Mechanical and Biological Soil Decompaction for No-Tillage Maize Production

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Abstract: Soil structural quality in areas under a no-tillage system is altered after successive crops, where compaction is a recurrent problem. The objective of this study was to evaluate the effect of different forms of soil decompaction on maize grain production. A randomized split-plot block design with four replications was used, in a $5 \times 3 \times 2$ factorial arrangement, consisting of five forms of mechanical soil decompaction: ripping to a depth of 0.3 m, ripping to a depth of 0.5 m, subsoiling to a depth of 0.3 m, and subsoiling to a depth of 0.5 m, and no-tillage; three crop seasons: 2014/2015, 2015/2016, and 2016/2017; and two cover crops: sunn hemp and pearl millet. The soil resistance to root penetration (RP, 0.0–0.40 m), density (0.0–0.40 m), moisture (0.0–0.40 m), fresh (FB), and dry (DB) above-ground biomass of cover crops, and maize yield were evaluated. The subsoiling to a depth of 0.3 or 0.5 m results in higher production of sunn hemp biomass but has no effect on millet. Mechanical and biological soil decompaction improved maize grain yield throughout the seasons by at least 28% above the average yield in the study area region. The RP of up to 3.3 MPa did not negatively affect cover crop biomass production and maize grain. The association between the mechanical and biological decompaction method using cover crops provided greater resilience to the preparation carried out up to three years after the application of the treatments, resulting in greater corn grain productivity.

Keywords: ripper or subsoiler; decompression; no-tillage system; sunn hemp; pearl millet

1. Introduction

Maize (Zea mays L.) is one of the most grown cereals in the world, and the United States, China, and Brazil are responsible for more than 70% of the world’s production [1]. In Brazil, the estimated maize production for the 2018/2019 crop season is about 100.04 million Mg in a cultivated area of 17.49 million hectares [2]. In most of these areas, maize is grown under a no-tillage system (NTS). NTS has evolved technologically in the last 50 years and is now considered a primary system for sustainable agricultural production in the Brazilian Cerrado (Savannah-like biome), which currently accounts for over 50% of the national maize production [3].

Despite the benefits of NTS to the soil, some problems remain and need to be better assessed. A common problem in NTS is soil compaction due to the heavy machinery operations or operations performed under inappropriate soil moisture contents [4,5], and it is common for compacted soil layers to form between 0.1–0.2 m depth in almost all areas under NTS [6].
Soil compaction levels above the limits to root development hinder biological activity, reduce soil macroporosity, and alter the dynamics of air and water flow in the soil profile, negatively affecting the development of the plants [7,8]. However, Loss et al. [9] emphasized that the soil acquires sufficient structure and strength after a few years under NTS due to the stabilization of aggregates and can support machinery traffic without presenting significant compressibility. A recent global meta-analysis also reported that NTS could enhance soil structure due to the stabilization of soil aggregates [10].

Intermittent tillage using ripping and subsoiling can be used to alleviate soil compaction. These are the most used practices because they decrease soil bulk density, improve water storage and movement, and reduce soil resistance to penetration [11]. However, the effectiveness of soil tillage tends to disappear over time due to the natural reconsolidation of soil particles. Soil reconsolidation occurs during soil wetting and drying cycles, by raindrop impact and traffic of agricultural machinery during sowing, crop management, and harvest [12].

Soil reconsolidation after tillage can be reduced by using soil cover crop plants that can biologically alleviate compaction. Cover crop plants with taproot systems are commonly indicated for this purpose. Oilseed radish (Raphanus sativus L.), Pigeon pea (Cajanus cajan L.), Sunn hemp (Crotalaria juncea L.), and ruzigrass (Urochloa ruziziensis) are examples of cover crops that can grow through compacted soil layers, forming stable biopores and improving soil water infiltration [13,14]. The fibrous root system of plants of the Poaceae family (grasses) also favors soil aggregation, structure, and permeability, thereby improving soil physical quality [14–18].

The cover crops should not be restricted to only traditional crops since there are several alternatives of species, rotation combinations, and sowing periods [9,19,20]. Soil compaction alleviation and nutrient cycling provided by an appropriate choice of cover crop and rotation improve the production of subsequent crops, as found for maize, sorghum, common bean, and soybean [21].

