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Effect of Conservation Management on Oxisol in a Sugarcane Area Under a Pre-Sprouted Seedling System

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Abstract: Conservation soil management, such as no-tillage and Rip Strip®, can be developed as an alternative to degradation processes such as compaction. This study aimed to compare conventional and conservation soil tillage regarding their soil physical attributes, root system, and stalk yield for two years. The experiment was conducted on the premises of Fazenda Cresciúma in an area of Typic Eutrudox in the municipality of Jardinópolis, state of São Paulo, Brazil, with an experimental design in random blocks. The treatments evaluated for the transplanted sugarcane were as follows: CT—conventional tillage with disk harrow; CTS—conventional tillage with disk harrow and subsoiling; MT—minimum tillage with Rip Strip®; NT—no-tillage. The variables evaluated were dry root mass, soil bulk density (Bd), total porosity (TP), and stalk yield for sugarcane plant and first ratoon harvest. The results allowed us to observe that CT was the system that most reduced the TP (varying 0.44–0.47 m^3 m^{-3}), while MT was the one that presented fewer changes (TP varying 0.47–0.51 m^3 m^{-3}). NT obtained the highest stalk yield (123 Mg ha^{-1}) in the sugarcane plant cycle and greater amounts of roots in depths below 0.80 m. Conservation tillage by Rip Strip® proved to be a viable system for use in sugarcane because it provides greater dry root mass on the surface and maintenance of physical attributes compared to conventional tillage.

Keywords: Rip Strip; strip-till; soil compaction; mixed linear models

Citation: Oliveira, I.N.d.; Souza, Z.M.d.; Bolonhezi, D.; Tavares, R.L.M.; Lima, R.P.d.; Silva, R.B.d.; Araújo, F.S.; Lovera, L.H.; Lima, E.d.S.L. Effect of Conservation Management on Oxisol in a Sugarcane Area Under a Pre-Sprouted Seedling System. *Agriculture* **2024**, *14*, 1965. https://doi.org/10.3390/agriculture14111965

Academic Editor: Xiaoliang Qin

Received: 9 October 2024
Revised: 24 October 2024
Accepted: 30 October 2024
Published: 1 November 2024

1. Introduction

Sugarcane stands out in the Brazilian and international scenario for its high ethanol production capacity, being a sustainable alternative to the use of fossil fuels [1]. Brazil, as the world's largest producer, has a planted area of 9.8 million hectares, estimated for the 2021 harvest, and both sugar and ethanol can be produced [2]. Despite the crop's great significance, stalk yield stagnation has been observed over the years at approximately 75 Mg ha^{-1} [2].

Typically, the sugarcane cycle lasts between 5 and 7 years and is divided into two main phases: plant cane and ratoon cane. Plant cane is the first cycle after the seedlings are planted. During this period, the plant develops its root system and establishes itself in the field.

Ratoon cane is the regrowth of the cut plant, and with each subsequent cut, the cane is said to enter a new ratoon cycle. Sugarcane is a semi-perennial crop, meaning it can be harvested several times before needing to be replanted, which provides continuous productivity for several years. However, sugarcane productivity tends to decrease with each new ratoon cycle due to soil depletion and the accumulation of pests and diseases.

Another reason for the stagnation in sugarcane yield is associated with highly compacted soils caused mainly by tillage operations and machine traffic [3], with machines becoming increasingly larger and heavier, especially at harvesting [4].

Such soil compaction causes several problems for producers and for the sustainability of the production system, such as increased soil bulk density [5], reduced water availability quantified by optimal water interval [6], and increased mechanical resistance of the soil to penetration [7]. Thus, it has become necessary to think about new strategies of soil management, including conservation management, based mainly on minimum soil tillage and permanent cover on the soil surface. By reducing soil tillage, these crop management systems provide benefits such as increased crop yield, despite an apparent increase in soil bulk density [8].

The use of conservation systems results in the preservation of soil structural quality compared to conventional tillage, regardless of soil texture [9]. In addition, it also improves the chemical attributes of the soil, an important factor for crop growth and yield [10]. The no-tillage system traditionally brings long-term benefits [11], as it recommends permanent vegetation cover, minimal soil disturbance, and crop diversification; therefore, it is important to evaluate these tillage systems over time in order to quantify their effects throughout the cycles.

However, for many agricultural crops, no-tillage is not yet a consolidated practice, as is the case with sugarcane cultivation, where the soil is disturbed during crop renewal (after approximately 5–7 years of cultivation). Such soil disturbance aims to eliminate remains of ratoon crops in the soil, decompact it, correct acidity, and improve fertility.

In sugarcane cultivation, there is a continuous effort to adapt the implements already used in other crops in order to reduce product development costs. One of these implements is Rip Strip®, a soil tillage machine designed for peanut crops, which tills in just one pass with the straw still on the soil surface [12]. Among the advantages of Rip Strip® is soil management without the need to remove straw from the surface, increasing soil protection. In addition, two operations are performed with a single piece of equipment, thus saving fuel and time.

Rip Strip® was developed by Kelley Manufacturing Co. (KMC) (Tifton, GA, USA) to support conservation management in peanut crops in the United States. It is still not widely used in sugarcane cultivation, being an innovation for this crop. Since peanuts are commonly used as a cover crop for sugarcane, the use of this equipment can bring benefits to producers when used in both crops.

In the study by [13], in which pre-sprouted sugarcane seedlings were planted in soil conservation management systems, it was found that minimum cultivation with Rip Strip® provided a reduction in the soil's resistance to penetration, with average values in the row and between rows, even in months with greater rainfall, benefiting the physical attributes of the soil, such as microporosity, macroporosity, total porosity, and soil density in the surface layers (0.00–0.05 and 0.05–0.10 m). Nevertheless, the use of minimum localized tillage (planting row) in sugarcane showed equal results to no-tillage for yield in the first ratoon cycle and superior results to conventional tillage using equipment adapted for the crop [14].

Thus, there is still much to study about soil management methods for sugarcane cultivation in Brazil in order to increase its yield, which is the main focus of producers, in addition to finding more sustainable ways of planting the crop. Therefore, this study aimed to compare conventional (disk harrow operation and subsoiling) and conservation (no-tillage and minimum tillage with Rip Strip®) management systems regarding their soil physical attributes, root system, and stalk yield for two years.

2. Materials and Methods

2.1. Experiment Location and Area History

The experiment was developed in the premises of Fazenda Cresciúma in the municipality of Jardinópolis, state of São Paulo, Brazil, at the following geographical coordinates: 20°57′59″ S and 47°49′25″ W, 540 m above sea level, with the terrain ranging from flat to gently undulating (Figure 1).

