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Article

Conservation agriculture: an alternative for climate change mitigation in the semiarid central plateau of Mexico

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Abstract

Modifications produced by conservation agriculture on the dynamics of carbon in the soil result in an increase in carbon in the soil fraction and greatly reduce carbon oxidation processes by decreasing the mechanical manipulation of the soil. The objective of this study was to evaluate the cumulative effects of 25 years of conservation agriculture as a means to improve the resilience capacity of agricultural soils in the face of climatic fluctuations and promote increased yields, decreased erosion and greenhouse gas emissions. In a long-term experiment (1995-2020), under an irrigated corn-triticale rotation, the following two soil management systems were evaluated: 1) conventional tillage (Br + Ra); and 2) zero tillage plus 33% soil cover with harvest residues (LC+33% C). The variables evaluated were: soil organic carbon, stability of aggregates in water through mean weight diameter (MWDa), saturated hydraulic conductivity (Ks), bulk density (($_b$) and grain and forage yield. The results showed that, in LC + 33%, carbon presented significantly higher values of SOC (23.8 Mg ha^{-1}), MWDa (1.2 mm), Ks (8.5 cm h^{-1}) and lower ($_b$ (1.19 Mg m^{-3}) vs Br + Ra, which is favorable for the sustainability and resilience of the soil structural system. CA improves the soil variables assessed and improves soil quality by increasing soil organic carbon.

Keywords:

carbon, climate change, conservation agriculture, organic matter, tillage.

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Introduction

The conventional agriculture practiced by the farmer in the semiarid Central Plateau of north-central Mexico, which is based on the work of land fallowing and harrowing to turn the arable layer, is mainly responsible for soil degradation. This system, which began more than half a century ago, today is shown to be unsustainable, as it constitutes a model that emits greenhouse gases (GHGs) and does not contribute to the conservation and improvement of natural resources (air, soil and water) (Cotler *et al*., 2016).

One of the consequences of the intensive tillage system in relation to climate change is the reduction of soil carbon sequestration (sink effect), whose direct result is the decrease in the content of soil organic carbon (SOC), the main component of soil organic matter (SOM), therefore, SOC is an indicator of soil quality, agronomic sustainability and environmental resilience (Lal, 2003; Osuna-Ceja *et al*., 2006; Carvalho-dos Santos *et al*., 2012; Van der Wal and de Boer, 2017).

For his part, Reicosky (2011) argues that intensive agriculture has contributed to the loss of between 30% and 50% of SOC in the last two decades of the last century and continues to this day. In addition, he mentions that the tillage work of conventional systems has a negative effect on the soil in several aspects: it mainly promotes the loss of SOM, which is lost between 20 and 30% in just two years of intensive cultivation.

Soil quality can be understood as ‘the attribute of soil to sustain the development of a crop without causing land degradation or environmental deterioration’ (Bone *et al*., 2010; Cotler *et al*., 2016) or be interpreted as a link between conservation strategy, management practices and the achievement of the main objectives of sustainable agriculture (Udawatta *et al*., 2009; FAO, 2017). The edaphic quality is composed of the state of its inherent and dynamic properties such as the content of SOM, which is related to functions on the physical, chemical and biological behavior of the soil, affecting its fertility and productivity, diversity of organisms or microbial products in a given time (Bautista *et al*., 2004).

The efficiency and quality of the SOM that is incorporated into the soil consequently affects the edaphic quality, which will be a function of the rate at which it becomes part of SOC (Cloter *et al*., 2016). SOC is the main component of SOM. As an indicator of soil health, SOC is important for its contributions to food production, climate change mitigation and adaptation, and the achievement of the sustainable and resilient development goals (FAO, 2017). Also, SOC improves the structural stability of the soil by promoting the formation and stabilization of aggregates, which, together with porosity, ensure sufficient aeration and infiltration of water for better plant growth (De León-González *et al*., 2000).

