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Mechanical Chiseling Versus Root Bio-Tillage on Soil Physical Quality and Soybean Yield in a Long-Term No-Till System

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Abstract: Occasional mechanical intervention can help alleviate compaction symptoms in no-till systems, but its effects compared to well-established crop rotation systems are uncertain. Thus, the aim of this study was to evaluate the effects of mechanical and biological chiseling of the soil (via millet and sunn hemp cover crops) on soil physical properties, root development, and soybean yield in a long-term experiment. The treatments consisted of crops rotations used in the spring harvest: (I) triticale (autumn–winter), millet (spring), and soybean (summer); (II) triticale (autumn–winter), sunn hemp (spring), and soybean (summer); and (III) triticale (autumn–winter), fallow/soil chiseling (spring), and soybean (summer). Mechanical chiseling reduced bulk density and penetration resistance in the upper 0.10 m layer by 6% and 37%, respectively. However, its effects did not extend below this depth. Conversely, millet and sunn hemp maintained higher penetration resistance in surface layers but reduced resistance in deeper layers (0.20–0.40 m) by up to 27% compared to chiseling. These cover crops also improved root growth (up to 71% higher root dry mass), soil microporosity, and total porosity. Notably, sunn hemp enhanced water infiltration (151 mm accumulated) and basic infiltration rate (180 cm h^{-1}), outperforming chiseling by 30% and 85%, respectively. Soybean yield was highest under sunn hemp, with an 18% increase over chiseling. Thus, growing millet and sunn hemp in a long-term production system can improve the soil's physical properties, ensuring better infiltration, storage, and availability of water in the soil for plants.

Keywords: biopores; cover crops; deep root systems; *Crotalaria juncea*; *Pennisetum glaucum* L.

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1. Introduction

Considering global population rise, one of the main challenges for agriculture is producing enough food to meet the increasing demand without sacrificing ecosystem services including carbon sequestration, nutrient supply, and water cycle management [1–3]. Studies have shown the annual losses of ecosystem services resulting from soil degradation surpasses USD 10 billion/year [4,5]. According to projections from the Food and Agriculture Organization of the United Nations (FAO), more than 33% of soils worldwide are in a

moderate to severely degraded state, and the main causes include poor soil management and agricultural intensification [6]. Conservation agriculture stands out as an alternative for food production with minimized environmental degradation [7].

One of the most important soil conservation practices worldwide is no-till, which was first adopted in the late 1970s in Brazil in the Paraná state [8]. The benefits from this conservative system include the reduction of soil erosion due to the permanent soil cover, which contributes to the increase in organic matter, nutrients, water availability, greater soil biological diversity, and rise and/or protection in the soil carbon stock [9]. In addition to the numerous benefits from no-till, the climate conditions in Brazil allow successive harvests in parts of the country, enhancing the economic gain of crop production. However, from a long-term perspective, the traffic of larger and heavy machines and implements needed in the no-till system over time may reduce the system sustainability [10–12]. Along with the absence of diversified crop rotation, this machinery traffic, especially in wet soils, has contributed to soil degradation through soil compaction, increasing bulk density and reducing soil porosity, resulting in yield loss [13,14]. Furthermore, the impact of soil compaction will vary based on soil depth. Although some natural processes, such as soil expansion and contraction due to temperature changes, as well as concentration of greater volume of crop roots in the surface layers, can help in remediating topsoil compaction, compaction in subsoils is generally considered more difficult to remediate [15–17]. Some studies indicate that compaction in the subsoil can become cumulative and semi-permanent [18,19].

Strategic or occasional tillage is a management technique that can be used to counteract the adverse consequences of intensive farming systems [20]. Typically, it comprises a mechanical intervention, periodically, to remove any physical barriers to plant root growth [21,22]. The mechanical intervention to mitigate soil compaction in no-till systems can be soil chiseling and/or subsoiling [9], whereby a single strip of soil is mobilized, maintaining at least 30% of the soil surface covered, characterizing a minimum tillage system [23]. Studies show that both strategies can increase soil physical quality [24] and improve crop yield [25,26].

However, one of the concerns is the duration of the positive effects of soil chiseling on the physical characteristics of the soil. Studies indicate that the beneficial effects of chiseling typically do not exceed more than a year, making it necessary to perform the operations annually [22,27–29]. In addition, a chisel can break the continuity of the pores, impacting negatively on water infiltration, and as a result, affect the water storage and availability to plants [30–32]. Chiseling can also reduce root development in depth [33], increasing the susceptibility of plants in prolonged dry periods, reducing crop yield under rainfed conditions [10,34].

An alternative to mechanical intervention is the use of cover crops with a deep and vigorous root system, thereby helping to mitigate the negative consequences associated with compaction [29,35]. This is also known as biological drilling or bio-tillage [36], biological subsoiling [37], or even as biological chiseling [33]. Some well-known deep rooting species used in this instance are Millet and Sunn hemp [29,35]. While millet, a monocotyledon species, has a deep and voluminous root system, Sunn hemp is a dicotyledon species that has a pivoting and aggressive root system. Thus, the benefits promoted by the roots in structuring the soil, as well as the channels resulting from their growth (stable biopores), can promote better conditions for the development of the roots of the successor crop, enabling access to water and nutrients contained in deeper layers and, thus, avoiding possible losses in production, especially if prolonged periods of water deficit occur [30,38–40].

Although previous research has compared the effects of soil scarification and cover crops on different aspects of the agricultural production environment, most was carried out on short- or medium-term implementation experiments or did not evaluate the effects

in deeper layers of soil [29,39]. There is an urgent need for studies in well-consolidated environments to obtain more accurate and reliable data to support future farmer decision making [33,41]. Considering that soybean is an important agricultural commodity and among the main crops susceptible to adverse environmental conditions and management of the production environment [42,43], our hypothesis was that the long-term use of cover crops would be a better alternative than chiseling to improve the physical properties of the soil in the surface and subsurface, resulting in an increase in soybean grain productivity.

2. Materials and Methods

2.1. Study Site

The research was carried out at São Paulo State University farm in Botucatu, São Paulo State (22°49′ S and 48°25′ W, at an altitude of 780 m). The soil of the experimental area is a Typic Rhodudalf [44], classified as a clayey texture. In November 2017, soil sampling was performed at 0.0–0.2 m depths for soil chemical [45] and soil texture [46] characterization (Table 1).

