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Organic carbon stock changes and crop yield in a tropical sandy soil under rainfed grains-cotton farming systems in Bahia, Brazil[1]

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ABSTRACT

Most studies about soil organic carbon stock changes in the Cerrado (Brazilian Savanna) biome are either related to field data collected in clayey Ferralsols or different land uses, as if they were in equilibrium. This study aimed to evaluate the effect of tillage systems and crop sequences on the soil organic carbon stock and crop yield, in a sandy Ferralsol from Bahia, Brazil. The experimental design was randomized blocks, with four replicates. Soil samples were collected after five years of cotton, soybean and maize monocropping under heavy disk harrow and leveling harrow (conventional tillage), and of crop rotation of cotton, soybean and maize with green manure or cover crop (no-tillage). Additional samples were collected from a non-cultivated site (Neotropical Savanna, Cerrado *sensu stricto*). Soil conservation practices such as no-tillage and crop rotation with cover crop and green manure favored the soil organic carbon stock at the 0-40 cm layer, with the highest values reaching 36.03 Mg ha^{-1}. The accrued soil carbon stock under conventional tillage and monoculture of cotton, maize and soybean was lower than under no-tillage, which ranged from 30.9 to 54.9 %, with the soil organic carbon stock increasing at the annual rate of 2.36 Mg ha^{-1} during five years. The no-tillage, with the soybean-maize-cotton rotation, in combination with cover crop and green manure, increased the cotton and soybean yields, with a simultaneous organic carbon accumulation in the sandy soil.

KEYWORDS: *Gossypium hirsutum*, soybean, maize, no-tillage, soil carbon accrual.

RESUMO

Mudanças no estoque de carbono orgânico e produtividade de culturas em solo arenoso tropical sob sistemas de produção de grãos-algodão em sequeiro na Bahia, Brasil

A maioria dos estudos sobre mudanças no estoque de carbono orgânico do solo no bioma Cerrado está relacionada a dados coletados em Latossolos argilosos ou sob diferentes usos da terra, como se estivessem em equilíbrio. Objetivou-se avaliar os efeitos de tipos de preparo do solo e de sequência de culturas sobre o estoque de carbono orgânico do solo e a produtividade das culturas, em Latossolo arenoso, na Bahia. O delineamento experimental foi o de blocos casualizados, com quatro repetições. Amostras de solo foram coletadas após cinco anos de monocultivo de algodão, soja e milho e de uso de grade de discos pesada e grade niveladora (preparo convencional), e de rotação das culturas do algodão, soja e milho com adubo verde ou planta de cobertura (plantio direto). Amostras adicionais foram coletadas em área não cultivada (Cerrado *sensu stricto*). Práticas de conservação do solo como o não revolvimento e rotação de culturas com planta de cobertura e adubo verde favoreceram o estoque de carbono orgânico do solo na camada de 0-40 cm, com os maiores valores atingindo 36,03 Mg ha^{-1}. O acúmulo de carbono no solo sob preparo convencional e monocultivo de algodão, milho e soja foi menor do que sob plantio direto, que variou de 30,9 a 54,9 %, com o estoque no plantio direto aumentando à taxa anual de 2,36 Mg ha^{-1} durante cinco anos. O plantio direto, com a rotação soja-milho-algodão, combinada com planta de cobertura e adubo verde, aumentou a produtividade do algodão e da soja e acumulou carbono orgânico no solo arenoso.

PALAVRAS-CHAVE: *Gossypium hirsutum*, soja, milho, plantio direto, acúmulo de carbono no solo.

INTRODUCTION

It is long well-known that the soil organic matter and its carbon pool play an important role in both the physical (Madari et al. 2005) and chemical (Mendonça & Rowell 1996, Ramos et al. 2018) properties of soils under crop cultivation, in Brazil.

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Production systems that promote soil organic carbon accumulation are very important for a sustainable agricultural production (Gan et al. 2011). Conservation agricultural practices tend to balance the emission of CO_2, one of the greenhouse gases, by increasing the soil organic carbon (Paustian et al. 2016). However, only at the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, in December 2015, soil carbon and agriculture were on the global agenda for the first time in two decades (Lal 2016). There is momentum for global action on soil organic carbon to address multiple sustainability goals (Vermeulen et al. 2019). In this regard, Brazil's nationally determined contribution to reducing its greenhouse gas emissions in 2025 and 2030 includes soil carbon accumulation through the adoption of management practices of carbon farming, including restoration of degraded pastures, biological nitrogen fixation and no-tillage (NT) systems (UNFCCC 2020).

The Brazilian agriculture is characterized by a large number of farms using NT, which cover approximately 33.0 M ha, although not all areas show a permanent year-round soil cover provided by cover crop residues. In the western region of the Bahia State, where most of the soybean and cotton crops occur in the Cerrado (Brazilian Savanna) biome, the area under NT increased from 636,251 ha to 1.44 M ha between 2006 and 2017 (Fuentes-Llanillo et al. 2021).