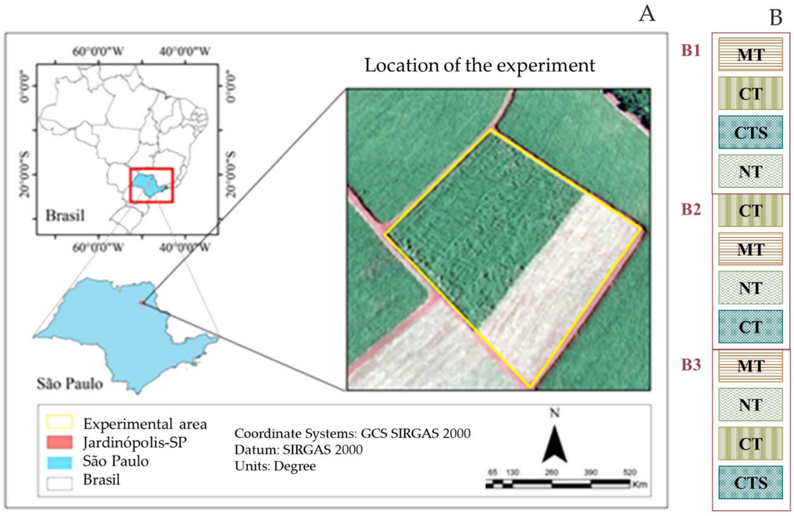

Figure 1. Location of the sugarcane experimental area in the municipality of Jardinópolis, state of São Paulo, Brazil. (**A**) = sketch of the experimental area; (**B**) = arrangement of treatments in the experimental area. CT = sugarcane transplanted with conventional tillage with disk harrow; CTS = sugarcane transplanted with conventional tillage with disk harrow and subsoiling; MT = sugarcane transplanted with minimum tillage with Rip Strip®; NT = sugarcane transplanted with no-tillage.

The climate of the region is humid subtropical (Cwa according to Köppen's classification), with minimum and maximum temperatures of 19 and 25 °C, respectively (Figure 2) and an annual precipitation around 1427 mm [15]. The soil in the area was classified as Typic Eutrudox, according to the Brazilian Soil Classification System [SBCS] [16], or as Oxisol, according to the Soil Taxonomy System [17].

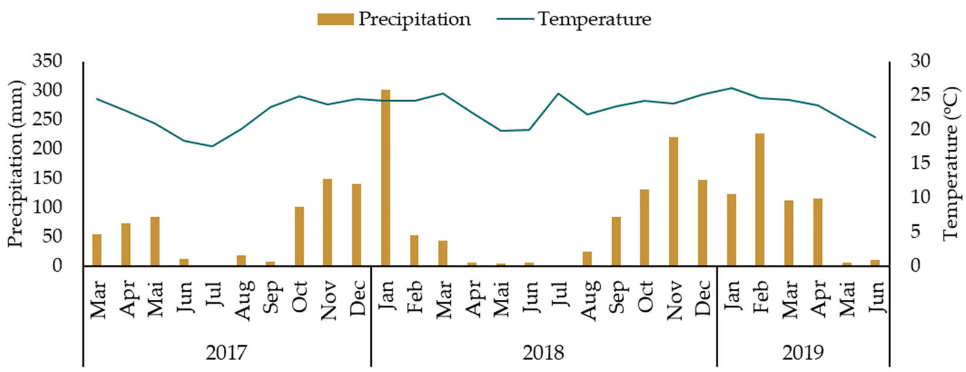

Figure 2. Precipitation (mm) and maximum and minimum temperatures in the municipality of Jardinópolis, state of São Paulo, Brazil.

The experimental area is a three-hectare sugarcane field with a history of seven mechanized cuts and no burning. Prior to the planting of sugarcane, the area was cultivated with soybeans in direct sowing on straw. Soybean sowing was carried out on 11 November 2016 using a Jumil Exacta 7090 pd seeder with nine rows pulled by a Valtra® BH 180 tractor equipped with GPS, whose static mass is 9.92 Mg, with maximum stresses of 130 kPa on the front wheels and 157 kPa on the rear wheelset [4]. The population of soybean plants used was 320 thousand ha^{-1} of the Syngenta 1366c variety, with an approximate cycle of 115–120 days. The land had 14.7 Mg ha^{-1} of straw dry matter at the time of the direct sowing of soybeans. This straw originated from sugarcane with a history of 7 mechanized cuts and without burning. The soybeans were dried naturally and harvested at the R8 stage (final stage of development, or "full maturity"), and then soil management treatments were installed.

Soil correctives were applied at a dose of 1.0 Mg ha^{-1} of agricultural gypsum and 2.0 Mg ha^{-1} of dolomitic lime (PRNT 85%) on the straw of raw and freshly harvested soybean. The treatments using conventional tillage required a Baldan® disk harrow with fourteen 32″ disks and a Stara subsoiler with five rods regulated to the depth of 0.40 m, driven by a Valtra® a144 tractor.

The sugarcane transplanting took place on 27 and 28 March 2017 with a transplanter machine. Fertilization consisted of the supply of 30 kg ha^{-1} of N, 150 kg ha^{-1} of P_2O_5, and 50 kg ha^{-1} of K_2O by the application of 500 kg ha^{-1} of the 6–30-10 formulation. At the time, 0.5 L ha^{-1} of the fungicide Comet (pyraclostrobin) was applied, in addition to the insecticide Fipronil (0.25 kg ha^{-1}). The same transplanter was used in the four soil management treatments. The machine consists of two plows, a fertilizer reservoir, a spray tank for insecticides, support for pre-sprouted seedling trays, and a carousel-type seedling distribution system.

The transplanter machine was regulated to distribute seedlings every 0.60 m. The sugarcane variety used was CTC 9003 (AGmusa System). Since the Rip Strip® system had been implemented 15 days earlier, a GPS-equipped tractor was used to randomize treatments in each block. Therefore, it was necessary to use a tractor with an extended gauge of 3.0 m to perform the transplanting in the Rip Strip® tillage, thus avoiding traffic with a tractor wheelset in the previously prepared groove.

Rip Strip® tillage preparation involves using adjustable subsoiler rods, set between 0.76 and 1.02 m, to cut the remains of the previous culture and perform subsoiling. The cutting disk, with a diameter of 60.96 cm, is used to cut straw while toothed disks remove it, forming a 20 cm wide strip that can be displaced up to 45°. Rip Strip® equipment from KMC, Kelley Manufacturing Co, was used for strip-tillage. The Rip Strip equipment was developed for peanuts and originally used for four rows spaced 0.90 m apart. In each row, there is a coulter mounted in front of an in-row subsoiler regulated to a depth of 0.45 m, followed by fluted coulters and a rolling crumble basket to prepare a seedbed approximately 0.40 m wide. For sugarcane, it was necessary to remove two rows to accommodate the 1.5 m row spacing.

In the NT system, the straw was maintained on the soil surface. Figure 3 presents a timeline of what happened in the area with the evaluated moments of collection.