Table 1. Chemical and granulometric analysis of soil, at a depth of 0.00–0.20 m, with crop rotation of millet, sunn hemp, and occasional chiseling.

Spring Management	pH	P	OM	H + Al	Ca	Mg	K	Sand	Silt	Clay
	$CaCl_2$	mg dm^{-3}			$mmol_c$ dm^{-3}			g kg^{-1}		
					0.00–0.20 m					
Millet	4.8	47.7	27.3	55.0	7.7	2.5	5.7			
Sunn hemp	5.2	43.2	31.1	46.5	8.4	3.5	5.1	110	245	645
Chiseling	5.3	42.5	26.7	41.5	8.3	3.5	6.9			
					0.20–0.40 m					
Millet	4.4	29.4	22.3	59.0	7.1	1.7	5.2			
Sunn hemp	4.7	22.9	21.3	50.4	4.6	2.9	4.1	116	220	664
Chiseling	4.8	30.1	23.1	44.9	4.8	1.7	6.0			

pH: active acidity; P: exchangeable phosphorus; OM: organic matter; H + Al: potential acidity; Ca: exchangeable calcium; Mg: exchangeable magnesium; K: exchangeable potassium; $CaCl_2$: 0.01 M calcium chloride solution; mg dm^{-3}: milligram per cubic decimeter; mmolc dm^{-3}: millimol charge per cubic decimeter; g kg^{-1}: gram per kilogram.

The climate in the area is classified as Aw according to Köppen characterized by a megathermic climate (cold season absent or barely perceptible), with a dry winter and rainfall concentrated in the summer. The highest rainfall occurs between November and April, and the dry season is from May to October, with a minimum temperature of 17.2 °C and a maximum of 26.5 °C, with July being the coldest month with a current average temperature of 18.3 °C [47]. The mean temperature and rainfall data during the experiment are shown in Supplementary Material S1.

2.2. Treatments and Experimental Design

The experiment was set up in 2003, growing triticale (*X Triticosecale* Wittmack) during the autumn–winter season, followed by spring management according to each treatment, i.e., millet (*Pennisetum glaucum* L.), sunn hemp (*Crotalaria juncea* L.), or fallow (with sporadic chiseling of the soil), and during the summer season, soybeans [*Glycine max* (L.) Merril] were grown as the main crop. This crop rotation sequence was repeated between 2003 and 2017. On the fallow plots during the spring harvest, the soil was chiseled in 2003, 2009, 2013, and 2016. The experiment was set up as a randomized blocks design with four replications and three treatments. The treatments consisted of the crops/management used in the spring harvest using the following crop rotations: (I) triticale (fall-winter), millet (spring), and soybean (summer); (II) triticale (fall-winter), sunn hemp (spring), and soybean (summer); (III) triticale (fall-winter), fallow/soil chiseling (spring), and soybean

(summer). Each experimental unit covered 40 m^2 (8 × 5 m), with 4 m spacing between plots and between blocks.

Mechanical chiseling of the soil was performed using a chisel with seven shanks set on two parallel bars and spaced 0.60 m from each other within the bars resulting in effective 0.30 m between drill spacings. The shanks were tilted forward at an angle of 25°, and the effective depth of action was around 0.30 m. A cylinder was attached to the equipment to break up the larger clods and level the soil surface.

2.3. Experiment Conduction

In the autumn–winter triticale, cultivar IPR 111 was sown on 10 April 2017 using a continuous-flow seeder, with a sowing density of 230 seeds m^{-2} and row spacing of 0.17 m. After the triticale was harvested in August of 2017, the weeds were chemically managed. Then, at the start of the first rain, in October, spring planting was carried out. Millet (cultivar BRS-1501) and sunn hemp (cultivar IAC KR-1) were sown using a continuous flow seeder, with a row spacing of 0.17 m and a sowing density of 200 seeds m^{-2}. Prior to flowering, the spring plants were chemically desiccated.

Following this, in December 2017, soybean (cultivar TMG 7062) was sown with a row spacing of 0.45 m, at a density of 300,000 plants ha^{-1}. The seeds were treated with the fungicide Carboxin + Thiran, the insecticide Thiamethoxam, the inoculant *Bradyrhizobium* sp., and the micronutrients Co and Mo. Liquid inoculant was used to inoculate the seeds, at a dosage calculated to provide 1.2 million viable cells per seed [48]. Fertilization at sowing was carried out with 60 kg ha^{-1} of K_2O and 60 kg ha^{-1} of P_2O_5, using KCl and single super phosphate, respectively, following the recommendations for the crop [49]. Pre-harvest desiccation of the soybeans was carried out at phenological stage R7.3 (when most of the seeds had a yellowish tegument with a shiny surface and were already detached from the pod), with the herbicide Diquate (0.40 kg i.a. ha^{-1}) in March 2018. The crop was harvested 111 days after sowing.

2.4. Soil and Plant Assessments

2.4.1. Root Development

Soybean root development was assessed using root length density and root dry mass. The soybean root system was assessed at the full flowering stage of soybean (R2 stage). The root system was sampled using a cup-type auger, at depths 0.00–0.10, 0.10–0.20, and 0.20–0.40 m, taking four sub-samples from each plot, totaling 12 samples per treatment and 36 samples in the experiment, considering the three depths.

The samples were washed in sieves of 1 mm size, and the roots were manually separated from the soil using tweezers before being stored under 8 °C in a refrigerator in a solution of alcohol 30%. Later, the root samples were scanned with a 250 dpi resolution scanner, and the root length density (cm of root per cm^{-3} of soil) was determined using the software WinRhizo (Pro version 2019). Then, the root dry mass was determined by oven-drying the root samples at 60 °C for 48 h and adjusting to kg ha^{-1}.

