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Article

Indicators of soil quality and sustainable productivity with conservation agriculture

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Abstract

The intensive use of the disc plow and its turning action in the agricultural soils of the semi-arid of Mexico has generated severe degradation of physical and chemical properties. This study aimed to evaluate the structural state of a soil (Xerosol) subjected to conservation agriculture to know the soil quality indicators (SQIs) and sustainability indices. In a long-term experiment (1995-2020), under a corn-triticale rotation under irrigation, two soil management systems were evaluated: 1) conventional tillage and 2) conservation agriculture. The indicators evaluated were texture, bulk density, soil organic carbon, structural stability index, aggregate stability by mean weight diameter, total porosity, pore distribution, air-filled porosity, moisture constants (θ_s , FC and PWP), stored water sheet, saturated hydraulic conductivity, pH, electrical conductivity, and grain and forage yield. The results showed a statistical difference between conventional tillage and conservation agriculture (#= 0.05) in 18 of the 19 SQIs analyzed. The highest estimated sustainability was for CA, with 85%, compared to conventional tillage, which was 59%. Conservation agriculture presented greater structural stability with higher porosity values and lower bulk density, which is favorable for the sustainability of soil structure and crop yields.

Keywords:

aggregate stability, conservation agriculture, MESMIS, soil organic carbon, sustainability.

Introduction

Soil is a natural resource whose use is unsustainable under intensive agriculture and it has been shown that intensive agriculture negatively affects quality in its three main aspects: physical, chemical, and biological (Astier-Calderón *et al*., 2002; Dexter, 2004; Navarro *et al*., 2008). Conventional agricultural crop production systems practice intensive tillage and apply external inputs as strategies to increase soil fertility and yield.

The consequences of intensive tillage decrease soil quality, which is reflected in compaction problems, low water infiltration rates, poor aeration, loss of soil biodiversity, soil and water contamination due to the excessive use of agrochemicals and increased erosion (Verhulst *et al*., 2015).

On the contrary, conservation agriculture (CA) generates greater sustainability for crop production, with attributes of productivity, stability, and resilience, by positively impacting soil quality as a result of the improvement of its physical, chemical, and biological properties (Torres *et al*., 2006; Verhulst *et al*., 2015; FAO, 2016).

The main advantages of CA are increasing the content of organic matter (as well as carbon sequestration) in the soil surface, contributing to the structural development and stability of aggregates, increasing water retention, reducing runoff and soil erosion (Verhulst *et al*., 2015). This promotes an increase in the physical quality of the soil and the environment (Dexter, 2004).

To quantify the changes in the physical quality of the soil that CA produces in the long term, it is essential to measure qualitative indicators and indices through the evaluation of soil properties (physical, chemical and biological), which must be easy to measure, even the most sensitive changes generated by the set of management practices (zero tillage, retention of residues on the surface, and crop rotation) that CA integrates, to magnitudes that would explain soil quality, which is a practical step aimed at having sustainability and environmental resilience (Dexter, 2004; Navarro *et al*., 2008; Verhulst *et al*., 2015).

These changes in the physical attributes associated with tillage practices present symptoms that have a common cause: the deterioration of the soil structure (geometric and topological arrangement of the pores that form between the soil aggregates and their stability in time and space). Water and gas flows and root growth are associated with this attribute of the porous medium (Osuna *et al*., 2006; Martínez and Gómez, 2012).

This study aimed to evaluate the structural state of a soil (Xerosol) subjected to conservation agriculture to know the soil quality indicators (SQIs) and sustainability indices.

Materials and methods

The trial was conducted at the San Luis Experimental Field, which is located at the 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 precipitation and temperature is 210 mm and 16.2 °C and the soil is a Xerosol (CGSNEGI, 1995) with a clay-sandy loam texture, with pH of 8.1, with 1.4% OM and EC of 0.81 dS m^{-1}, with compaction problems throughout the profile. Water for irrigation registered 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) CT-conventional tillage fallow plus harrowing (Fa + Ha) and 2) conservation agriculture (CA) with a corn-triticale rotation. Each experimental unit had 240 m^2 and two replications were used (Martínez *et al*., 2019).