The adoption of NT is of particular relevance in western Bahia, where vast areas are covered with sandy soils such as Neossolos Quartzarênicos (Arenosols) and light-textured, acidic Latossolos Vermelhos and Vermelho-Amarelos (Ferralsols) (Castro et al. 2010, Fontana et al. 2016). However, in the Cerrado biome, most studies about soil carbon stock changes at depth are either related to field data collected in clayey soils or different land uses, as if they were in equilibrium (Carvalho et al. 2010, Dionizio et al. 2020). Furthermore, there are discrepancies regarding the potential of NT and other conservation systems to increase the soil organic carbon (Powlson et al. 2014, Corbeels et al. 2016), and such discrepancies are associated with the variability of crop biomass production, input of carbon (Ogle et al. 2012) and N to the soil (Yue et al. 2016), as well as soil texture (Piccoli et al. 2016), in addition to the intrinsic environmental conditions, especially temperature and humidity (Lal et al. 2015, Piccoli et al. 2016), characteristics that are closely related to the soil organic matter dynamics.

Research is needed on how different soil managements such as NT, heavy harrowing, crop succession and crop rotation with cover crops/green manures affect the crop yield and carbon accumulation of sandy soils in the long term. Thus, this study aimed to evaluate tillage and crop systems on soil carbon stock changes at depth and yield performance of soybean, cotton and maize grown in the sandy soil of western Bahia State, Brazil.

MATERIAL AND METHODS

The research was carried out under rainfed conditions, in Luís Eduardo Magalhães, Bahia state, Brazil (12º05'36"S, 45º42'38"W and 753 m of altitude), between September 2012 and August 2017. The soil type is Ferralsol (FAO 2015) or Latossolo Vermelho-Amarelo, A moderado (Santos et al. 2018). The Köppen-Geiger classification is Aw (tropical Savanna climate with dry-winter characteristics), with average annual rainfall of 1,100 mm, concentrated from November to April.

Before 2012, the area was under cowpea (*Vigna unguiculata*), a staple food in the rural areas of Northeastern Brazil. The main soil characteristics before setting up the experiment in the area previously under cowpea cultivation are shown in Table 1. By the end of September 2012, the experimental area received 2,000 kg ha^{-1} of calcitic limestone, with a 90 % neutralizing value, and 700 kg ha^{-1} of phosphogypsum, followed by subsoiling at the 35-cm soil depth, disk plowing and light harrowing. Single superphosphate (400 kg ha^{-1}) was applied and disk harrowing was performed again for incorporation.

Six crop treatments were applied (Table 2), consisting of monocropping of *Gossypium hirsutum* (cotton - Gh), soybean (S) and maize (M), and crop rotations with *Urochloa ruziziensis* (ruzigrass - Rg) and *Sorghum bicolor* (sorghum - So) as cover crops and *Crotalaria ochroleuca* (crotalaria - Cr) as green manure: CTS, CTM and CTGh - conventional tillage (CT) of the soil and monoculture of soybean (S), maize (M) and cotton (Gh) followed by winter fallow, respectively; no-tillage (NT) system with soybean between November and March in rotation with maize mixed with ruzigrass (Rg) between November and July (NTSM); NT with first-crop soybean between

Table 1. Soil chemical characteristics and particle-size distribution at the 0-20 and 20-40 cm depth layers, before the beginning of the experiment.

Depth	$pH^{(1)}$	$P^{(2)}$	$K^{(3)}$	$Ca^{(4)}$	$Mg^{(5)}$	$H + Al^{(6)}$	$EB^{(7)}$	$CEC^{(8)}$	$BS^{(9)}$	$OC^{(10)}$	Clay	Silt	Sand	$BD^{(11)}$
cm		mg dm^{-3}			$mmol_c$ dm^{-3}				%	g kg^{-3}		g kg^{-1}		kg dm^{-3}
0-20	6.2	1.4	0.30	3.9	4.6	15.1	8.8	23.9	36.8	3.59	150	75	775	1.75
20-40	6.1	1.8	0.36	4.5	4.3	15.1	9.2	24.3	37.9	3.35	162	87	771	1.74

[1] pH in water (soil:water = 1:2.5); [2] available phosphorus and [3] exchangeable potassium, extracted by Mehlich-1; [4] exchangeable calcium and [5] magnesium, extracted by KCl 1 mol L^{-1}; [6] potential acidity, extracted by calcium acetate (0.5 mol L^{-1}; pH 7.0); [7] sum of exchangeable bases (EB) = Ca + Mg + K; [8] cation exchange capacity (CEC) = H + Al + EB; [9] base saturation (BS): percentage of the cation exchange capacity that is occupied by Ca^{2+}, Mg^{2+}, K^{+} = EB/CEC × 100; [10] soil organic matter by wet combustion followed by colorimetric determination; [11] soil bulk density by the volumetric ring method. The methodologies are described in Teixeira et al. (2017).

Table 2. Description of treatments with soil management systems, crop rotation and succession for maize, cotton and soybean production, in a sandy soil of the Bahia State, Brazil.

