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Simulation of soil organic carbon changes in Vertisols under conservation tillage using the RothC model

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ABSTRACT: The purpose of this study was to determine the measured and simulated rates of soil organic carbon (SOC) change in Vertisols in short-term experiments when the tillage system is changed from traditional tillage (TT) to conservation tillage (CT). The study was conducted in plots in four locations in the state of Michoacán and two locations in the state of Guanajuato. In the SOC change simulation, the RothC-26.3 carbon model was evaluated with different C inputs to the soil (ET1-ET5). ET was the measured shoot biomass (SB) plus estimated rhizodeposition (RI). RI was tested at values of 10, 15, 18, 36 and 50 % total biomass (TB). The SOC changes were simulated with the best trial where ET3 = SB + (0.18*TB). Values for model efficiency and the coefficient of correlation were in the ranges of 0.56 to 0.75 and 0.79 to 0.92, respectively. The average rate of SOC change, measured and simulated, in the study period was 3.0 and 1.9 Mg ha^{-1} yr^{-1}, respectively; later, in a simulation period of 45 years, SOC change was 1.2 ± 0.8. In particular, without making adjustments in the RothC parameters and with information on measured plant residue C inputs to the soil, it was possible to simulate changes in SOC with RothC and estimate trends over a period of more than 45 years.
Keywords: land use change, conservation agriculture, carbon sequester

Introduction

Soil organic carbon (SOC) in land ecosystems worldwide is nearly double that stored in the atmosphere: 1462-1548 Pg carbon (C) at 1 m deep compared with 760 Pg C in the atmosphere (1 Pg = 1 × 10^{15} g) (Batjes, 1996). Consequently, slight changes in this soil stock can cause large variations in atmospheric carbon flows. In general, SOC changes are based on direct methods in the field and the laboratory and on indirect methods such as the use of carbon models, among others, that have also been used in long-term experiments (Post et al., 2001). The RothC-26.3 model has been used in the prediction of SOC changes in diverse systems and soils around the world and the input data required to run it are readily available (Coleman and Jenkinson, 1996). In its parameterization, RothC requires the total amount of carbon added to the soil, including carbon from root system on a monthly basis. However, the contribution of C from the root system, or rhizodeposition, which includes root exudation and death, is still uncertain (Rees et al., 2005). In this respect, Ludwig et al. (2007) state that the use of experimental data on crop and harvest residues in SOC prediction models may be more appropriate.

In Mexico, changes in SOC have been assessed in short-term experiments using the RothC-26.3 model with direct measurements in agricultural, forest, grassland and grazing systems by González-Molina et al. (2011). In this study, the agricultural systems were on Ferrasol and Phaozem soils and tepetates, and RothC performance was positive with model efficiency values of 0.78 and 0.92, using a total of 106 data.

Vertisols account for nearly 9.5 million hectares of the country's soils (Ortíz, 1997). In the Bajío region, where our study was conducted, vertisols are potentially highly productive (Follett et al., 2005). However, recently, the fertility of these soils has diminished because of intensive agriculture. A number of farmers have adopted conservation tillage as a viable option for increasing soil organic matter, which reduces production costs and increase profits.

The aims of this study were (1) to evaluate the performance of RothC in Vertisols with different C inputs to the soil (measured shoot biomass and rhizodeposition estimated in short-term experiments); and (2) to determine the measured and simulated rate of SOC change as well as trends in simulated SOC changes.

Materials and Methods

Experimental sites

This study was conducted in experimental plots with Vertisols in four locations in the state of Michoacán and two in Guanajuato. The Michoacán plots are located in the Cuitzeo basin in Indaparapeo, Álvaro Obregón, Queréndaro I and Queréndaro II. In Guanajuato, the plots are located in Celaya and Villa Diego. The Cuitzeo Basin has an area of 1,050 km^2 and occupies an important portion of the Morelia-Queréndaro Irrigation District. Table 1 indicates the geographic location and climate and soil characteristics of each location.

Table 1 – General climate and soil characteristics of the study sites.

