Soil organic carbon accumulation in a Mollisol amended with mineral and organic fertilizers under conventional tillage and no-till systems

Nicoloso Rodrigo S.[1*], Amado Telmo J. C.[2], Rice Charles W.[3]
(1) EMBRAPA Swine and Poultry, 897000-000, Concórdia, SC, BR.
(2) Federal University of Santa Maria, 97105-900, Santa Maria, RS, BR.
(3) Kansas State University, 66502, Manhattan, KS, US.
*Corresponding author: rodrigo.nicoloso@embrapa.br

Abstract

Soils are critical to global C cycling being a source or sink to atmospheric CO_2 according its management. The conversion from conventional tillage (CT) to no-till (NT) system could promote the increase of SOC stocks. Extra C input in manure-amended soils could enhance the NT system efficiency on increasing SOC stocks. In order to address this hypothesis, a long-term experiment in a Mollisol from Kansas (US) including tillage systems and nitrogen sources was investigated over 15 years addressing temporal SOC dynamics. CT soils presented a lower SOC storage capacity than NT soils. Organic fertilization had limited effect over SOC stocks under CT. Under NT, raw manure did not promoted significant increase of C sequestration rates in relation to mineral fertilizer, while composted manure enhanced SOC accumulation, promoted C saturation of superficial soil layer and C translocation to subsurface layer.

Introduction

Soils are a key component in the global C cycle. Soil organic matter (1550 Pg C up to 1 m depth) contains about twice as much C than earth's atmosphere (780 Pg C) and up to three times more C than vegetation (500-650 Pg C) [1]. Agriculture can affect C exchange among these pools and be a source or sink to atmospheric CO_2 according to soil management. Conventional agriculture under intensive tillage could deplete soil organic carbon (SOC) stocks emitting CO_2 to the atmosphere with different intensities depending on climate and soil type [2]. However, adoption of no-tillage (NT) and better husbandry practices can recover SOC stocks [3,4]. Soils could sequester atmospheric CO_2 for up to 20 to 50 years according C input levels until reach a new SOC stocks equilibrium or saturation [5,6].

Many long-term experiments have consistently found a linear increase of SOC stocks in the actively managed soil zone (<30 cm) in response to increasing C inputs with larger C recovery in NT than CT soils [7,8]. However, manure amendment [4] and recalcitrant C sources (composted manure) could increase C humification rate, leading to a larger SOC accumulation in NT soils. In order to address this hypothesis, a long-term experiment in a Mollisol from central Kansas (USA) including contrasting tillage systems (CT and NT) was extensively investigated over 15 years to evaluate temporal SOC dynamics under increasing C input levels promoted by different N fertilization rates (0 and 168 kg N ha^{-1} yr^{-1}) and sources (mineral and organic).

Material and Methods

Experimental site and treatments description

This research was (based) carried out (on) in a long-term experiment established in 1990 at the North Farm of Kansas State University in Manhattan, KS (39º 12' 42" N, 96º 35' 39" W). The local average annual precipitation is 800 mm and the annual mean temperature is 11.4ºC. The soil was in this site is a moderately well-drained Kennebec silt loam (fine-silty, mixed, superactive mesic Cumulic Hapludoll). The experiment was arranged in a split-plot randomized blocks with four replications in plots with corn (*Zea mays* L.). The tillage systems investigated were the main plots and nitrogen sources were the sub-plots. The tillage systems were CT with chisel plow and offset disk pre-planting, and NT by planting directly through the crop residues with minimum soil disturbance. The N treatments were different sources: 168-kg N ha^{-1} as ammonium nitrate (MF), 168-kg N ha^{-1} as manure (OF), and a control (CO) without N amendment. Until 2001, the manure input was fresh and after 2002 the manure was composted.

C inputs

The aboveground C input by vegetation to the soil was calculated by quantifying the aboveground biomass production by each crop and considering a carbon content of 40%. The soil carbon input by manure amendment was estimated by the manure C/N ratio [9] considering its total nitrogen content.

Soil sampling and C stocks determination

Soil samples were taken in the 0-5, 5-15 and 15-30 cm soil layers using a 5 cm diameter soil probe in the 2nd, 5th, 9th, 12th, 13th, 14th, and 17th year of the experiment. Soil samples were air-dried, sieved (<2-mm), roots removed, and sub-samples were finely ground for C content determination by dry combustion in a C/N elemental analyzer (Flash EA 1112 Series, Thermo Scientific, Waltham, MA). The C stocks were calculated considering the soil bulk density determined of the collected soil cores. The C stocks through time evaluation were adjusted to the soil bulk density determined in 1990 for the comparison of equivalent soil masses [10].

Statistical analysis

Analysis of Variance was performed using SAS PROC MIXED [11] and the means were compared by the differences in LS means. Temporal SOC dynamics was evaluated by the significance of the determination coefficient (r^2) of the fitted equations using linear regression analysis or forward stepwise regression analysis performed by the software TableCurve 2D v5.01 [12]. The results were considered significantly different at $p<0.05$.

