

# **THE EFFECTS OF CONSERVATION AGRICULTURE ON CROP PERFORMANCE, SOIL QUALITY AND POTENTIAL C EMISSION REDUCTION AND C SEQUESTRATION IN CONTRASTING ENVIRONMENTS IN MEXICO**

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## **INTRODUCTION**

Global food security, global environmental preservation as well as farmer level increased livelihood should be the main goals of a sustainable farming system in today's world plagued by degraded soils as a result of unsustainable crop management practices. The multitude of rural farmers as well as the three billion urban consumers must rely on sustainable food production systems for their livelihoods. Current agricultural management systems are threatened by increasing competition for ever-scarce water resources combined with continued use by most farmers of highly inefficient irrigation systems. Despite the availability of improved varieties with increased yield potential, the potential increase in production is not attained because of poor crop system management (Reynolds and Tuberosa, 2008). Persistent use of conventional farming practices based on extensive tillage have magnified soil erosion losses and the soil resource base has been steadily degraded, especially when tillage is combined with in situ burning of crop residues (Montgomery, 2007). Many soils have been worn down to their nadir for most soil parameters essential for effective, stable and sustainable crop production including soil physical factors (structure/aggregation, to enhance water use efficiency by fomenting improved water infiltration into the soil), soil chemical factors (especially soil organic matter, salinity, sodicity and nutrient balance) and soil biological diversity factors (marked reductions for most positive biological soil entities combined with the likely facilitation of soil-borne pathological organisms). Soil degradation in all its nefarious forms is not a prelude to mass starvation, as analysts once feared. Nevertheless, it is eroding crop yields and contributing to malnourishment in many corners of the globe (Science, 11 June 2004, p 1617).

Therefore, it is of paramount importance for farmers, small-scale and large, in both developing and developed countries, to employ appropriate crop management technologies that will not only generate cost-effective, stable crop production opportunities and allow varieties to yield well but which will also conserve the integrity and sustainability of the soil resource base while ensuring the efficient use of scarce water resources. In order to be able to develop the sustainable wheat and maize based systems, the International Maize and Wheat Improvement Center (CIMMYT) operates a unique set of long-term experiments for comparison of different Conservation Agriculture (CA)-based systems with traditional farming systems. Those experiments are a platform that generates strategic research output. A selection of results will be presented from

two locations in Mexico representing maize and wheat based rainfed and irrigated production systems.

## **MATERIALS AND METHODS**

### **The rainfed long-term tillage and bed planting trial in central Mexico**

The rainfed, long-term experiments are located in El Batán in the semiarid, subtropical highlands of Central Mexico (2240 m a.s.l.; 19.318N, 98.508W). The soil has good chemical and physical conditions for farming. The major limitations are periodical drought, periodical water excess and wind and water erosion. The mean annual temperature is 14°C (1990-2001) and the average annual rainfall is 600 mm y<sup>-1</sup>, with approximately 520 mm falling between May and October. Short, intense rain showers followed by dry spells typify the summer rainy season and the total yearly potential evapotranspiration of 1900 mm exceeds rainfall throughout the year. The El Batán experiment station has an average growing period of 152 days. The soil is a fine, mixed, thermic Cumulic Haplustoll (Soil Survey Staff, 2003) (Cumulic Phaeozem (IUSS Working Group WRB, 2006)).

Standard practices in both the long-term tillage and bed planting trial include the use of recommended crop cultivars, with maize planted at 60,000 plants ha<sup>-1</sup> in 75-cm rows and wheat planted in 20-cm rows at 100 kg seed ha<sup>-1</sup>. Both crops are fertilized using urea at 120 kg N ha<sup>-1</sup>, with all N applied to wheat at the 1st node growth stage (broadcast) and to maize at the 5-6 leaf stage (surface-banded). Weed control is done using appropriate, available herbicides as needed and no disease or insect pest controls are utilized, except for seed treatments applied by commercial seed sources. Planting of both maize and wheat depends on the onset of summer rains but is usually done between June 5 and 15.