Treatments[(1)]	Crop season				
	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017
CTS	S/Fallow	S/Fallow	S/Fallow	S/Fallow	S/Fallow
CTM	M/Fallow	M/Fallow	M/Fallow	M/Fallow	M/Fallow
CTGh	Gh/Fallow	Gh/Fallow	Gh/Fallow	Gh/Fallow	Gh/Fallow
NTSM	S/Fallow	M + Rg	S/Fallow	M + Rg	S/Fallow
NTSMGh	S/Cr	M + Rg	Gh/Fallow	S/Cr	M + Rg
NTSGh	S/So	Gh/Fallow	S/So	Gh/Fallow	S/So

[(1)] CTS, CTM and CTGh: conventional tillage (CT) with soybean (CTS), maize (CTM) and cotton (CTGh), respectively; NTSM: no-tillage (NT) with soybean in rotation with maize plus ruzigrass (Rg); NTSMGh: NT with first-crop soybean and second-crop *Crotalaria ochroleuca* (Cr) in rotation with maize plus ruzigrass and cotton; NTSGh: NT with first-crop soybean and second-crop sorghum (So) in rotation with cotton. The NTSMGh treatment was designed so that in all the harvest seasons there were cotton, maize and soybean crops to compare their yields annually with those obtained in the CT and monoculture.

November and March and second-crop crotalaria (Cr) between March and July in rotation with maize mixed with ruzigrass between October and May, followed by cotton between December and July (NTSMGh); NT with first-crop soybean between November and March and second-crop sorghum (So) between March and July in rotation with cotton between December and July (NTSGh). The experimental design was randomized blocks, with four replicates. In addition, experimental measurements were made in a secondary non-cultivated area (Cerrado *sensu stricto*) adjacent to the experiment. Each experimental plot measured 400 m^2 (20 m x 20 m).

In the treatments with CT, the soil was prepared annually between the end of September and the beginning of October, after the beginning of the rainy season. Tillage consisted of one heavy disk harrow operation at a depth of approximately 15-20 cm, followed by a leveling harrow. Another leveling harrow operation was performed at one or two days before sowing soybean, maize or cotton.

Over five years, soybean and maize were sown with 50 cm spacing between rows, and 76 cm for the cotton crop. In each season, regardless of the treatment, just one commercial cultivar (the recommended one for the region), as well as recommended plant populations and fertilizations, were used, with identical row spacing and identical chemical management of pests, diseases and weeds, when needed. The plant populations per hectare ranged from 200,000 to 280,000, 55,000 to 65,000 and 100,000 to 120,000, respectively for soybean, maize and cotton, depending on the cultivar used in each season.

The soybean fertilization was performed in all years at the sowing time with 7 kg ha^{-1} of N, 87.5 kg ha^{-1} of P_2O_5, 56 kg ha^{-1} of K_2O, 45.5 kg ha^{-1} of Ca, 28 kg ha^{-1} of S and traces of micronutrients (B, Cu, Mn and Zn), as well as 60 kg ha^{-1} of K_2O as topdressing at 25 days after emergence (DAE). For maize and cotton, 20 kg ha^{-1} of N, 136 kg ha^{-1} of P_2O_5, 64 kg ha^{-1} of K_2O, 32 kg ha^{-1} of Ca, 20 kg ha^{-1} of S and traces of micronutrients (B, Cu, Mn and Zn) were applied at the sowing time, and the following topdressing fertilization schemes were used: two applications of 90 kg ha^{-1} of N and 50 kg ha^{-1} of K_2O for maize; and two applications of 76.5 kg ha^{-1} of N and 25.5 kg ha^{-1} of K_2O for cotton. Previously to sowing, the soybean seeds were inoculated with *Bradyrhizobium japonicum*.

In two NT treatments (NTSMGh and NTSGh), after the soybean harvest, the area was cultivated with *Crotalaria ochroleuca* or *Sorghum bicolor*. Two days before sowing these species, the volunteer soybean plants and weeds were desiccated with paraquat (400 g ha^{-1} of the active ingredient). *Urochloa ruziziensis* (ruzigrass) was sown in the same row as the maize, and the forage seeds were mixed and placed in the soil along with the maize-sowing fertilizer. The equivalent of 6 kg ha^{-1} of ruzigrass seeds with 100 % cultural value was used. During the maize cultivation, a subdose of nicosulfuron was used, corresponding to 6 g ha^{-1} of the active ingredient, at the beginning of the ruzigrass tillering. After the maize harvest, ruzigrass was grown separately, desiccated with glyphosate (1,400 g ha^{-1} of the active ingredient) at the end of July and 15 days before the sowing of the cotton. In the NT treatments, the ruzigrass that preceded maize, as well as sorghum and *C. ochroleuca*, were also desiccated with the same recommended dose of glyphosate in July of each year and at 15 days before sowing the commercial crop.

Cotton, soybean and maize were harvested at three random points, each one composed of 4 rows of 5 m in length. The data from the three points were summed, and the results were transformed into kg ha^{-1} of soybean, maize or seed cotton yields.

In August 2017, soil samples were collected at three depth intervals (0-10 cm, 11-20 cm and 21-40 cm). Analogous samples were taken at the non-cultivated Cerrado from three pits positioned 100 m apart. The soil organic carbon concentration was measured by wet combustion, followed by colorimetric determination (Cantarella et al. 2001), and expressed on a volumetric basis and converted to a gravimetric basis, according to the pedotransfer function described by Cordeiro et al. (2020), using the total sand concentration. The soil bulk density was determined using a volumetric ring, and the estimates of the soil organic carbon stocks in Mg ha^{-1} at the 0-20 and 0-40 cm depths were based on quantification in equivalent soil masses, as soil bulk density differed among the treatments (Sisti et al. 2004).