Likewise, the presence of carbon in the soil leads to a greater resistance of aggregates to the impact of external forces (rain or irrigation, tillage, etc.), by improving the water retention capacity in the soil, increasing the content of microbial biomass and nutrient recycling (Osuna-Ceja *et al*., 2006; Sandoval-Estrada *et al*., 2008). However, the dynamics of carbon stores and their quality are highly influenced by any change in agronomic management practices (Bernoux *et al*., 2006; Docampo, 2010), especially those involving the exposure and destruction of soil aggregates.

In this context, over the last fifty years, there has been a great discussion about the impacts that the use of plow and harrow have on the quality of soils (Lal, 2007). Soil inversion, the destruction of aggregates by agricultural implements, unprotects and exposes to the weather the SOM that is occluded in small aggregates (Alonso and Aguirre, 2011), which can oxidize as carbon dioxide (CO_2) (Bedard-Haughn *et al*., 2006); whereas when harvest residues are left on the soil surface, their incorporation is done through the activity of soil fauna (e.g. earthworms and other organisms), without destruction of aggregates, where SOM can remain immobilized (Dendooven *et al*., 2012; Cloter *et al*., 2016).

In Mexico, exhaustive crops such as corn, sorghum, wheat and barley, which cover more than 55% of irrigated and rainfed land (SIAP-SADER, 2019), are mostly subject to conventional tillage.

In this system, soils remain uncovered most of the year after harvest, since *esquilmos* (residues of leaves and stems that remain on the ground after harvesting the grain or seed) are removed from the ground to be used as livestock feed (Fuentes *et al*., 2001; Villegas *et al*., 2001), as direct grazing or are burned (Cotler *et al*., 2016); especially in the north-central region of the country (Martínez and Osuna, 2017).

The loss of SOM leads to a decrease in fertility, a reduction in moisture retention capacity and a loss of productivity, which results in the need to increase the application of fertilizers to maintain yields (Alonso and Aguirre, 2011). One of the biggest problems faced by farmers when tilling the soil is the progressive loss of SOM (Cotler *et al*., 2016).

The objective of this study was to evaluate the capacity of CA as a means to recover and conserve the quality of agricultural soils in the face of climate change and thereby promote the increase of yields, the reduction of erosion processes and the mitigation of GHGs, after 25 years of management with CA compared to the conventional agriculture system.

Materials and methods

The trial was carried out at the San Luis Experimental Field, which is located at geographical coordinates 22° 13’ 45.8’’ north latitude and 100° 51’ 01.5’’ west longitude at an altitude of 1 838 m. The average annual rainfall and temperature are 210 mm and 16.2 °C. The soil of the experimental unit is of the Phaeozem type, with a clayey-sandy loam texture, with an alkaline pH of 8.1, with 1.4% OM and EC of 0.81 dS m^{-1} with strong compaction problems throughout the profile. Water for irrigation recorded an EC of 0.29 dS m^{-1} and SAR of 1.26, low in salinity and sodicity (Sarabia *et al*., 2011).

Since 1995, a long-term experiment (25 years) has been conducted under irrigation conditions, where two soil management systems were compared: 1) conventional tillage fallowing plus harrowing (Br + Ra); and 2) zero tillage plus 33% soil cover with harvest residues (LC+33% C), where practices of rotation of spring-summer (SS) and autumn-winter (AW) grass crops are carried out for grain and forage production. Each experimental unit had 240 m^2 and two repetitions were used (Martínez and Osuna, 2017).

Crop rotation was corn (*Zea mays* L.) SS and triticale (*Triticum aestivum* L.) AW. For corn, the established population density was 70 000 plants ha^{-1} and the fertilization doses were 200 kg ha^{-1} N, 100 kg ha^{-1} P_2O_5 and 00 kg ha^{-1} K_2O. For triticale, 80 kg ha^{-1} of seed was used and fertilization was 90 kg ha^{-1} N, 40 kg ha^{-1} P_2O_5 and 00 kg ha^{-1} K_2O in this case. In relation to weed control in the case of corn with LC + 33% C in all cultivation cycles, an application of pre-emergent herbicide atrazine was made at 0.75 kg ai. ha^{-1} after sowing, while in the conventional system Br + Ra, two mechanical weedings were performed at 21 and 35 das. Pest control was performed by applying the insecticide Spinetoram in doses of 0.75 ml ai. ha^{-1} for the control of fall armyworm.