Pearl millet, ruzigrass, and sunn hemp are commonly used in crop rotation systems with maize in Brazilian grain production areas, mainly in the Cerrado biome, where the winter is dry. This crop rotation combination is used due to (i) the high biomass produced, great residue persistence on the soil [20–23], and (ii) the high nutrient extraction capacity of both plant species. This combination of crop plants improves soil nutrient cycling and reduces the risk of nutrient losses by leaching [24].

Soil decompaction carried out by conventional methods using subsoilers has temporary effects and small residual effects, however, when associated with biological methods using cover plant species that have fibrous root systems and high biomass production, the effects of this decompaction tend to present greater resilience. and keep for longer, as it increases the stability of the soil structure, however, this association needs to be better evaluated in the long term.

The hypothesis evaluated in the present study is that the combination of mechanical and biological decompaction using cover crops results in higher yields of maize grown under a no-tillage system. Given this context, this study evaluated the effect of different forms of mechanical and biological soil decompaction on the production of corn grains cultivated in a no-tillage system in the Brazilian Cerrado biome.

2. Material and Methods

2.1. Experimental Area

The experiment was implemented in an experimental area of the Federal Institute of Triângulo Mineiro (IFTM), state of Minas Gerais, Brazil (19°39′19″ S, 47°57′27″ W, and 795 m of altitude), during 2014/2015, 2015/2016, and 2016/2017 crop seasons.

The study area was left fallow for 12 years, with the development of spontaneous vegetation (Cerrado biome). In 2012, a no-tillage system was introduced. In 2014, the soil of the area was tilled to alleviate soil compaction, mechanically (tillage) and biologically using cover crops.
The soil of the study area was classified as an Oxisol of sandy clay loam texture [25]. The 0–0.4 m soil layer presented the following physical properties: 210 g kg⁻¹ of clay; 710 g kg⁻¹ of sand; 80 g kg⁻¹ of silt. The chemical analysis showed: a pH (H₂O) of 6.3; 19 mg dm⁻³ of P (anion exchange resin); 2.3 mmolc dm⁻³ of K⁺; 22 mmolc dm⁻³ of Ca²⁺; 10 mmolc dm⁻³ of Mg²⁺; 20 mmolc dm⁻³ of H⁺Al; 16 g dm⁻³ of soil organic matter, and base saturation of 68%, according to the method described by Teixeira et al. [26].

The climate of the region is classified as Aw, tropical hot, with a hot and rainy summer, and a cold and dry winter [27]. The region presents a mean annual rainfall depth of 1600 mm and a mean annual air temperature of 22.6 °C [28]. The total rainfall depths, measured with a rain gauge in a meteorological station installed next to the experimental area, were 1092, 1430, 1571, and 1264 mm in 2014, 2015, 2016, and 2017, respectively (Figure 1).

![Figure 1](image-url)  
**Figure 1.** Monthly rainfall depths in 2014, 2015, 2016, and 2017 in Uberaba, MG, Brazil. Source: Adapted from Inmet [28].

### 2.2. Experimental Design

The experiment was conducted in a 5 × 3 × 2 triple factorial arrangement [five soil tillage activities to reduce soil compaction: 1—ripping to a depth of 0.3 m; 2—ripping to a depth of 0.5 m; 3—subsoiling to a depth of 0.3 m; 4—subsoiling to a depth of 0.5 m; and 5 —no tillage (Control treatment); three consecutive crop seasons (2014/2015, 2015/2016, and 2016/2017), and two cover crops (sunn hemp—Crotalaria juncea L.; and Pearl millet—Panicum italicum L.] in a randomized split-plot block design with four replications. The area of each experimental unit (plot) was 50 m² (5 × 10 m), which encompassed eight rows spaced 0.5 m apart.

Soil physical attributes were determined before the application of the soil treatments (September to October 2014) to characterize the occurrence and level of soil compaction in the area. The second phase of the experiment started after the soil compaction characterization; the soil tillage treatments were applied in October (2014) and the cover plants were sown in November (2014), with no soil fertilizer application. The tractor used for all soil activities was a Ford 7630 (4 × 4, 105 HP), and the implements used were: a subsoiler with seven shanks (60 cm long) and a ripper with seven shanks (60 cm long).