Analysis of variance was performed in R (R Development Core Team 2019) to assess the effects of the various sources of variation, i.e., tillage and crop rotation treatments on soil carbon concentrations and soil carbon stocks. The significance level was set at $p < 0.05$. Analysis of variance was also performed for the cotton, maize and soybean yields, considering only the treatments with CT under monocropping and the treatment with NT under cotton-soybean-maize rotation. The results obtained from 2014-2015 were considered because, in the NTSMGh, two prior harvests (2012-2013 and 2013-2014) had been cultivated with the previous crops, thus completing at least the first crop rotation and succession cycle for each production system. For the cotton, maize and soybean yields, the effect of the year was considered in the analysis of variance. Within each year and crop, the mean yield values were compared by the Student's t-test at 5 % of significance. Comparisons between cultivated and non-cultivated sites must be viewed with care, because the area under non-cultivated Cerrado was not part of the experimental design in 2012, and the sample collection was performed differently.

RESULTS AND DISCUSSION

After five years of soil cultivation under contrasting tillage and crop rotations, the soil organic carbon concentrations ranged from 2.96 g kg^{-3} at the 20-40 cm depth under conventional tillage with soybean to 5.91 g kg^{-3} at 0-10 cm under NTSMGh, and were similar or higher than those observed in soils under non-cultivated Cerrado (Table 3). The average soil organic carbon concentrations of the

Table 3. Soil organic carbon concentration (g kg^{-3}) of a sandy soil from the Bahia State, Brazil, under non-cultivated Cerrado and five years under different soil managements and crop systems.

Depth (cm)	CTS	CTM	CTGh	NTSM	NTSMGh	NTSGh	Cerrado
0-10	3.54 b (0.43)	3.66 b (0.50)	3.78 b (0.38)	5.38 ab (1.64)	5.91 a (0.44)	5.29 ab (0.68)	3.28 (0.17)
10-20	3.36 b (0.16)	3.16 b (0.18)	3.06 b (0.22)	3.86 ab (0.64)	4.62 a (0.42)	4.42 a (0.55)	3.01 (0.19)
20-40	2.96 b (0.13)	3.00 b (0.13)	3.11 b (0.45)	3.57 ab (0.41)	4.08 ab (0.54)	4.78 a (1.04)	2.68 (0.31)

CTS, CTM and CTGh: conventional tillage (CT) with soybean (CTS), maize (CTM) and cotton (CTGh), respectively; NTSM: no-tillage (NT) with soybean in rotation with maize plus ruzigrass; NTSMGh: NT with first-crop soybean and second-crop *Crotalaria ochroleuca* in rotation with maize plus ruzigrass and cotton; NTSGh: NT with first-crop soybean and second-crop sorghum in rotation with cotton; Cerrado: non-cultivated site. Means followed by the same letter in each row do not differ by the Tukey test at 5 % of significance. Values inside parentheses are the standard deviation of the means.

area under non-cultivated Cerrado are commonly observed in Cerrado *sensu stricto* (Tivet et al. 2012), a physiognomy largely present in this region (Dionizio et al. 2020). If compared to soils under non-cultivated Cerrado, slight changes or increases in the soil organic carbon concentrations in cultivated soils have been already reported for similar soils and the same region, and are likely owing to the improved fertility of cultivated soils and higher C input by crop plants (Bayer et al. 2006). In contrast, Silva et al. (1994), studying the same soil type and a real-farm situation, reported relative soil carbon losses of 80 % at 0-15 cm, after 5 years of soybean-fallow cultivation under CT. In our study, the slight changes in the soil organic carbon concentration were likely owing to conditions prevailing in the field plot experiments, in which the high rain erosivity combined with soil erodibility factors are largely reduced. The decrease of the soil organic carbon concentration at depth is caused by less amount of carbon input from plant residues, when compared to the top soil layer.

The soil tillage and crop systems had also a significant effect on the soil carbon stock changes at both the soil depths of 0-20 ($F = 9.03$; $p \leq 0.001$) and 0-40 cm ($F = 15.74$; $p \leq 0.001$). While the soil carbon stocks under tillage and monocropping showed average values between 24.81 and 25.36 Mg ha^{-1} at the 0-40 cm depth, the soils under no-tillage and crop rotation with cover crops, including green manure (*Crotalaria ochroleuca*), showed average values between 31.71 and 37.54 Mg ha^{-1} (Table 4). In the CT treatments, intensive heavy disk harrow operations coupled with poor cropping systems that included fallow periods and monoculture, combined with a light and poorly structured soil, the soil organic matter will hardly be higher than for the soil under Cerrado. On the other hand, no soil disturbance with high input of crop residues provided by the cover crop (ruzigrass) and green manure (*C. ochroleuca*), which are present in the NTSMGh treatment, are part of the good management practices, in convergence with the main principles of conservation agriculture and promoting soil carbon sequestration (Bayer & Dieckow 2020).