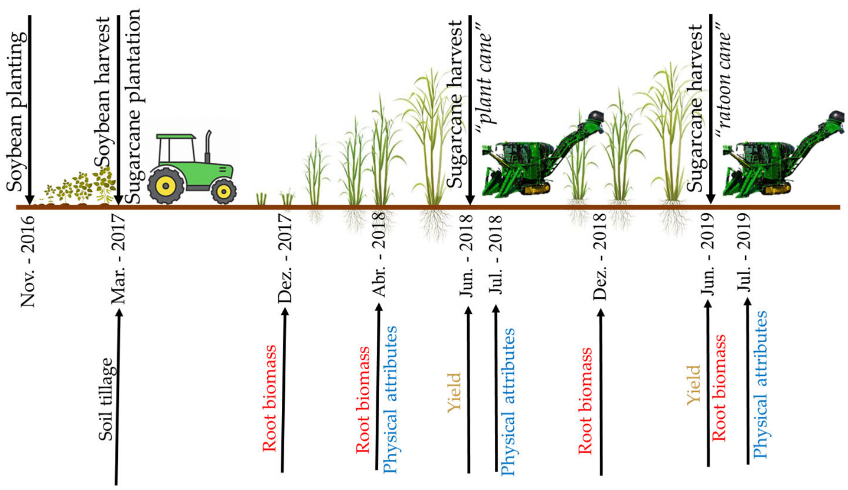

Figure 3. Chronology of the execution of the experiment in the study area of Fazenda Cresciúma, in the municipality of Jardinópolis, state of São Paulo, Brazil. Adapted from [18].

2.2. Characterization

The clay fraction was used to quantify goethite (Gt) and hematite (Hm) by XRD powder. Previously, oxides were concentrated by boiling in NaOH 5M, using the method by [19] as modified by [20] (Table 1).

Table 1. The characterization of the experimental area of sugarcane after the soybean harvest in March 2017, located in the municipality of Jardinópolis, state of São Paulo, Brazil.

Depth	Bd	DC	MiP	MaP	TP	TS	Clay	Silt
(m)	(Mg m^{-3})	(%)	------ (m^3 m^{-3}) -----			---------- (g kg^{-1}) --------		
0.00–0.05	1.29	88	0.35	0.09	0.44	218	503	278
0.05–0.10	1.25	85	0.34	0.12	0.46	219	533	247
0.10–0.20	1.18	81	0.34	0.17	0.51	217	535	247
0.20–0.40	1.27	87	0.33	0.15	0.48	210	545	244
0.40–0.60	1.28	88	0.34	0.13	0.48	216	523	261

Depth	Fe_2O_3	Fed	Feo	Kt	Gb	Gt	Hm	Gb/(Gb + Kt)	Kt/(Kt + Gb)
(m)				g kg^{-1}					
0.00–0.05	138	69	3	356	644	45	54.3	64.4	0.26
0.05–0.10	171.7	70.7	2.9	360	640	47.3	54.3	64	0.26
0.10–0.20	163.3	68.3	3.4	357.3	642.7	44.3	53	64.27	0.26
0.20–0.40	134	69.3	3.3	358.3	641.7	50.7	48.7	64.17	0.26
0.40–0.60	134	66.7	3.7	322.3	677.7	38.7	55.3	67.77	0.23

Bd = soil bulk density; DC: degree of compaction or relative density DC = (Bd/Bdmax) × 100; MiP = microporosity; MaP = macroporosity; TP = total porosity; TS = total sand; Fe_2O_3 = total iron; Fed = iron dithionite; Feo = iron oxalate; Kt = kaolinite; Gb = gibbsite; Gt = goethite; Hm = hematite.

Measurements were carried out with a Mini-Flex Rigaku II spectrometer (20 mA, 30 kV) using Cu Kα radiation and a scan rate of 1° 2θ min^{-1}. The Hm/(Gt + Hm) ratio was estimated by comparing the areas under the peaks for the two oxides with their proportions in mixed Gt—Hm patterns.

The Hm and Gt in the clay fraction were calculated from the difference between free iron (Fed) and low crystallinity (Feo) and the Kt/(Kt + Gb) ratio [20]. Kaolinite and gibbsite are mineralogical components that exert greater influence on the physical properties of the BW horizon of Eutrudox [21].

2.3. Experimental Design and Treatments

A randomized complete block design was used, consisting of four tillage systems (treatments) and three replications, totaling twelve plots. The experimental plots (7.5 m wide × 200 m long = 1500 m^2) were cultivated with five furrows of sugarcane at 1.5 m of inter-row spacing.

The four evaluated treatments are as follows: CT = sugarcane transplanted with conventional tillage with disk harrow (tillage depth of 0.40 m); CTS = sugarcane transplanted with conventional tillage with disk harrow and subsoiling (tillage depth of 0.40 m); MT = sugarcane transplanted with minimum tillage with Rip Strip® (tillage depth of 0.45 m); NT = sugarcane transplanted with no-tillage. The planting rows were set in a parallel direction to the largest dimension of the plot; that is, at a length of 200 m.

2.4. Soil Collection to Determine Soil Physical Attributes

The three collections of preserved samples were performed two months before the harvests and twenty days after the harvests, both in the sugarcane plant and first ratoon cycle (Figure 3), at depths of 0.00–0.05 m, 0.05–0.10 m, 0.10–0.20 m, and 0.20–0.40, in order to study the effect of compaction on soil structure according to depth (Figure 4). The preserved samples were collected in stainless steel volumetric rings, each with an approximate height of 0.05 m and an internal diameter of 0.05 m.

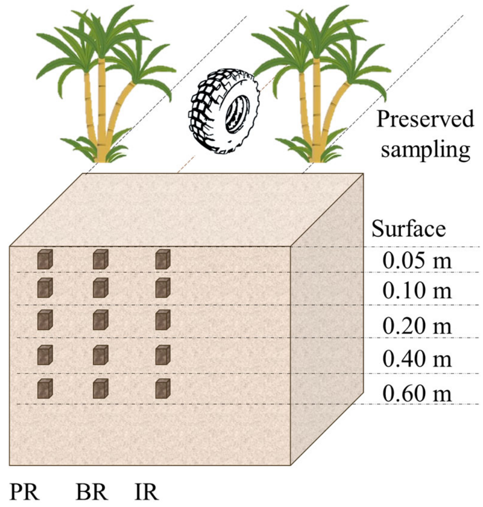

Figure 4. Location of collection points in the experimental area located in the municipality of Jardinópolis, state of São Paulo, Brazil. PR = planting row, BR = bed row, and IR= inter-row.

Soil bulk density (Bd): determined by using the volumetric ring (0.05 m in height by 0.05 m in diameter) method, with the mass of the dry soil, oven-dried at 105 °C for 24 h, divided by the volume of the sample [22].

Total porosity (TP): based on the pore volume of the soil. It was assumed that the water density is 1000 kg m^{-3}, and the TP was the ration of mass of water (obtained by the difference between saturated soil and oven-dried soil) by volume. The microporosity (Mi) was determined by the suction table method, applying a water column with a height of 0.60 m (0.006 MPa) in the saturated samples. The macroporosity (Ma) was determined by the difference between the TP and Mi [22].