The harvest of grain corn was carried out manually when the grain showed approximately 15% moisture. Two random samples of 6 m length per treatment were harvested in the two central furrows of each experimental unit. In the case of triticale, it was harvested when the grain was in a milky-doughy state and two samples of 1 m^2 were taken per treatment.

In the corn harvest stage of the 2020 spring-summer (S-S) cycle, soil samples were collected at a depth of 0-10 cm, in which the following were determined: texture (% clay, silt and sand), MC-moisture constants (at saturation $\#_s$, field capacity FC and permanent wilting point PWP), pH, electrical conductivity (EC), organic matter (OM) and soil organic carbon (SOC).

The following procedures were used: texture (Bouyoucos hydrometer), MC in pressure plate and membrane, EC in extract, pH in a water:soil ratio of 2.5:1 (Page *et al*., 1982), OM was performed with the Walkley and Black method (AS-07) and in the case of SOC, it was determined with soil samples prepared according to the AS-01 method (SEMARNAT, 2000).

The bulk density (p_b) was determined by the double-cylinder auger (Jury *et al*., 1991). Total porosity (f_T) was estimated based on the actual density (p_a), equal to 2.65 Mg m^{-3}. The distribution of corresponding pores of the total pore space of the soil was determined from the moisture retention curves (Dexter, 2004).

The following was estimated: the stability of soil aggregates in water by means of the mean weight diameter (MWD_a) according to Franzluebbers *et al*. (2000), the structural stability index (SSI) according to Duval *et al*. (2015), and saturated hydraulic conductivity (K_s) with the method of Reynols and Elrick (1990).

The following was performed: analysis of variance according to a completely randomized design with two replications of the measured variables, mean tests using Tukey’s criterion (0.05), and pairwise correlation of parameters of the measured attributes. The statistical analysis system, version 9.1.3 (SAS, 2013) was used and a sustainability analysis was carried out using the Ameba-type radial diagram (Masera *et al*., 2000).

Results and discussion

A difference was detected between CA and CT (α= 0.05) in the contents of sand and silt (Table 1); there was no statistical difference in clay, although this did not modify the textural clay-sandy loam classification (Verhulst *et al*., 2015). In bulk density (p_a), there were statistical differences (α= 0.05) between treatments (Table 1). The lowest value occurred in the treatment with CA + 33% C, which was attributed to the development of a better porous structure caused by the higher content of organic matter (OM) and the absence of compaction due to the transit of machinery (Hamza and Anderson, 2005).

Table 1. Effect of soil management systems on sand, silt, and clay contents, bulk density (p_b), organic matter (OM), soil organic carbon (SOC), structural stability index (SSI), and mean weight diameter of water-stable aggregates (MWD_a). San Luis Experimental Field, 2020.

Systems	Sand	Silt	Clay	p_b	OM	SOC	SSI	MWD_a
		(g kg^{-1})		(Mg m^{-3})	(g kg^{-1})		(%)	(mm)
				0-10 cm				
Conventional tillage	413.8 b	327 a	259.2 a	1.37 a	12.66 b	6.74 b	2.91 b	0.14 b
Conservation agriculture	502.3 a	220.8 b	276.9 a	1.19 b	45.92 a	20.06 a	11.49 a	1.2 a
CV (%)	7.43	13.89	8.09	4.94	12.86	24.14	16.1	18.28

Averages with different letters in a column by parameter are statistically different according to Tukey (0.05).

The SOC values at 0-10 cm were statistically different between both management systems (α= 0.05). The highest value of SOC is presented by the soil under CA compared to the soil with CT (Table 1). This reflected the greater mass of roots and the accumulation of plant residues in the topsoil that exist under the CA system, compared to the soil cultivated with CT (Duval *et al*., 2015).