At the 0-40 cm depth, the soil carbon stocks in NT soils were 58, 80 and 87 % higher in the areas under NTSM, NTSMGh and NTSGh, respectively, in relation to the soil under non-cultivated Cerrado. Annually, the plant residue added by native Cerrado vegetation is approximately 3.8 Mg ha^{-1} (Castro & Kauffman 1998) and, under CT and NT, the amounts of crop residues added are 3.5 and 7.4 Mg ha^{-1} year^{-1}, respectively (Bogiani et al. 2020). The top 20-cm soil layer for both the CT and NT soils contained between 45.6 and 52 % of the total soil carbon stock measured at the 0-40 cm depth. At the 0-40 cm depth, the highest amount of soil carbon stock was in the NT soil with crop rotations containing green manure in combination with a cover crop (NTSMGh) and the system with first-crop soybean and second-crop sorghum in rotation with cotton (NTSGh), which were, respectively, 10.7 and 12.2 Mg ha^{-1} higher than the highest value observed in the CT treatments (25.36 Mg ha^{-1} under CTGh). At the 0-20 cm depth, the difference of the soil carbon stock between the highest amount under NT soil (NTSMGh) and the highest amount under CT soil (CTS) was 6.67 Mg ha^{-1}, while, at 0-40 cm, the average difference was 11.2 Mg ha^{-1}. The soil carbon stock was not significantly influenced by crop rotation in all the NT systems.

Table 4. Soil carbon stocks (Mg ha^{-1}) in sand soil from the Bahia State, Brazil, under non-cultivated Cerrado and after five years with different soil tillage and crop systems.

Treatments(1)	Depth (cm) 0-20	Depth (cm) 0-40	Accrued carbon(2) (%)
	Mg ha^{-1}		
CTS	12.07 b (0.69)	24.81 c (0.89)	2.4
CTM	12.03 b (1.71)	24.87 c (1.48)	2.6
CTGh	11.95 b (0.72)	25.36 bc (1.92)	4.7
NTSM	16.23 ab (3.89)	31.71 ab (4.10)	30.9
NTSMGh	18.74 a (1.77)	36.03 a (1.13)	48.7
NTSGh	17.12 a (1.71)	37.54 a (5.15)	54.9
Cerrado	9.31 (1.22)	20.06 (1.65)	-

(1) CTS, CTM and CTGh: conventional tillage (CT) with soybean (CTS), maize (CTM) and cotton (CTGh), respectively; NTSM: no-tillage (NT) with soybean in rotation with maize plus ruzigrass; NTSMGh: NT with first-crop soybean and second-crop *Crotalaria ochroleuca* in rotation with maize plus ruzigrass and cotton; NTSGh: NT with first-crop soybean and second-crop sorghum in rotation with cotton; Cerrado: non-cultivated site. (2) Accumulated soil carbon stock at 0-40 cm = [(soil carbon stock under cropping system - soil carbon stock before setting up the field experiment)/soil carbon stock before setting up the field experiment] × 100. Means followed by the same letter in each column do not differ by the Tukey test at 5 % of significance. Values inside parentheses are the standard deviation of the means.

Regarding the carbon stocks accrued to the soil as influenced by tillage and crop rotation management, and having the soil carbon stock under non-cultivated Cerrado as a reference, NT soils with a more diversified crop rotation or high-C input by crop residues, such as maize and ruzigrass, showed the highest soil carbon accumulation between 30.9 % under NTSM and 54.9 % under NTSGh. The results for accrued soil carbon under NT were lower than those found by Ferreira et al. (2021), in a similar soil type in the region (109 %), likely owing to a richer plant diversification in the rotation (including pearl millet and brachiaria with maize, soybean and cotton) than the crop rotation in the present study.

In 2012, at the beginning of the study, the estimated C stock in the soil at 0-40 cm was 24.23 Mg ha^{-1}, in an area under continuous tillage, for cowpea cultivation. Therefore, the soil cultivation under NT for five years was very effective in increasing the soil C stock, indicating that the NT system (NTSMGh), based on the cultivation of soybean, maize and cotton integrated with ruzigrass, due to the high C input, had a high potential to reverse the process of soil degradation and C decline, agreeing with the results reported by Sá et al. (2015). The NT with first-crop soybean and second-crop sorghum in rotation with cotton (NTSGh) also had a similar effect to the NTSMGh in increasing the soil C stock. This study shows that, in five years, the soil C stock in the area under NT increased by 11.8 Mg ha^{-1}, a value obtained from the difference between the final average soil C stock (36.03 Mg ha^{-1}) of the NTSMGh treatment and the initial C stock in the soil of the experiment (24.23 Mg ha^{-1}) at 0-40 cm. Despite the high annual rate of soil C accumulation in five years (2.36 Mg ha^{-1} $year^{-1}$ at the 0-40 cm depth), sandy soils are less structured, with a poor soil aggregation decreasing the physical protection of organic matter from decomposition (Freixo et al. 2002, Donagemma et al. 2016). Hence, the soil C may decrease fast if the soil management changes to intensive tillage with monocropping and fallow periods.

The seed cotton and soybean yields were significantly influenced by the treatment and year, and, for soybean, there was also a significant treatment and year interaction. The seed cotton yield was significantly higher in the NTSMGh than for CTGh (Table 5), and, in the 2015/2016 and 2016/2017 seasons, it was 27.3 (347 kg ha^{-1} fiber) and 22.4 % (336 kg ha^{-1} fiber) higher, respectively.