2.5. Stalk Yield

The stalk yield during both cycles was determined prior to harvesting the experimental area in three central rows of sugarcane per plot, where 15 m was allocated for sugarcane plant and 3 m for ratoon, randomly. The plants were collected and subjected to sprouting at the height of the apical meristem and to defoliation. Subsequently, the material was weighed and the results were expressed in tons of sugarcane per hectare (Mg ha^{-1}).

2.6. Proctor Test

The Proctor test was performed according to the procedures of the Brazilian Association of Technical Standards [23] with a cylinder of 2.5 kg at a height of 30 cm, compacting the soil in three layers with twenty-five strokes with five different moistures. Because the soil was homogeneous in texture, a sample was collected at the layer of 0.00–0.60 m [24,25] in the area where the maximum density of 1.46 Mg^{-3} m was obtained.

The degree of soil compaction (DC) was calculated by the following equation, according to [26]:

$$DC = (Bd/Bdmax) \times 100 \quad (1)$$

where Bd is the soil bulk density and Bdmax is the maximum soil bulk density obtained in the laboratory by the Proctor test. The maximum soil bulk density value of 1.46 Mg m^{-3} obtained in this study was similar to that obtained by [26] for Eutrudox.

2.7. Dry Root Biomass

Root system evaluation was conducted according to the methodology described by [27]. Stainless steel probes measuring 1.0 m in length and 0.055 m in internal diameter

(SONDATERRA®) were used to collect soil samples at depths of 0.00–0.20 m, 0.20–0.40 m, 0.40–0.60 m, 0.60–0.80 m, and 0.80–1.00 m (Figure 4). The evaluations were carried out at the midpoint and end of the sugarcane plant cycle (December 2017 and April 2018) and at the midpoint and end of the first ratoon cycle (December 2018 and June 2019). They were collected in the region of the planting row, inter-row, and bed row on both sides of the plant.

After the samples were collected, the roots were separated from the soil in the laboratory by wet sieving (2.0 mm mesh). The separated roots and rhizomes were washed under running water [28,29]. Subsequently, the roots were dried in a ventilated oven at 65 °C for 24 h. The dry material masses were then obtained [30] to determine the dry matter content and were extrapolated per hectare.

Dry root biomass was calculated according to [27], as described by the equations below:

$$DRB = (RD \times SV) \tag{2}$$

where DRB = dry root biomass (kg ha^{-1}); RD = root density (g dm^{-3}); and SV = soil volume represented at each sampled point (m^3 ha^{-1}).

$$RD = DM/Vm \tag{3}$$

where DM = dry mass of roots (g) and Vm = sampled probe volume (dm^{-3}).

2.8. Statistical Analysis

The comparison between treatments for the degree of compaction was performed in a randomized block design with subdivided plots. R software (R (4.1.2)) was used for analysis of variance by the F-test ($p \leq 0.05$), and the means were compared by Tukey's test ($p \leq 0.05$).

The preserved samples collected at different locations (planting row, bed row, and inter-row) were used for an average calculation to obtain a single value.

The physical attributes of soil, roots, and stalk yield were analyzed by using the linear mixed model adjusted in the R software with the lmer function of the lme4 package [31], allowing us to deal with correlated data, such as repeated measures. Replicas were defined with random effects, and soil management and harvest years were considered fixed effects. The treatments and their interactions were analyzed when $p \leq 0.05$. The reported means were square means and were compared using the difflsmeans lmerTest package [32].

3. Results

3.1. Soil Physical Attributes

In the April 2018 sampling, soil management methods did not influence the total porosity (TP) values within each depth (Table 2). The stability of the values for conservation management systems occurred for the TP, although this attribute presented less variation between the tillage methods (Table 2).

For the July 2018 collection, significant differences occurred only at the 0.00–0.05 m and 0.20–0.40 m layers and, for July 2019, at 0.10–0.20 m. For TP, there were no differences between treatments in the April 2018 collection; therefore, the differences occurred after the harvester traffic (July 2018 and 2019), in which CT presented lower values of 0.47 and 0.45 m^3 m^{-3} for July 2018 in the 0.00–0.05 m and 0.20–0.40 m layers, respectively, and of 0.44 m^3 m^{-3} for July 2019 in the 0.10–0.20 m layer. MT presented the highest TP values: 0.51 and 0.47 m^3 m^{-3} for the collection in July 2018 at 0.20–0.40 m and July 2019 at 0.10–0.20 m, respectively.

Table 2. The total porosity and degree of compaction of the soil samples with a preserved structure during three soil collections for the sugarcane area in the municipality of Jardinópolis, state of São Paulo, Brazil.

Microporosity ($m^3\ m^{-3}$)			Macroporosity ($m^3\ m^{-3}$)			Total Porosity ($m^3\ m^{-3}$)			Tillage
July/19	**July/18**	**April/18**	**July/19**	**July/18**	**April/18**	**July/19**	**July/18**	**April/18**	
0.41 Ab	0.39 Bb	0.55 Aa	0.07 Aa	0.08 Aa	0.07 Aa	0.48 Ab	0.47 Bb	0.62 Aa	CT
0.41 Ac	0.44 Ab	0.53 Aa	0.08 Aa	0.08 Aa	0.08 Aa	0.48 Ab	0.51 Ab	0.60 Aa	NT
0.41 Ab	0.43 Ab	0.52 Aa	0.11 Aa	0.08 Aa	0.07 Aa	0.53 Ab	0.51 ABb	0.60 Aa	MT
0.40 Ab	0.42 ABb	0.52 Aa	0.09 Aa	0.08 Aa	0.08 Aa	0.50 Ac	0.54 Ab	0.60 Aa	CTS
0.38 Ab	0.39 Bb	0.54 Aa	0.08 Aab	0.10 Aa	0.05 Ab	0.46 Ab	0.49 Ab	0.59 Aa	CT
0.37 Ac	0.43 Ab	0.52 Aa	0.07 Aa	0.07 Aa	0.05 Aa	0.44 Ac	0.50 Ab	0.57 Aa	NT
0.38 Ac	0.42 ABb	0.51 Aa	0.10 Aa	0.07 Aab	0.05 Ab	0.48 Ab	0.49 Ab	0.56 Aa	MT
0.38 Ab	0.39 Bb	0.54 Aa	0.08 Aab	0.11 Aa	0.06 Ab	0.46 Ab	0.5 Ab	0.60 Aa	CTS
0.36 ABb	0.39 ABb	0.52 Aa	0.07 Ab	0.09 ABa	0.05 Ab	0.44 Bc	0.49 Ab	0.57 Aa	CT
0.38 ABc	0.41 ABb	0.5 Aa	0.08 Aa	0.06 Ba	0.05 Ab	0.46 Abb	0.47 Ab	0.56 Aa	NT
0.38 Ac	0.41 ABb	0.51 Aa	0.09 Aa	0.08 ABa	0.05 Ab	0.47 Aa	0.50 Ab	0.56 Aa	MT
0.36 Bc	0.38 Bb	0.52 Aa	0.07 Aab	0.10 Aa	0.06 Ab	0.43 Bc	0.48 Ab	0.58 Aa	CTS
0.37 Ab	0.38 Bb	0.52 Aa	0.09 Aa	0.07 Aa	0.06 Aa	0.46 Ab	0.45 Bb	0.58 Aa	CT
0.37 Ac	0.41 Ab	0.50 Aa	0.08 Aa	0.06 Aa	0.07 Aa	0.45 Ab	0.48 ABb	0.57 Aa	NT
0.37 Ac	0.41 Ab	0.51 Aa	0.10 Aa	0.09 Aa	0.06 Aa	0.47 Ab	0.51 Ab	0.58 Aa	MT
0.36 Ab	0.38 Bb	0.52 Aa	0.08 Aab	0.09 Aa	0.05 Ab	0.45 Ac	0.48 Bb	0.57 Aa	CTS

