

## Soil physical properties and soil organic carbon content in northeast Brazil: long-term tillage systems effects

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**ABSTRACT:** Concerns about the negative effects of agriculture on soil physical quality and soil organic carbon (SOC) pools have spurred on the adoption of conservation tillage systems in tropical regions. This study aimed to evaluate the long-term impacts (16<sup>th</sup> year) of conventional (CT), minimum (MT) and no-tillage (NT) practices and different cover crops (sunn hemp and a bean/millet sequence) on soil physical properties and SOC content of a corn cultivated Ultisol in the northeast of Brazil. Soil bulk density (Bd), soil penetration resistance (SPR), soil aggregation, and total aggregate-associated carbon (C) (4-2 mm) were evaluated. Tillage practices exerted strong control on soil physical properties and total aggregate-C content but were influenced by cover crop species. Minimum tillage presented the lowest Bd, irrespective of cover crop, while NT with bean/millet sequence resulted in the lowest SPR. However, as regards soil aggregation and total aggregate-C, the results indicated that there were no differences between MT and NT, with both systems presenting greater mean weight diameter (MWD) and total aggregate-C content than CT. Total aggregate-C content in the 0.00-0.05 m soil layer in conservation tillage was increased by the adoption of a bean/millet sequence. Increased mechanical disturbance through CT practices was harmful to Bd, soil aggregation and SOC accrual. Overall, more conservative tillage practices and the proper choice of cover crops might yield greater soil quality. Low intensity of soil disturbances due to the adoption of MT favors soil aggregation and the accrual of SOC in weakly structured soils through increases in contact between organic and mineral particles while not causing significant destruction of soil aggregates.

**Keywords:** no-till cropping systems, minimum-tillage, soil bulk density, mean weight diameter, total aggregate-associated carbon

## Introduction

Soil degradation is a recurrent problem in tropical countries that implies declining ecosystem services and soil quality. Soil physical degradation involves reduction of soil structure, leading to soil compaction, wind and water erosion and soil organic carbon (SOC) mineralization. Although certain classes of soil are more prone to degradation, for instance, Inceptisols and Ultisols (Carvalho et al., 2014), soil mismanagement and land misuse, *i.e.* indiscriminate plowing and negative SOC budgets may exacerbate soil quality decline (Lal, 2015). Ultisols cover *c.a.* 20 % of the land area of northeastern Brazil and, specifically in the region of the coastal tableland, are characterized by low natural fertility and cation exchange capacity in the upper horizons, along with hard setting behavior in subsurface soil horizons (cohesive horizons).

Positive effects on soil porosity (Gao et al., 2017), aggregate stability (Moraes et al., 2016) and soil organic matter (SOM) stocks (Sá et al., 2009) across a wide range of soil types and climates are attributable to conservation tillage systems. However, the beneficial influence of conservation tillage practices, such as no or reduced soil disturbance, cover cropping and residue retention on soil physical properties and SOM apparently rely on site-specific interactions, post-adoption period, climate

conditions, the properties of the former management system, and the choice of cover crop species (Derpsch et al., 2014; Hubbard et al., 2013). Nonetheless, most conservation tillage studies in Brazil have concentrated on Oxisols in the southern region (Moraes et al., 2016; Sá et al., 2009; Suzuki et al., 2013), while data to support the decision regarding the adoption of conservation tillage in northeastern Brazil are scarce.

The overarching goal of this work was to expand our knowledge of the impact of conservation agriculture on soil physical quality and SOC content in a particular data-scarce region in Brazil. To that end, we took advantage of a long-term experiment of sweet corn production in an Ultisol in the region of the coastal tableland in northeastern Brazil and analyzed soil bulk density (Bd), soil penetration resistance (SPR), soil aggregation and total aggregate-associated carbon (C) content in the 16<sup>th</sup> year of conventional (CT), minimum (MT) and no-tillage (NT) adoption combined with different cover crops.