The soybean yield under NT, in a biannual rotation with maize and cotton, was 27.6 and 29.1 % higher in 2014/2015 and 2016/2017, respectively, than under CTS (Table 5). Taking the average for the last three years, the soybean yield under NT was 497 kg ha^{-1} higher than that of soybean under CTS. In the 2015/2016 harvest, the soybean yield under NT was 11 % lower than under CTS, a finding most likely related to the toxicity in soybean caused by the 2,4-D applied for the chemical control of cotton stalk regrowth from the previous harvest (2014/2015). According to Silva et al. (2011), soils with higher sand concentrations favor a greater residual effect of 2,4-D and, in the present study, the soybean was sown after the first rainfall, and there might not have been enough time for 2,4-D degradation in the NT soil.

The maize yield was statistically similar between NT and CT (Table 5), i.e., under NT, the maize intercropped with ruzigrass did not reduce the grain yield because the forage was appropriately managed with a subdose of nicosulfuron, so it did not compete with maize.

The greater cotton and soybean yields under NT are most likely related to the improvement of the production environment. According to Steiner et al. (2011), the soil organic carbon increase is associated with a better retention of soil moisture and a better soil structure, in addition to a greater cation retention, resulting in more sustainable agricultural production systems.

Table 5. Soybean, maize and seed cotton yields (kg ha^{-1}) in sandy soil under no-tillage and conventional tillage with monoculture.

Treatments[(1)]	Crop season				
	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017
	kg ha^{-1}				
CTS	S (2,737)	S (2,894)	S (2,418 b)	S (3,850 a)	S (3,418 b)
CTM	M (7,244)	M (9,061)	M (9,120 a)	M (8,731 a)	M (4,512 a)
CTGh	Gh (4,046)	Gh (4,014)	Gh (3,744 a)	Gh (3,179 b)	Gh (3,745 b)
	S (2,762)/Cr	M (9,111) + Rg	Gh (4,166 a)	S (3,426 b)/Cr	M (4,283 a) + Rg
NTSMGh	M (7,327) + Rg	Gh (4,514)	S (3,338 a)/Cr	M (8,648 a) + Rg	Gh (4,584 a)
	Gh (4,096)	S (3,673)/Cr	M (10,585 a) + Rg	Gh (4,046 a)	S (4,414 a)/Cr

[(1)] CTS, CTM and CTGh: conventional tillage (CT) with soybean (CTS), maize (CTM) and cotton (CTGh), respectively; NTSMGh: no-tillage with first-crop soybean and second-crop *Crotalaria ochroleuca* (Cr) in rotation with maize plus ruzigrass and cotton. Within each year (starting in 2014-2015) and crop, the means followed by the same letter in each column do not differ by the Student's t-test, at 5 % of significance.

The results of the present study indicate that the cotton crops grown under NT in sandy soils of the Cerrado region of Bahia, in addition to enabling yield gains, had a high potential for soil C storage, what would contribute to the Brazil's compliance with international agreements for mitigation of CO_2 emissions and reduction of greenhouse gases.

CONCLUSIONS

1. The soil conventional tillage and monoculture of soybean, maize and cotton, followed by winter fallow, are ineffective to increase the soil organic carbon stocks;
2. The soil organic carbon stock up to 40 cm of the soil profile in the area under no-tillage increased by 11.8 Mg ha^{-1}, in five years;
3. No-tillage cotton in rotation with soybean and maize, in combination with cover crop and green manure, increases both the cotton and soybean yields, with a simultaneous organic carbon accumulation under sandy soil.

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REFERENCES

BAYER, C.; DIECKOW, J. Lessons learnt from long-term no-till systems regarding soil management in humid tropical and subtropical regions. *In*: YASH, P. D.; DALAL, R. C.; MENZIES, N. W. (ed.). *No-till farming systems for sustainable agriculture*: challenges and opportunities. Cham: Springer, 2020. p. 437-457.

BAYER, C.; MARTIN-NETO, L.; MIELNICZUK, J.; PAVINATO, A.; DIECKOW, J. Carbon sequestration in two Brazilian Cerrado soils under no-till. *Soil &Tillage Research*, v. 86, n. 2, p. 237-245, 2006.

BOGIANI, J. C.; FERREIRA, A. C. de B.; BORIN, A. L. D. C.; SOFIATTI, V.; PERINA, F. J. *Sequestro de carbono em sistemas de produção de grãos e fibras em solo arenoso do Cerrado da Bahia*. Campinas: Embrapa Territorial, 2020. (Boletim de pesquisa e desenvolvimento, 34).

CANTARELLLA, H.; QUAGGIO, J. A.; RAIJ, B. V. Determinação da matéria orgânica. *In*: RAIJ, B. V.; ANDRADE, J. C. de; CANTARELLA, H.; QUAGGIO, J. A. (ed.). *Análise química para avaliação da fertilidade de solos tropicais*. Campinas: Instituto Agronômico, 2001. p. 173-180.

CARVALHO, J. L. N.; RAUCCI, G. S.; CERRI, C. E. P.; BERNOUX, M.; FEIGL, B. J.; WRUCK, F. J.; CERRI, C. C. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. *Soil & Tillage Research*, v. 110, n. 1, p. 175-186, 2010.

