fallow)	wheat - wheat - sunflower	Dryland	USA, Great Plains	Loam		NT vs. MT vs. TA Nitrogen rates were 0.034, 0.067, and 0.101 t N ha^{-1}	12 years experiment	During the 12 years in the 0 - 15 cm soil depth, there is a net loss (-1.7 t of C ha^{-1}) in SOC with TA, a slight gain (0.3 t of carbon ha^{-1}) and ca 2% of the residue C sequestered with MT, a larger gain (2.8 t of carbon ha^{-1}) and ca 16% of the residue C sequestered with NT. This more intensive rotation system under NT proves to be the most efficient in storing SOC in this study.	Halvorson *et al.* (2002)

[9] **Sunflower** = *Helianthus annuus*

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	sunflower - fallow					NT vs. MT vs. TA Nitrogen rates were 0.045 t N ha^{-1}		SOC mass does not increase during the 12 years in the sunflower - fallow system with none of the tillage systems. Since the plot area was in a more intensive cropping system (i.e. with less frequent fallow period) from 1951 to 1983, the soil in 1983 is possibly at a higher level of SOC than could be sustained by the sunflower - fallow.	
	maize - soybean vs.		USA, Kansas - Manhatten			TA	8 years experiment	Higher C sequestration achieved with no addition of N-fertilizer.	Havlin *et al.* (1990)
	continuous soybean								
	maize - soybean vs.					TA	8 years experiment	No C sequestration achieved.	
	continuous maize								
	sorghum - soybean					NT vs.	11 years experiment	Higher C sequestration achieved under NT.	
Arable land	maize - soybean - winter wheat	Moist			Gleyic and Orthic Luvisol	NT with no cover crops	15 years experiment	The total SOC balance after the conversion to NT follows:	VandenBygaart *et al*. (2002)

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS		AUTHOR
Arable land (cont.)								• In the 0 - 15 cm layer-there is a gain of SOC in 63% of the profiles.	It's reasonable to believe that if cover crops were used, higher average SOC gains in the surface layer might have been achieved and SOC balance for the whole profile pushed towards positive values.	
								• In the 15 - 30 cm layer - there is a loss of SOC in 76% of the profiles.	The SOC loss in the 15 - 30 cm deep layer of soils with thicker Ap horizons (depression areas) was higher than the total SOC gain, pushing the balance for the total profile sampled (0 - 45 cm) towards negative values. Lower SOC at the 15 - 30 cm depth after the conversion to NT can be interpreted to be due to the reduced deposition from upslope from tillage translocation and reduced water runoff (in sloping soils with shallow Ap horizon the conversion to NT might have resulted to a better water use efficiency) thanks to the adoption of NT. The increase in deep-burrowing earthworm species after conversion to NT can also be accounted as factor in the decrease in SOC in some profiles. Earthworm numbers were not determined in this study.	
								• In the 30 - 45 cm layer there is a gain of SOC in 66% of the profiles.		
								The ability of NT to sequester C is higher in drylands, which explains why the conversion to NT in the sloping soils with shallow Ap horizon has resulted to a better water use efficiency, whereas in the depression areas with greater initial SOC contents water may have been non-limiting even before the change in management.		

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS		AUTHOR
					Gray-Brown Luvisol	NT vs. TA	Comment on data reviewed by Vanden Bygaart *et al.* and reported in their paper.			Vanden Bygaart *et al.* (2003)
	maize - wheat - soybean		Canada, Ontario				Soil depth sampled: 45 cm. 37 out of 38 experiments are based on 1 soil profile sampled each.	Most of the cases in which NT relative to TA does not increase C storage are associated with this rotation and show the following patterns:	SOC gains due to adoption of NT occur mainly at initial SOC levels <45 t ha^{-1}.	
				Silt loam				6/9 of the experiments		
				Sand loam				17/24 of the experiments		
				Clay loam				2/4 of the experiments		
								The limited number of replications seems to be a factor for statistical unreliability.		
	continuous barley		Canada, Quebec	Clay	Humic Gleysol		Soil depth sampled greater than 30 cm.	Higher values for C sequestration under TA relative to NT in Humic Gleysols under can be interpreted to be due to the inappropriate crop rotation adopted. Further, initial SOC content >2% in the A horizon doesn't suit low C/N ratio residues regimes.		
			Canada, Quebec	Clay loam	Humic Gleysol					

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
			Canada, Quebec	Silt loam	Humic Gleysol				
			Canada, Ontario	Sand loam	Melanic Brunisol			Higher values for C sequestration under NT relative to TA.	
			Canada, Alberta	Loam	Gray Luvisol			Higher values for C sequestration under NT relative to TA.	
			Canada, Alberta	Loam	Black Chernozem			Higher values for C sequestration under NT relative to TA: Chernozemic soils show a greater ability to store SOC under NT.	
	continuous maize		Canada, Ontario	Sand loam, loam sand	Gray-Brown Luvisol		Soil depth sampled greater than 30 cm.	Lower values for C sequestration under NT relative to TA.	
				Clay loam	Luvic Gleysol			Lower values for C sequestration under NT relative to TA.	
				Silt loam	Melanic Brunisol			Lower values for C sequestration under NT relative to TA.	
				Sand loam	Melanic Brunisol			Higher values for C sequestration under NT relative to TA.	
	wheat - barley - soybean		Canada, Prince Edward Island		Gray-Brown Luvisol		Soil depth sampled greater than 30 cm.	Lower values for C sequestration under NT relative to TA.	
					Humo-Ferric Podzol			Lower values for C sequestration under NT relative to TA: Podzolic orders show a low storage potential.	

