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Critical Limits for Soybean and Black Bean Root Growth, Based on Macroporosity and Penetrability, for Soils with Distinct Texture and Management Systems

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Abstract: Soil compaction is a worldwide problem in agricultural areas, and it is important to define soil properties and reference values that allow knowledge of the compaction level for decision making. The objective of this study was to define the critical values of physical properties associated with the compaction of soils. Three Ultisols and two Oxisols, under different management systems, were collected at different depths for an evaluation of particle size, volumetric moisture, bulk density, and porosity. In the field, soil resistance to penetration and the root length of the soybean and edible black bean crop were measured. The soil profiles presented horizontal layers with similar resistance, but in some cases, there is discontinuity of these layers, which allows the roots to use the zones of lower resistance to deepen in the profile. The values of bulk density and resistance to penetration critical to soybean and edible black bean (only in sandy loam soil) root growth, according to soil textural class, are: sandy loam = 1.66 Mg m^{-3} and 1.5 to 2 MPa; loam and clay loam = 1.52 Mg m^{-3} and 1 to 1.5 MPa; silty clay loam and silty clay = 1.32 Mg m^{-3} and 1.5 to 2 MPa; and clay = 1.33 to 1.36 Mg m^{-3} and 2 to 3.5 MPa.

Keywords: critical bulk density; critical macroporosity; profile of soil resistance to penetration; soil compaction; soil management; no-tillage; chiseling

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1. Introduction

Soil compaction is a worldwide problem in agricultural areas. With soil compaction, there are several negative effects on soil functioning, from its direct interference on nutrient uptake by plants, such as phosphorus and potassium that are absorbed by plants by diffusion, to reduced crop productivity, increased production costs, and reduction in leaf area due to the increased production of abscisic acid by plant roots [1]. Reduced root growth and changes in soil physical properties due to compaction have been observed in many crops, such as soybean [2–7], corn [8–12], wheat [13–16], edible black beans [17–24], rice [25,26], cassava [27–31], onions [32], Crambe [33], sugarcane [34,35], tobacco [36], cover crops [37,38], pastures/grasslands [39–45], and forest plantations [46–51].

In several of these studies, the existing compaction state was increased by additional wheeling, or compaction alleviation was tested by tillage (inversion and/or chiseling) and the use of cover crops. Nonetheless, only few of these studies searched for critical limits for root growth and crop yield. Furthermore, it is important to stress the existence of a feedback mechanism where, for instance, soil fertility affects the plant's response to soil compaction. For example, wheat growth in response to physical impairment in the soil is dependent on the availability of P [52].

Given the need to implement sustainable soil management to recover degraded soils and improve soil health, providing food and clean water, maintaining biodiversity, ensuring carbon sequestration, and increasing resilience to climate change, it is necessary, among others actions, to prevent and mitigate soil compaction [53]. For more sustainable soil management, it is important to define soil properties and reference values that allow a knowledge of the compaction levels for decision making regarding compacted layer management strategies. Among the properties used to identify compacted layers and the effects of soil use and management, bulk density and mechanical resistance to penetration have been widely used. For example, Silva et al. [54] used these properties to identify the level of soil compaction in a watershed, while Queiroz et al. [55] used them to evaluate different agroecosystems in the Brazilian semiarid region.

Soil resistance to penetration indicates the level of compaction and resistance to root penetration, which is used in the assessment of soil quality in agricultural areas and in decision making regarding the need or not of mechanical soil tillage to reduce it and reduce physical restrictions on plant root development [56]. Aiming at better soil management, Spliethoff et al. [57] evaluated the spatial variability of penetration resistance in an experimental area of 0.2 ha with different sampling grids in an Oxisol. Further, Andrade et al. [58] evaluated the spatial variability of soil resistance to penetration in coffee plantations to obtain information about compaction and support decision making regarding the performance of the subsoiling operation.

Some studies indicated bulk density values [4,36,59–62] and resistance to penetration [59,63–66] as being critical or limiting to plant root growth. However, there is still a need for further studies to validate those values already identified or to present new values. In addition, crops have different responses to soil limitations; soil bulk density is dependent on soil texture [19] and penetration resistance varies according to soil moisture, bulk density, and texture [38,67–69] according to the three-dimensional variability of the soil and the presence of biopores in compacted soil layers [13,70–72] that enable root growth. All these variables make it difficult to define critical or limiting values for plants, but they should be pursued.