Sites/Characteristics§	Indaparapeo	Álvaro Obregón	Queréndaro I	Queréndaro II	Celaya	Villa Diego
Longitude	101°00'-101°30' W	101°00'- 101°30' W	101°00'-101°30' W	101°00'-101°30' W	100°48' W	101°11' W
Latitude	19°59'-19°30' N	19°59' -19°30' N	19°59'-19°30' N	19°59'-19°30' N	20°31' N	20°23' N
Altitude	1840	1840	1840	1840	1750	1748
MAT (°C)	19	19	19	19	19	19
MAP (mm)	637	637	637	637	617	646
pH	8.1	7.5	7.5	8	7.5	7.1
SOM (%)	3.2	2.3	3.5	3.2	1.5	2.8
Extractable P-Olsen (ppm)	41 to 65	28 to 41	19 to 37	10 to 32	15 to 24	51

§MAT = mean annual temperature; MAP = mean annual precipitation; SOM = soil organic matter.

Agronomic management

In each location a conservation tillage (CT) plot was established where the previous system had been traditional tillage (TT). The CT plots were located on flat land with slopes of less than 1 % and available irrigation. Maize, sorghum, wheat and legumes (faba beans, common beans or chick peas) were planted in rotations of gramineae-gramineae and gramineae-legume. Maize and sorghum were planted in the spring-summer cycle, while wheat and legumes were planted in the autumn-winter cycle. The CT system incorporated 30 to 100 % of the crop residues (CrR) into the soil and tillage was minimal. The CrR were chopped and distributed over the soil homogeneously before their incorporation into the soil. In the case of the Queréndaro II plot, 30 % of the CrR were incorporated, and in the Indaparapeo and Álvaro Obregón plots, the soils were irrigated with wastewater from the city of Morelia. In Michoacán and Celaya, the CT system was assessed from 2007 to 2012. However, in Villa Diego, the CT system was implemented in 1987, so that the assessment period was 24 years. In the Michoacán plots, wheat is planted in 1.6 m wide beds, separated by irrigation ditches. Maize is planted in double rows on the same beds. In the case of the locations of Celaya and Villa Diego, the wheat is planted in autumn in two rows on 0.76 cm wide beds, while maize is planted on the same beds in a single row. Table 2 gives details of the agronomic management.

Table 2 – Agronomic crop management under conservation tillage in the study localities.

Locality	Plant residue incorporation (%)	Year	Crop cycle§	
			S-S	A-W
Indaparapeo	100	1	maize	fallow
		2	sorghum	safflower
		3	maize	wheat
		4	fallow	wheat
Álvaro Obregón	100	1	maize	beans
		2	maize	chick peas
		3	maize	faba beans
		4	maize	wheat
Queréndaro I	30	1-4	maize	wheat
Queréndaro II	100	1-4	maize	wheat
Celaya	100	1-4	maize	wheat
Villa Diego	100	1-24	maize	wheat

§S-S = Spring-Summer; A-W = Autumn-Winter.

Direct measurement of SOC

Direct measurement of SOC consisted of the following activities: soil sampling, sample preparation, and analytical determination and calculation of SOC (Mg ha^{-1} yr^{-1}). In the field, at the end of the crop cycle, soil samples were taken at increasing depths: 0-5, 5-15 and 15-30 cm. At all of the sites, soil sampling was done before implementing CT and on four sampling dates after CT had been implemented. In Villa Diego, additionally, sampling was done 3, 11 and 24 years after CT implementation. The sample from each experimental plot consisted of 22 sub-samples collected at random with a stainless steel drill. The samples were dried in the shade at ambient temperature, ground with a wooden mallet, sifted through a 2 mm mesh, and homogenized. For analytical determination of soil organic matter (SOM), a small 10 g subsample was prepared; this subsample was ground and sifted through a number 30 mesh. SOM was determined following the Walkley and Black method described by Jackson (1958). To determine total carbon, a 10 g sub-sample of soil was ground and sifted through a number 100 mesh to homogenize it. Total carbon was measured in an automatic C analyzer. Inorganic C was also measured with this equipment, and SOC was estimated by subtracting inorganic C from total C. Also, soil pH was measured in water at a ratio of 1:2 and extractable phosphorus was determined following the Olsen method.