2.4.2. Soil Physical Properties

Soil physical properties were evaluated by analyzing macroporosity, microporosity, total porosity, soil density, and soil penetration resistance. The samples were collected at the R2 stage of soybean. To evaluate the porosity and soil density characteristics, samples with structure preserved were collected in trenches, using volumetric rings measuring 5.0 cm in height by 4.8 cm in internal diameter, in the layers of 0.00–0.10, 0.10–0.20, and 0.20–0.40 m depth. Two volumetric rings were collected per depth in each plot.

In the laboratory, the undisturbed samples were saturated by gradually increasing the water level for 72 h. Then, all saturated samples were weighed and subjected to a −0.006,

−0.33, and −1.5 MPa tension on porous plates in Richard's pressure chamber [50]. Upon achieving stability at each tension, the samples were weighed and dried in an oven at 105 °C for 48 h and weighed again. The soil bulk density was calculated by the ratio between the dry weight and the volume of the samples. The total porosity was calculated from the difference between the saturated weight and dry weight of the samples. Macroporosity was determined by the water content difference between the water-saturated samples and those subjected to a −0.006 MPa tension. Microporosity was calculated as the difference between the total porosity and macroporosity [51].

The penetration resistance test was performed at three points per experimental unit, in soil in friable condition, using an Impact Penetrometer (model IAA/Planalsucar–Stolf, Piracicaba, SP, Brazil), and the data were calculated in a data computational program in EXCEL-VBA [52].

2.4.3. Soil Water Infiltration

Soil water infiltration (WI) was evaluated by the concentric ring infiltrometer method [53]. This methodology is based on the use of two rings of 0.30 m in height, one with 0.30 m and the other with 0.60 m in diameter, positioned concentrically on the ground. The rings were driven vertically 0.15 m into the ground. After filling the total volume of the rings with water, the infiltration reading was performed on the inner ring with the aid of a ruler. The reading was performed until the infiltration rate in the inner ring became constant, that is, with five equal measurements with an interval of 30 min. Infiltration readings were taken at the following time intervals: five readings at one-minute intervals; five readings at two-minute intervals; five readings at five-minute intervals; five readings at ten-minute intervals; five readings at fifteen-minute intervals; five readings at twenty-minute intervals; and finally, five readings with intervals of thirty minutes, to confirm stabilization in the infiltration rate, determining the WI accumulated over time, based on Equation (1) [54,55].

$$WI = k \times T^{n} \quad (1)$$

where WI is the accumulated water infiltration in the soil (cm); k is the soil-dependent constant; T is the time (min); and n is the soil-dependent constant ranging from 0 to 1.

Using the WI data obtained in the field, the basic infiltration rate (BIR) was calculated according to the Kostiakov–Lewis model (Equation (2)) [54,55].

$$BIR = 60 \times a \times k \times T^{a-1} + i_f \quad (2)$$

where BIR is the basic infiltration rate of water in the soil (cm h^{-1}); a and k are statistical parameters soil-dependent constant; T is the time (min); and i_f is the final infiltration rate (cm h^{-1}).

The parameters a and k were estimated using the Gauss–Newton method, minimizing the sum of the squares of the deviations in relation to the infiltration rate values obtained in the field tests.

2.4.4. Storage and Availability of Water in the Soil

Soil water content was assessed using a Diviner 2000® capacitance probe (SentekPt Ltd.a, Stepney, Australia 2009) in PVC access tubes previously installed in each plot. Water content monitoring was assessed at depths of 0.00–0.10, 0.10–0.20, and 0.20–0.40 m, with readings at 1, 3, 5, 8, and 15 days after rainfall (DAR). For this assessment, rainfall above 10 mm was considered.

Soil water content was assessed throughout the soybean cycle. Based on the soil water content, water storage and soil water availability for plants were determined. The

difference in water content between field capacity (FC) and permanent wilting point (PWP) was considered the available water to plants. The FC and PWP were determined in Richard's pressure chamber, −0.33 and −1.5 MPa, respectively [50]. Volumetric ring collection and procedures for analysis followed the methodology described in Section 2.4.2. (Soil physical properties).

2.4.5. Soybean Grain Yield

The soybean grain yield was estimated after the grains' physiological maturity, harvesting the plants from the useful area of each experimental unit (4.5 m^2) and discarding the edges, and the water content of the grains was corrected to 130 g kg^{-1}.

2.5. Statistical Analysis

The data were tested for normality using the Anderson–Darling test and homoscedasticity using the Levene test. After that, the data on root development, soil physical properties, and grain yield were subjected to analysis of variance and the *t*-test to compare means ($p < 0.05$). The results of water content stored in the soil and water available for absorption by plants (difference in water content between field capacity and permanent wilting point) in days after rainfall (DAR) were subjected to the nonparametric Kruskal–Wallis test (non-normal data), and the means were compared by the Tukey test ($p < 0.05$).

3. Results

3.1. Root Development

In general, the cultivation of cover crops favored the root development of soybeans at different soil depths when compared to fallow plus occasional chiseling, with this behavior being verified by the variables of root length density and root dry mass (Figure 1). Considering the soil profile evaluated (0.00–0.40 m), the rotation with millet and crotalaria resulted in a 26% higher soybean root length density when compared to occasional chiseling. Regarding root dry mass, rotation with millet and sunn hemp resulted in an increase of 71 and 55%, compared to occasional chiseling, respectively (Figure 1). In general, soil chiseling resulted in lower root development of soybean plants after 14 years (Figure 1).