The rainfed long-term tillage experiment was started in 1991. In 1990 the entire experimental area was treated with a broad-spectrum contact herbicide one month after the rains began, then seeded to barley in late July (Fischer et al., 2002a, b). Individual plots are 7.5 m by 22 m. The experimental design consists of a randomized complete block with two replications. There are 32 treatments in all. The core set of 16 management practices considered in this study was based on variation of crop rotation, tillage/planting methods and crop residue management. Crop practices included continuous wheat, continuous maize and rotation of wheat and maize. Residue was kept in the field or removed for fodder. Retained residues were incorporated with conventional tillage (CT), or left on the flat with zero tillage (ZT).

The rainfed raised bed planting trial was started in 1999 and individual plots measured 6 m by 20 m with 8 raised beds of 75 cm width. The experiment included two replicates in a randomized complete block design with 14 treatments of which we considered 12 treatments that include four management factors. The first factor is tillage: 1) CT with raised beds formed after each crop (CB) 2) ZT with continued reuse of the existing raised beds (re-shaped if required) (PB). The second factor is residue management: 1) all above ground crop residues chopped and kept in the field whether incorporated for CB or retained on the soil surface for PB, 2) all crop residues removed by baling for fodder and 3) crop residues partly removed, wheat residues cut by combine, and maize residues cut just below the ear. Tied-ridges (T) and open furrows (NT) between the raised beds are the third factor, while both phases of the maize-wheat rotation is the fourth.

## The irrigated long-term tillage trial in north Mexico

The experiment began in 1992 at the research station “Centro de Investigaciones Agrícolas del Noroeste” (CIANO), near Ciudad Obregón, state of Sonora, Mexico (Lat. 27.33° N, Lon. 109.09° W, 38 masl). The mean annual temperature is 25.8°C (1985-1999) and average annual precipitation 407 mm, with a minimum of 175 in 1987 and a maximum of 728 mm in 1990 (<http://www.inegi.gob.mx>). The soil type at the CIANO station is a coarse sandy clay, mixed montmorillonitic Typic Calciorthid (Calcic Vertisol), low in organic matter (< 1%) and slightly alkaline (pH 7.7). A detailed description of plot management has been reported in Limon-Ortega et al. (2000). Both crops were irrigated and managed in an annual rotation: wheat as a winter crop planted in late November to early December and harvested in May, followed by maize as summer crop planted in June on the same whole plots each year and harvested in October. Both crops were planted on 0.75 m raised beds with wheat in two rows seeded 20 cm apart and maize in one row. Irrigation was applied in furrows. The experiment included three replicates of each treatment in a randomized complete block design with a split plot treatment arrangement. Main plots consisted of tillage-straw factors as follows:

1. *CTB-straw incorporated*. Conventional tillage with beds formed after each crop. Wheat and maize residues were plowed under.
2. *PB-straw burned*. No tillage with continual reuse of existing beds, which were re-formed as needed. Residues of both wheat and maize were burned.
3. *PB-straw removed*. No tillage with continual reuse of existing beds, which were re-formed as needed. Residues of both wheat and maize straw were removed by baling.
4. *PB-straw partly removed*. No tillage with continual reuse of existing beds, which were re-formed as needed. Maize residues were removed by baling and wheat straw kept on the soil surface.
5. *PB-straw retained*. No tillage with continual reuse of existing beds, which were re-formed as needed. Maize and wheat residues were kept on the soil surface.