Results and Discussion

During the evaluated period, no increase in SOC stocks were noticed in CT CO and CT MF treatments in any of the investigated soil layers (Figure 1). There was a slight but not significant increase in SOC at 0-5 cm soil layer of the CT MF treatment (0.12 Mg ha^{-1} yr^{-1}, P= 0.11386). The SOC stocks increased in the 0-5 cm soil layer of the NT CO and NT MF treatments resulting in a significant carbon sequestration rate of 0.23 Mg ha^{-1} yr^{-1} (P=0.00639) and 0.32 Mg ha^{-1} yr^{-1} (P=0.00477), respectively. When taken in account the 0-30 cm soil layer the SOC increase rate was even higher (0.63 Mg ha^{-1} yr^{-1}, P=0.00831) in the NT MF treatment, yet no significant changes on SOC stocks were noticed in the cumulative soil layer for the NT CO treatment. The higher soil carbon sequestration rate in the 0-30 cm was due to increase of soil C in the 5-15 and 15-30 cm soil layers. In this treatment, the increase of SOC stocks in the 0-5 cm soil layer represented more than 50% of the total increase of the 0-30 cm soil layer. SOC increase rate verified on 0-30 cm soil layer of NT MF treatment is similar to the average C sequestration rate of 0.57±14 Mg ha^{-1} yr^{-1} promoted by the conversion of CT to NT verified in a global assessment of 276 long-term experiments [13].

Treatments CT OF and NT OF showed a distinct SOC accumulation pattern according to the kind of manure applied. On average, the composted manure (5.2 Mg ha^{-1} yr^{-1}) had twice the annual C input as fresh manure (2.5 Mg ha^{-1} yr^{-1}). In the first 10 years of fresh manure amendment, both CT OF and NT OF resulted in a linear SOC increase in both 0-5 and 0-30 cm soil layers. For these treatments, the soil C sequestration rates in the first 10 years were 0.48 and 0.91 Mg ha^{-1} yr^{-1} (P=0.04351 and P=0.00881), respectively in the surface 0-5 cm, and 1.33 and 0.72 Mg ha^{-1} yr^{-1} (P=0.01310 and P=0.00536), respectively in the cumulative 0-30 cm layer. The higher increase in CT OF in the cumulative layer was due to the SOC increase in the 5-15 cm soil layer with a rate of 0.63 Mg ha^{-1} yr^{-1} (P=0.00785), while the NT OF showed a slight but significant decrease of -0.11 Mg ha^{-1} yr^{-1} (P=0.01362) in this soil layer in the same period. The increase of SOC stocks at the 5-15 m soil layer in the CT OF treatment can be attributed to the physical redistribution of the SOC and the added manure-C with the chisel plow operation [14,15].

After 2002, the manure source was changed to composted manure. Despite the higher C input rates in this period, the SOC stocks in the CT OF treatment stabilized at 15.88 and 21.52 Mg ha^{-1} in the 0-5 and 5-15 cm soil layers, respectively. Apparently the soil under CT had reached a new steady state after increasing SOC content from 1.66 to 2.72% and 1.39 to 1.83% between 1992 and 2007 in the 0-5 and 5-15 cm soil layers, respectively. In the NT OF treatment, SOC in the 0-5 cm soil layer increased kinetically (P=0.02984) to 28.03 Mg ha^{-1}, while the 5-15 cm soil layer increased linearly (0.82 Mg C ha^{-1} year, P=0.02775) to 19.88 Mg C ha^{-1} between 2002 and 2007. The soil under NT apparently had reached a new equilibrium after an increasing SOC content from 1.58 to 4.61% between 1992 and 2007 just in the 0-0.05-m soil layer. The increase of SOC stocks in the underlying 5-15 cm soil layer, under undisturbed conditions, is an evidence of C translocation from the surface in NT OF treatment. In the cumulative 0-0.30 m soil layer, the SOC increase presented the same pattern of the superficial layer, either in CT OF or NT OF treatments due to the higher contribution of the 0-0.05-m soil layer to the soil carbon sequestration rates, since about 44 and 88% of the total SOC increase was promoted by the superficial soil layer in CT OF and NT OF treatments, respectively.