Sunn hemp and pearl millet were mechanically sown in rows spaced 0.2 m apart, using 25 and 50 seeds per meter, respectively. No fertilizer amendments were applied to the
cover crops. In February of 2015, 2016, and 2017, soon after the cover crop burnout, by applying glyphosate and 2,4-D dimethylamine salt, at 2 kg ha$^{-1}$ and 2 L ha$^{-1}$, respectively), maize seeds (Agroceres VTPRO2) were sown at 0.05 m depth using 3 seeds per meter and spacing between rows of 0.5 m, as recommended by the seed company, to achieve 60,000 plants per hectare.

Soil chemical characteristics defined the maize fertilizer requirements [29], which were 400 kg ha$^{-1}$ of the 8-28-16 N-P$_2$O$_5$-K$_2$O formulation at sowing, and 140 kg ha$^{-1}$ of N and 80 kg ha$^{-1}$ of K$_2$O as topdressing at 20 and 40 days after sowing. Fertilizers were applied with the aid of a manual cultivator. Usual cultural practices (control of weeds, pests, and diseases) were carried out as necessary to ensure that there were maize productions in all crop seasons.

2.3. Soil Physical Attributes

Soil mechanical resistance to penetration (RP) was measured at the beginning of the experiment, in October 2014, and at the end of the experiment, in May 2018, using an impact penetrometer (Planalsucar/IAA) with a 30$^\circ$ conical tip [30], always at the same time of the year (month and day). Ten aleatory and representative points in each experimental plot were assessed for soil resistance to penetration in the 0–0.1, 0.1–0.2, 0.2–0.3, and 0.3–0.4 m soil layers. Field data were obtained as number of impacts (N) and expressed in kgf cm$^{-2}$ through the equation: $R$ (kgf cm$^{-2}$) = 5.6 + 6.98 N [31]. These values were multiplied by 0.098 to convert them into MPa units [32].

Soil bulk density (SD) was determined in undisturbed soil samples by the volumetric ring method. Soil samples were collected in stainless steel rings (48 mm in diameter and 53 mm in height) with the aid of an Uhland auger, sampling three rings for each soil layer (0–0.1 0.1–0.2; 0.2–0.3, and 0.3–0.4 m) in 2014 and 2018. The soil samples were then dried at 105$^\circ$C for 24 h [26].

Gravimetric soil water contents (g g$^{-1}$) were determined in soil samples collected on the same day and from the same soil layers, two samples per plot were homogenized and assessed for wet and dry soil weights. The soil samples were placed in aluminum containers, weighed, and dried in a forced air circulation oven at 105$^\circ$C for 24 h [26].

2.4. Plant Biomass Attributes

In January of each crop season (2014/2015, 2015/2016, 2016/2017), fresh above-ground biomass (FB) and dry above-ground biomass (DB) of the cover crops were determined in samples collected at two randomly selected points (1 m$^2$) within each plot, when more than 50% of the plants had reached the flowering stage. FB was collected on the same day and placed in a forced air circulation oven at 65$^\circ$C for 72 h until constant weight to determine DB. The results of FB and DB were expressed as Mg ha$^{-1}$. After the plant biomass sampling, the burnout of cover crops was carried out as previously explained.

2.5. Maize Grain Yield

Maize plants on the four central rows of each plot, which were 4 m long, were manually harvested 100 days after sowing (e.g., physiological maturation). The maize ears harvested were threshed and weighed to obtain the grain yield, which was expressed as Mg ha$^{-1}$. A sample was placed in a forced air circulation oven at 65$^\circ$C for 72 h to determine the dry weight and corrected to 13% moisture. Maize moisture content was determined on 100 grains, which were weighed before and after drying in a forced air circulation oven at 65$^\circ$C for 72 h.

2.6. Statistical Analysis

The data were tested for normality of residues, homogeneity of variance, and block additivity by the Shapiro-Wilk, Bartlett, and Tukey tests, respectively. The data was then evaluated by ANOVA’s test, considering a split-plot design, where the factorial tillage activities x cover crops were considered a plot factor, and the crop seasons were considered
as a subplot factor. When significant differences were found (p < 0.05), the means were compared by Tukey’s test (p < 0.05). Analysis was done using CORE R 4.0.0.