CT = sugarcane transplanted with conventional tillage with disk harrow; CTS = sugarcane transplanted with conventional tillage with disk harrow and subsoiling; MT = sugarcane transplanted with minimum tillage with Rip Strip®; NT = sugarcane transplanted with no-tillage. Different lowercase letters indicate a significant difference throughout crop cycles for the same soil management, while different uppercase letters indicate a significant difference between crop systems within each crop cycle by Least Squares with lmerTest ($p < 0.05$).

CTS was statistically equal to NT in the collection in July 2018 for the layer of 0.00–0.05 m, with higher values than CT; however, in July 2019, all soil preparations were statistically equal (Table 2) because, before the harvester traffic, the soil was disaggregated and the traffic caused soil structuring and an increase in the TP, especially in microporosity. In the case of NT, due to its better natural structure and biopores, there was no compaction, but CTS presented an increase in compaction, represented by higher microporosity. Except for this collection, as well as for the degree of compaction (DC), the TP presented higher values for conservation management than for conventional ones, especially after the traffic of the harvester.

For the TP, all management methods reduced their values between April 2018 and July 2018, with a statistical decrease between the collections of July 2018 and 2019 (Table 2). CTS reduced the values for the TP in the layers of 0.00–0.05 m, 0.10–0.20 m, and 0.20–0.40 m, with a reduction of 10% (from 0.48 to 0.43 $m^3\ m^{-3}$ at 0.10–0.20 m). NT, CT, and MT presented lower values for the TP in the layers of 0.05–0.10 m and 0.10–0.20 m, respectively.

In addition to total porosity and degree of compaction, the effects of soil management methods on soil structural stability can be evaluated by the distribution of pores by size, especially macropores, which may be more sensitive than total porosity. Soil physical attributes presented differences between tillage methods in all collections and were directly influenced by agricultural traffic, especially by the harvester (Table 2).

Regardless of collection and depth, macropores remained below 0.10 $m^3\ m^{-3}$, and it is verified that most of the porosity is made up of micropores (Table 2). For microporosity, tillage in all layers presented reductions between the collections of April 2018 and July 2019. The greatest reductions occurred for CT and CTS in the 0.05–0.10 m layer (0.54 to 0.38 $m^3\ m^{-3}$) and in the 0.10–0.20 m layer (from 0.52 to 0.36 $m^3\ m^{-3}$) (Table 2).

The collection in April 2018 did not present any differences between tillage methods in any of the layers, while the collection in July 2019 presented differences only for the 0.10–0.20 m layer, with the highest values for NT and MT (0.38 $m^3\ m^{-3}$) and the lowest for CTS (0.36 $m^3\ m^{-3}$) (Table 2). In the collection in July 2018, shortly after the harvest of the sugarcane plant, all layers showed differences. In all layers, in general, NT and MT obtained the highest values, while CT mostly obtained the lowest values. The behavior of the tillage methods was the same in all collections, with higher TP values in the 0.00–0.10 m layer and equal or close values in the layers below.

For the 0.00–0.05 m and 0.05–0.10 m layers, soil tillage for the transplanted sugarcane did not reach the critical limit of 87% of degree of compaction [33]. On the other hand, regardless of the tillage methods for transplanting sugarcane, the highest degrees of compaction were observed for the layers of 0.10–0.20 m and 0.20–0.40 m (Figure 5), indicating that the traffic of machinery and soil tillage distributed stresses that modified the soil structure up to a depth of 0.40 m.

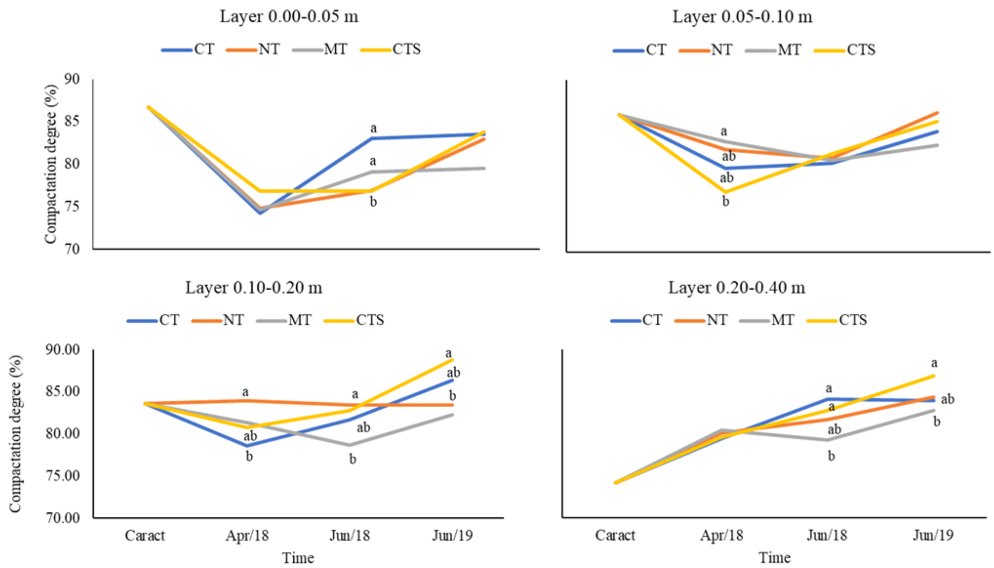

Figure 5. Degree of compaction (%) of soil samples with a preserved Eutrudox structure during three soil collections for the sugarcane area in the municipality of Jardinópolis, state of São Paulo, Brazil. CT = sugarcane transplanted with conventional tillage with disk harrow; CTS = sugarcane transplanted with conventional tillage with disk harrow and subsoiling; MT = sugarcane transplanted with minimum tillage with Rip Strip®; NT = sugarcane transplanted with no-tillage. Different letters indicate significant differences between soil tillage methods with a 5% probability by Tukey's test ($p \leq 0.05$).