## Materials and Methods

### Site description and experimental design

The study was carried out at an experimental site located in São Cristóvão, SE, Brazil (10°55'24" S; 37°11'57" W) at an altitude of approximately 25 m above sea level. The local climate is tropical (As), according to

Köppen's classification with wet winters and dry summers (Alvares et al., 2013). Mean annual temperature and precipitation have been, on average, 26.7 °C and 1,084 mm, respectively, over the last two decades. The soil was classified as a Typic Hapludult (Soil Survey Staff, 2014), weakly structured, with 790 g kg<sup>-1</sup> sand, 70 g kg<sup>-1</sup> clay and 140 g kg<sup>-1</sup> silt, and mineralogy dominated by quartz and kaolinite to a depth of 0.20 m. Ultisols from this region have for decades been exploited for sweet corn production by smallholder farmers. Corn is cultivated between one and three times a year at sites with or without irrigation, respectively, and tillage practices such as plowing and harrowing are commonly employed in this region.

The experiment had been annually repeated through 15 years. First, the experimental area was equally split into three plots. Next, each plot was divided into six experimental units (EU) (6 × 10 m), 1 × 10 m distant from each other.

Three tillage practices (CT, MT and NT) were laid out as whole plots. In each plot, the cover crops, sunn hemp (*Crotalaria juncea* L.) and a bean/millet (*Phaseolus vulgaris* L. / *Pennisetum glaucum* L.) sequence, were randomly distributed across the EU, with three replicates each. Conventional tillage consisted of moldboard plowed to a depth of 0.20 m followed by two harrowings down to the same depth to break the clods. Minimum tillage consisted of only two 0.20 m harrowing. Soil tillage practices were implemented twice a year, preceding cover crop and corn seeding. In NT treatments, seeds were sown directly without plowing or harrowing, and weeds chemically controlled with glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] and 2.4 D (2,4-dichlorophenoxyacetic acid).

Over the course of this experiment, cover crops were sown manually (0.50 × 0.20 m) each year between Jan and Mar and were cut ~ 75 days after seeding. Sunn hemp was cropped from the beginning of the experiment, while bean was cultivated for 12 years and then replaced by millet. Both cover crops received 27 kg ha<sup>-1</sup> N, 15 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> and 40 kg ha<sup>-1</sup> K<sub>2</sub>O at sowing.

Mechanical corn (*Zea mays* L.) sowing at 62,500 seeds ha<sup>-1</sup> (0.80 × 0.20 m) was carried out annually between Apr and June. Liming and mineral fertilization were applied according to recommendations by Sobral et al. (2007). Irrigation was applied through an overhead sprinkler system during cover crop and corn growth as needed based on rainfall events. After the sweet corn harvesting, the aboveground biomass was cut and disposed of on the soil surface.

### Soil sampling and laboratory measurements

Soil sampling was carried out in the 16<sup>th</sup> year of experiment cultivation, soon after sweet corn harvesting. Undisturbed soil samples were obtained from the center of the 0.00-0.10 and 0.10-0.20 m layers, using cores with a 0.04 m diameter and 0.05 m in height, to determine Bd and soil moisture content. Three cores were obtained

for each depth and replicate. Soil penetration resistance was measured using a digital penetrometer model and recorded at each 0.01 m increment down to a depth of 0.20 m. Soil penetration resistance at 0.00-0.10 and 0.10-0.20 m was calculated as the mean SPR measured at each soil depth. Ten SPR measurements were made per EU without manipulating the soil moisture content, *i.e.* under field conditions.

Subsequently, an additional undisturbed soil sample was randomly collected at each EU from a center point in the 0.00-0.05, 0.05-0.10 and 0.10-0.20 m soil layers, air-dried, and gently crushed to obtain 4 to 2 mm sized aggregates. For aggregate stability, a subsample of the air-dried aggregates (4-2 mm) was slowly rewetted by capillarity and then separated by wet-sieving as adapted from the Yoder method: 25 g were transferred to a set of sieves with 2, 1, 0.5, 0.205 and 0.106 mm apertures, and submerged in distilled water at room temperature for eight minutes at roughly 30 rpm. Each sample was analyzed in duplicate. Aggregate stability was measured by mean weight diameter (MWD), based on the proportion of total dry weight retained in each sieve and the mean diameter of each fraction size. To determine total aggregate-associated C content, a subsample of the same air-dried initial class 4-2 mm aggregate was sieved (< 2 mm) to determine SOC (Yeomans and Bremner, 1988). Thus, rather than SOC content from < 2 mm soil samples, we determined the total aggregate-associated C, *i.e.*, the total C content associated with the initial 4-2 mm aggregate-size class. This SOC fraction was used because it represents a fraction which is sensitive to organic fresh inputs and soil disturbances, and plays a critical role in the aggregation of sandy soils (Elliott, 1986; Six et al., 2004; Six and Paustian, 2014).