Bulk density (BD) was obtained with the cylinder method and was calculated as the ratio of dry soil weight to soil volume. Dry soil weight was the mineral soil plus humified soil, without plant residues (PR) or rocks. Soil volume was calculated by subtracting volume of PR and stones from total volume.

To avoid an effect of bulk density in determining SOC changes (Mg ha^{-1}), the Ellert and Bettany (1995) approach was used. This approach eliminates the effect of differences in soil mass due to management practices when amounts of carbon in soils are compared. This is achieved by using an equivalent soil mass (ESM) in the Ellert and Bettany (1995) equations: $T_{add} = (M_{soil,\ equiv} - M_{soil,\ top}) / \ell b$, where T_{add} = additional thickness of the top layer, necessary to obtain ESM (m); $M_{soil,\ equiv}$ = ESM is the heaviest equivalent soil mass (Mg ha^{-1}); $M_{soil',\ top}$ = soil mass in the top layer or genetic horizon (Mg ha^{-1}), ℓb = bulk density of the top layer (Mg m^{-3}). The equivalent C mass was also obtained: $M_{carbon,\ equiv} = M_{carbon\ top} + M_{carbon,\ Tadd}$. Where $M_{carbon,equiv.}$ = mass of C by unit of area in an ESM (Mg ha^{-1}); $M_{carbon,\ top}$ = mass of C in the top layer of soil (Mg ha^{-1}); and $M_{carbon,Tadd.}$ = mass of additional C in the layer below the topsoil (Mg ha^{-1}).

Carbon inputs to soil from plant residues

Crop C input to soil (ET) was the sum of shoot biomass (SB) plus estimated rhizodeposition (RI), that is, SB+RI. SB comprised the PR left on the soil surface, which were measured every year of the study in the following way. At the end of the crop cycle, fresh weight was obtained from a sample of 1 m^2 of aboveground PR; from this sample a sub-sample was taken and placed in an oven at 75 °C for 48 h. With these data, moisture content and quantity of dry matter were determined by subtracting the moisture content from the weight of the field sample; the amount of C in the PR was the product of the total dry matter multiplied by 45 % of the C concentration, considered in this study, based on the measurements of Figueroa-Navarro et al. (2005).

Rhizodeposition was estimated as a proportion of total biomass (TB). According to Kuzyakov and Domansky (2000), in cereals RI is 20 to 30 % of total C assimilated in photosynthesis. Nguyen, (2003) reported that around 50 % of the C fixed in net photosynthesis is transferred below ground and partitioned between root growth, rhizosphere (root plus microbial) respiration and addition to soil organic matter. In our study, whose aim was the evaluation of Roth C performance in simulating SOC changes, rhizodeposition was tested within a wide range (10 to 50 %) of total biomass (TB): 10, 15, 18, 36 and 50 %. Thus, ET1= SB + (0.10*TB); ET2 = SB + (0.15*TB); ET3 = SB + (0.18*TB); ET4 = SB + (0.36*TB); ET5 = SB + (0.50*TB) was evaluated. TB was determined with the following expression: TB = HI/Y, where HI = harvest index and Y = crop yield (minus 14 % moisture). Both were average values of the crops harvested in the study locations. The information necessary for calculation of soil C inputs from crop residues is given in Table 3.

Model RothC

The RothC model of Coleman and Jenkinson (1996) is a multi-compartment model. The compartments contain materials classified by their rate of decomposition; four are active and one is inert: (i) easily decomposed plant matter (DPM); (ii) resistant plant matter (RPM); (iii) microbial biomass (BIO); (iv) humified organic matter (HUM); and (v) inert organic matter (MOI). During RothC simulation, ET that enter the soil are separated into DPM and RPM, depending on their origin (crops, grassland or forests). These decompose and form BIO, HUM and CO_2 as a function of the soil clay content. The BIO and HUM generated decompose to produce more BIO and HUM. Active compartments undergo first order kinetic decomposition and each has a constant rate of decomposition (k) per year: DPM (10), RPM (0.3), BIO (0.66) and HUM (0.02). Decomposition of the active compartment is given by the expression $Y = Y_0 (1 - e^{-abckt})$, where Y_0 is initial C; a, b and c are factors that modify k (temperature, moisture, soil cover, respectively); and t is 1/12 to obtain monthly decomposition rate.