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The structural stability index (SSI) is an estimator of the 'resilience capacity' of soil structure, which relates SOC to soil texture (silt + clay). The values of the structural stability index (SSI) indicate a statistical difference ($\alpha= 0.05$) between treatments (Table 1), so a higher structural state of the soil was observed in the CA compared to the CT.

Table 1 showed that structural stability through MWD_a exhibited differences ($\alpha= 0.05$) between treatments. CA presented a moderately stable MWD_a value with an average value of 1.2 mm, compared to CT with an average value of 0.14 mm, considered a very unstable structural state (Le Bissonnais, 1996). MWD_a increased over time in CA due to the contribution of residues, suggesting an effect of OM on increasing structural stability within the first 10 cm of depth. This was manifested after 25 years with CA, where the soil tends to present structural resilience.

Total porosity and its classification into macropores, mesopores, and micropores reported differences between treatments ($\alpha= 0.05$). CA presented the highest values compared to CT. This indicates that the continuous contributions of residues and their surface decomposition increase the incorporation of OM into the soil and promote the development of a more porous structure (Osuna *et al*., 2006). This study showed that continued tillage significantly decreased these different pore classes by approximately 12, 14, and 15%, respectively, compared to CA.

In the case of CT, fallow plus harrowing causes significant damage to structural stability, thus reducing porosity, water infiltration and gas exchange, and negatively affecting root growth and development and its contribution to the aerial part of the nutrients and water necessary for the development of the plant (Ceballos *et al*., 2010).

For air-filled porosity (f_a), there were differences ($\alpha= 0.05$) between management systems. In the f_a mean test (Table 1), CA had a higher volumetric air content than CT, which is 14% higher. This trend correlates with the decrease in f_{ma} and f_{me} detected in the soil with the CT.

The value of saturated water content (θ_S) was higher for CA (0.496 $cm^3\ cm^{-3}$) than for CT (0.419 $cm^3\ cm^{-3}$) for the depth of 0-10 cm ($\alpha= 0.05$) (Table 2). The water contents at FC and PWP were different ($\alpha= 0.05$), also higher for CA than for CT, giving higher values of usable moisture in terms of sheet (S_u), which was attributed to the fact that porosity and OM content were higher in CA compared to CT. Similar results have been reported by Rubio *et al*. (2008).

Table 2. Effect of soil management systems on total porosity (f_T) and its classification: macropores (f_{ma}), mesopores (f_{me}), and micropores (f_{mi}) and air-filled porosity (f_a), saturated water content (θ_S), field capacity (FC), permanent wilting point (PWP), usable water sheet (S_u), and saturated hydraulic conductivity (K_S). San Luis Experimental Field, 2020.

Systems	f_T	f_{ma}	f_{me}	f_{mi}	f_a	Θ_S	FC	PWP	S_u	K_S
	($cm\ cm^{-3}$)								(cm)	($cm\ hr^{-1}$)
0-10 cm										
CT	0.49 b	0.06 b	0.221 b	0.204 b	0.282 b	0.419 b	0.316 b	0.166 b	1.97 b	0.154 b
CA	0.55 a	0.067 a	0.252 a	0.235 a	0.321 a	0.496 a	0.377 a	0.192 a	2.29 a	8.5 a
CV (%)	6.09	4.98	3.27	2.88	2.35	6.91	9.12	7.89	7.91	32.12

Conventional tillage (CT); conservation agriculture (CA). Averages with different letters in a column by parameter are different. Tukey (0.05).

In relation to K_s, it was observed that it was higher in CA compared to CT, which confirms the degradation of the structure due to soil tillage. The analysis of the data shows that water mobility is clearly higher in soil with CA, evidencing its greater capacity to transport and redistribute water through the porous medium due to the creation of large, stable, and continuous pores that produce higher infiltration rates in the arable layer (Shukla *et al*., 2003; Navarro *et al*., 2008).