(cont.)

PRIOR HISTORY	CROP ROTATION	CLIMATE	LOCATION	SOIL texture	SOIL type	AGRIC. SYSTEM	EXPERIMENT DETAILS	RESULTS	AUTHOR
	continuous wheat		Canada, Ontario	Sand loam	Melanic Brunisol		Soil depth sampled greater than 30 cm.	Higher values for C sequestration under NT relative to TA.	
	fallow - wheat		Canada, Prairie Province					C storage rate calculated as the effect of the conversion from TA to NT is much lower than that estimated by West and Post (2002): 0.05 ± 0.16 t of C ha^{-1} y^{-1} vs. 0.57 ± 0.14 t of carbon ha^{-1} y^{-1}.	

ANNEX 4
SOC accumulation in deeper soil layers under the CA management system

LOCATION	EXPERIMENT DURATION	RESULTS	AUTHOR
USA, north	22 years	The carbon stock under CA to a depth of 122 cm is 10.6 t ha^{-1} greater than that under TA.	Doran *et al.,* 1998
Brazil, south	13 years	Where complex rotations are adopted, soil carbon stocks under CA are approximately 17 t ha^{-1} higher than under TA, and that 46 to 68% of carbon gains occurs at 30 - 85 cm depth.	Sisti *et al.,* 2004
Brazil, south	17 years	Samplings to 107.5 cm depth in an Acrisol demonstrate the significant potential of legume crops and nitrogen fertilisation under CA to improve SOC stocks: the average carbon sequestration rate of legume-based cropping systems (with N-fertilizer) in the whole 0 - 107.5 cm layer was 1.42 t carbon ha^{-1} $year^{-1}$.	Diekow *et al.,* 2005
Brazil, south	15 - 26 years	The experiments on free-draining Ferralsols under rotations containing intercropped or cover-crop legumes show annual SOC accumulation rates of between 0.04 and 0.88 t ha^{-1} to 30 cm and from 0.48 to 1.53 t $ha^{-1}y^{-1}$ when considering the soil profile down to 100 cm depth.	Boddey *et al.,* 2009a
Brazil, south	13 years	When green-manure cover crops are part of the rotation soil carbon stocks were approximately 17 t ha^{-1} higher under CA than under TA.	Sisti *et al.,* 2004
Spain, south	20 years	SOC was monitored through 90 cm depth and it was found that this sequestered 15 t carbon ha^{-1} more under CA than under TA for the wheat - faba bean rotation. When single portions of the soil profile are considered, it is interesting to observe that the increase of stocked SOC in the top layer (0 - 15 cm) in TA systems is associated with a much greater systematic decline in the bottom layer (60 - 90 cm) than in NT systems. An explanation for this seems to be the presence of a plough pan that prevents a homogeneous distribution of the organic carbon throughout the profile.	López-Bellido *et al.,* 2010
USA, Indiana	28 years	10 t ha^{-1} greater SOC content under CA than in mouldboard ploughed trials at a 0 - 100 cm depth in a dark-colored Chalmers silty clay loam in Indiana.	Gál *et al.,* 2007
Australia		Higher SOC concentrations at 230 cm depth in Vertisols when compared with other soil types in Australia.	Knowles and Singh, 2003

Glossary

Ageing	Deposition of polysaccharides and other organic cementing agents by microbial activity.
Barley	*Hordeum vulgare*
Carbon budget	Carbon input versus output at a given time.
Carrying capacity	Number of heads of livestock that can be supported per unit of land area. Also known as maximum stocking rate.
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% 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%, >60-90% and >90% ground cover, measured immediately after the direct seeding operation. Area with less than 30% 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.
Controlled traffic	Restriction of all heavy wheel traffic to permanent traffic lanes.
Crop residues	Crop residues include any biomass left in the field after the principal economic components of the crop have been harvested.
Drylands	Areas characterized by lack of water, which constrains their two major interlinked services of primary production and nutrient cycling (FAO, 2005a).
Edaphon	Soil microorganisms and fauna.
Global Warming Potential	Index developed by IPCC to quantify the ability of a gas to trap the infrared radiation (i.e. heat) relative to the ability of the same amount of the CO_2 reference gas to trap heat in a given time horizon. The global warming potential of any gas depends on its radiative forcing and on its lifetime (IPCC, 2007).
Hairy vetch	*Vicia villosa* L.
Intensive crop rotation	Crop rotation characterized by high species density in space and in time that produce high amounts of crop residues, and maintain the soil surface permanently covered to "close the window" between the wet and the dry season.
Lablab	*Lablab purpureus* (L.) Sweet, *Dolichos lablab* L.
Maize	*Zea mays*
Mechanical soil tillage	Any mouldboard and/or disc ploughing, chiselling, disking; mechanical intervention to structure the soil in a different way