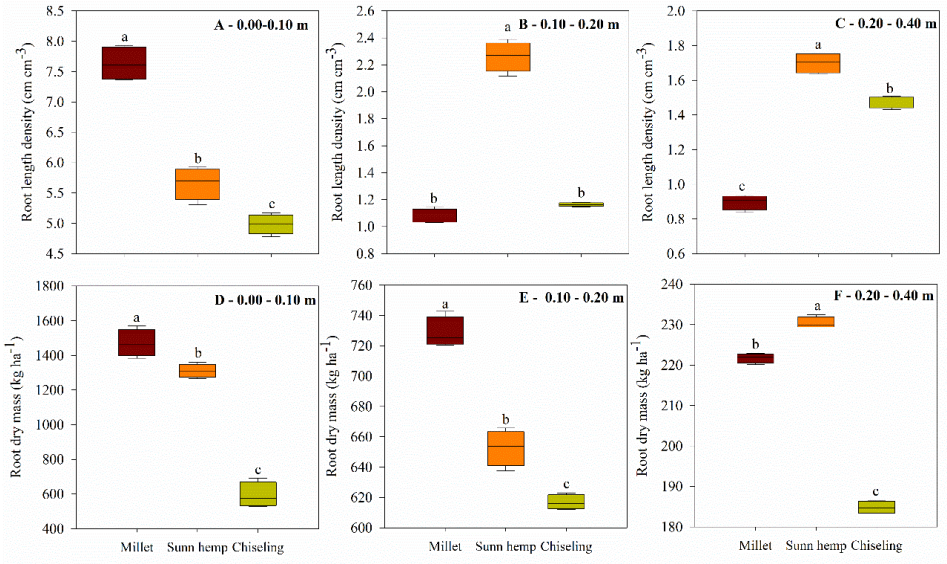

Figure 1. Length density (**A**–**C**) and dry mass (**D**–**F**) of soybean roots cultivated in succession to millet, sunn hemp, or soil chiseling in a long-term experiment, at depths of 0.00–0.10 (**A**,**D**), 0.10–0.20 (**B**,**E**), and 0.20–0.40 m (**C**,**F**). Different lowercase letters indicate significant differences by Student's *t*-test ($p < 0.05$).

When comparing cover crops, millet provided greater soybean root length density in the 0.00–0.10 cm layer and greater root dry mass above 0.20 cm (Figure 1A,D,E). Conversely, sunn hemp allowed for higher root length density in the 0.10–0.20 and 0.20–0.40 cm layers (Figure 1B,C) and higher dry mass of soybean roots at a depth of 0.20–0.40 m (Figure 1F).

3.2. Soil Physical Properties

Occasional chiseling provided greater soil macroporosity in the 0.00–0.10 m layer (Figure 2A) and in the 0.20–0.40 m layer. In the deepest layer, there was no difference in the volume of macropores obtained with sunn hemp cultivation and chiseling (Figure 2C). There was no effect of treatments on macroporosity in the 0.10–0.20 m layer (Figure 2B).

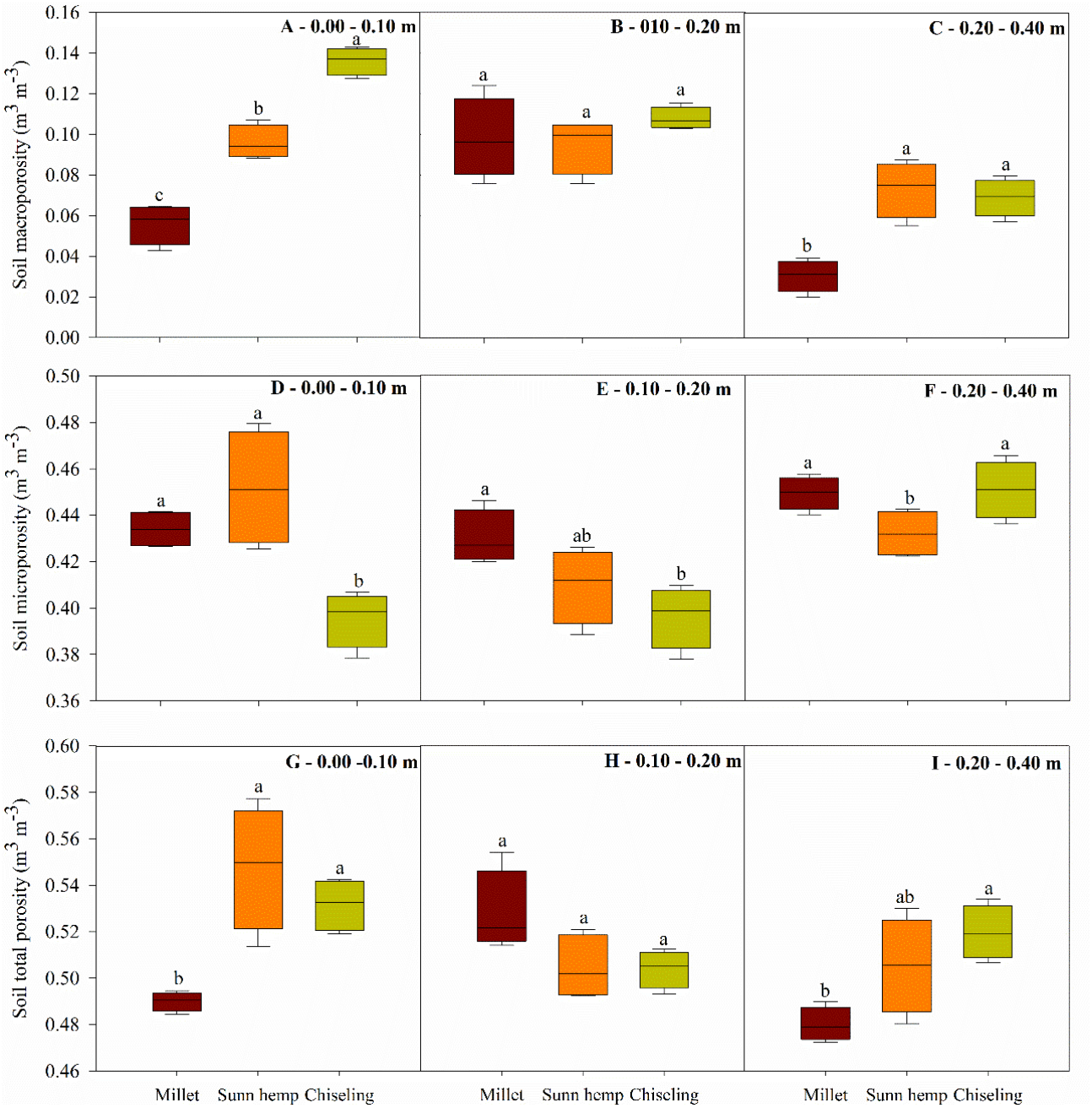

Figure 2. Macroporosity (**A**–**C**), microporosity (**D**–**F**), and total porosity (**G**–**I**) of soil in soybean cultivated in succession to millet, sunn hemp, or soil chiseling in a long-term experiment, at depths of 0.00–0.10 (**A**,**D**,**G**), 0.10–0.20 (**B**,**E**,**H**), and 0.20–0.40 m (**C**,**F**,**I**). Different lowercase letters indicate significant differences by Student's *t*-test ($p < 0.05$).