CASTRO, E. A. de; KAUFFMAN, J. B. Ecosystem structure in the Brazilian Cerrado: a vegetation gradient of aboveground biomass, root mass and consumption by fire. *Journal of Tropical Ecology*, v. 14, n. 3, p. 263-283, 1998.

CASTRO, K. B.; MARTINS, E. S.; GOMES, M. P.; REATTO, A.; LOPES, C. A.; PASSO, D. P.; LIMA, L. A. S.; CARDOSO, W. S.; CARVALHO JUNIOR, O. A.; GOMES, R. A. T. *Caracterização geomorfológica do município de Luís Eduardo Magalhães, oeste baiano, escala 1:100.000*. Planaltina, DF: Embrapa Cerrados, 2010. (Boletim de pesquisa, 288).

CORBEELS, M.; MARCHÃO, R. L.; SIQUEIRA, N. M.; FERREIRA, E. G.; MADARI, B. E.; SCOPEL, E.; BRITO, O. R. Evidence of limited carbon sequestration in soils under no-tillage systems in the Cerrado of Brazil. *Scientific Reports*, v. 6, e21450, 2016.

CORDEIRO, F. R.; CESÁRIO, F. V.; FONTANA, A.; ANJOS, L. H. C. dos; CANTO, A. C. B. do; TEIXEIRA, W. G. Pedotransfer functions: the role of soil chemical properties units conversion for soil classification. *Revista Brasileira de Ciência do Solo*, v. 44, e0190086, 2020.

DIONIZIO, E. A.; PIMENTA, F. M.; LIMA, L. B.; COSTA, M. H. Carbon stocks and dynamics of different land uses on the Cerrado agricultural frontier. *Plos One*, v. 15, n. 11, e0241637, 2020.

DONAGEMMA, G. K.; FREITAS, P. L. de; BALIEIRO, F. de C.; FONTANA, A.; SPERA, S. T.; LUMBRERAS, J. F.; VIANA, J. H. M.; ARAÚJO FILHO, J. C. de; SANTOS, F. C. dos; ALBUQUERQUE, M. R. de; MACEDO, M. C. M.; TEIXEIRA, P. C.; AMARAL, A. J.; BORTOLON, E.; BORTOLON, L. Characterization, agricultural potential, and perspectives for the management of light soils in Brazil. *Pesquisa Agropecuária Brasileira*, v. 51, n. 9, p. 1003-1020, 2016.

FERREIRA, A. de O.; SÁ, J. C. M.; LAL, R.; AMADO, T. J. C.; INAGAKI, T. M.; BRIEDIS, C.; TIVET, F. Can no-till restore soil organic carbon to levels under natural vegetation in a subtropical and tropical Typic Quartzipisamment? *Land Degradation & Development*, v. 32, n. 4, p. 1742-1750, 2021.

FONTANA, A.; TEIXEIRA, W. G.; BALIEIRO, F. D. C.; MOURA, T. P. A. de; MENEZES, A. R. de; SANTANA, C. I. Características e atributos de Latossolos sob diferentes usos na região oeste do estado da Bahia. *Pesquisa Agropecuária Brasileira*, v. 51, n. 9, p. 1457-1465, 2016.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). *International soil classification system for naming soils and creating legends for soil maps*. Rome: FAO, 2015. (World soil resources reports, 106).

FREIXO, A. A.; MACHADO, P. L. O. A.; SANTOS, H. P.; SILVA, C. A.; FADIGAS, F. S. Soil organic carbon and fractions of a Rhodic Ferralsol under the influence of tillage and crop rotation systems in Southern Brazil. *Soil & Tillage Research*, v. 64, n. 3-4, p. 221-230, 2002.

FUENTES-LLANILLO, R.; TELLES, T. S.; SOARES JUNIOR, D.; MELO, T. R. de; FRIEDRICH, T.; KASSAM, A. Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil & Tillage Research*, v. 208, e104877, 2021.

GAN, Y.; LIANG, C.; WANG, X.; MCCONKEY, B. Lowering carbon footprint of durum wheat by diversifying cropping systems. *Field Crops Research*, v. 122, n. 3, p. 199-206, 2011.

LAL, R. Beyond COP 21: potential and challenges of the "4 per thousand" initiative. *Journal of Soil and Water Conservation*, v. 71, n. 1, p. 20A-25A, 2016.

LAL, R.; NEGASSA, W.; LORENZ, K. Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, v. 15, n. 1, p. 79-86, 2015.

MADARI, B. E.; MACHADO, P. L. O. A.; TORRES, E.; ANDRADE, A. G. de; VALENCIA, L. I. O. No-tillage and crop rotation effects on soil aggregation and organic carbon in a Rhodic Ferralsol from southern Brazil. *Soil & Tillage Research*, v. 80, n. 1-2, p. 185-200, 2005.

MENDONÇA, E. S.; ROWELL, D. L. Mineral and organic fractions of two Oxisols and their influence on effective cation-exchange capacity. *Soil Science Society of America Journal*, v. 60, n. 6, p. 1888-1892, 1996.

OGLE, S. M.; SWAN, A.; PAUSTIAN, K. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture, Ecosystems & Environment*, v. 149, n. 1, p. 37-49, 2012.