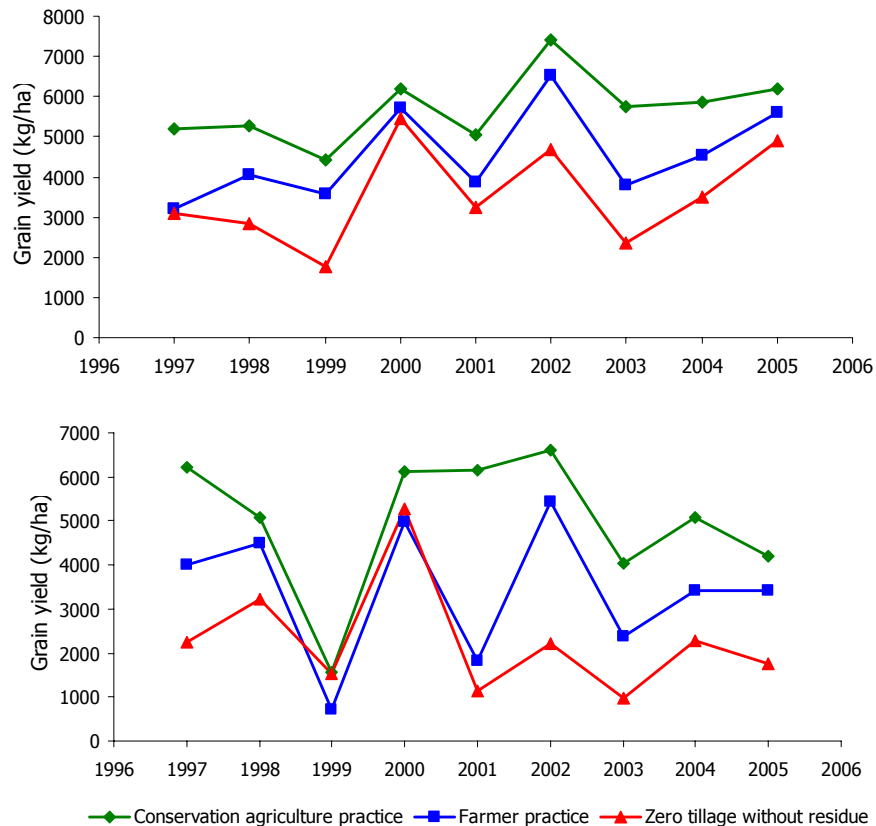
Split plots during the winter comprised seven N treatments, but for this study we chose a set of three N treatments (0, 150, and 300 kg N ha<sup>-1</sup>). Maize received a uniform application of 150 kg N ha<sup>-1</sup>. In both situations, N fertilizer was applied as urea in the bottom of the furrow and incorporated through irrigation. Each year wheat and maize received 45 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> banded in the furrow and incorporated through cultivation when reshaping beds. Detailed Materials and Methods can be found in the publications referred to.

## RESULTS AND DISCUSSION

### Rainfed long-term tillage and bed planting trials in Central Mexico

For the rainfed trial both for maize and wheat, ZT with full residue retention and crop rotation led to the highest and most stable yields (Table 1, Fig 1), as well as improved soil chemical and physical conditions. In contrast, ZT with residue removal, the lowest yielding practice (Table 1, Fig 1), led to low aggregate stability, high penetration resistance, plus surface slaking resulting in low time-to-pond values and high runoff. The traditional farming system (monocropping and crop residue removal) showed intermediate yields and soil physical conditions (Govaerts et al., 2005). The multivariate assessment of soil quality grouped treatments into three clusters: ZT with retention of residue, ZT with residue removal and CT (Fig 2). Results show that with ZT

residue retention is absolutely crucial to maintain good soil physical conditions. ZT with residue retention resulted in increased soil organic matter in the top soil. Residue retention is less effective in increasing soil quality under CT than under ZT. Potential constraints under ZT, such as compaction, were clearly circumvented by retaining residue in the field. Leaving residue and incorporating it in the soil results in very little differences compared to residue removal under CT (Govaerts et al., 2006). CT with residue retention resulted in an immediate CO<sub>2</sub> flux right after all tillage operations, while ZT with residue retention maintains its constant baseline emissions (Fig 3).