It should also be noted that even in the collection of soil samples carried out in March 2017, the degrees of compaction were greater than 85% in the layers of 0.00–0.05 and 0.05–0.10 m. For this depth, NT presented the highest values in the first two collections (84% and 83%, respectively), but the lowest (83%) in the third, along with MT (82%), besides being the only tillage method to obtain equal values in all collections. The reverse effect was obtained by CTS, with the lowest value (77%) recorded in April 2018 and the highest (89%) in 19 July.

Degrees of compaction greater than 85% in the 0.15–0.45 m layer were observed for a Eutrudox structure and can be considered restrictive to achieving the optimal yield of sugarcane [34].

In the 0.00–0.05 m layer (Figure 5), the difference occurred in the collection in 18 July, with the highest value for CT (83%) and the lowest for NT (77%), while in the 0.05–0.10 m layer, the difference occurred for the collection in 18 April, with the highest value for MT (83%) and the lowest for CTS (77%). In the 0.20–0.40 m layer, the highest values occurred in the two collections after machine traffic (July 2018 and 2019) for CTS (83% and 87%, respectively) and CT (84% for both), while MT presented the lowest values (79% and 83%, respectively).

Thus, conventional management systems initially had equal or lower values for the DC (Figure 5) compared to conservation management systems, but over time, this effect was reversed, with lower values than conservation management systems, which remained constant. CTS was the tillage method with the highest values of DC, increasing between the three collections from 77% to 85% in the 0.05–0.10 m layer, from 81% to 89% in the 0.10–0.20 m layer, and from 80% to 87% in the 0.20–0.40 m layer, an increase of about 10% compared to the initial values in all these layers.

For a better evaluation between the degree of compaction and macroporosity, their figures were plotted in Table 3 to evaluate the maximum compaction degree for correct air circulation in the soil, which occurs at 0.10 m^3 m^{-3}. In this study, compaction values greater than 74–78% were considered restrictive to achieving root growth and soil physical quality. Therefore, it is observed that the effects of soil tillage and machine traffic were concentrated in the layer of 0.10–0.40 m (Table 2).

Table 3. Relationship between degree of compaction (%) and macroporosity (m^3 m^{-3}) for three soil collections in a sugarcane area for the sugarcane plant and first ratoon cycles.

Limiting DC	R^2	b	a	Layer (m)
74%	0.24 *	0.85	−1.14	0.0–0.05
77%	0.17 *	0.86	–0.88	0.05–0.10
78%	0.18 *	0.86	–0.76	0.10–0.20
78%	0.25 *	0.84	–0.61	0.20–0.40

The constants a and b refer to DC = a × Ma + b, DC = degree of compaction and Ma = macroporosity. * Significant at 5% probability.

3.2. Root System

The amount of dry root biomass differed significantly ($p < 0.05$) when time was evaluated (after one cycle of sugarcane plant and three of ratoon) for all soil layers (Figure 6A,B). From 0.00 to 0.80 m, no differences in root biomass were observed between the systems. However, for the 0.80–1.00 m layer, there was a significant effect of the interaction between the evaluation time and management systems (Figure 6B).

Thus, it was possible to observe that in the soil, at the depth of 0.00 to 0.80 m, the amount of root biomass presented decay functions, with the second degree polynomic model for the 0.00–0.20 m layer and the linear model for the layers of 0.20–0.40 m, 0.40–0.60 m, and 0.60–0.80 m. That is, there was a trend to decrease over time, with quantities of 1237, 696, 547, and 392 kg ha^{-1} for 0.00–0.20, 0.20–0.40, 0.40–0.60, and 0.60–0.80 m, respectively, in the last cycle (Figure 6A).

Nevertheless, when the deepest layer (0.80–1.00 m) was evaluated, there were differences in the amount of dry biomass according to the management system. CT showed a linear decrease in the amount of biomass over time, with an accumulation of up to 282 kg ha^{-1} in the last evaluation, which corresponds to the first ratoon cycle (Figure 6B).

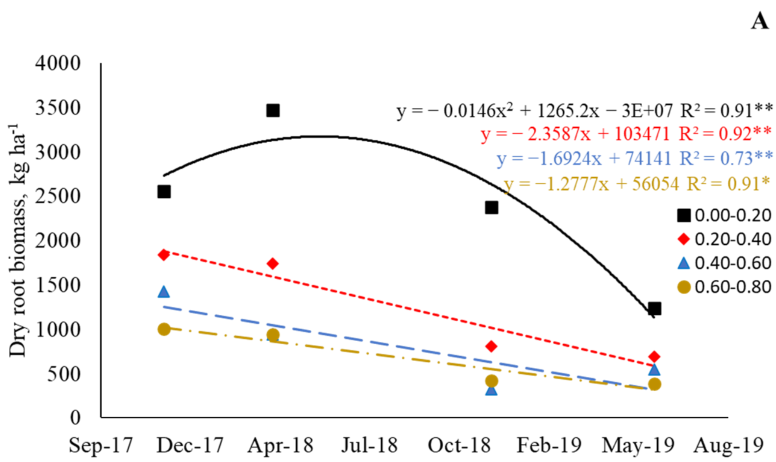

Figure 6. *Cont.*

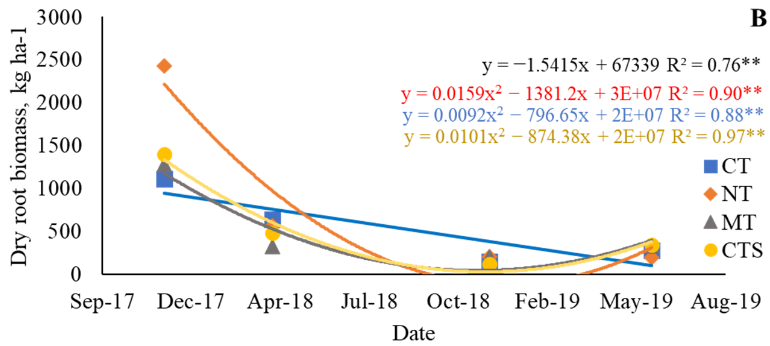

Figure 6. Dry root biomass in soil depth ranging from 0.00 to 0.80 m (**A**) and 0.80 to 1.0 m (**B**) during four collections in a sugarcane area in the municipality of Jardinópolis, state of São Paulo, Brazil. CT = sugarcane transplanted with conventional tillage with disk harrow; CTS = sugarcane transplanted with conventional tillage with disk harrow and subsoiling; MT = sugarcane transplanted with minimum tillage with Rip Strip®; NT = sugarcane transplanted with no-tillage. The letters mean that the means differed from each other with 5% probability by Tukey's test ($p \leq 0.05$); ns: not significant for each evaluated period. The *, ** means regression test significance at 5 and 1% probability, respectively.