In general, treatments with cover crops had greater microporosity and total porosity, regardless of depth. Millet promoted greater microporosity, regardless of depth (Figure 2D) and 0.10–0.20 m layers (Figure 2E), and it was similar to occasional chiseling in the 0.20–0.40 m layer (Figure 2F). For total porosity, millet and scarification resulted in larger total pore volumes in the 0.00–0.10 (Figure 2G) and 0.20–0.40 m (Figure 2I) layers. In the 0.10–0.20 m layer, spring management did not affect total soil porosity, although the results had a similar trend to that observed for microporosity (Figure 2H).

Occasional chiseling promoted lower soil bulk density and lower penetration resistance to the soil in the surface layer (Figure 3A,D). No differences between treatments were observed for soil bulk density at other depths (Figure 3B,C). However, millet cultivation had similar penetration resistance to chiseling treatment for the 0.10–0.20 m (Figure 3E) layer and the lowest in the deepest layer (Figure 3F).

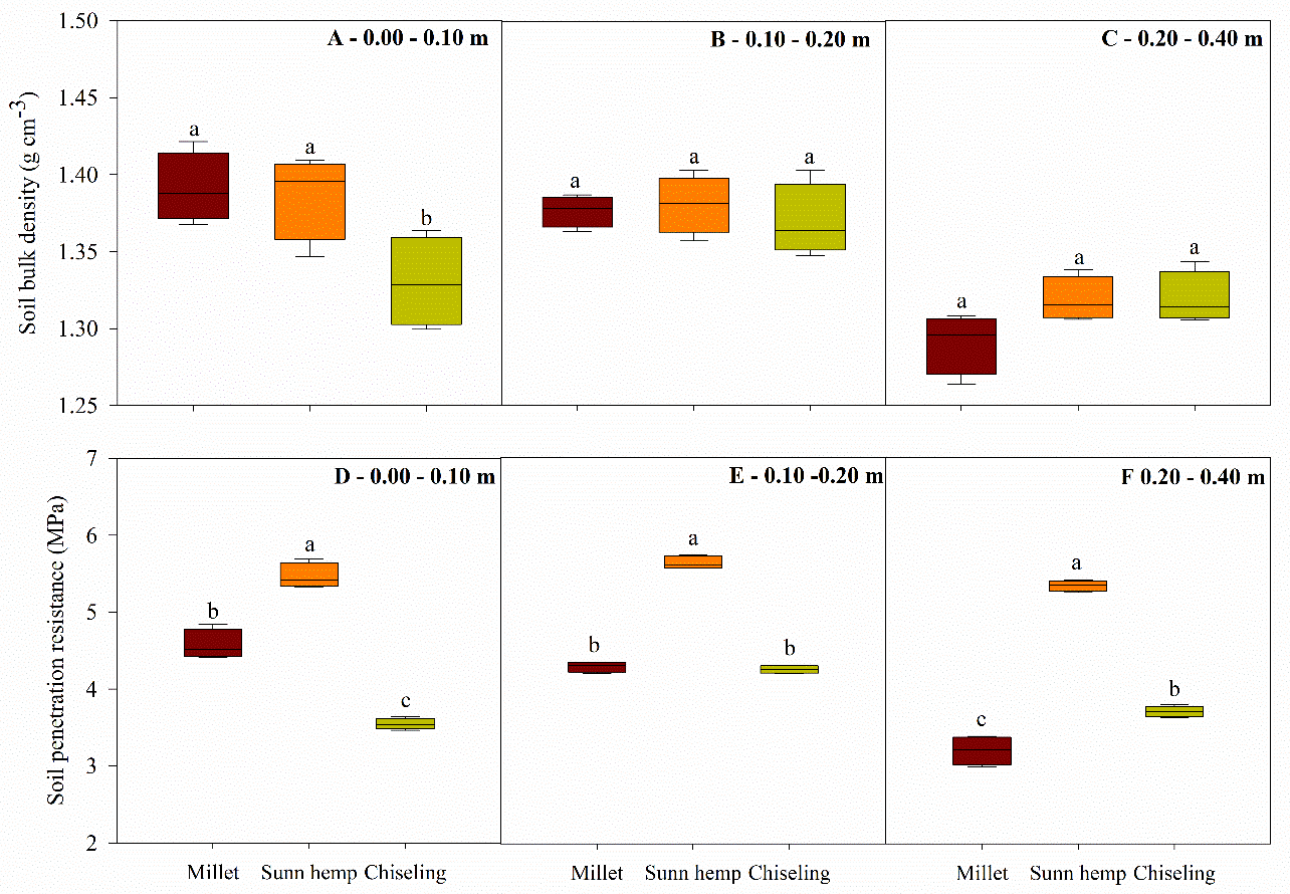

Figure 3. Bulk density (**A**–**C**) and penetration resistance (**D**–**F**) of soil in soybean cultivated in succession to millet, sunn hemp, or soil chiseling in a long-term experiment, at depths of 0.00–0.10 (**A**,**D**), 0.10–0.20 (**B**,**E**), and 0.20–0.40 m (**C**,**F**). Different lowercase letters indicate significant differences by Student's *t*-test ($p < 0.05$).

3.3. Infiltration, Storage, and Availability of Water in the Soil

From the very beginning of the test, sunn hemp had higher soil water infiltration (WI), which totaled to 151 mm in 250 min. As a result, the sunn hemp WI was 11% and 30% higher, respectively, than for millet and chiseling (Figure 4A).

In the first five minutes of evaluation, the rotation with sunn hemp had a greater basic infiltration rate (BIR), reaching a rate of 180 cm h^{-1}. Compared to values achieved with millet and chiseling, this value was 56% and 85% higher, respectively. However, at

the conclusion of the evaluation period, all treatments had a similar stabilized soil water velocity, averaging 24.68 cm h^{-1} (Figure 4B).