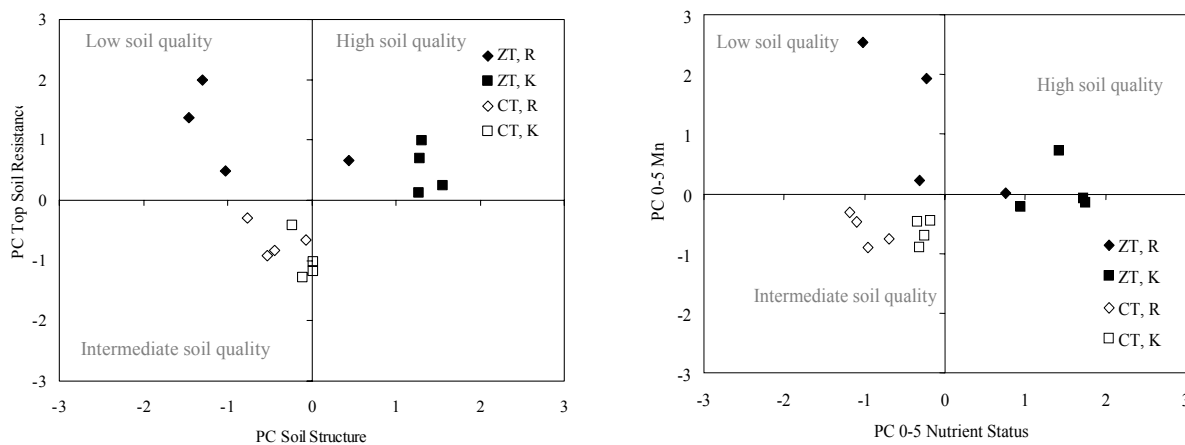


**Figure 1. Yields in CIMMYT’s long-term tillage trial in El Batán: high and stable yields with conservation agriculture for wheat (above) and maize (below). Adapted from Govaerts et al. (2005).**

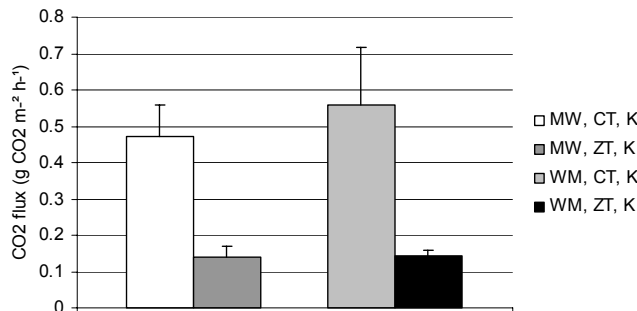
**Table 1. Yield results (t/ha at 12% H<sub>2</sub>O), CIMMYT long-term tillage trial, El Batán, Mexico, 1997-2005.**

	Zero-tillage		Conventional tillage	
	Maize	Wheat	Maize	Wheat
Monoculture + residue	4.3	5.3	3.5	4.9
Monoculture - residue	2.2	4.4	3.4	4.3
Rotation + residue	5.1	5.4	4.2	4.9
Rotation - residue	4.0	3.4	3.8	4.4

The percentage of small and large macroaggregates and mean weight diameter was significantly larger in permanent raised beds (respectively 8.29% and 0.71 mm) compared to conventionally tilled raised beds (respectively 2.87% and 0.50 mm) both with full crop residue retention (average for maize and wheat) and permanent raised beds with removal of the residue (respectively 3.53%, 33.98% and 0.53 mm). The C and N content of the coarse particulate organic matter (cPOM) and microaggregates within the macroaggregates was significantly larger in permanent raised beds compared to conventionally tilled raised beds, while C and N content of the cPOM was significantly lower when residue was removed or partially removed compared to the soil where the residue was retained (Table 2; Lichter et al., 2008).