Microaerophilic organisms	Microorganisms that require oxygen to survive, but at lower levels than are present in the atmosphere.
Mineralization of organic matter	Biological oxidation to carbon dioxide and water with liberation of the mineral nutrients.
Minimum tillage	Agricultural systems based on the minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions; the tillage reduction can be in intensity of tillage, depth of tillage or time involved (number of machinery passes for all tillage operations).
No-till	Agricultural systems where soil-disturbing activities are limited only to those necessary to plant seeds, and place nutrients. Crops are planted directly into a seedbed that has not been tilled since the previous seedbed.
Oat	*Avena sativa*
O horizon	Soil layer with a high percentage of organic matter that is sometimes present covering the upper mineral horizon designated as A horizon. This latter is the horizon where organic material mixes with inorganic products of weathering.
Pea	*Pisum sativum*
Physicochemical aggregates	Macroaggregates held together by mineral electrostatic interactions.
Pigeon pea	*Cajanus cajan*
Priming effect	Mobilization by microbial decomposition of stable SOC stimulated by the addition of substrates with readily available energy.
Puddling	Intensive mixing of soil under wet conditions for rice to create a hard pan, level the soil and remove the soil structure; it can be done by the combination of tractor wheels or animal hooves with tillage implements such as ploughs, rotary cultivators or harrows.
Rice	*Oryza sativa*
Sesbania	*Sesbania sesban*
Soil biota	Soil is a complex habitat for diverse biota and predator-prey relationships. Soil organisms, spending all or a portion of their life cycles within the soil or on its immediate surface (including surface litter and decaying logs), make up the diversity of life in the soil and are responsible, to a varying degree depending on the system, for performing a range of processes important for soil health and fertility in soils of both natural ecosystems and agricultural systems. A brief description (FAO 2005b) of organisms that are commonly found in the soil, based on the FAO soil bulletin 80, follows. Microorganisms include algae, bacteria, cyanobacteria, fungi, yeasts, myxomycetes, actinomycetes. These are able to decompose and transform organic matter into nutrients that are assimilated by plants. Their populations are very sensitive to depth and are highly disrupted by mechanical soil disturbance. Likewise, various members of the microfauna (such as collembola, mites, nematodes and protozoa) generally live in the soil water films and feed on microflora, plant roots, other microfauna and sometimes larger organisms, and are therefore important to release nutrients immobilized by soil microorganisms. Mesofauna includes mainly microarthropods feeding on organic materials, microflora, microfauna and other invertebrates. Macrofauna species are visible to the naked eye and include vertebrates and invertebrates (such as snails, earthworms, soil arthropods) that feed in or upon the soil, the surface litter and their components. In both natural and agricultural systems, soil macrofauna are important regulators of decomposition, nutrient cycling, soil organic matter dynamics and pathways of water movement as a consequence of their feeding and burrowing activities, such that leaf litter and other materials become buried, eventually migrating slowly to the base of the A horizon (the definition is given along with that of O horizons).

Soil structure	Arrangement of primary soil particles into secondary units (i.e. peds), which in turn are characterized on the basis of size, shape and grade. The arrangement of solids and voids existing at a given time determines structural form, the ability to retain this arrangement under different stresses determines structural stability, and the capacity of the soil to recover structure or stability after a stress is removed is called resiliency is (Kay, 1990).
Soybean	*Glycine max*
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).
Tillage erosion	Net downslope translocation of soil by tillage implements, exposing subsoil at the crest while burying soil at the bottom.
Tobacco	*Nicotiana tabacum*
Velvetbean	*Mucuna pruriens*
Vetch	*Vicia spp.*
Water stable aggregates	Aggregates that can resist air drying and quick submersion in water before sieving.
White lupin	*Lupinus albus* L.
Winter wheat	*Triticum aestivum* L.
Xenobiotic	Chemical compound which is found in a living organism but which is foreign to it.




Soil Organic Carbon Accumulation and Greenhouse Gas Emission Reductions from Conservation Agriculture: A literature review

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 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. Tillage-based production systems should therefore be transformed so that the future production intensification can be achieved sustainably. Conservation Agriculture, a system avoiding or minimizing soil disturbance, combined with soil cover and crop diversification, is considered to be such sustainable production system. However, there appears to be certain degree of uncertainty about the role of Conservation Agriculture in carbon sequestration and 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 traditional tillage agriculture and Conservation Agriculture with respect to their effects on soil carbon pools. The study attempts to reduce the existing uncertainty about the impact of soil management practices on soil carbon and is addressing scientists as well as policy makers to facilitate decision making regarding future farming models.

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