Table 3 – Information necessary for calculation of C inputs to soil from crop residues under conservation tillage in the study localities.

Site/Variable§		HI	Y	TB	SB	RI1¶	RI2	RI3	RI4	RI5
			Mg C ha^{-1} yr^{-1}							
Indaparapeo and Álvaro Obregón	Maize	0.5	5.4	10.1	4.7	1.0	1.5	1.8	3.7	5.1
	Safflower	0.2	3.1	3.1	2.5	0.3	0.5	0.6	1.1	1.6
	Wheat	0.4	1.2	7.6	4.5	0.8	1.1	1.4	2.7	3.8
	Beans	0.8	0.5	1.5	0.4	0.2	0.2	0.3	0.5	0.8
	Faba beans	0.3	0.7	1.4	0.9	0.1	0.2	0.2	0.5	0.7
	Chick peas	0.7	2.6	1.0	0.3	0.1	0.1	0.2	0.3	0.5
	Sorghum	0.4	5.0	7.0	4.4	0.7	1.0	1.3	2.5	3.5
Queréndaro I	Maize	0.8	3.1	6.4	1.4	0.6	1.0	1.1	2.3	3.2
	Wheat	0.7	5.4	4.4	1.4	0.4	0.7	0.8	1.6	2.2
Queréndaro II	Maize	0.6	3.1	9.4	4.0	0.9	1.4	1.7	3.4	4.7
	Wheat	0.4	3.3	7.8	4.7	0.8	1.2	1.4	2.8	3.9
Celaya	Maize	0.4	2.2	9.2	5.9	0.9	1.4	1.7	3.3	4.6
	Wheat	0.3	2.9	6.7	4.5	0.7	1.0	1.2	2.4	3.3
Villa Diego	Maize	0.5	1.5	6.1	3.2	0.6	0.9	1.1	2.2	3.0
	Wheat	0.5	5.4	2.9	1.4	0.3	0.4	0.5	1.0	1.4

§HI = harvest index; Y = yield; TB = total biomass; SB = measured shoot biomass; RI = Rizodeposition. ¶RI1 = TB*0.10; RI2 = TB*0.15; RI3 = TB*0.18; RI4 = TB*0.36; RI5 = TB*0.50.

RothC model simulations

RothC simulation was divided into two stages: (1) initialization and (2) scenario construction. The first was done with information from the TT system, considered the baseline because it is the traditional soil management system in the Bajío region. The second stage was run with information from the CT system.

The RothC model was initialized to obtain initial C content of the active compartments in the condition of soil equilibrium. This was achieved by running the model iteratively 10,000 years with information on climate, soil, DPM/RPM ratio, IOM (inert organic matter) and C entry into the soil of RothC (ET). Data on climate include average monthly air temperature (°C), precipitation (mm) and evaporation (mm) (AMT, AMP and AME, respectively) (National Water Commission, 2014). Inputs, such as initial SOC, ET, whether the soil is bare or has plant cover, percent clay in soil and soil sampling depth were obtained from TT before CT began. The DPM/RPM ratio was recommended by RothC with a value of 1.44 for crops and managed grasses (59 % are DPM and 41 % are RPM (Coleman and Jenkinson, 1996). Inert organic matter (Mg ha^{-1}) was obtained following Falloon et al. (1998): IOM = 0.049 × TOC$^{1.139}$, where TOC is organic carbon (Mg ha^{-1}). The C contribution to soil by ET at time 0 (RothC ET) was obtained when executing RothC with climate information, initial SOC value, percent clay, sampling depth and months with plant cover (8). Some entry parameters for execution of the model are shown in Table 4.

In the second stage, RothC was run with the C value of the active compartments and with information on climate, soil DPM/RPM ration and IOM from the previous stage. Scenarios were simulated with information from the CT system: soil plant cover (12 months) and different ET (ET1–ET5).

To determine the rate of SOC change in the Vertisols under CT, the RothC was run for a 100-year period with the best ET test.