For the other systems, there was a decrease in the first and second collections, followed by a tendency to accumulate root biomass in the later periods. In the last cycle, second degree polynomic equations indicated amounts ranging from 345 to 282 kg ha^{-1} for areas with NT, MT, and CTS. Significant differences between the systems were only detected for the first day of collection, and the NT area showed the highest accumulation of root biomass, with 2429.67 kg ha^{-1}, compared to the other systems, which presented amounts ranging between 1396.61 and 1115.76 kg ha^{-1} (Figure 6B).

3.3. Stalk Yield

For stalk yield in the sugarcane plant cycle (2018) and the first ratoon cycle (2019) (Figure 7), there were differences between the tillage methods in the sugarcane plant cycle, where NT obtained the highest value (123 Mg ha^{-1}), followed by CT (116 Mg ha^{-1}), MT (112 Mg ha^{-1}), and CTS (111 Mg ha^{-1}). All treatments showed reductions between the cycles. For the first ratoon, the tillage methods obtained statistically equal values ranging from 96 Mg ha^{-1} (NT) to 89 Mg ha^{-1} (MT).

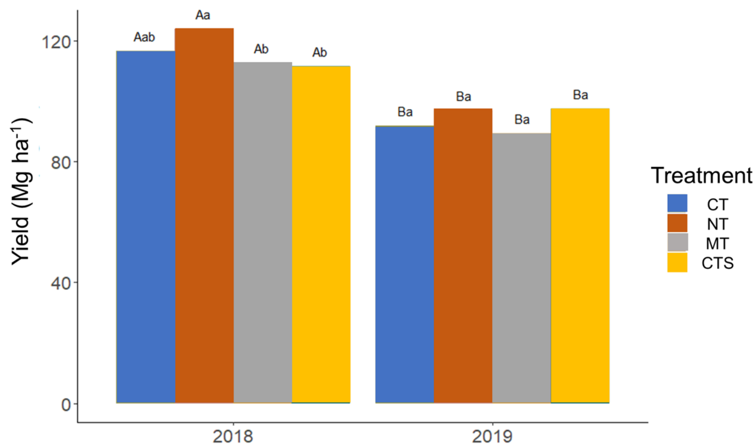

Figure 7. Stalk yield for the sugarcane plant cycle (2018) and first ratoon cycle (2019) for the sugarcane area in the municipality of Jardinópolis, state of São Paulo, Brazil. CT = sugarcane transplanted with

conventional tillage with disk harrow; CTS = sugarcane transplanted with conventional tillage with disk harrow and subsoiling; MT = sugarcane transplanted with minimum tillage with Rip Strip®; NT = sugarcane transplanted with no-tillage. The letters mean that the means differed from each other with 5% probability by Tukey's test ($p \leq 0.05$); the uppercase letters differ between collections (2018 vs. 2019) and the lowercase letters between tillage systems within the same samples collection.

4. Discussion

4.1. Effects of Tillage on Soil Physical Attributes

In addition to the soil chemical attributes, it is important to evaluate the physical attributes and their behavior throughout the cycles. It is known that the moment of harvest is the biggest cause of compaction in sugarcane areas, mainly due to the excessive weight of transshipment and harvester applied in the area [4,35,36].

In addition, the total porosity values observed for the sampling carried out in April 2018 reflected the effects of soil preparation, with the increase in values being comparable to the sampling in March 2017 after the soybean harvest (Tables 1 and 2). This value increased because soil microporosity also increased compared to the values in March 2017, before cane implementation (Table 1), and in April 2018, for cane plant (Table 2).

During the April 2018 collection (before the harvest of the sugarcane plant), there was traffic of all implements in the area, except for harvester and transshipment. This tends to increase the soil bulk density and microporosity.

The collection in July 2018 was different from April 2018 due to the traffic of the harvest and from July 2019 due to the traffic of all implements and harvest during the ratoon cycle. The effects that occurred in the area between cycles were temporally verified (Table 2), proving that traffic over time promotes increased soil compaction [4,5].

The differences in the DC and TP occurred in the collection of July 2018. For the April and July 2018 collections, higher soil bulk densities were shown in NT at 0.10–0.20 m and in CT at 0.00–0.05 m and 0.20–0.40 m. This behavior was reversed in the July 2019 collection by evaluating the layers in which significant differences occurred. Furthermore, CTS obtained higher values and MT lower ones regarding the DC (Figure 5).

In Eutrudox soil in the city of Lencóis Paulista, deep tillage with Penta equipment (Mafes Equipamentos Agrícolas) provided lower soil bulk density values and higher total porosities, according to results observed by [34]. These authors also observed that with the passage of the cycles, the beneficial effect was mitigated. Deep tillage causes soil disruption, presenting lower bulk density and higher porosities [37]; however, as heavier machinery travels on the ground, there is a rebound effect, with the soil becoming more compacted than in other tillage methods.

One of the advantages of using the degree of compaction (DC) is that it standardizes the density values regardless of the type of soil evaluated, making it an attribute independent of texture. The values found for the DC ranged between 74% and 87% (Figure 6), being in line with those found in the literature for sugarcane, which, for areas with sugarcane plant and first ratoon, vary between 77% and 87% [38].

As in this study, ref. [39] found that until the first sugarcane ratoon, there is a small increase in the DC, but that with the passage of the harvests, close to the third ratoon, there is a greater increase, along with a drop in the organic carbon content. With this, the authors suggest that long-term studies should be carried out on the degree of compaction using Rip Strip and no-tillage up to the fourth ratoon to evaluate the effects of these tillage methods in the long term.

Clay soils, due to their natural characteristics, have fewer macropores and more micropores than sandy soils. With this, traffic directly affects their structure throughout the cycles, obtaining differences between tillage methods even for sugarcane ratoon, although traditionally, there were no differences in soil physical attributes after the first ratoon, as observed by [9], who, in evaluating a clay soil, found no differences between no-tillage and conventional tillage, except in the sugarcane plant cycle. In addition, due to the texture, the soil contains fewer macropores, with values lower than 0.10 $m^3\ m^{-3}$ during all assessments, even with a DC below 80%.

Tillage and machine traffic increased THE compaction with each cycle, sequentially increasing the DC and reducing the TP in all evaluated layers (Table 2). Due to traffic, a continuous increase in the Bd and a reduction in the TP in sugarcane areas can be observed [3,9,36].

MT did not improve the soil structure or increase Bd values over the cycles up to a depth of 0.20 m. The TP, due to its greater sensitivity to traffic, was changed for all tillage methods, but in conservation systems, the values rose between the collection of April 2018 and July 2018, stabilizing in July 2019. Conventional tillage methods in each collection increased their TP up to a depth of 0.40 m, corroborating the results obtained by [9], who evaluated clay soil in a sugarcane area and verified increased compaction throughout the cycles.