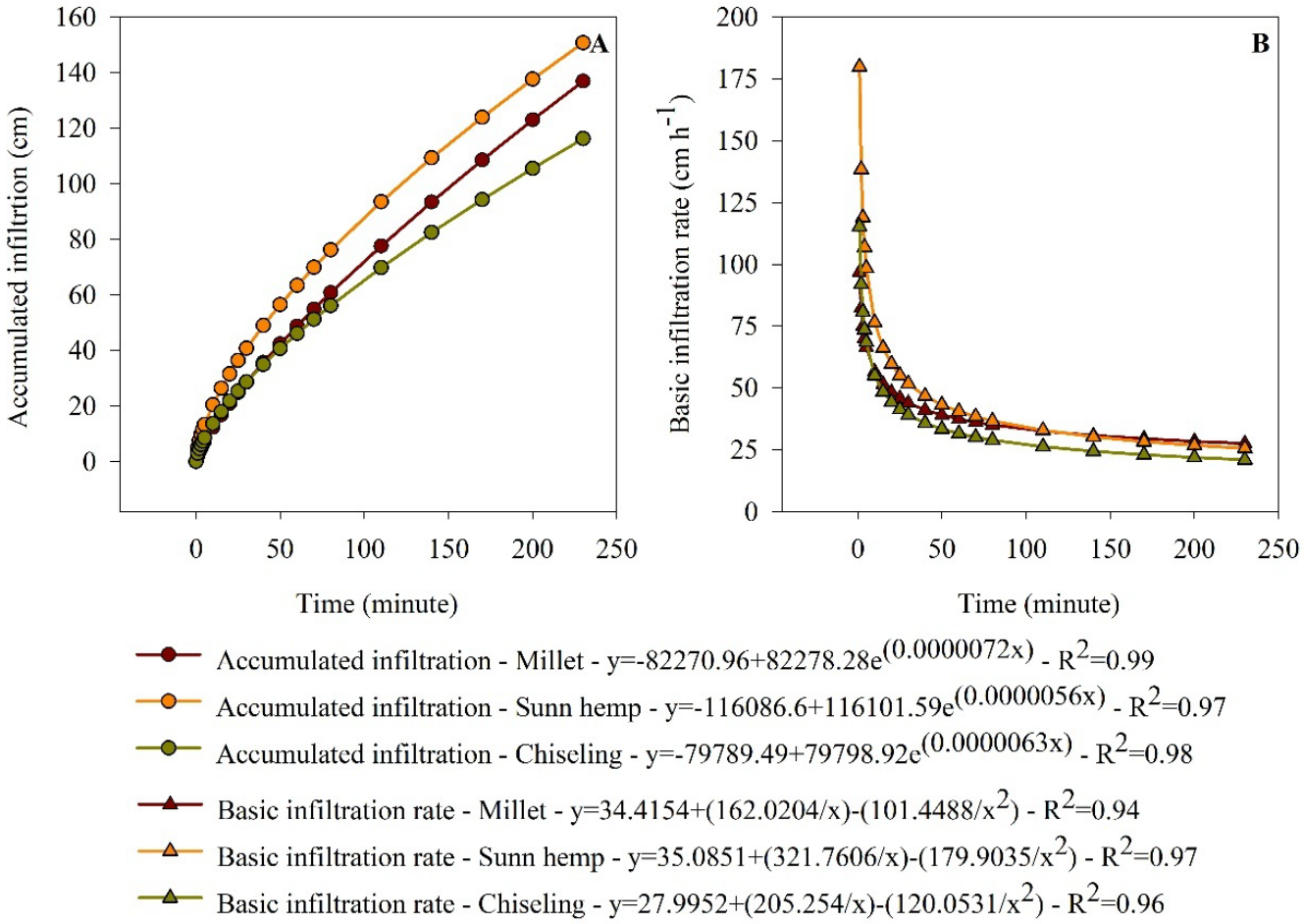

Figure 4. Accumulated infiltration (**A**) and basic infiltration rate (**B**) of water into the soil under crop rotation with millet, sunn hemp, or soil chiseling in a long-term experiment.

Regarding the water content, there was a difference only in the first DAR, at depths of 0.00–0.10 and 0.20–0.40 m (Figure 5A,C). Millet stored a greater amount of water in the first DAR, in the surface layer, compared to the treatment with sunn hemp, with an average stored water content 23% higher (Figure 5A). The other treatments did not significantly differ. At depth (0.20–0.40 m), the treatment with occasional chiseling stored 17% more water compared to cover crops in the first DAR (Figure 5C).

It is worth noting the rotation with millet in the layer below 0.10 m at 1, 3, 5, 8, and 15 DAR stored water content within the range of water available to plants, which can be verified by the presence of the third quartile between FC and PWP (Figure 5B,C). When using sunn hemp as a cover crop, in the surface layer, the highest frequency of available water occurred only in the fifth DAR. In the 0.10–0.20 m depth, at 8 and 15 DAR, there was water stored in the availability range, while in the deeper layer (0.20–0.40 m), there was water available at all DAR (Figure 5). The stored water for chiseling was in the range of availability to plants in the 0.00–0.10 m layer at 5, 8, and 15 DAR; in the intermediate depth at all DAR; and in the subsurface from the third DAR onwards (Figure 5). However, it is important to note that the PWP in millet and chiseling, at all depths, was higher compared to sunn hemp (on average 4% higher) (Figure 5).