Determination of corn and triticale yield

15% moisture. Two 6 m long samples per treatment were randomly harvested in the two central furrows of each experimental unit. In the case of triticale, it was harvested when the grains presented a milky-doughy state and two samples of 1 m^2 per treatment were taken and it was expressed as dry matter yield.

Sampling and determination of soil variables

In the harvest stage of grain corn of spring-summer (SS)-2020, eight undisturbed soil samples per treatment were collected at 0-10 cm depth. Bulk density (($_b$) was calculated as the ratio of the dry soil mass at 105 °C (M_{ds}) to the total volume (V_t) occupied by this undisturbed soil mass, and it was determined at each sampling point using the double-cylinder auger (Jury *et al*., 1991). The soil samples were dried in a forced-air oven (40 °C) for 24 h and passed through a 0.5 mm sieve.

Soil organic carbon (SOC) was determined with soil samples prepared according to method AS-01 (SEMARNAT, 2000). The determination of soil organic matter (SOM) was carried out based on the method by Walkley and Black (AS-07), which is based on the oxidation of SOC by means of a solution of potassium dichromate and the heat of reaction generated when mixed with concentrated sulfuric acid.

The amount of carbon stored (CS) in the soil was estimated with the following equation: CS= SOC * ($_b$ * Pm * 10 000. Where: CS= carbon stored (Mg ha^{-1}). SOC= percentage of organic carbon in the soil [% ($_b$= bulk density (Mg m^{-3})]. Pm= depth of soil cover (m). The stability of soil aggregates in water was estimated using the mean weight diameter (MWD_a) according to Franzluebbers *et al*. (2000). Saturated hydraulic conductivity (K_s) was estimated according to Reynols and Elrick (1990).

Statistical analysis

All variables (of yield of both crops and of the soil) were performed an analysis of variance under a completely randomized design, where the two soil management systems were considered as treatments and the Tukey mean comparison test (α= 0.05) was used by means of the Statistical Analysis Systems software, version 9.1 (SAS, 2013).

Results and discussion

Statistical significance was detected between the two soil management systems (#= 0.05) in the content of SOC, ($_b$, MWD_a and K_s (Table 1). The results of the statistical analysis indicated that, except for ($_b$, the other variables presented significantly higher values in zero tillage with 33% cover, as a result of a greater accumulation of organic matter in the treatment LC + 33% C (SOM= 5.4%) compared to the treatment Br + Ra (SOM= 1.7%) in the 0-10 cm of the soil. This indicates that stubble tends to favor soil quality when it remains above ground, which was reflected in an increase in SOC at that depth (Table 1).

Table 1. Mean values of variables studied in two soil management systems.

Systems	SOC (Mg ha^{-1})	($_b$ (Mg m^{-3})	MWD_a (mm)	K_s (cm hr^{-1})
Br + Ra	9.2 b	1.37 a	0.14 b	0.154
LC + 33% C	23.8 a	1.19 b	1.2 a	8.5
CV%	24.42	4.94	18.28	32.12

SOC= soil organic carbon; ($_b$= bulk density; MWD_a= mean weight diameter of water-stable aggregates; K_s= hydraulic conductivity; Br + Ra= fallowing plus harrowing or conventional tillage and LC + 33% C= zero tillage plus 33%cover or conservation agriculture. Averages with different letters in a column by parameter are statistically different according to Tukey (0.05).

On the contrary, the treatment without residues (Br + Ra) had a significantly lower level (p= 0.05) of SOC than the treatment with residue cycling (LC + 33% C), which suggests the high degree of deterioration of this conventional system. This significant increase in SOC in the surface layer of the soil shows the importance of residue cycling as a sustainable and resilient practice over time, which also reduces CO_2 emissions into the atmosphere and mitigates climate change processes, which coincides with some authors such as Bronick and Lal (2005).