Thus, the use of NT with surface trash (crop residue) addition and minimum tillage can bring benefits to the structural quality of the soil in sugarcane cultivation, according to the history of the adoption of the system, providing important information for the sugarcane market. Unlike the results observed in other studies [6,7,9], our study found that conservation management systems are favorable for improving soil structure, maintaining its quality throughout the cycles, and conventional management systems reduce soil structure at each cycle, in line with the results by [40].

A long-term trial with NT in a sugarcane/soybean crop system, combined with surface liming (4 Mg ha^{-1}), showed improvements in topsoil hydrophysical attributes [41] and compromised the structural quality of soil less compared with conventional tillage [42].

4.2. Effects of Tillage on Dry Root Biomass

As for soil physical attributes (Table 2), from the root system (Figure 6B), we noticed that the use of NT was favorable for the soil structure, obtaining the highest values of root biomass in the 0.80–1.00 m layer after the first sugarcane plant cycle. Since NT maintains the soil structure more preserved and favors the creation of biopores [43], it causes roots to reach deeper layers of soil, such as below 0.80 m.

Therefore, the area with NT promoted a greater amount of roots in depth, which is essential for the better absorption of water and nutrients. Many studies of the root system evaluate up to the layer of 0.60 m, as it is the one with the largest amount of roots [18,27], but our results show that, when comparing conservation and conventional management systems, one must evaluate deeper levels (up to 1.00 m) because there are important differences that are not concentrated in the surface layer, such as physical attributes.

This was confirmed in this study, which showed that, at 0.00–0.80 m, it was not possible to detect differences in the root biomass between the systems. Possibly, the decrease in root dry biomass at this depth (0.00–0.80 m) (Figure 6A) is due to the effects of soil tillage, disturbing the soil and causing weak root permanence.

However, below 0.80 m, there was a difference after the sugarcane plant cycle. After this cycle, the systems tend to promote the accumulation of root biomass in the layer below 0.80 m, except for in the area with the conventional system, whose tendency was a reduction in the roots in the soil profile; that is, including all layers evaluated. This shows that the effect of deep tillage causes soil disruption [37] and promotes less root establishment in the soil profile, which may compromise stalk yield.

4.3. Relationship of Physical Attributes and Dry Root Biomass with Stalk Yield

The tillage method that obtained the highest productivity of straw in the sugarcane cycle (Figure 7) was no-tillage (NT), followed by conventional tillage (CT), minimum tillage (MT), and conventional tillage with subsoiling (CTS). During the first ratoon cycle, all stalk yields were equal. In the direct planting system, productivity fluctuations between years are common, especially at the beginning of system installation. This was confirmed in studies by [6,7].

CTS showed lower stalk yields in the sugarcane plant cycle (Figure 7), and, during the June 2018 collection, it was the tillage method that obtained the lowest DC in the 0.00–0.05 m layer (Table 2) and the second highest DRB in the first evaluation (December/17) (Figure 6). This result corroborates those found by [34], in which subsoiling initially seems to be beneficial, but throughout the cycles, its effects are reversed.

NT showed the highest stalk yield (Figure 7). This is in line with [11], in which no-tillage, by maintaining the soil structure, preserving the continuity of pores and favoring the fauna of the environment and biopores, was beneficial for the soil, making it more resistant to mechanization impacts and better structured, an effect called "age-hardening phenomena". According to [44] "age-hardening phenomena" means to increase the number and strength of bonds among soil particles, leading to higher soil cohesion. And longer times under no-tillage improves the soil structure and soil load support capacity.

Regarding physical aspects, NT presents a higher Bd at the beginning of the cycle (Table 2). However, due to the fact that keeping the soil in its most natural and structured form favors the better establishment and development of the plant (Figure 5), its roots went deeper than in the other treatments during the sugarcane plant cycle, standing out as an alternative for times of water deficit (Figure 2), in which the plant most needs water [45].

The conventional management systems (CT and CTS) were those that, over the cycles, increased the Bd and reduced the TP in the studied depths (Table 2). The positive effects of mechanization remained during the sugarcane plant cycle and degraded over time (Table 2), becoming denser than in the conservation management systems.

The stalk yield did not differ for the first ratoon cycle, and this effect can be found in the literature when evaluating different soil tillage methods [6,7]. Nevertheless, differences between the methods after the harvest of the sugarcane plant are an innovation brought about by the use of Rip Strip®, as there are still no results of its use in sugarcane. The authors suggest more long-term studies using this implement, possibly with an entire sugarcane cycle.

Planting with the use of pre-sprouted seedlings was affected by the different soil tillage systems. Despite the difference in planting when compared with the use of sugarcane pieces, in which a different machine is used and the plant is already more evolved with a developed root system [46], previous soil tillage affected plant development. The use of no-tillage is feasible, bringing yield and sustainability benefits to sugarcane, with advantages for the producer.

5. Conclusions

Tillage with subsoiling was the management system with lower stalk yields and greater increases in the degree of compaction and reduction in soil porosity throughout the cycles. In contrast, no-tillage and minimum tillage with Rip Strip® were the tillage methods in which the degree of compaction and total porosity of the soil were least affected over the two cycles. This may have affected root maintenance, i.e., in general, in the no-tillage system, there was greater dry root biomass in depth in the sugarcane plant cycle, while minimum tillage with Rip Strip® provided greater dry root mass in the 0.00–0.2 m layer.

The yield of the sugarcane crop was higher in the sugarcane plant cycle (2018) compared to the sugarcane ratoon cycle (2019) regardless of the soil management method. In the sugarcane plant cycle, no-tillage provided a higher stalk yield compared to Rip Strip® and conventional tillage with disk harrow and subsoiling.

The adaptation of Rip Strip® for sugarcane was valid, maintaining the degree of soil compaction throughout the cycles, being an option for sugarcane implantation or cycles of renovation.

Author Contributions: Conceptualization, I.N.d.O., D.B. and Z.M.d.S.; methodology, I.N.d.O. and D.B.; software, I.N.d.O.; validation, D.B., R.P.d.L. and Z.M.d.S.; formal analysis, I.N.d.O., D.B. and R.L.M.T.; investigation, I.N.d.O. and D.B.; resources, Z.M.d.S.; data curation, I.N.d.O., L.H.L. and E.d.S.L.; writing—original draft preparation, I.N.d.O.; writing—review and editing, D.B., Z.M.d.S., F.S.A. and R.L.M.T.; visualization, I.N.d.O. and R.L.M.T.; supervision, Z.M.d.S. and R.B.d.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the AGRISUS Foundation—Sustainable Agriculture (grant number PA n° 2059/17) and CNPq—Brazilian National Council for Scientific and Technological Development for the doctoral scholarship of first author I.N.O. (great number 141083/2018-2).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data availability statements are available in the https://hdl.handle.net/20.500.12733/1641761.

Acknowledgments: We would like to thank Fazenda Cresciúma, located in Jardinópolis, for providing the experimental area.

Conflicts of Interest: The authors declare no conflicts of interest.

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