### Data analysis

Data normality was assessed by the Shapiro-Wilk test, and Box-Cox data transformation was carried out when the normality assumption was not met. Statistical analysis of the data (Bd, SPR, MWD and total aggregate-C content) was performed using a three-way repeated measure ANOVA procedure with tillage practices, cover crops and soil layer as independent factors. The independent factor interactions inside ANOVA were decomposed and means were compared by post-hoc Tukey's test ( $p < 0.05$ ). All statistical analyses were carried out using the Sisvar® program (version 5.6).

## Results

### Bulk density and soil penetration resistance

Cover crops had little or no effect on Bd and SPR (Table 1). Conversely, Bd was affected by tillage practices: Bd in both soil layers was lower in MT than in CT and NT, but there was no difference between CT and NT.

Soil penetration resistance in the 0.00-0.10 m soil layer did not differ between tillage practices in sunn

hemp plots; however, it should be considered that MT and NT had lower soil moisture content than CT (Table 1). In bean/millet plots, NT resulted in the lowest SPR in both soil layers. Cover crops influenced SPR in the 0.10-0.20 m soil layer, *i.e.* a lower SPR was observed on bean/millet than on sunn hemp plots under NT practices (Table 1). Conversely, cover crop species did not alter SPR in MT treatment; although, sunn hemp had a higher soil moisture content than bean/millet plots.

### Soil aggregation and total aggregate-associated carbon content

The tendency was for the tillage effects on MWD and total aggregate-C content to be limited to the uppermost soil layer (0.00-0.10 m) and to be dependent

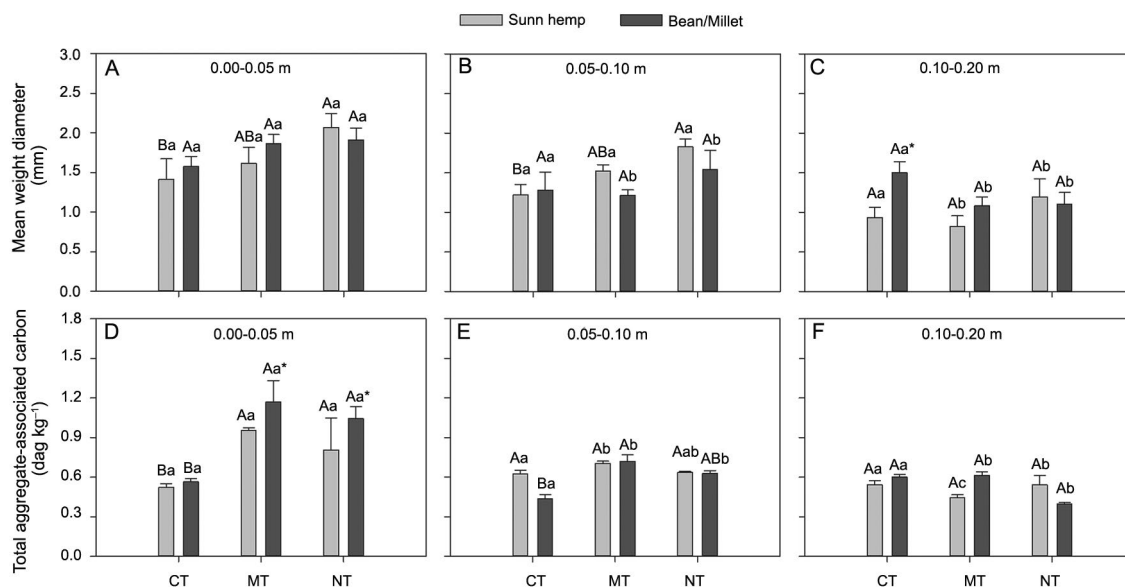
upon the cover crop species (Figure 1A, B, D and E). No-tillage resulted in higher MWD in the 0.00-0.10 m soil layer than CT in plots with sunn hemp but did not differ from MWD under MT (Figure 1A and B). There was no difference in MWD in the bean/millet plots caused by tillage practices (Figure 1A, B and C). Mean weight diameter decreased with depth in MT and NT, while no change was observed in CT (Figure 1A, B and C). In the 0.10-0.20 m soil layer of CT, bean/millet plot resulted in greater aggregate stability than sunn hemp (Figure 1C).