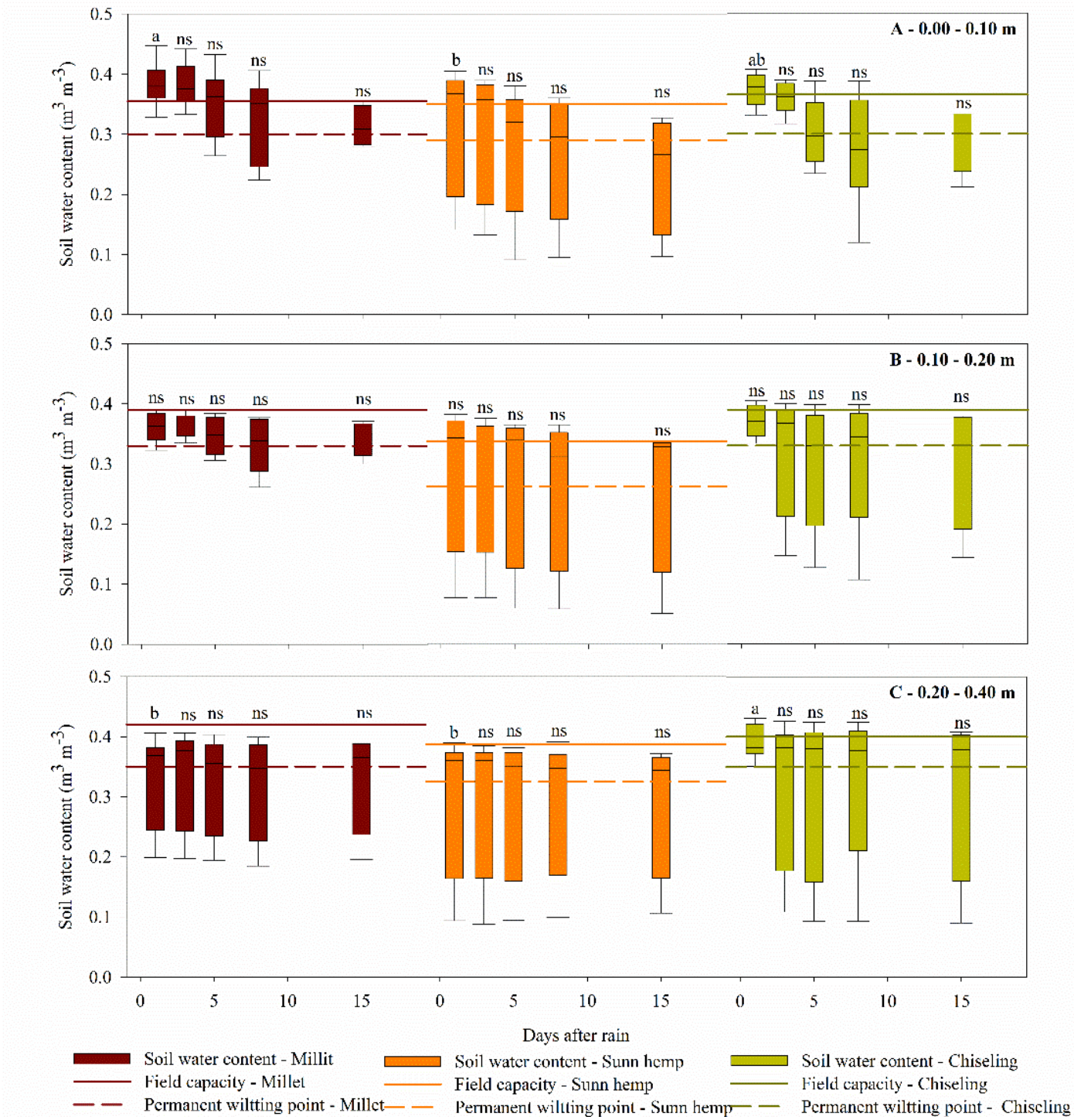

Figure 5. Water content stored in the soil and water available for absorption by plants (content between field capacity (FC) and permanent wilting point (PWP)) in days after rainfall (DAR) in crop rotation with millet, sunn hemp, or soil chiseling, in a long-term experiment, at depths of 0.00–0.10 (**A**), 0.10–0.20 (**B**), and 0.20–0.40 m (**C**). Different lowercase letters indicate significant differences between treatments on the same DAR reading via the Tukey's test ($p < 0.05$); ns: treatments do not differ from each other on the same DAR reading via the Kruskal–Wallis's test ($p < 0.05$).

3.4. Soybean Grain Yield

The highest soybean yields were obtained in the cover crop treatments. However, the rotation with sunn hemp produced 2% and 18% higher yields than those obtained with millet and occasional chiseling, respectively (Figure 6).

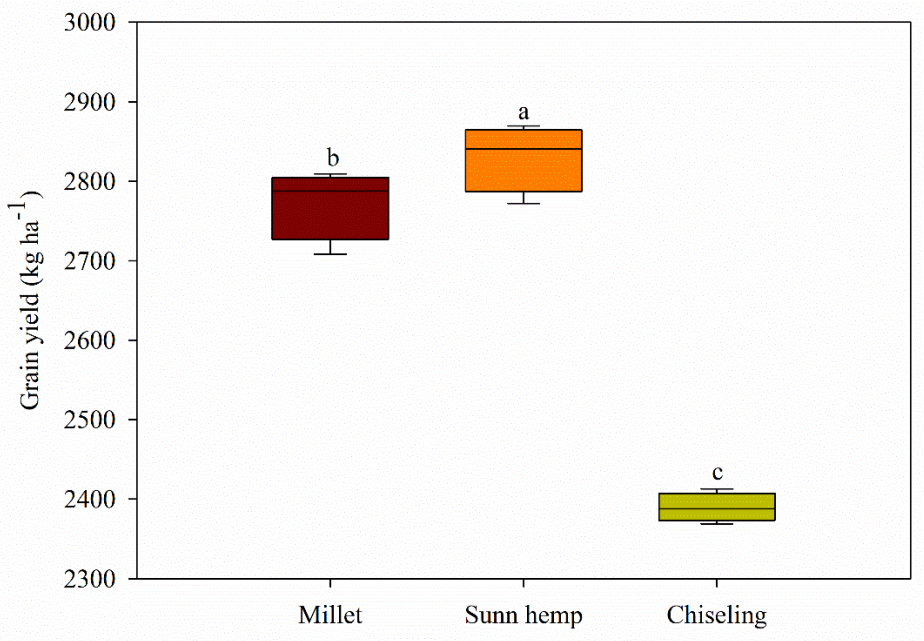

Figure 6. Yield of soybean grains grown in succession to millet, sunn hemp, or soil chiseling in a long-term experiment. Different lowercase letters indicate significant differences by Student's *t*-test ($p < 0.05$).