Evaluation of SOC changes

Model performance was evaluated using pairs of SOC data, observed and simulated. The statistics used were the coefficient of correlation (r), mean square root of the error (MSRE), model efficiency (EF) and relative error (ER) as defined by Smith et al. (1997). The coefficient of determination (R^2) and the m parameter of the simple linear regression equation were also used. The MSRE value was in the range of 0 to ∞, EF from -∞ to 1, and ER from -∞ to ∞. In an ideal test, MSRE and ER are equal to 0 and R^2 and EF are equal to 1.

Measured and simulated rates of SOC were obtained after 4 years and 24 years depending on the location. The expression was the following: CR = SOC_{final} – $SOC_{initial}$/# years, where CR = change rate (Mg C ha^{-1} yr^{-1}); SOC_{final} = final SOC; $SOC_{initial}$ = initial SOC; and # years = number of years under CT to obtain the trend in SOC changes over time. To determine the trend in simulated SOC changes over time, CR was also estimated after 45 years of CT using the same equation.

Results and Discussion

The results of RothC performance in Vertisols with different C entries into the soil can be seen in Table 5. MSRE values were in the range of 12-16 %, lower than those reported by Gonzalez-Molina et al. (2011) for agricultural systems in Mexico (25-36 %). ER was in the range of -6 to 8 %. For the EF parameter, there were positive values of 0.56-0.77 when using the criterion of Ludwig et al. (2010) who studied soil C dynamics under different tillage systems. For EF, the prediction of changes in SOC was satisfactory (EF ≥ 0.7), except in the case where ET5 = SB + (0.50*TB). The r values indicated a degree of association between measured values and simulated values in the order of 0.79 to 0.92. The m value indicated that the model was in the range of 0.92 to 1.0 and slightly underestimates the simulated values, relative to those measured at 8 %. In the case where R^2 was positive, it indicated that the simulation described the measured values, as well as the mean of the measurements, which were in the order of 0.55 to 0.85 (Figure 1A, B, C and D).

ET3 = SB + (0.18*TB) was the trial in which RothC performed the best and corresponded to the contribution of C to the soil by the root system as reported by Kuzyakov and Domansky (2000). Thus, ET3 was selected to simulate the rate of SOC change (Table 5).

Table 4 – Data necessary for simulating carbon changes.

Location/Variable§	$SOC_{initial}$	IOM	PR_RothC	Clay	SPC
	Mg ha^{-1} yr^{-1}			%	months
Indaparapeo	73	6.4	3.94	52	8
Álvaro Obregón	80	7.2	4.34	50	12
Queréndaro I	87	7.9	4.72	50	12
Queréndaro II	87	7.9	5.15	34	12
Celaya	31	2.4	1.33	64	12
Villa Diego	44	3.6	1.60	58	12

§SOC = soil organic carbon; IOM = inert organic matter; PR = plant residues; PR_RothC = plant residues was obtained when executing RothC; SPC = soil plant cover.

Table 5 – Statistics indicating RothC performance with different C inputs to soil in Vertisols under conservation tillage.

C input to soil (ET)/Statistics§	ER	MSRE	EF	r
ET1 = SB+(0.10*TB)¶	8	12	0.75	0.92
ET2 = SB+(0.15*TB)	6	12	0.77	0.91
ET3 = SB+(0.18*TB)	5	12	0.77	0.91
ET4 = SB+(0.36*TB)	-1	13	0.72	0.86
ET5 = SB+(0.50*TB)	-6	16	0.56	0.79

§ER = relative error; MSRE = Mean square root error; EF = model efficiency; r = coefficient of correlation. ¶SB = measured shoot biomass; TB = total biomass.

The average rates of SOC change measured and simulated (Table 6) during the study period were higher than those reported in the literature, 3.0 and 1.9 (Mg ha^{-1}), respectively (Table 6). In Celaya, Mexico, Follett et al. (2005) reported a measured SOC sequester rate of 0.3 to 2.8 Mg ha^{-1} yr^{-1} for conditions similar to those in our study: vertisols, conservation tillage, short-term experiment (5 years) and crop rotation (wheat-maize and wheat-beans-maize and beans in summer and beans in winter). In long-term experiments, West and Post (2002) report a C sequester rate of 0.57 $\pm$ 0.14 Mg C ha^{-1} yr^{-1} when TT changes to no till, while Lal (2001), for the same case, reports SOC changes of 0.1 to 1.3 Mg ha^{-1} yr^{-1}.