Therefore, the objective of this work was to define the critical values of some physical properties associated with the compaction of Ultisols and Oxisols submitted to different management systems.

2. Materials and Methods

To carry out this study, five soils in five municipalities from Rio Grande do Sul State (Figure 1), Brazil, under different management systems, were studied in the first semester of 2004. Although the data are from 2004, this scientific topic is still current and relevant, since there is still little information available on critical values, especially bulk density and soil resistance to penetration associated to soil compaction in soils with different texture. The soils under study were: Argissolo Vermelho Distrófico arênico, Argissolo Vermelho Distrófico latossólico, Argissolo Vermelho–Amarelo Alumínico típico, Latossolo Vermelho Distrófico típico, and Latossolo Vermelho Aluminoférrico típico, according to the “Brazilian System of Soil Classification” [73] or, respectively, Ultisols and Oxisols [74].

In some soils, the sampling was carried out at the headboard/turning point of the planting area, searching for samples with higher levels of soil bulk density, resulting in samples with a range of bulk density values, including values that may be critical for root growth and/or represent soil physical degradation. During the conduction of this study, with the exception of the chisel management of Argissolo Vermelho Distrófico arênico (Ultisol), which had edible black bean crop in the area, the other managements were with soybean crop. The managements/tillage in each soil and the weather conditions [75] were as follows:

(1) Argissolo Vermelho Distrófico arênico (Ultisol): Soil sampling in an experimental plot and production area of the Department of Soils of the Federal University of Santa Maria (UFSM), municipality of Santa Maria, Rio Grande do Sul State, at 151 m altitude,

with the following managements: experimental plot in which it received chiseling in the year 2002 and no-tillage in the following years, and prior to chiseling it had been under no-tillage for approximately 8 years (Chisel); production area for 12 years under no-tillage (NT); and headboard/turning point of the area for 12 years under no-tillage (NTC). The annual climatic characteristics of the municipality are: minimum, average, and maximum temperature of, respectively, 6.3 °C, 19.2 °C, and 25.2 °C; average relative humidity of 77%; and accumulated rainfall of 1624.9 mm;

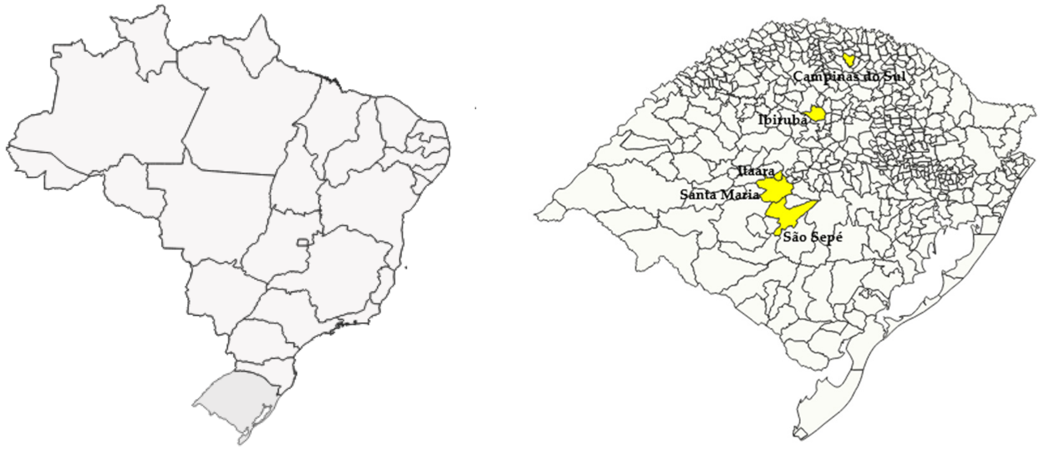
(2) Argissolo Vermelho Distrófico latossólico (Ultisol): Soil sampling from two farms in the municipality of São Sepé, Rio Grande do Sul State, at 85 m altitude, with managements: Farm 1—four years under no-tillage, with pasture cultivated prior to the beginning of the no-tillage system (NT); headboard/turning point of farm 1 (NTC 1); Farm 2—potato cultivation in 2002 and no-tillage in the following years (potato); and Farm 2—headboard/turning point of the area for four years under no-tillage (NTC 2). The climatic characteristics of the municipality are not available, but the municipality borders Santa Maria (Figure 1);

(3) Argissolo Vermelho-Amarelo Alumínico típico (Ultisol): Soil sampling from two farms in the municipality of Itaara, Rio Grande do Sul State, at 425 m altitude, with the managements: Farm 1—conventional tillage from 1980 to 1995, and no-tillage in the following years (NT 1); Farm 1 headboard/turning point (NTC); Farm 2—no-tillage since 1986 and in winter there is animal grazing for 90 days in ryegrass sown in the area and harvested (NT 2); and Farm 2—potato planting with conventional tillage in 1998, chiseling in 2000, and no-tillage in the following years (potato). The climatic characteristics of the municipality are not available, but the municipality borders Santa Maria (Figure 1).