3. Results

3.1. Soil Physical Attributes

The RP measurements in 2014 showed the presence of a compacted soil layer (0.1 to 0.2 m), with RP ranging from 3.30 to 3.35 MPa (Figure 2), which was minimized by using tillage and cover crops to alleviate soil compaction. The effects persisted until 2018, even after the traffic of field machinery and implements in the area for sowing, cultural management, and harvest operations.

![Figure 2. Mean soil resistance to penetration (RP) (left graph) and soil bulk density (SD) (right graph) at the beginning (2014) and end (2018) of the experiment. Bars with the same letter in the same soil layer are not statistically different from each other by Tukey’s test (p > 0.05).](image)

The results of RP showed statistical differences among crop seasons only in the deepest layer (0.3–0.4 m), with a decrease in RP in 2018 (1.87 MPa) compared to 2014 (2.87 MPa). Despite the absence of statistical differences in the 0.1–0.2 m and 0.2–0.3 m soil layers, decreases of 28% in the 0.1–0.2 m, and 33% in the 0.2–0.3 m were found from 2014 to 2018.

The soil bulk density (SD) varied from 1.46 to 1.71 kg dm$^{-3}$ and was similar among soil layers (Figure 2), except for the soil surface layer (0–0.1 m) in 2018, which presented a lower SD when compared to 2014. These RP and SD values were found when the soil moisture of the evaluated layers presented means of 0.28 g g$^{-1}$ in 2014 and 0.29 g g$^{-1}$ in 2018, indicating that this parameter did not affect the results.

3.2. Cover Crop

The results of the triple factorial ANOVA are shown in Table 1. The interaction between crop seasons and soil tillage treatments was significant (p < 0.05) for FB and DB. In 2016/2017, the soil tillage treatment with ripping to a depth of 0.3 m presented the lowest FB, and the treatment with subsoiling to a depth of 0.3 m presented the highest DB (Table 2).

The total FB of cover crops consistently increased over the crop seasons; however, the DB in the 2015/2016 and 2016/2017 crop seasons were similar, but higher than that found in the 2014/2015 crop season, except for the treatment with subsoiling to a depth of 0.5 m, which did not differ between the 2014/2015 and 2015/2016 crop seasons (Table 2).

The interaction between cover crops and tillage treatments showed that areas with subsoiling to a depth of 0.3 or 0.5 m presented higher sunn hemp FB and DB productions than those with the other treatments. However, the same result was not found for pearl millet biomass, which presented no significant differences among tillage treatments (Table 3).
Table 1. Analysis of variance (F test) of the triple factorial (soil tillage treatment, crop season, cover crop) for fresh above-ground biomass (FB) and dry above-ground biomass (DB) of the cover crop at the end of the crop cycle, and maize grain yield (GY).

| Source                        | DF | FB       | DB       | GY       |
|-------------------------------|----|----------|----------|----------|
| Soil tillage (ST)             | 4  | 6.06 **  | 2.52 *   | 6.70 **  |
| Crop season (CS)              | 2  | 455.61 **| 44.47 ** | 0.79 ns  |
| Cover crop (CC)               | 1  | 0.42 ns  | 1.51 ns  | 0.03 ns  |
| ST × CS                       | 8  | 2.67 *   | 2.31 *   | 3.78 **  |
| ST × CC                       | 4  | 2.85 *   | 1.03 ns  | 0.88 ns  |
| CS × CC                       | 2  | 68.12 ** | 54.71 ** | 1.46 ns  |
| ST × CS × CC                  | 8  | 0.42 ns  | 1.51 ns  | 0.03 ns  |

General mean - 43.620 10.025 9.249
Standard deviation - 6.888 2.748 0.732
Coefficient of variation (%) - 15.791 27.408 7.919

DF: degrees of freedom. Soil tillage: ripping to a depth of 0.3 m; ripping to a depth of 0.5 m; subsoiling to a depth of 0.3 m; subsoiling to a depth of 0.5 m; and no-tillage. Crop season: 2014/2015, 2015/2016, and 2016/2017. Cover crops: sunn hemp and pearl millet. Analysis was performed considering a split-plot design. *: significant by the F test at 5%. **: significant by the F test at 1%. ns: not significant by the F test.