Table 6 – Rate of SOC change, measured and simulated after conversion from Traditional Tillage to Conservation Tillage.

Sites/Variables§	$SOC_{initial}$	Rate of SOC change		
	Mg ha^{-1} yr^{-1}			
		$Measured_{(study\ period)}$	$Simulated_{(study\ period)}$	$Simulated_{45\ years}$
Indaparapeo	73	$1.3_{(4\ years)}$	$1.3_{(4\ years)}$	0.9
Álvaro Obregón	80	$5.5_{(4\ years)}$	$1.8_{(4\ years)}$	0.8
Queréndaro I	87	$-0.8_{(4\ years)}$	$0.0_{(4\ years)}$	0.1
Queréndaro II	87	$4.5_{(4\ years)}$	$2.5_{(4\ years)}$	1.2
Celaya	31	$6.3_{(4\ years)}$	$4.8_{(4\ years)}$	2.6
Villa Diego	44	$0.9_{(24\ years)}$	$1.3_{(24\ years)}$	1.4
Average		3.0	2.0	1.2
Standard deviation		2.7	1.6	0.8

§SOC = Soil organic carbon.

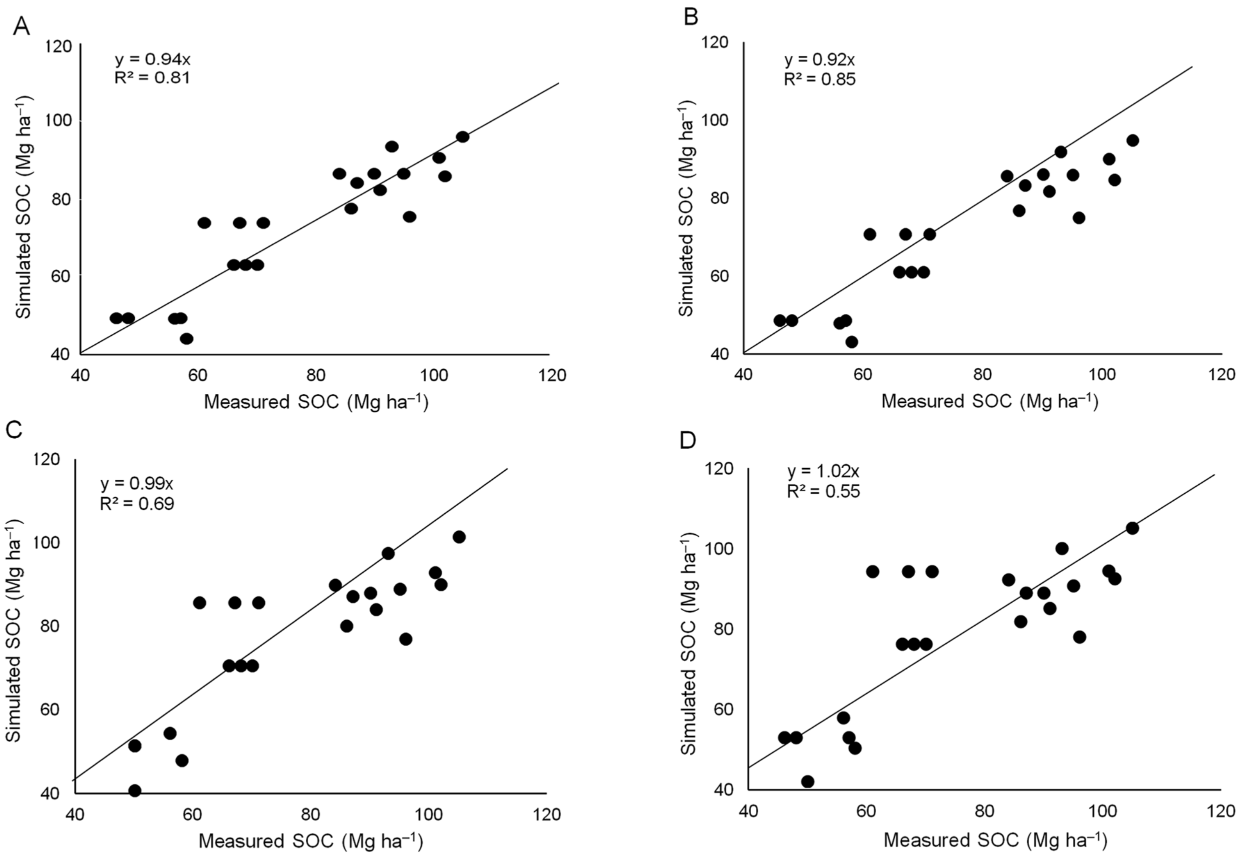

Figure 1 – Fit of the RothC model with different C inputs to the soil (A) ET3 = ET3 = SB + (0.18*TB); (B) ET1 = SB + (0.18*TB); (C) ET4 = SB + (0.36*TB) and (D) ET5 = SB + (0.50*TB) in Vertisols under conservation tillage; SB = measured shoot biomass; TB = total biomass; SOC = Soil organic carbon.

We consider that high measured and simulated SOC change rates over a short assessment time are preliminary results because the soil has not yet reached a state of equilibrium due to the PR incorporated under CT management. According to Nieto et al. (2010), soils can reach equilibrium if the type of soil management is maintained for more than 30 years. However, the degree of association between SOC change rate (Table 3) and entry of C from measured PR (Table 6) was high (r = 0.86). This trend could be seen in Queréndaro I where, unlike other plots, the rate of change was negative because only 30 % of harvest residues were added. In the study of Follett et al. (2005), excluding the C contribution by rhizodeposition, this correlation was lower (r = 0.63), highlighting the importance of root C contribution to the soil in estimating the SOC change rate, as was also indicated by Ludwig et al. (2007) and Senapati et al. (2014).