**Figure 2. Biplot of the principal components of the physical (left) and chemical (right) properties of the CIMMYT’s long-term tillage trial in El Batán (Adapted from Govaerts et al., 2006) with with K= the residue is kept in the field; R= residue is removed; CT= conventional tillage; ZT= zero tillage.**



**Figure 3. Effect of tillage on the respiration of CO<sub>2</sub> (g m<sup>-2</sup> h<sup>-1</sup>) right after the second tillage operation in the long-term tillage trial, El Batán, México with M= maize; W= wheat; K= the residue is kept in the field; R= residue is removed; CT= conventional tillage; ZT= zero tillage, the first letter of the rotation indicates the residue in the field.**

Recent studies have revealed that the fraction of microaggregates occluded in the macroaggregates can serve as an indicator for C sequestration in agroecosystems, in particular in ZT systems (Denef et al., 2004). The primary evidence that aggregate structure physically protects organic matter from microbial decomposition is provided by studies in which aggregates are crushed or ground. Carbon and N mineralization rates increased when the aggregate structure was disrupted. This was attributed in these studies to the exposure of organic matter, which was previously inaccessible to microbial attack (Oades, 1984; Elliott and Coleman, 1988). A similar process occurs during tillage in the field. Because the OM binding microaggregates together is generally assumed to be recalcitrant and in smaller pores that cannot be accessed by microorganisms, it is expected that organic matter associated with microaggregates will decompose more slowly than that associated with macroaggregates. Although the input of crop residues was similar in conventionally tilled raised beds with full residue retention and permanent raised beds with full residue retention (Sayre et al., 2005), the amount of C in the microaggregates differed. Tillage will change the macroaggregate turnover and Six et al. (1998; 1999) suggested that increased macroaggregate turnover under CT is a primary mechanism causing a decrease of soil C. In the by Six et al. (1998; 1999) proposed conceptual model, the increase in macroaggregate turnover induced by tillage yields fewer new microaggregates-within-macroaggregates and subsequently new free microaggregates compared to no tillage. Enhanced C stabilization within the microaggregate-within-macroaggregate fraction under permanent raised beds compared to conventionally tilled raised beds was related to the dynamic ‘behaviour’ rather than the ‘amount’ of the microaggregates (and the macroaggregates that protect them). In other words, similar to the conceptualized importance of both amount and turnover of macroaggregates for C sequestration upon reduced physical disturbance (Six et al., 1999), the differences in C concentration within the fraction of microaggregates occluded in the macroaggregates among management systems can be linked to differences in amount and stability as well as turnover of the microaggregates within macroaggregates (Denef et al., 2007). Permanent raised bed planting with retention of crop residue results in more stable macroaggregates and as such a reduced erosion potential, as well as an increased protection of C and N in the microaggregates within the macroaggregates, as compared to conventionally tilled raised beds (Lichter et al., 2008).

**Table 2. Total C and N content (mg kg<sup>-1</sup>) for the different size fractions after microaggregate isolation of macroaggregates for the different treatments of the bed planting sustainability trial, El Batán, Mexico (Adapted from Lichter et al., 2008).**

Treatment	cPOM <sup>a</sup>		Microaggregates within macroaggregates		Silt and clay fraction of macroaggregates	
	Carbon	Nitrogen	Carbon	Nitrogen	Carbon	Nitrogen
Tillage <sup>b</sup>	(mg kg <sup>-1</sup> )					
PB K	18.56 A	1.97 A	19.35 A	2.10 A	13.82 A	1.70 A
CB I	8.56 B	1.05 B	15.25 B	1.75 B	11.87 A	1.49 A
Residue management <sup>c</sup>						
PB K	18.56 A	1.87 A	19.35 A	2.09 A	13.82 A	1.70 A

PB P	9.83 B	1.20 B	17.11 A	1.91 A	14.29 A	1.66 A
PB R	8.61 B	1.29 B	16.05 A	1.86 A	14.19 A	1.72 A

<sup>a</sup> cPOM: coarse Particulate Organic Matter,

<sup>b</sup> PB K: Permanent Beds with residue retained, CB I: Conventional Beds with residue incorporated,

<sup>c</sup> PB K: Permanent Beds with residue retained, PB P: residue partial retained and PB R: residue removed.