PAUSTIAN, K.; LEHMANN, J.; OGLE, S.; REAY, D.; ROBERTSON, G. P.; SMITH, P. Climate-smart soils. *Nature*, v. 532, n. 7597, p. 49-57, 2016.

PICCOLI, I.; CHIARINI, F.; CARLETTI, P.; FURLAN, L.; LAZZARO, B.; NARDI, S.; BERTI, A.; SARTORI, L.; DALCONI, M. C.; MORARI, F. Disentangling the effects of conservation agriculture practices on the vertical distribution of soil organic carbon: evidence of poor carbon sequestration in north-eastern Italy. *Agriculture, Ecosystems & Environment*, v. 230, n. 1, p. 68-78, 2016.

POWLSON, D. S.; STIRLING, C. M.; JAT, M. L.; GERARD, B. G.; PALM, C. A.; SANCHEZ, P. A.; CASSMAN, K. G. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, v. 4, n. 8, p. 678-683, 2014.

R DEVELOPMENT CORE TEAM. *R*: a language and environment for statistical computing. 2019. Vienna: R Foundation for Statistical Computing. Available at: http://www.R-project.org. Access in: Feb. 2020.

RAMOS, F. T.; DORES, E. F. de C.; WEBER, O. L. dos S.; BEBER, D. C.; CAMPELO JUNIOR, J. H.; MAIA, J. C. de S. Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. *Journal of the Science of Food and Agriculture*, v. 98, n. 9, p. 3595-3602, 2018.

SÁ, J. C. M.; SÉGUY, L.; TIVET, F.; LAL, R.; BOUZINAC, S.; BORSZOWSKEI, P. R.; BRIEDIS, C.; SANTOS, J. B. dos; HARTMAN, D. da C.; BERTOLONI, C. G.; ROSA, J.; FRIEDRICH, T. Carbon depletion by plowing and its restoration by no-till cropping systems in Oxisols of subtropical and tropical agro-ecoregions in Brazil. *Land Degradation & Development*, v. 26, n. 6, p. 531-543, 2015.

SANTOS, H. G. dos; JACOMINE, P. K. T.; ANJOS, L. H. C. dos; OLIVEIRA, V. A. de; LUMBRERAS, J. F.; COELHO, M. R.; ALMEIRA, J. A. de; ARAÚJO FILHO, J. C. de; OLIVEIRA, J. B. de; CUNHA, T. J. F. (ed.). *Brazilian soil classification system*. 5. ed. Brasília, DF: Embrapa, 2018.

SILVA, F. M. L.; CAVALIERI, S. D.; SÃO JOSÉ, A. R.; ULLOA, S. M.; VELINI, E. D. Atividade residual de 2,4-D sobre a emergência de soja em solos com texturas distintas. *Revista Brasileira de Herbicidas*, v. 10, n. 1, p. 29-36, 2011.

SILVA, J. E. da; LEMAINSKI, J.; RESCK, D. V. S. Perdas de matéria orgânica e suas relações com a capacidade de troca catiônica em solos da região de Cerrados do oeste baiano. *Revista Brasileira de Ciência do Solo*, v. 18, n. 3, p. 541-547, 1994.

SISTI, C. P. J.; SANTOS, H. P.; KOHHANN, R.; ALVES, B. J. R.; URQUIAGA, D.; BODDEY, R. M. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. *Soil & Tillage Research*, v. 76, n. 1, p. 39-58, 2004.

STEINER, F.; PIVETTA, L. A.; CASTOLDI, G.; COSTA, M. S. de M.; COSTA, L. A. de M. Carbono orgânico e carbono residual do solo em sistema de plantio direto, submetido a diferentes manejos. *Revista Brasileira de Ciências Agrárias*, v. 6, n. 3, p. 401-408, 2011.

TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. *Manual de métodos de análises de solo*. 3. ed. Brasília, DF: Embrapa, 2017.

TIVET, F.; SÁ, J. C. M.; BORSZOWSKEI, P. R.; LETOURMY, P.; BRIEDIS, C.; FERREIRA, A. O.; SANTOS, J. B.; INAGAKI, T. I. Soil carbon inventory by wet oxidation and dry combustion methods: effects of land use, soil texture gradients, and sampling depth on the linear model of C-equivalent correction factor. *Soil Science Society of America Journal*, v. 76, n. 3, p. 1048-1059, 2012.

UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC). *Nationally determined contribution*: NDC registry. 2020. Available at: https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx. Access on: Feb. 9, 2021.

VERMEULEN, S.; BOSSIO, D.; LEHMANN, J.; LUU, P.; PAUSTIAN, K.; WEBB, C.; AUGÉ, F.; BACUDOO, I.; BAEDEKER, T.; HAVEMANN, T.; JONES, C.; KING, R.; REDDY, M.; SUNGA, I.; UNGER, M. V.; WARNKEN, M. A global agenda for collective action on soil carbon. *Nature Sustainability*, v. 2, n. 1, p. 2-4, 2019.

YUE, K.; PENG, Y.; PENG, C.; YANG, W.; PENG, X.; WU, F. Stimulation of terrestrial ecosystem carbon storage by nitrogen addition: a meta-analysis. *Scientific Reports*, v. 6, e19895, 2016.