4. Discussion

Greater root development favors better exploitation of the soil for water and nutrients, providing greater stability in production, especially during periods of prolonged drought [56,57]. This advantage is enhanced when there is greater root development in the subsurface. In this study, soybeans grown after millet and crotalaria showed greater root development at depth in the soil profile (Figure 1). Inagaki et al. [33] found similar results for soybean root growth when comparing soil chiseling to the introduction of bio-tillage, using radish in crop rotation.

Since this is a long-term experiment, greater growth of soybean roots in the subsurface (0.20–0.40 m) in the millet and crotalaria treatments must be associated with the greater root development of the previous crops (millet and sunn hemp) [58], which, when decomposing, left root channels in the soil (biopores), guiding the deep growth of the soybean roots, thus promoting a more expansive exploration of the soil profile [40,59]. Continuous biopores act as pathways, connecting the soil surface to deeper layers, providing greater root colonization at depth, soil aeration, and water infiltration into the soil [39].

Compared to the treatment with occasional chiseling, cover crops obtained a 17% higher soybean yield (Figure 6) due to the greater quantity of subsurface roots combined with the stored and available water content in these treatments. Colonizing soil profiles with roots is a way to increase soil organic matter content in subsoil, helping to rebuild degraded soils and creating channels that facilitate water infiltration and root growth of species with poor penetration potential in compacted soils [60,61]. Enhancing soil porosity will also limit the buildup of ethylene, which can act as a trigger to slow down root growth in soils with high bulk density [62].

In addition, the growth and development of roots in the soil profile contributes to improving the soil's physical and hydraulic properties [39,57], as can be seen in the results of this research (Figures 2–4). During the growth process, the expansion of roots brings the soil particles closer together, supporting the development of soil structure and porosity [63]. Plant roots fill the soil's macroporosity, providing stability to the aggregates, and when

decomposing, they generate organic compounds, releasing substances that cement the macroaggregates, favoring the infiltration and retention of water in the soil [64–67].

Besides these hydro-physical effects, biopores provide a favorable microclimate for root growth, as there is a higher organic matter content (SOM), either from root exudates or even from the decomposition process of dead roots. SOM plays an important role in root development, as it acts as a source and reservoir of nutrients and complexes metals such as Al and Mn, reducing their toxic effect on the plant [68,69].

There was a higher densification in the surface layer in the treatments with cover crops (and without tillage), indicated by the porosity, soil density, and penetration resistance parameters (Figures 2 and 3). Although the chiseling of the soil promoted an increase in soil porosity, which was higher compared to the biological tillage treatments (Figure 2), this did not result in greater root development in the soybean (Figure 1). The increase in total porosity promoted by the action of mechanical implements to mobilize the soil and breakup compaction does not guarantee greater root growth, as it destroys the continuity of the pores [29,70]. Furthermore, the penetration resistance was higher in the cover crop treatments, varying from 4.5 to 5.5 MPa in the first layer for millet and sunn hemp, respectively (Figure 3). Critical levels of compaction that limit root penetration and crop yields vary by crop and soil texture class, but penetration resistance values > 2 MPa in coarse-textured soils and >3 MPa in fine-textured soils can be critical limits [34,71]. Nevertheless, the growth of the root system and the grain yield of the soybean plants were not negatively affected (Figures 1 and 6). Since there was no soil disturbance in these treatments and this is a long-term experiment, greater continuity of the biopores along the soil profile is expected, which contributes to the root development of successive crops [38]. In addition, in the subsurface, the cover crops were able to improve the soil's porosity characteristics, something the mechanical chiseling was unable to achieve (Figure 2).

Soil porosity is responsible for aeration and water supply to plants. Macropores improve soil aeration, root growth, and water infiltration, while microporosity support water retention in the soil [72,73]. Once this water was already in the soil profile, sunn hemp treatment had greater water storage within the range of availability to the plants at the different DARs, especially in the subsurface (Figure 5). It is worth noting that chiseling showed similar results at a depth of 0.20–0.40 m. However, this treatment led to soils more susceptible to drought hypothesized as the root depth was smaller and less available water (FC–PWP). These results could be related to the lower grain yield. The millet rotation not only increased topsoil water storage, but also made water available to subsurface plants from the third day after rain (Figure 5). Compared to sunn hemp, however, it had lower accumulated water infiltration and basic infiltration rates (Figure 4). These results may be related to greater soil coverage with crop residues during soybean cultivation. Millet crop has greater potential for biomass production and C/N ratio, compared to sunn hemp [74], which favors soil water conservation. Greater soil coverage and straw persistence reduces water evaporation throughout crop cultivation, contributing to greater water storage and availability [75]. In addition, straw on the soil reduces the impact of rain on the soil surface and the water infiltration rate [76], which explains the lower infiltration and basic infiltration rate, as well as the greater storage and availability of water in the soil.

While this study provides results from just one harvest, it is worth noting that this is a long-term experiment. As such, it is a well-established environment in which the soil properties have stabilized, ensuring greater reliability of the data. As conservation agricultural practices become more widespread, data such as these provide important information to support farmer decision making, especially when plants can be used to enhance soil properties over mechanical interventions.

5. Conclusions

Growing millet and sunn hemp as cover crops and for biological tillage in a long-term production system can improve the soil's physical properties, ensuring better infiltration, storage, and availability of water in the soil for plants, especially in systems with rotation with sunn hemp. In addition, the insertion of cover crops significantly favors root development and grain yield of soybeans grown in succession. Importantly, we found chiseling improves the porosity characteristics of the soil on the surface, but this does not benefit the process of water infiltration along the profile and root development in the subsurface, resulting in a soil more susceptible to drought. Our study shows that changes in the root growth environment promoted by cover crops can be a determining factor in soybean productivity. In addition, our results show that in no-tillage systems, high penetration resistance values do not necessarily indicate limitations to soybean root growth, and that water infiltration results may better explain the compaction state and restrictions to root growth.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15051249/s1. Supplementary Material S1. Means temperature and rainfall in fall–winter and spring–summer seasons since experiment implementation (1985–2018) (A), and means monthly temperature and rainfall between the years 1985 and 2018 and during the 2017/18 season (B).

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Abbreviations

The following abbreviations are used in this manuscript:

BIR	basic infiltration rate
DAR	days after rainfall
FC	field capacity
PWP	permanent wilting point
WI	soil water infiltration

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