The mean pH values were 7.9 for CA and 8.3 for CT, with a significant difference ($\alpha= 0.05$). The tendency of this parameter to decrease in soil with CA is probably due to the accumulation of OM in the topsoil since it generates acidity due to the decomposition process or perhaps it may be due to the acidifying effect of fertilizers with nitrogen and phosphorus applied more superficially in CA than with CT (Verhulst *et al*., 2015; Báez *et al*., 2017). On the other hand, EC presented values of 0.76 and 1.4 dS m^{-1} and there was a difference between both treatments (α= 0.05). The highest value occurred in the soil with CA; however, this parameter is still below the critical value indicated (< 3) (Shukla *et al*., 2003).

A correlation (p< 0.05) was found between 138 of the 171 pairs of soil attributes. p_a was strongly and negatively correlated with f_a, f_T, f_{ma}, MWD_a, and SSI (r ≥0.8). There were high positive correlations between MWD_a and SSI, SOC, K_S, θ_S, OM and f_{ma} (r >0.82) and negative correlations with pH and S_u (r ≥0.72). K_s was highly and positively correlated with OM, SOC, SSI, θ_s, f_{ma}, f_a, and f_T (r ≥0.74) and negatively correlated with pH (r= -0.80). EC and pH were negatively correlated (r= -0.9). On the contrary, OM was significantly and positively correlated with SOC, SSI, f_{ma}, and f_a (r ≥0.74) and S_u was significantly correlated with f_{me}, f_{mi}, f_T, f_{ma}, and f_a (≥0.72).

The physical quality of the soil is defined based on its intrinsic properties, as well as its productive capacity, and environmental buffers (Astier-Calderón *et al*., 2002). CA produces an improvement in the physical quality of the soil since, in general, increases and decreases in the value of some attributes related to the structure and its stability are observed.

For example, the rate of infiltration or aeration may increase due to an increase in the number of macropores, a greater size and stability of aggregates, and a greater amount of OM, which produce increases in the transmission and availability of soil water for plants in the long term (25 years), which coincides with other authors (Navarro *et al*., 2008; García *et al*., 2018).

By means of the AMEBA-type radial diagram (Masera *et al*., 2000), it was possible to graphically visualize the deficiencies of each management system based on the selected indicators (Figure 1). CA had a sustainability value of 85%, while CT reached 59% (Table 3). CA tended towards the optimal value of sustainability in most attributes, while CT retracted towards the center of the graph (Figure 1). It is inferred that soil quality with CA is in an efficient and more sustainable condition than CT (Alonso, 2004; Altieri and Nicholls, 2005).

Figure 1. Comparison of the sustainability of conventional tillage (CT) and conservation agriculture (CA) through the framework for assessing natural resource management systems incorporating sustainability indicators (MESMIS, for its acronym in Spanish).