Table 2. Fresh above-ground biomass (FB) and dry above-ground biomass (DB) of cover crops at the end of the crop cycle in different treatments for soil compaction alleviation in three consecutive crop seasons.

| Soil Tillage Treatment | 2014/2015 FB | 2015/2016 FB | 2016/2017 FB | 2014/2015 DB | 2015/2016 DB | 2016/2017 DB |
|------------------------|---------------|--------------|--------------|---------------|--------------|--------------|
| NT                     | 21.24 Ac      | 31.75 Bb     | 72.26 Aa     | 6.42 Ab       | 9.46 Aa      | 10.78 Ba     |
| Rip30                  | 21.23 Ac      | 33.62 Bb     | 60.35 Ba     | 6.71 Ab       | 9.68 Aa      | 12.15 Ba     |
| Rip50                  | 25.54 Ac      | 36.99 Bb     | 73.85 Ba     | 7.50 Ab       | 10.17 Aa     | 12.31 Ba     |
| Sub30                  | 25.01 Ac      | 45.57 Ab     | 67.74 Aa     | 7.94 Ab       | 8.53 Ab      | 16.99 Aa     |
| Sub50                  | 27.74 Ac      | 38.79 Bb     | 72.61 Aa     | 7.86 Ab       | 10.81 Aa     | 13.10 Ba     |

CV (%) - 15.79 27.40

Means followed by the same uppercase letter comparing soil treatments, or lowercase letter comparing crop seasons, are not significantly different from each other by Tukey’s test (p < 0.05). NT: no-tillage; Rip30: ripping to a depth of 0.3 m; Rip50: ripping to a depth of 0.5 m; Sub30: subsoiling to a depth of 0.3 m; Sub50: subsoiling to a depth of 0.5 m; CV: coefficient of variation.

Table 3. Fresh above-ground biomass (FB *) and dry above-ground biomass (DB *) at the end of the crop cycle of sunn hemp and pearl millet under different treatments to alleviate soil compaction.

| Soil Tillage Treatment | Sunn Hemp FB | Pearl Millet FB | Sunn Hemp DB | Pearl Millet DB |
|------------------------|--------------|----------------|-------------|----------------|
| NT                     | 40.46 Ba     | 43.04 Aa       | 8.13 Ba     | 9.62 Aa       |
| Rip30                  | 41.70 Ba     | 35.10 Bb       | 9.29 Ba     | 9.73 Aa       |
| Rip50                  | 42.82 Ba     | 48.10 Aa       | 8.98 Ba     | 11.01 Aa      |
| Sub30                  | 47.06 Aa     | 45.15 Aa       | 11.26 Aa    | 11.04 Aa      |
| Sub50                  | 48.09 Aa     | 44.67 Aa       | 10.93 Aa    | 10.27 Aa      |

CV (%) - 15.79 27.40

Means followed by the same uppercase letter comparing soil treatments, or lowercase letter comparing cover crops, are not significantly different from each other by Tukey’s test (p < 0.05). NT: no-tillage; Rip30: ripping to a depth of 0.3 m; Rip50: ripping to a depth of 0.5 m; Sub30: subsoiling to a depth of 0.3 m; Sub50: subsoiling to a depth of 0.5 m; * = mean of 2014/2015, 2015/2016 and 2016/2017 crop seasons; CV: coefficient of variation.

The FB and DB of pearl millet were higher than those of sunn hemp in the first crop season (2014/2015). Contrastingly, in 2015/2016, sunn hemp showed higher FB and DB.
Table 4. Fresh above-ground biomass (FB) and dry above-ground biomass (DB) at the end of the crop cycle of sunn hemp and pearl millet in three consecutive crop seasons.

| Crop Season | Sunn Hemp FB Mg ha⁻¹ | Sunn Hemp DB Mg ha⁻¹ | Pearl Millet FB Mg ha⁻¹ | Pearl Millet DB Mg ha⁻¹ |
|-------------|-----------------------|----------------------|-------------------------|-------------------------|
| 2014/2015   | 14.22 Cb              | 30.95 Bb             | 3.44 Cb                 | 9.26 Aa                 |
| 2015/2016   | 43.74 Ba              | 34.08 Ba             | 10.20 Ba                | 10.61 Ab                |
| 2016/2017   | 71.12 Aa              | 64.60 Ab             | 15.50 Aa                | 11.12 Aa                |

Means followed by the same uppercase letter comparing crop seasons, or lowercase letter comparing crop seasons, are not significantly different from each other by Tukey’s test (p < 0.05). CV = coefficient of variation.