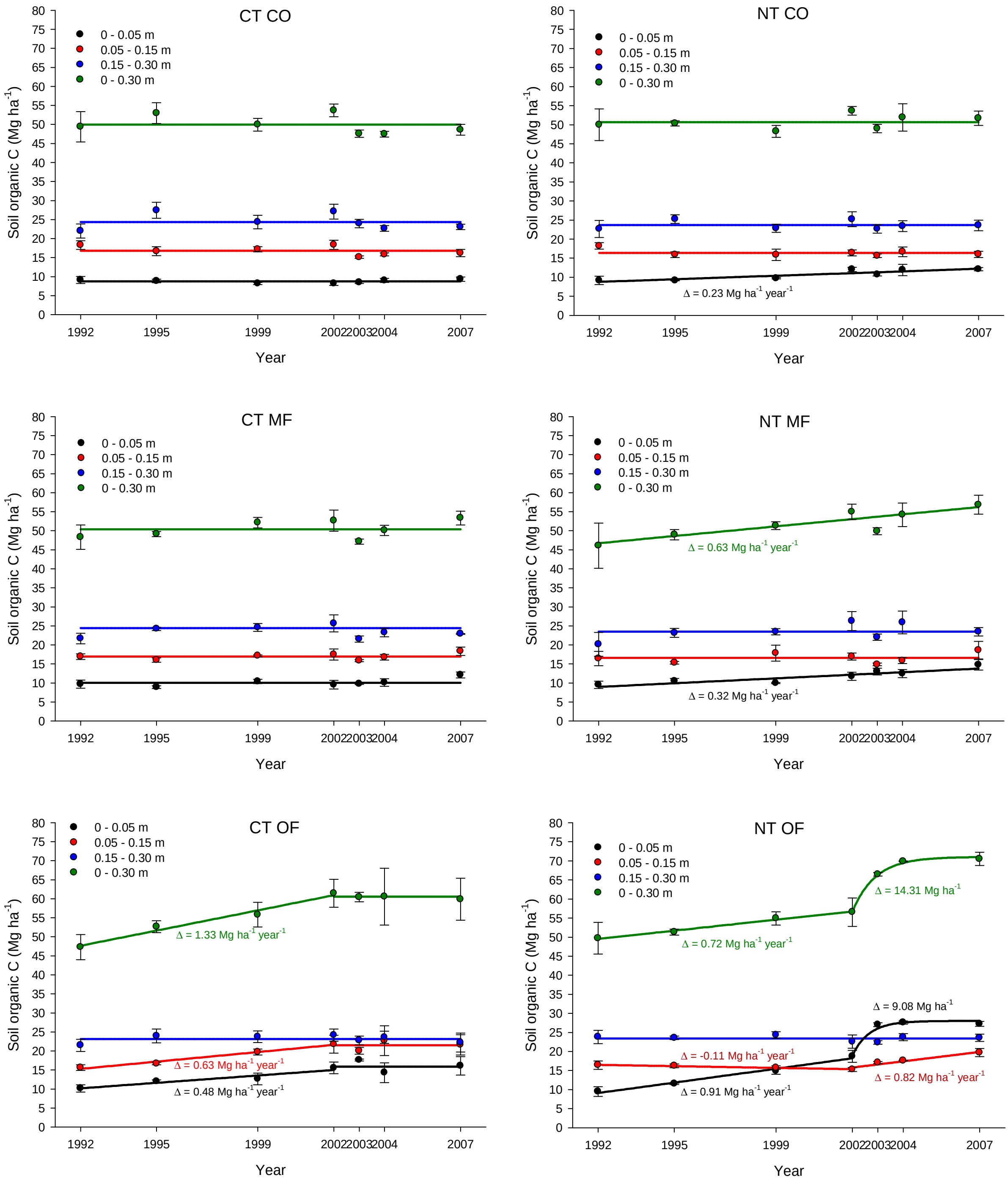

Figure 1. SOC temporal dynamics in the 0-0.05, 0.05-0.15, 0.15-0.30, and 0-0.30 m soil layer of a Mollisol as affected by (a) conventional tillage (CT), (b) no-tillage (NT), control without nitrogen (CO), mineral fertilizer (MF), and organic fertilizer (OF) management practices. The vertical bars are the mean's standard errors (n=4).

Conclusion and perspectives

Under normal C inputs (crop residues) with or without mineral N fertilization SOC stocks did not increase on the tilled system. The accumulation of SOC in the tilled soil (disturbed system) was only possible when additional C was imported into the system by fresh or composted manure, but even then soil C levels where below than no-till agroecossystem. NT resulted in soil C sequestration even with low C inputs as evidenced by the no N fertilizer (control) treatment. After 17 years of continuous NT system under regular C inputs (maize crop residues) no evidences were found supporting reduction of soil C sequestration rates neither a new SOC equilibrium level was achieved as could be expected. Under manure amendment, the NT soil presented a larger SOC storage capacity. SOC accumulation in sub-surface soil layers under SOC saturated topsoil layer indicate that NT potential for atmospheric CO_2 sequestration is larger than previously supposed. These results confirm the relevance of tillage effect on long-term SOC dynamics and manure amendment to increase soil's potential as atmospheric CO_2 sink. Further research is still needed to elucidate the mechanisms controlling soil C translocation when topsoil layers reach C saturation.

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