The mean value of MWD_a in conventional tillage showed a low value, which indicates weak structural stability. However, zero tillage with residues presented a significantly higher mean value (p= 0.05) of MWD_a with respect to the treatment Br + Ra within the first 10 cm of depth. This denotes a higher proportion of macroaggregates due to the effect of SOM on increasing structural stability (Sandoval-Estrada *et al*., 2008). This improved water infiltration (Sánchez *et al*., 2008), it also reduces soil erosion (Cadena *et al*., 2012) and decreases compaction (López *et al*., 2018).

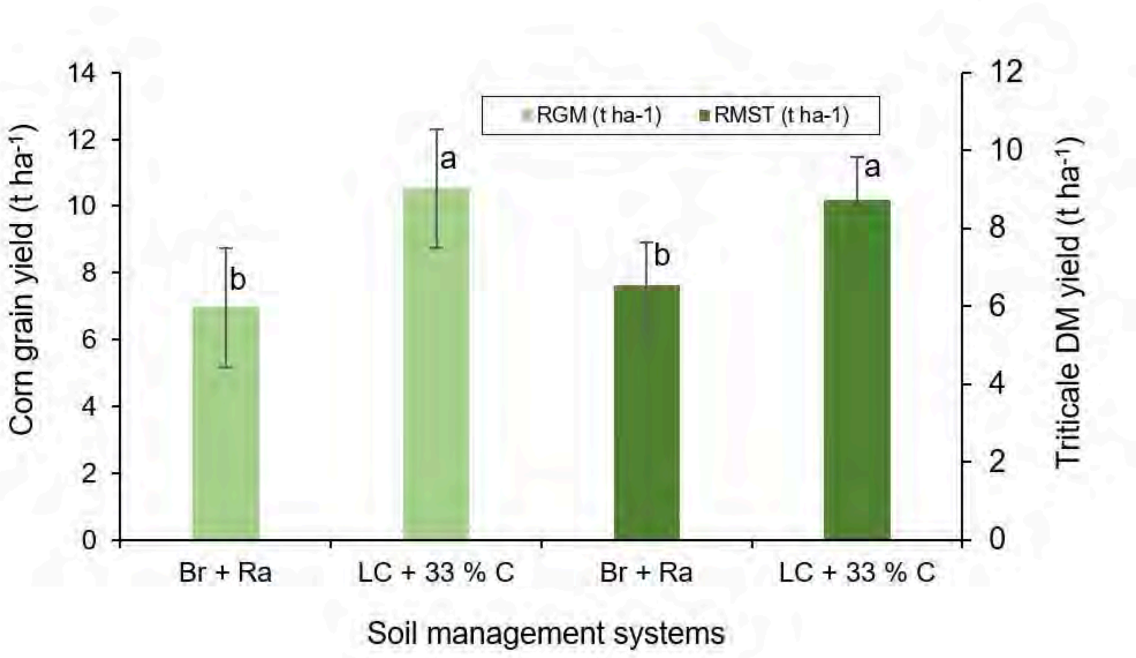
The comparison of values of saturated hydraulic conductivity (K$_s$) between both soil management systems shows that LC + 33% C presented a significantly higher (*p*# 0.05) infiltration rate in relation to Br + Ra. This was largely due to the increase in SOC in the first centimeters of the soil as a result of the contribution of stubble, which corroborates the goodness of the system LC+33% C in the creation of large, stable and continuous pores in the soil profile.

This contradiction with having smaller pore sizes within aggregates in soils with conservation tillage reflects the importance of root decomposition and the action of soil fauna in producing continuous and stable pores (Rachman *et al*., 2003).

Corn and triticale yield

The yields of corn grain (RGM) and triticale dry matter (RMST) in rotation for the spring-summer and autumn-winter 2020 cycles are shown in Figure 1. The statistical analysis for RGM and RMST of both crops reported differences between means of treatments (*p*= 0.05), favorable to the treatment of zero tillage with residues. These differences are attributed to the improvement of soil quality indicators (($_b$, MWD$_a$ and K$_s$) as well as the higher level of SOC achieved and its relationship with long-term soil structure changes (Sandoval-Estrada *et al*., 2008).