Adopting NT and MT resulted in total aggregate-C increase ( $\sim 80\%$ ) in the 0.00-0.05 m soil layer compared with CT (Figure 1D). Conversely, there was no difference in total aggregate-C content in the 0.05-0.10 m soil layer caused by tillage practices under sunn hemp

**Table 1** – Effects of tillage practices [conventional (CT), minimum (MT) and no-tillage (NT)] and cover crops on soil bulk density, soil penetration resistance and soil moisture.

Tillage	Cover crops	Bulk density (g cm <sup>-3</sup> )		Soil penetration resistance (MPa)		Soil moisture (g g <sup>-1</sup> )	
		0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m	0.00-0.10 m	0.10-0.20 m
CT	sunn hemp	1.63 ( $\pm$ 0.04) Aa	1.70 ( $\pm$ 0.05) Aa	1.88 ( $\pm$ 0.08) Ab	5.05 ( $\pm$ 0.24) Ba	0.09 ( $\pm$ 0.02) Aa	0.05 ( $\pm$ 0.01) Ab
	bean/millet	1.64 ( $\pm$ 0.05) Ab	1.77 ( $\pm$ 0.04) Aa	2.06 ( $\pm$ 0.09) ABb	5.13 ( $\pm$ 0.24) Ba	0.10 ( $\pm$ 0.02) Aa	0.06 ( $\pm$ 0.02) Ab
MT	sunn hemp	1.42 ( $\pm$ 0.02) Ba	1.47 ( $\pm$ 0.04) Ba	2.36 ( $\pm$ 0.11) Ab	6.27 ( $\pm$ 0.30) Aa	0.05 ( $\pm$ 0.00) Ba	<b>0.06</b> ( $\pm$ 0.02) Aa
	bean/millet	1.47 ( $\pm$ 0.02) Ba	1.48 ( $\pm$ 0.04) Ba	2.52 ( $\pm$ 0.07) Ab	6.55 ( $\pm$ 0.10) Aa	0.05 ( $\pm$ 0.01) Ba	0.03 ( $\pm$ 0.01) Bb
NT	sunn hemp	1.63 ( $\pm$ 0.07) Aa	1.67 ( $\pm$ 0.05) Aa	2.31 ( $\pm$ 0.13) Ab	<b>6.27</b> ( $\pm$ 0.48) Aa	0.05 ( $\pm$ 0.01) Ba	0.04 ( $\pm$ 0.01) Aa
	bean/millet	1.58 ( $\pm$ 0.03) ABb	1.71 ( $\pm$ 0.05) Aa	1.94 ( $\pm$ 0.04) Bb	4.07 ( $\pm$ 0.01) Ca	0.06 ( $\pm$ 0.02) Ba	0.03 ( $\pm$ 0.01) Bb

Means ( $\pm$  standard error) followed by different uppercase letter within the same cover crop and soil layer indicate differences between tillage practices; Different lowercase letters indicate difference between soil layers within the same tillage and cover crop, and bold number indicates difference between cover crops within the same tillage and soil layer. Differences were analyzed using Tukey's post-hoc test at  $p < 0.05$ .