(4) Latossolo Vermelho Distrófico típico (Oxisol): Soil sampling in two farms in the municipality of Ibirubá, Rio Grande do Sul State, at 416 m altitude, with the managements: Farm 1—chiseling in the winter of 2002 and no-tillage in the following years (NT 1); headboard/turning point of farm 1 (NTC 1); Farm 2—chiseling in the winter of 2000 and no-tillage in the following years (NT 2); and headboard/turning point of farm 2 (NTC 2). The annual climatic characteristics of the municipality are: minimum, average, and maximum temperature of, respectively, 12.8 °C, 17.8 °C, and 24.9 °C; average relative humidity of 77%; and accumulated rainfall of 1205.9 mm;

(5) Latossolo Vermelho Aluminoférrico típico (Oxisol): Soil sampling from three farms in the municipality of Campinas do Sul, Rio Grande do Sul State, at 583 m altitude, with managements: Farm 1—no-tillage for 10–12 years (NT 1); Farm 1—no-tillage for 10–12 years and received chiseling in the winter of 2003 and subsequent sowing of oats (Chisel); Farm 2—pasture cultivated in winter (Pasture); Farm 2—no-tillage for 10 years (NT 2); and Farm 3—no-tillage for 10–12 years (NT 3); and headboard/turning point of farm 3 (NTC). The climatic characteristics of the municipality are not available, but the municipality is near Erechim, with annual minimum, average, and maximum temperature of, respectively, 5.9 °C, 18.2 °C, and 23.3 °C; average relative humidity of 79%; and accumulated rainfall of 1737.5 mm.

Soil samples with unpreserved structure were collected in the 0–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, and 0.25–0.30 m layers of each soil and passed through a 2.0 mm mesh sieve to evaluate particle size distribution by the method of pipette [76], with three replicates. The dispersion of soil samples was carried out by horizontal shaking at 120 rpm for 4 h, using 100 mL "snap cap" glasses containing 20 g of soil, 10 mL of 6% NaOH (chemical dispersant), 50 mL of distilled water, and two nylon spheres weighing 3.04 g, diameter 0.0171 m, and density 1.11 Mg m^{-3} [77]. The clay (particles < 0.002 mm in diameter) was determined by pipetting, the sand was separated into coarse (diameter between 2 and 0.25 mm) and fine (diameter between 0.25 and 0.053 mm) by sieving, and the silt (diameter between 0.053 and 0.002 mm) by calculating the difference of the sum of clay and sand. The results of particle size distribution were used for their textural classification, in the textural triangle from "National Resource Conservation Service/United States Department of Agriculture" [78].



(**a**) (**b**)

Figure 1. (**a**) Map from Brazil, with Rio Grande do Sul State highlighted; (**b**) map from Rio Grande do Sul State with the municipalities São Sepé, Santa Maria, Itaara, Ibirubá, and Campinas do Sul highlighted. Maps without scale.

To collect soil samples with preserved structure, three trenches were opened in each management, close to each other, thus avoiding variability between samples. In each trench, samples with preserved structure were collected in metal rings of 0.0300 m in height and 0.0555 m in diameter in the 0–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, and 0.25–0.30 m soil layers. After preparing the samples, they were saturated by capillarity, weighed, and sent to the tension table, where a tension of 6 kPa was applied. After two days on the tension table, the samples were weighed and dried at a temperature of 105 °C, where they remained for two days and then weighed. After all these procedures, bulk density, total porosity, macroporosity, and microporosity were calculated [76].