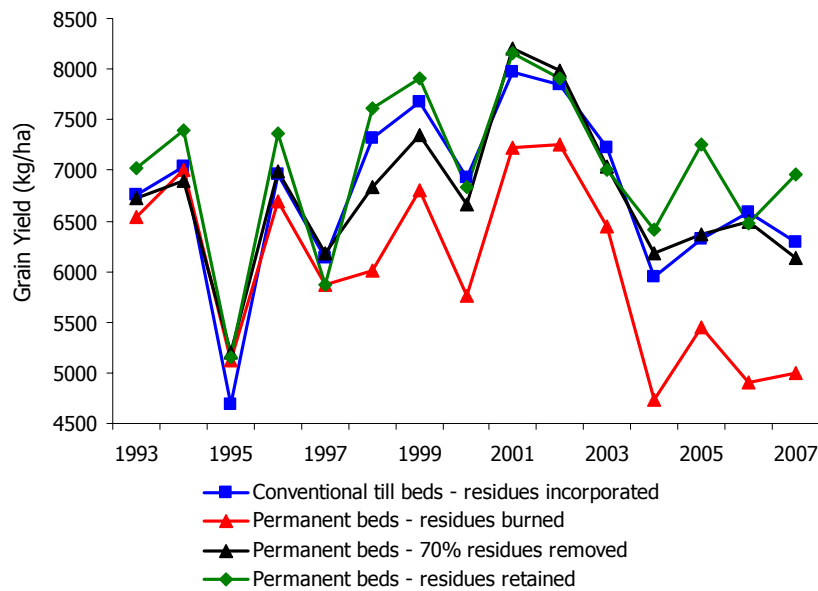
Values with the same letter within the same category are not significantly different from each other ( $P < 0.05$ )

It remained to be seen how other greenhouse gas emissions and dynamics of C and N might be altered by tillage. Soil was characterized and emissions of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> and dynamics of NH<sub>4</sub><sup>+</sup>, NO<sub>2</sub><sup>-</sup> and NO<sub>3</sub><sup>-</sup> were monitored in a laboratory experiment. The CO<sub>2</sub> emission was 1.2 times and the emission of N<sub>2</sub>O 2.3 times larger in soil under conventionally tilled raised beds compared to permanent raised beds both with full residue retention, while the increase in concentration of NO<sub>3</sub><sup>-</sup> was 0.05 mg N kg<sup>-1</sup> soil in the former and 2.38 in the latter. It was found that conservation agriculture in its version of permanent raised bed planting with crop residue retention can be a good alternative to improve soil quality when organic material is retained while decreasing emissions of N<sub>2</sub>O and CO<sub>2</sub> compared to soil under conventionally tilled raised beds (Patiño-Zúñiga et al., 2008).

### **Irrigated long-term bed planting sustainability trial in northern Mexico**

Under irrigated conditions we compared different bed planting systems (conventional tilled beds and permanent beds) for a wheat-maize rotation. Residue management varied from full to partial retention and residue burning. As can be observed in Fig 4, there have been large annual changes in wheat yields. Low wheat yields in 1995 and 2004 were the result of extended warm, cloudy periods during the first half of the crop cycles. There were no significant wheat yield differences between any of the tillage/residue management practices for the first 5 years (10 crop cycles). However, the key outcome seen in Fig 4 is that yield differences between management treatments clearly diverged after 5 years with a dramatic overall reduction in the yield for permanent beds where all residues had been routinely burned. In contrast to rainfed low rainfall areas, for irrigated agriculture systems (at least for tropical, semi-tropical and the warmer, temperate areas), the application of irrigation water appears to “hide or postpone” the expression of the degradation of many soil properties associated with continuous residue burning until they reach a level that no longer can sustain yield even with irrigation. Research to characterize tillage and residue management issues must include a time horizon of more than five years to insure that potential differences between management practices have adequate time to be expressed. Full retention and partial retention of residues had a similar yield expression, indicating that for irrigated systems with the associated high residue yields, substantial amounts of residue probably can be removed for other economic uses without suffering a yield decline. In addition, although the yields of properly managed permanent beds are not markedly higher than conventional till

beds with residue incorporation in permanent bed production costs are markedly lower (Sayre et al., 2005).