3.3. Maize Grain Yield

The factors studied presented a significant three-way interaction for maize grain yield (Table 1). In 2014/2015, 2015/2016, and 2016/2017 crop seasons, maize grain yield ranged between 8.55 and 9.77, 8.44 and 9.80, and 8.06 and 10.21 Mg ha⁻¹ when grown on sunn hemp residues, and between 8.77 and 9.57, 8.70 and 10.95, and 8.04 and 10.17 Mg ha⁻¹ when grown on pearl millet residues, respectively (Table 5).

Table 5. Grain yield of maize grown on sunn hemp and pearl millet cover crop residues under different soil tillage treatments in three consecutive crop seasons.

| Soil Tillage Treatment | 2014/2015 | 2015/2016 | 2016/2017 |
|------------------------|-----------|-----------|-----------|
|                        | Sunn Hemp | Pearl Millet | Sunn Hemp | Pearl Millet | Sunn Hemp | Pearl Millet |
| NT                     | 8.55 Aa   | 8.77 Aa    | 9.00 Ab   | 10.95 Aa    | 9.48 Aa   | 8.04 Bb     |
| Rip30                  | 9.31 Aa   | 9.01 Aa    | 8.44 Aa   | 8.70 Ba     | 8.06 Ba   | 8.55 Ba     |
| Rip50                  | 9.13 Aa   | 9.12 Aa    | 9.23 Aa   | 9.00 Ba     | 9.65 Aa   | 10.17 Aa    |
| Sub30                  | 8.95 Aa   | 9.13 Aa    | 9.80 Aa   | 9.01 Ba     | 9.88 Aa   | 9.15 Ba     |
| Sub50                  | 9.77 Aa   | 9.57 Aa    | 9.46 Aa   | 9.53 Ba     | 10.21 Aa  | 9.87 Aa     |

CV (%) 7.92

Means followed by the same uppercase letter comparing soil treatments, or lowercase letter comparing cover crops, in each crop season, are not significantly different from each other by Tukey’s test (p < 0.05). NT: no-tillage; Rip30: ripping to a depth of 0.3 m; Rip50: ripping to a depth of 0.5 m; Sub30: subsoiling to a depth of 0.3 m; Sub50: subsoiling to a depth of 0.5 m. CV = coefficient of variation.

Thus, no differences in maize grain yield were found between cover crop and soil tillage treatments in the 2014/2015 crop season (Table 5). In 2015/2016, the control treatment (no tillage) presented higher grain yield when maize was grown on pearl millet residues. Contrastingly, in 2016/2017, the highest grain yield was found when maize was grown on sunn hemp residues (Table 5).

In the 2016/2017 crop season, the lowest grain yield of maize grown sunn hemp residues was found for the treatment with ripping to a depth of 0.3 m. Contrastingly, the lowest yield in the area with pearl millet residues was found for the control treatment, and for the treatments with ripping to a depth of 0.3 m and subsoiling to a depth of 0.3 m (Table 5).

4. Discussion

The results found for soil resistance to penetration in the present study contrast with those found by Santos et al. [12], who reported that decreases in soil compaction following
deep tillage tend to rapidly disappear due to soil reconsolidation in subsequent crop seasons. The results of the present study show that the use of pearl millet or sunn hemp cover crops delays soil reconsolidation, as they promote soil decompaction and biological reaggregation. The use of cover crops preceding main crops is important, as soil compaction problems can be effectively attenuated by continuous soil cultivation.

The improvement in soil reaggregation by using cover crops may have contributed to the lower soil bulk density (SD) found for the 0.0–0.10 m layer in 2018 compared to 2014 (Figure 2). Similar results were reported by Bertollo et al. [14], who evaluated the action of the root system of ruzigrass grown before the summer soybean/maize and winter wheat/oat rotations under a no-tillage system (NTS) and found that the ruzigrass contributed to the soil structuring, resulting in SD lower than those obtained after soil ripping operations for two years in an Oxisol under NTS.