Soil mechanical resistance to penetration was quantified in the field with a digital penetrometer brand Remik CP 20 Ultrasonic Cone Penetrometer, manufactured by Agridry Rimik Pty Ltd., Toowoomba City, Australia Country, with electronic data storage and conical tip with a penetration angle of 30°. The readings were taken at every 0.015 m depth and, with the exception of the Latossolo Vermelho Aluminoférrico, where the readings were taken between the seeding lines, for the other soils the measurements were made at the seeding line and at 0.10, 0.20, and 0.30 m to the left and to the right of the seedling line, forming a profile of mechanical resistance to penetration.

Volumetric soil moisture at the time of evaluation of mechanical resistance to penetration was obtained from soil samples with preserved structure, for 0–0.05, 0.05–0.10, 0.10–0.15, 0.15–0.20, 0.20–0.25, and 0.25–0.30 m soil layers.

The evaluation of the root growth of soybean (and edible black bean in the chisel management of Argissolo Vermelho Distrófico arênico) was carried out in open trenches at the sampling sites to assess the physical properties of the soil. The trenches were opened until the depth of growth of the root system, which was exposed, and the depth of growth was measured with a measuring tape. In the Latossolo Vermelho Distrófico típico (Oxisol), this evaluation was not performed.

Pearson correlation analysis was performed between the physical properties of the soil.

3. Results and Discussion

The soils presented a wide range of granulometric variations and textural classes, with the clay contents between 86 and 612 g kg^{-1} and total sand between 76 and 674 g kg^{-1} (Table 1).

Table 1. Distribution of particles by size and textural class for the different layers of Ultisols and Oxisols under study.

Layer, m	Sand			Silt	Clay	Textural Class
	Total	Coarse	Fine			
	g kg^{-1}					
Argissolo Vermelho Distrófico arênico (Ultisol)						
0–0.05	674	203	471	240	86	Sandy loam
0.05–0.10	660	196	464	237	103	Sandy loam
0.10–0.15	655	187	468	253	92	Sandy loam
0.15–0.20	654	189	465	256	90	Sandy loam
0.20–0.25	653	204	449	253	94	Sandy loam
0.25–0.30	669	200	469	244	87	Sandy loam
Argissolo Vermelho Distrófico latossólico (Ultisol)						
0–0.05	439	252	187	350	211	Loam
0.05–0.10	408	246	162	326	267	Loam
0.10–0.15	399	245	154	342	259	Loam
0.15–0.20	389	240	149	336	275	Clay loam
0.20–0.25	358	219	139	324	318	Clay loam
0.25–0.30	354	214	140	308	338	Clay loam
Argissolo Vermelho-Amarelo Alumínico típico (Ultisol)						
0–0.05	161	55	106	503	336	Silty clay loam
0.05–0.10	149	54	95	468	383	Silty clay loam
0.10–0.15	146	57	89	459	395	Silty clay loam
0.15–0.20	144	59	85	443	413	Silty clay
0.20–0.25	133	55	78	442	425	Silty clay
0.25–0.30	123	51	72	428	449	Silty clay
Latossolo Vermelho Distrófico típico (Oxisol)						
0–0.05	345	119	226	227	428	Clay
0.05–0.10	335	116	219	225	440	Clay
0.10–0.15	338	112	226	210	452	Clay
0.15–0.20	338	116	222	202	460	Clay
0.20–0.25	312	111	201	196	492	Clay
0.25–0.30	297	108	189	198	505	Clay
Latossolo Vermelho Aluminoférrico típico (Oxisol)						
0–0.05	127	13	114	368	505	Clay
0.05–0.10	120	10	110	352	528	Clay
0.10–0.15	121	11	110	340	539	Clay
0.15–0.20	120	11	109	334	546	Clay
0.20–0.25	118	10	108	339	543	Clay
0.25–0.30	76	7	69	312	612	Clay

With increasing soil bulk density, there was a decrease in macroporosity and microporosity. The increase in total porosity was associated with the increase in macroporosity and microporosity, and increased macroporosity was associated with lower microporosity (Table 2). Soil granulometry was associated with the physical properties of the soil (Table 2), where the increase in the sand content and the decrease in the silt and clay contents were related to an increase in bulk density, while a decrease in the sand content and increase in silt and clay correlated with increase in total porosity and microporosity.

Table 2. Pearson correlation between the physical properties of the soil, considering all data from Ultisols and Oxisols.