**Figure 1** – Mean weight diameter of water-stable aggregates and total aggregate-associated carbon content in different soil layers [0.00-0.05 (A and D), 0.05-0.10 (B and E) and 0.10-0.20 m (C and F)] in the 16<sup>th</sup> year of conventional (CT), minimum (MT) and no-tillage (NT) practices adoption. Bars represent mean values and error bars one standard error. Bars with same uppercase letter within each soil layer and cover crop denote that tillage practices are not significantly different; same lowercase letter within a tillage practice and cover crop denotes that soil layers are not significantly different; asterisks indicate significant difference between cover crops within same tillage practice and soil layer. Differences were analyzed using Tukey's post-hoc test at  $p < 0.05$ .

treatments, while it was lower in CT ( $0.44 \text{ dag kg}^{-1}$ ) than in MT ( $0.72 \text{ dag kg}^{-1}$ ) when bean/millet was cropped (Figure 1E). The bean/millet sequence enhanced total aggregate-C content in the 0.00-0.05 m soil layer in MT and NT (Figure 1D). Similar to MWD, total aggregate-C content in conservation tillage (MT and NT) decreased with the soil depth (Figure 1D, E and F). Neither tillage practices nor cover crops induced changes in total aggregate-C content in the 0.10-0.20 m soil layer (Figure 1F).

## Discussion

Long-term experiments may provide more reliable assessments and minimize the varied Bd response (increase, decrease or null effects) to tillage practices observed across a wide range of soil types (Lozano et al., 2016; Obalum and Obi, 2010). Changes in Bd caused by tillage are frequently overshadowed by short-term alterations in SOM content (Heuscher et al., 2005), soil water regime and crop rooting (Strudley et al., 2008).

Annual plowing was expected to reduce soil compaction by the maintaining of a fairly loose structure or increasing soil porosity (Dam et al., 2005). However, CT adoption resulted in higher Bd compared with MT (Table 1). Probably, the enhancement of C oxidation stimulated by intensive soil disturbance during CT practices (Figure 1D and E) led to increased Bd values, as previously reported for low-C soils (Keller and Håkansson, 2010). However, our findings did not entirely align with the opposite assumption, *i.e.*, a reduced intensity in soil manipulation that leads to higher SOC content could also promote Bd reduction (Parihar et al., 2016). Herein, no differences in total aggregate-C content between NT and MT were observed, but NT presented increased Bd (Figure 1D, E and F; Table 1). Cumulative pressure from machinery traffic, particle resettlement and macroporosity reduction are frequently related to soil compaction in NT systems (Silva et al., 2012; Strudley et al., 2008). Thus, our findings indicated that SOC alone cannot alleviate soil compaction to a critical level, but low-intensity tillage practices may soften compaction while not reducing the accrual of SOC.

It is important to highlight that our experiment simulated one single corn cultivation per year. Increases in Bd may be intensified at sites where irrigation allows for more than one cultivation per year, which is a common practice in the region. Concerns about Bd increase are relevant because soil compaction has demonstrated negative impacts on corn nutrient uptake (Miransari et al., 2009), growth (Abu-Hamdeh, 2003) and yields (Gregorich et al., 2011). In particular, the soil studied here had already presented a natural hard-setting behavior which imposes physical restriction on plant roots exploring deeper horizons, and consequently, a greater Bd in the upper soil layer (0.20 m depth) could exacerbate such restriction. For instance, in the year studied, the corn ear index (total ear number/total

plant number) in NT was  $\sim 30\%$  lower than in MT (data not shown).

A distinct degree of water saturation can lead to differences in SPR values, whereby drier conditions would enhance soil strength, such as SPR (Busscher et al., 1997; Gao et al., 2012). In the present study, where tillage and cover crops were also influencing soil moisture and SPR (Table 1), this relationship, however, was not straightforward. No-tillage in combination with bean/millet sequence showed the lowest SPR in the 0.20 m depth even under the driest soil moisture condition compared to CT or NT/sunn hemp treatments (Table 1). Biopores produced by plant roots and soil fauna are particularly important in undisturbed soils (Angers and Caron, 1998) where their preservation creates a network of channels whereby subsequent crop roots easily propagate (Suzuki et al., 2013), hindering possible negative alterations in Bd. Thus, the deeper and dense root system of millet combined with the probable preserved biopores from beans compared with fewer roots of sunn hemp taproot system (Calonego et al., 2017) seem to offer an effective solution to reducing the soil physical constraints to plant growth in Ultisols under the NT system.