Figure 1. Average yield of corn grain (RGM) and triticale dry matter (RMST) under two soil management systems. Averages with different letters in the column are statistically different according to Tukey (0.05). The bars mean standard error of the mean n= 4.



This is a way of making it evident that conservation agriculture (CA) is a production alternative that increases sustainability through establishing a degree of resilience (ability to return the soil to its original condition after a disturbance) and is associated with the potential to reduce the emission of greenhouse gases (Lal, 2003).

With CA, SOC increases significantly. In the semiarid Central Plateau region of north-central Mexico, this increase can reach 1.6 times more SOC in the first 10 cm, compared to the conventional system after 25 years or a rate of increase of SOC of 0.58 Mg ha^{-1} year^{-1} (Follett *et*

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al., 2005). In this research, SOC in CA was 2.6 times higher than in conventional management, which represents an average rate of 0.95 Mg ha^{-1} year^{-1} over the 25 years of the study.

This increase is directly correlated with the accumulation of crop residues on the surface, which, by decreasing their contact with soil microorganisms, caused a slower decomposition of the SOM (Salinas-García *et al*., 2002), thus increasing the amount of SOC sequestered (Follet *et al*., 2005). The increase in SOC is evident in the first centimeters of soil (Fuentes *et al*., 2010) and manages to reach twice the SOC in the first ten centimeters, compared to conventional tillage, which favors the formation and stabilization of aggregates (Castellanos-Navarrete *et al*., 2012).

This long-term research showed significant results after 25 years and demonstrates how CA recovers and maintains the potential of the soil and, at the same time, influences the amount of SOC that it can store. In the same sense, this system proposes a sustainable condition of the land that establishes the reconstruction of carbon stocks in the soil based on the rates of accumulation of plant residues or biomass on the soil and the decrease of atmospheric CO_2 and the slowdown of global warming (Caviglia *et al*., 2016; Cotler *et al*., 2016).

The adoption of a CA with sustainable land management to increase SOC and reduce CO_2 emissions would be a resilient alternative to complement the efforts of the great environmental challenges: climate change, land degradation and loss of biological diversity. From another point of view, it is pointed out that carbon capture is a responsibility to offer healthy alternatives and new benefits to farmers in the arid and semiarid zones of Mexico.

The increase in SOM that is linked to multiple basic functions of the soil and means a mitigation of GHGs and global warming. All of the above results because the SOM causes a 'series of conditions or functions' that are related to soil properties, the buffer effect, resilience capacity and sustainability (Burbano-Orjuela, 2018).

This implies the development of a CA in which the carbon content present in the SOM is considered (Burbano-Orjuela, 2018). By retaining a greater amount of SOC, CA has the potential to reduce CO_2 emission. Under this criterion, it is estimated that the conversion of 2.5 million hectares of crops under conventional tillage in the arid and semiarid region of north-central Mexico to CA could allow the net sequestration of 58 g cm^{-2} year^{-1} (Dendooven *et al*., 2012).

While this research showed the various ecological, economic, and environmental benefits of CA, it is also important to recognize certain limitations that indicate that this technology requires specific conditions (surface residue management) for each situation in order to achieve sustainable land use under this system. This condition may limit the adoption of this technology by farmers in some regions, especially in the semiarid region of north-central Mexico, because they use crop residues as fodder to feed livestock (CENAPROS, 2001). If this situation arises, the producer can use half of the residues and leave the other half in the field, since the adoption of CA requires a progressive conversion of the entire production system (Beuchelt *et al*., 2015).

CO_2 sequestration in soil

The adoption of CA means a drastic reduction in tillage operations, a reduction that, in the case of the direct sowing method, reaches the total elimination of mechanical work to alter the arable layer of the soil. This reduction influences the volume of CO_2 emissions that is produced, on the one hand, due to the rupture of soil aggregates and the consequent gas exchange that occurs after tillage, and on the other, to fuel consumption and energy consumption caused by carrying out soil tillage operations (González-Sánchez *et al*., 2012).