The RP found for 2014 and 2018 were within the range of 2.0 to 4.0 MPa (Figure 2), considered high by the classification proposed by Arshad et al. [32]. Despite the maize grain yield being above the mean found in the region of the experimental site, the RP found may have caused restrictive effects on plant root development.

However, the comparison of the RP among crop seasons (2014 to 2018) showed a decrease in RP in the 0.10–0.40 m layers (Figure 2). This decrease may be due to the combined use of mechanical (ripping or subsoiling) and biological (sunn hemp and pearl millet cover crops) decompaction. According to Guedes Filho et al. [33], the use of only mechanical soil decompaction, without the use of cover crops, is not a recommended practice to improve the soil structural quality, since soil macroaggregates are broken by the mechanical action of the shanks.

According to Silva et al. [34], the RP found for a similar soil to that in the present study was limiting for root growth when higher than 2.0 MPa. However, Grant et al. [35] considered RP between 1.5 and 3.0 MPa as restrictive to plant development in clayey soils. The SD found for 2014 and 2018 were below 1.6 kg dm$^{-3}$, which is considered critical for crop development [36], but not limiting for maize grain yield.

The RP found for the Oxisol (710 g kg$^{-1}$ of sand) was not within the range considered critical for the development of crops. According to Sene et al. [31], the RP considered critical to root development for sandy soils ranges from 6.0 to 7.0 MPa, and approximately 2.5 MPa for clayey soils. Assis et al. [37] found similar results when evaluating SD and RP in Oxisol with 750 g kg$^{-1}$ of sand; they found SD of 1.56 kg dm$^{-3}$ and RP ranging from 3.0 to 6.0 MPa in the 0.0–0.40 m layer.

Other studies carried out in the Cerrado biome have also shown that sunn hemp and pearl millet are plants that can produce great amounts of biomass and increase soil nutrient cycling [18]. The DB production of sunn hemp and pearl millet grown in the summer ranged between 7 and 12 Mg ha$^{-1}$ and 4 and 9 Mg ha$^{-1}$, respectively [8,20–23]; however, the DB of these cover crops is lower in the winter, ranging between 2 and 4 Mg ha$^{-1}$ and 3.5 and 5.3 Mg ha$^{-1}$, respectively [3,24].

The increases in sunn hemp and pearl millet biomass production over the crops seasons (Table 2) can be explained by the root system type of these plants, which can penetrate more compacted soil layers, as the pivoting system of Fabaceae species, or are more aggressive, occupying a greater soil volume, as the fasciculate of Poaceae species. In addition, these cover crops were grown between October and January of each crop season, a period of high rainfall depths in the study region, which provided ideal temperature and humidity conditions for the development of the crops (Figure 1).

However, some studies present diverging results in the same biome [38]. Nunes et al. [39] reported the DB of sunn hemp ranging between 2.4 and 2.5 Mg ha$^{-1}$. These low yields were explained in these studies by the water stress during the study period. Studies conducted by Assis et al. [22] and Torres et al. [23] with pearl millet found DB higher than 10 Mg ha$^{-1}$ when sown at the beginning of the rainy season (October).

The results found for areas with subsoiling to a depth of 0.30 or 0.50 m (Table 3) showed that FB and DB productions were higher when the soil decompaction was carried...
out using subsoiling, regardless of the cover crop used. This result was probably due to the ripper shank that penetrate the soil, which did not have the recommended shape to cause fractures in the soil structure and disrupt the most compacted layers.

According to Liu et al. [10], soil ripping and subsoiling are practices that improve the soil’s structural condition, ripping is recommended to turn the soil to a depth of 0.3 m, and subsoiling is recommended to mobilize soil layers below 0.3 m depth.

Studies conducted by Santos et al. [12], Torres et al. [5], and Silva et al. [6] have shown that the persistence of soil ripping effects is limited and tends to disappear due to soil reconsolidation after a few wetting and drying cycles. However, Rosa et al. [40] found that the soil still presented good structural conditions for crop development two years after soil ripping, but the soil presented low density and high total porosity.

The increase in cover crop biomass production over the years (Table 4) denotes the soil restructuring process, reflecting the effects caused by the soil decompaction with the implements used, the efficient biological decompaction of root systems of the Fabaceae species, and the aggressiveness of the Poaceae species in occupying spaces. These effects alleviated problems due to soil reconsolidation over wetting and drying cycles that naturally occur in agricultural areas, resulting in better edaphoclimatic conditions for the cover plants to develop, which confirms the hypothesis tested in this study.