The lack of soil disturbance and cover cropping have been related to mechanisms of water-stable aggregates formation, and assume greater importance in soils with low clay content and kaolinite predominance (Six et al., 2002b). Moreover, the slow macroaggregate turnover and its preservation in NT systems foster microaggregate formation within macroaggregates which is, in turn, effective for avoiding SOC oxidation (Dungait et al., 2012; Six et al., 2000a). In fact, in the present study, increased MWD at the 0.10 m depth was observed in NT systems compared with CT, but MWD did not differ between NT and MT (Figure 1A and B). Meanwhile, the total aggregate-C content in the 0.10 m depth found in NT and MT was higher than in CT, with a greater difference between tillage practices attributable to the adoption of the bean/millet sequence (Figure 1D and E).

It is intriguing that the adoption of harrowing in the 0.20 m depth in MT operations did not reduce aggregate stability compared with NT. The closer contact between cover crop residues and the soil microbial population in MT probably enhanced plant biomass decomposition and increased the particulate organic matter content (Dungait et al., 2012). Particulate organic matter plays a key role in aggregate formation, providing a binding agent for the formation of microaggregates (Beare et al., 1994). Furthermore, the low intensity of soil disturbance, *i.e.* only harrowing, might have promoted a stabilizing effect of clay particles on SOC (Six et al., 2002b). Thus, the feedback mechanism between mineral-and-organic particle contact, the accrual of SOC and soil aggregation (Beare et al., 1994; Six et al., 2000b) ensured the findings in the MT system. Conversely, a more thorough soil disturbance and incorporation of cover crop



residues due to CT operations led to a decrease in total aggregate-C content in the uppermost soil layer (Figure 1D and E) but did not affect it nor the MWD in deeper soil layers (Figures 1C and F). Therefore, the intensity of soil disturbance exerts a strong effect on soil aggregation and the accrual of SOC of weakly structured soils, but its influence is greater on surface layers.

Combining bean with millet as cover crops showed remarkable potential for increasing total aggregate-C in the 0.00-0.05 m soil layer, when associated with conservation tillage practices (Figure 1D), and for increasing MWD in deeper soil layers under CT (Figure 1C). The sunn hemp crop-based rotation has the disadvantage of a lower number of species which could have led to lower soil microbial diversity and thus reduced SOC (McDaniel et al., 2014). Furthermore, a faster decomposability of their residues due to its lower C/N ratio (Berg, 2014) might also be a disadvantage in a sandy, warm, and irrigated environment which probably resulted in lower aggregate stability and total aggregate-C content (Chivenge et al., 2011). Within the framework of agricultural production and the modest capacity for long-term SOC storage of sandy soils (Chivenge et al., 2007), even a slight SOC increment may positively influence sweet corn productivity (Oliveira et al., 2017) and maintain soil quality under the climate and soil conditions studied.

## Conclusions

The results provided here support the ideas behind conservation tillage systems, *i.e.* their benefits for soil quality. Compared with CT, the positive effects of conservation tillage systems on the accrual of SOC and soil aggregation are concentrated in the upper 0.00-0.10 m soil layer, while on soil Bd and SPR they extend to deeper layers (0.10-0.20 m). The bean/millet sequence performed better in terms of improving soil quality than sunn hemp. These results suggest that the beneficial effects of conservation tillage on soil physical properties and the accrual of SOC are reliant on the proper choice of cover crop species. The low intensity of soil disturbance caused by the adoption of MT may not be harmful to soil aggregation and SOC, while avoiding Bd increase. Thereby, MT assumes greater importance in long-term improvement of soil functioning and prevention of soil degradation of weakly structured Ultisols on the coastal tableland in northeastern Brazil.

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## Authors' Contributions

Conceptualization: Pedrotti, A. Data acquisition: Oliveira, F.C.C.; Souza, J.L.S.; Vieira, M.E.O. Data analysis: Oliveira, F.C.C.; Ferreira, G.W.D. Design of methodology: Oliveira, F.C.C.; Ferreira, G.W.D. Writing and editing: Oliveira, F.C.C.; Ferreira, G.W.D.; Souza, J.L.S.; Vieira, M.E.O.; Pedrotti, A.

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