**Figure 4. The effect of tillage and residue management on wheat grain yields (kg/ha at 12% H<sub>2</sub>O), CIMMYT long-term bed planting trial, Ciudad Obregón, Mexico, 1993-2006 (Adapted from Sayre et al., 2005).**

A clear decrease in stable macroaggregation was observed for conventional tilled beds compared to permanent beds with residue retention. Burning of residues also had a detrimental effect on soil aggregation although to a lesser extent than tillage (Table 3). Results indicate that the long-term use of a permanent beds with residue retention system from wheat and maize in rotation improves soil aggregation and stability and increases C and N from the soil microbial biomass over time. Treatments with CT have a reduced potential C source compared to permanent beds systems, except for permanent beds with all residues burned, because plant residues brought into immediate contact with the soil by tillage, decompose more rapidly compared to residues retained on the soil surface. The apparent amelioration of Na levels for permanent beds with partial or full residue retention may have tremendous relevance for irrigated saline areas (Table 3; Sayre et al., 2005; Limon-Ortega et al., 2006).

**Table 3. Effect of tillage and crop residue management on soil properties (0-7 cm) for the CIMMYT long-term bed planting trial, Ciudad Obregón, Mexico (Adapted from Sayre et al., 2005; Limon-Ortega et al., 2006).**

Tillage/Residue Management	% Organic Matter	Na ppm	Aggregate Distribution MWD <sup>#</sup>	Aggregate Stability MWD	SMB C <sup>β</sup> mg kg <sub>soil-1</sub>	SMB N <sup>ψ</sup> mg kg <sub>soil-1</sub>
Conventional Till Beds	1.23	564	1.32	1.262	464	4.88
Incorporated Residue Permanent Beds	1.32	600	0.97	1.12	465	4.46
Burn Residue						

Permanent Beds Partial Removal Residue	1.31	474	1.05	1.41	588	6.92
Permanent Beds Retain Residue	1.43	448	1.24	1.96	600	9.06
Mean	1.32	513	1.15	1.434	552	6.40
LSD (P=0.05)	0.15	53	0.22	0.33	133	1.60

# = Mean Weight Diameter;  $\beta$  = Soil microbial biomass – C content;  $\Psi$  = Soil microbial biomass – N content

### **Implementation of conservation agriculture through a network of hubs**

It is unlikely that complex, multi-component technologies such as CA can be successfully scaled out through traditional linear models of research and extension: instead they require the development of innovation systems to underpin the development of locally adapted systems. Therefore, CIMMYT aims at the set up of decentralized learning hubs within different farming systems and agro-ecological zones. In those hubs all different routes operated come together and in that one central point an intense contact and exchange of information is organized before everybody takes off again to focus on his/her part in the network. Because of the multi-faceted nature of CA technology development and extension, activities are concentrated in a few defined locations representative of certain farming systems rather than lower intensity efforts on a wide scale. Around those focal points a hub is developed. The hub provides benchmark sites for research on the impacts of CA on crops and the environment in the prevalent cropping systems of these regions, as well as providing the focal point for regional (agro-ecological) capacity-building and scaling out of research and innovation systems. Through the research and training, regional CA networks are established to facilitate and foment research and extension of CA innovation systems and technologies. In the hubs multiple actors within the production system (farmers, scientist, machine builders, decision makers, input suppliers, ...), come together, work together, and learn together in order to later multiply this effort in an intense extension and out-scaling process. Research at the hubs also provides an example of the functionality of CA systems, helping to break down the insidious culture of the plow. The hubs are linked to the long-term sustainability trials operated by CIMMYT to synthesize a global understanding of CA, and its adaptability to different environments, cropping systems and farmers' circumstances. The hub concept is the principle structure to work together with partners including farmers in well selected and important production systems:

- to test various best-bet technology options with farmers
- to integrate these options into practices that farmers can successfully manage to improve their farm level economics and family well-being
- to provide a demonstration platform to extend these technologies to surrounding farmers
- to provide a training/demonstration platform to bring technicians and extension agents (from NARS and NGO agencies) and farmers/farmer groups from other areas with similar production systems and conditions
- to provide a platform to do relevant research
- to provide the necessary structure to be able to capitalize on the environmental service function of implemented CA technologies (C credits, water quality credits, ...)