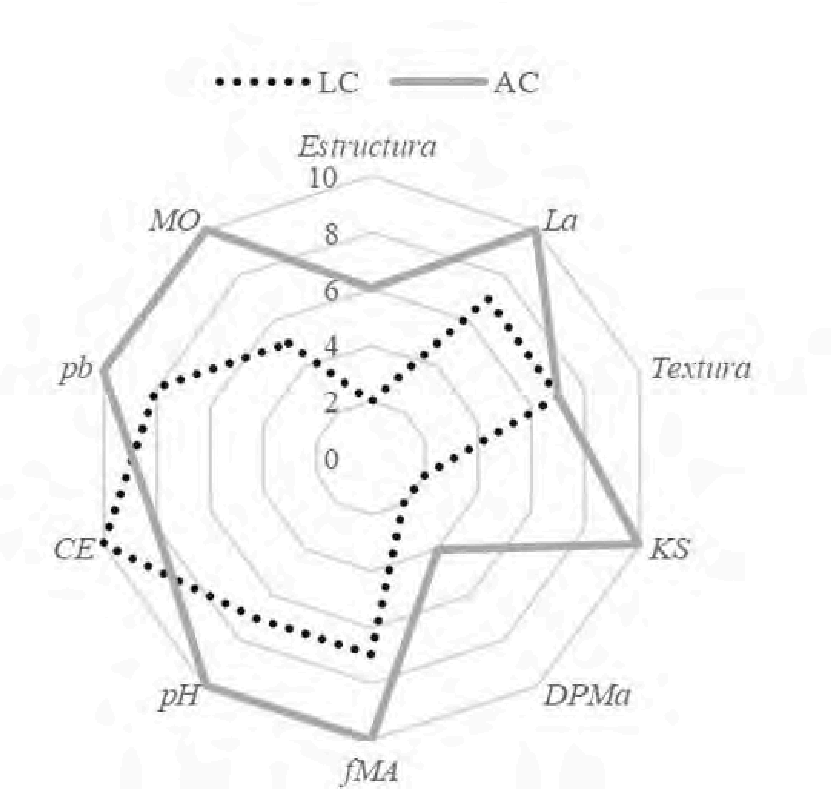

Table 3. Selection and weighting of soil indicators under two management systems. San Luis Experimental Field, 2020.

Indicator	RV	CT	CA
Structure stability	10	2	6
2. Usable water sheet (S_u , cm)	10	7	10
3.Texture type	10	7	7
4. Saturated hydraulic conductivity ($K_{s,}$ cm hr^{-1})	10	4	10
5. Mean weight diameter of water-stable aggregates (mm)	10	2	4
6. Porosity of macropores (cm cm^{-3})	10	7	10
7. pH of the saturation extract	10	7	10
8. E.C. of the saturation extract (ds m^{-1})	10	10	8
9. Bulk density (Mg m^{-3})	10	8	10
10. Organic matter (g kg^{-1})	10	5	10
Maximum possible favorable total (higher sum)	100	59	85

Shukla *et al*. (2003).

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The statistical analysis for grain and dry matter yield of corn and triticale reported a difference between management systems (α= 0.05) (Table 4). The higher grain and forage yields of corn and triticale obtained in CA are attributed to the improvement of soil quality, associated with the stability and resilience of the soil structure. The CA/CT ratio indicates that the relative yield of both crops in CA was 54 and 34% higher than CT due to the sustainable improvement of the physical, chemical, and biological attributes of the soil (Martínez-Gamiño *et al*., 2019).

Table 4. Average yield of grain and dry matter (DM) of corn and triticale with conventional tillage (CT) and conservation agriculture (CA). San Luis Experimental Field, 2020.

	Grain and DM yield (t ha^{-1})	
Rotation crops	**Corn**	**Triticale**
CT	6.9 b	6.5 b
CA	10.5 a	8.7 a
CA/CT (%)	154	134

CT= conventional tillage; CA= conservation agriculture; averages with different letters in a column are statistically different according to Tukey (0.05).

Conclusions

The soil studied is characterized by fragile structural stability. This problem is accentuated by the use of intensive tillage practices, such as ploughing and harrowing, which favor water and wind erosion in these semi-arid soils, making CA a more promising alternative for sustainable structural resilience in these soils with dry conditions.

The introduction of CA that combines the three management principles: zero tillage, retention of residues on the surface, and crop rotation, promotes the conservation and improvement of soil quality in the medium and long term, favors structural stability, and increases the content of SOC and the transmission and retention of water in the soil. This technique enables the development of sustainable agriculture in the semi-arid regions of Mexico.

In soil with CA, most of the attributes that represent physical, chemical, and water transmission properties were appropriate indicators to assess soil quality degradation since they showed sensitivity to the impact of tillage practices. This indicates that the structural system is susceptible to physical degradation; CA presented better structural stability and a greater increase in SOC, which is favorable for the sustainability of the soil structural system and crop yields.

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