The effects of ripping and subsoiling persisted satisfactorily for two years of cultivation, since the maize yield was, in general, similar among tillage treatments or between cover crop treatments. After three years of evaluation, tillage treatments, including ripping and subsoiling to a depth of 50 cm, presented higher maize grain yield, mainly when pearl millet was the preceding cover crop. Thus, the use of cover crops preceding the main crop, combined with deep soil turning, can maintain the maize grain yield for three crop seasons.

Assessing the performance of maize crops in soil with different compaction levels caused by traffic of agricultural machinery, Moraes et al. [41] for higher maize yields in the 2013/14 and 2014/15 crop season in experimental areas under no-tillage and areas with scarified soil; they explained this increase by the improvements in physical attributes, which positively affected the soil water retention curve.

In 2015/2016, the control treatment (no tillage) presented higher maize production than the treatments with ripping and subsoiling when grown on pearl millet residues (Table 5). This result indicates that soil cultivation under NTS using cover crops (Poaceae species) is effective for improving soil structuring, with a subsequent increase in crop yield. The results found in the present study confirm those of Bertollo et al. [14], who found that areas with reduced soil tillage with ripping and NTS with eight passes of a grain harvester (220 KPa) negatively affected soybean production; the highest soybean yield was found for the treatment with continuous NTS when soybean was grown after ruzigrass and wheat crops.

According to Torres et al. [42], crop rotations with pearl millet and sunn hemp, preceding or succeeding maize crops, have a positive effect on grain yield in regions of the Cerrado biome.

Higher grain yields were expected for the maize grown on sunn hemp residues, which is a cover crop from the Fabaceae family used as cover crops for improving nutrient cycling, especially N [43]. Sunn hemp also has a fibrous root system that penetrates deep and compacted soil layers, alleviating soil compaction and absorbing nutrients that can be lost by leaching. The recovered N plus the biologically fixed N considerably increases N contents incorporated into the soil [3,15]. However, Torres et al. [42] found higher grain yield when maize was grown on residues of pearl millet sown in November (rainy season); they explained that this higher yield was due to the high pearl millet biomass and nutrient cycling.

Despite the RP found in the present study can be considered high [32], the results of maize grain yield were above the means found in the study region [2], indicating that the soil compaction found was not enough to decrease grain production in the soil evaluated. However, Deperon Junior et al. [44] found decreases in grain yield of up to 22% for an RP
of 3.33 MPa, when compared to areas with no machinery traffic (1.53 MPa) in an Oxisol of sandy texture. Beutler et al. [45] found decreases in maize yield with only one passing of a 3 Mg tractor on an Oxisol (0.91 Mpa RP), reaching a decrease of 22% in grain yield in areas where an 8 Mg tractor passed 8 times (1.97 Mpa RP).

Decreases in maize grain yield of up to 23% were found by Freddi et al. [46] under RP ranging between 0.87 and 2.15 MPa, in sandy clay soil. These results indicate that increases in soil bulk density decrease maize grain yield; however, the intensity of this decrease is variable and mainly dependent on the soil’s physical and chemical characteristics.

A review study presented grain yields 28% to 62% higher than the mean maize grain yield found in the study region for maize grown on pearl millet residues, and 28% to 74% higher for maize grown on sunn hemp residues [1].

5. Conclusions

The subsoiling to a depth of 0.3 or 0.5 m results in higher sunn hemp biomass production, when compared to ripping to a depth of 0.3 or 0.5 m and no-tillage, but soil tillage treatments do not affect pearl millet biomass production.

The soil resistance to penetration of up to 3.3 MPa did not negatively affect cover crop biomass productions and maize grain yield in the Oxisol of sandy clay loam texture.

Mechanical and biological soil decompaction improved maize grain yield throughout the seasons by at least 28% above the average yield in the study area region.

The association between the mechanical and biological decompaction method using cover crops provided greater resilience to the preparation carried out up to three years after the application of the treatments, resulting in greater corn grain productivity, especially when the soil was turned to the depth of 0.50 m (ripping or subsoiling), regardless of the cover crop used (sunn hemp or pearl millet).

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