## **Extensive literature review**

In order to better understand the influence of the different components comprising CA (reduced tillage, crop residue retention and crop rotation) on SOC stocks, Govaerts et al. (2008) did an extensive literature search. This review summarized the potential impact of CA on C sequestration by examining the existing knowledge on C and N cycling in agriculture, synthesizing the influence of tillage, residue management and crop rotation on underlying soil process and summarizing the existing case study information on the influence of CA on C-stocks. General lessons were drawn and knowledge gaps identified. Some of the already existent reviews on the influence of agriculture and management on C sequestration made by West and Post (2002), Jarecki and Lal (2003), VandenBygaert et al. (2003), Blanco-Canqui and Lal (2008) were used as a basis and completed through further literature search. Based on the evaluation of the existing knowledge on C sequestration, there was opted to only include those results that came from measurements done to at least 30 cm deep after at least 5 years of continuous practice.

In general it was striking that for the developing world and the more tropical and subtropical areas information was missing on the influence of tillage and crop rotation on C storage. Very limited information was found on the influence of management changes on C stocks in the depleted soils (e.g. Africa, Central America, ...). Some information exists, but most of it was rejected for inclusion in the review as it did not meet the criteria to be reliable (depth of sampling, ...). It is of course clear that most information is coming from areas where reduced tillage and CA have been implemented already for a substantial time, however, in order to really quantify and understand underlying processes for C sequestration, serious knowledge gaps have to be bridged.

Govaerts et al. (2008) concluded based on this literature review that CA is characterized both by short-term maximization of crop production as well as by potential long-term sustainability (i.e. carbon storage) at microsite (i.e. soil aggregation studies) and farm level (i.e. yields analysis, profitability). Concerning the potential of CA as a strategy for C sequestration: in 8 of the 62 cases withheld, C stock decreased when changing to reduced tillage, in 21 of the cases there was no significant difference and in 33 case the C stock increased. Increasing crop rotation resulted in decreased stock in 22 of the 55 cases, in no significant difference in 5 the cases and in an increased C stock in 28 of the 55 cases. Most results were obtained at plot level and more holistic research at farm level including agro-ecosystem constraints is needed as well as total carbon sequestration budgets at regional and global level. Underlying mechanism to explain the different results seem not all clear. This confirms the need for the development of an international network of hubs that install working examples of CA within the different agro-ecological areas and farming systems. Only by connecting all these different sites together in a working network of excellence, the underlying mechanisms of C storage as influenced by CA can be revealed. Albeit the existing knowledge gaps, increasing evidence points to the validity of CA as a carbon storage practice and justifies further efforts on research and development.

## **CONCLUSIONS**

The studies indicate positive effects of CA on soil quality and that residue retention is critical to make minimum tillage systems work. The major potential for CA, however, as a climate mitigation strategy is based on its related productivity gains. Natural resource conservation

technologies were not implemented (or implemented only during periods when direct incentives were provided) because they did not lead to higher yields. CA has that unique combination of being a natural resource conservation technology that also increases productivity as well as farmer livelihoods. This can be the major driving factor for farmers to implement this soil carbon sequestration strategy, and thus, going beyond ineffective and expensive direct incentives. Apart from the obtained results, a review on CA and C sequestration prepared by the team revealed that carbon sequestration in CA needs more in depth research especially in the tropics. But even if C sequestration is not always obtained in all agro-ecological conditions, CA remains an important technology that improves soil processes, controls soil erosion, and reduces tillage related production costs, and these are sufficient reasons to promote the step-by-step conversion by adopting resource conserving technologies with as final goal CA.

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