With the change from conventional tillage to CA, the SOC content results in its increase in the soil fraction. In addition, CA greatly reduces carbon oxidation processes by decreasing mechanical soil manipulation. There is currently evidence in the literature where it is reported that from 1 Mg of C, 3.7 Mg of CO_2 is generated through microbial oxidation processes that take place in the soil (González-Sánchez *et al*., 2012).

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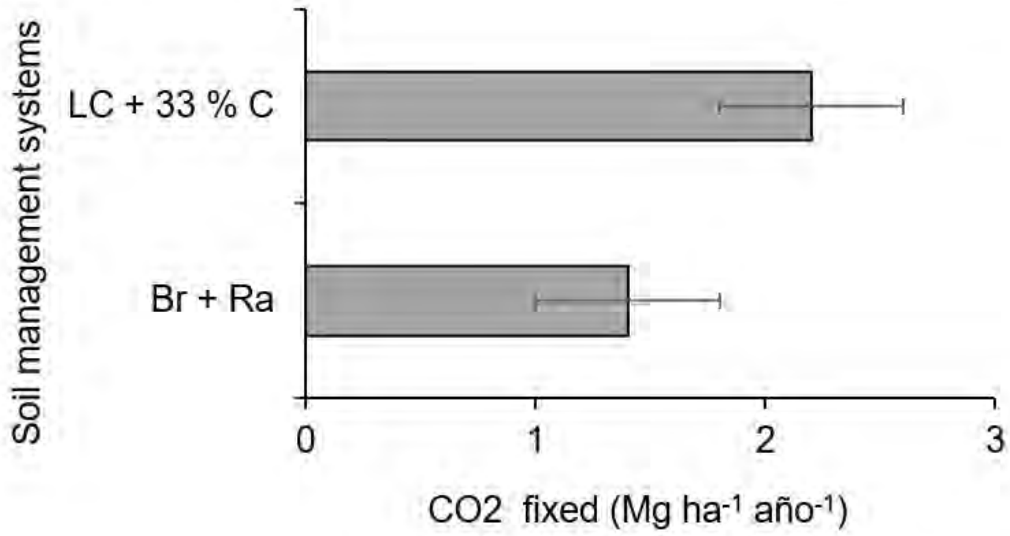
Therefore, the results of SOC obtained add a good amount of CO_2, it is estimated that CA fixed 2.2 Mg of CO_2 ha^{-1} year^{-1}, compared to Br + Ra with only 1.4 Mg of CO_2 ha^{-1} year^{-1} (Figure 2). Based on these data, and supported by the figures reported in scientific studies, it is possible to assume that, during the first 25 years of CA, it is likely to fix up to 57% more CO_2 per hectare per year compared to the conventional tillage system based on the use of moldboard plow and disc harrow.

Figure 2. Average values of CO_2 (Mg ha^{-1} year^{-1}) sequestered under two soil management systems.



Thus, the research resulted not only in greater control of soil erosion, but also in a decrease in SOM losses and CO_2 emissions that occur as a result of intensive soil tillage. The non-removal of the soil considered by CA improves its structure, increases the stability of the aggregates against disaggregation processes, allows greater protection of the SOM against attacks by soil microfauna and maintains the CO_2 resulting from the mineralization processes of the SOM 'sequestered' in the pore space of the soil (González-Sánchez *et al*., 2012).

Conclusions

Conventional agricultural activity generates greenhouse gases, which favors global warming. Conservation agriculture contributes to the sequestration of carbon in the soil and maintains a balance in favor of a lower release of CO_2. Conventional tillage based on the use of moldboard plow and disc harrow has led to a deterioration of the edaphological properties and a reduction in its productivity by causing changes in the edaphic structure that facilitate the oxidation of the SOM and the loss of stability of the soil aggregates.

After 25 years of experimentation with CA, the infiltration rate and the amount of water available were improved, erosion was decreased, yield was increased and GHG emission was mitigated. In addition, it constitutes a useful heuristic tool for the development of sustainable agriculture in the territories producing irrigated and rainfed crops in the arid and semiarid zones of north-central Mexico.

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