In our study, besides absolute values of SOC changes, direction and trends of the changes were obtained. These trends can be explained by the SOM conversion time (years) calculated by Jenkinson and Rayner (1977). According to these authors, the time of SOC change is defined as the relationship SOC of the active compartments / yearly input of plant residues. SOC conversion time calculated in this way was 8, 8, 17, 7, 2 and 7 years in the Indaparapeo, Alvaro Obregón, Queréndaro I, Quréndaro II, Celaya and Villa Diego sites, respectively. In Celaya, SOC changes were greater because C migrated faster. According to West and Post (2002), in long-term agricultural experiments worldwide, after a change from TT to NT (no till), a new equilibrium is achieved 40 to 60 years later. In our study of RothC performance, considering ET and that the most stable SOC changes were obtained after 45 years, we can state that SOC changes simulated in Vertisols, after a change in soil use from TT to CT, were in the range of 0.1 to 2.6 Mg ha yr^{-1} and, on average, were 1.2 Mg ha yr^{-1} (Table 6 and Figure 2).

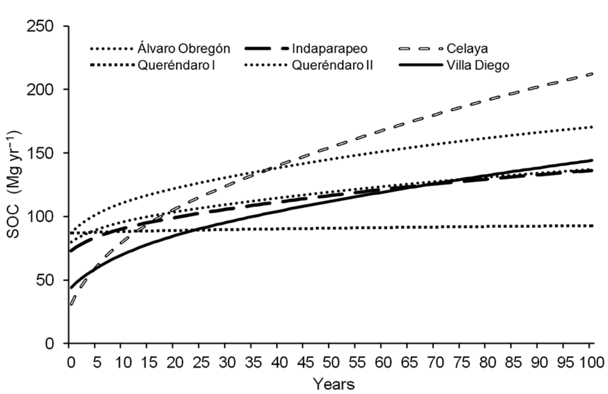

Figure 2 – Trends in SOC (Soil organic carbon) changes in vertisols cultivated under conservation tillage.

Conclusions

Values of measured SOC changes, when soil management is changed from traditional tillage to conservation tillage, in short-term experiments, were higher than those reported in the literature. The rates of SOC change simulated with RothC were evaluated where ET3 = SB + (0.18*TB) With the information on measured SOC and plant residues and the use of experimental data on crops and harvest residues, among others, it was possible to determine the rate, trend and direction of simulated SOC changes with the RothC over a period of more than 45 years.

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