	TP	Macro	Micro	TS	CS	FS	Silt	Clay
BD	−0.86 **	−0.55 **	−0.55 **	0.51 **	0.55 **	0.38 **	−0.17 *	−0.52 **
TP		0.38 **	0.81 **	−0.73 **	−0.80 **	−0.55 **	0.24 **	0.75 **
Macro			−0.22 *	0.18 *	0.06 ns	0.23 *	−0.03 ns	−0.20 *
Micro				−0.89 **	−0.88 **	−0.73 **	0.27 **	0.92 **

Sample size: 126 observations (21 managements/tillage for the five soils x six soil layers). BD: bulk density; TP: total porosity; Macro: macroporosity; Micro: microporosity; TS: total sand; CS: coarse sand; FS: fine sand. ns: no significative; ** significative at 1%; * significative at 5%.

A macroporosity value < 0.10 m^3 m^{-3} is considered by several authors to be critical for plant growth [79,80]. Thus, from the regression analysis between bulk density and macroporosity, it is possible to define the bulk density corresponding to this macroporosity value, which indicates the critical bulk density for soil aeration (BD_{macro}). For the Argissolo Vermelho Distrófico arênico (Ultisol), of the textural class sandy loam, the BD_{macro} = 1.66 Mg m^{-3}; for the Argissolo Vermelho Distrófico latossólico (Ultisol), of the textural class loam and clay loam, the BD_{macro} = 1.52 Mg m^{-3}; and for the Argissolo Vermelho–Amarelo Alumínico típico (Ultisol), of the textural class silty clay loam and silty clay, the BD_{macro} = 1.32 Mg m^{-3}, which was similar to the value for the Latossolo Vermelho Distrófico típico (Oxisol) (BD_{macro} = 1.33 Mg m^{-3}) and Latossolo Vermelho Aluminoférrico típico (Oxisol) (BD_{macro} = 1.36 Mg m^{-3}), both of the clay textural class (Table 3).

Table 3. Equations obtained by the relationship between macroporosity (macro) and bulk density (BD) for each soil class, and critical bulk density (BD_{macro}) corresponding to a macroporosity of 0.10 m^3 m^{-3}.

Soil	Equation	R^2	RMSE	BD_{macro}, Mg m^{-3}	Textural class
AVDA	Macro = 0.47146 − 0.22396 BD	0.50 **	0.02509	1.66	Sandy loam
AVDL	Macro = 0.59070 − 0.32295 BD	0.63 **	0.02607	1.52	Loam and clay loam
AVAAT	Macro = 0.51598 − 0.31617 BD	0.64 **	0.02407	1.32	Silty clay loam and silty clay
LVDT	Macro = 0.52469 − 0.31983 BD	0.84 **	0.01648	1.33	Clay
LVAT	Macro = 0.57691 − 0.35060 BD	0.70 **	0.03108	1.36	Clay

Sample size: 126 observations (21 managements/tillage for the five soils x six soil layers). AVDA: Argissolo Vermelho Distrófico arênico (Ultisol); AVDL: Argissolo Vermelho Distrófico latossólico (Ultisol); AVAAT: Argissolo Vermelho–Amarelo Alumínico típico (Ultisol); LVDT: Latossolo Vermelho Distrófico típico (Oxisol); LVAT: Latossolo Vermelho Aluminoférrico típico (Oxisol). RMSE: root mean squared error. ** significative at 1%.

From the BD_{macro} values and the textural class of the soils, the values were inserted into the textural triangle (Figure 2).

The BD_{macro} values (Table 3, Figure 2) are similar to those presented by Reichert et al. [61], who obtained critical bulk density values based on the least-limiting water range, and lower than those calculated from the equation (BDrest = −0.00071 clay + 1.86180) provided by Reichert et al. [19], obtained from critical bulk density values based on the root growth restriction of annual crops. Calculating bulk density from the equation proposed by Reichert et al. [19], the critical bulk density ranges for the soils in this study are: AVDA = 1.8 Mg m^{-3}, AVDL = 1.6 to 1.7 Mg m^{-3}, AVAAT = 1.5 to 1.6 Mg m^{-3}, LVDT = 1.5 to 1.6 Mg m^{-3}, and LVAT = 1.4 to 1.5 Mg m^{-3}. On the other hand, from the values presented by Reichert et al. [61], the bulk density ranges for some soils in this study are: AVDA = 1.7 to 1.8 Mg m^{-3}, AVDL = 1.4 to 1.5 Mg m^{-3}, AVAAT = not rated by Reichert et al. [61], and LVDT and LVAT = 1.3 to 1.4 Mg m^{-3}.

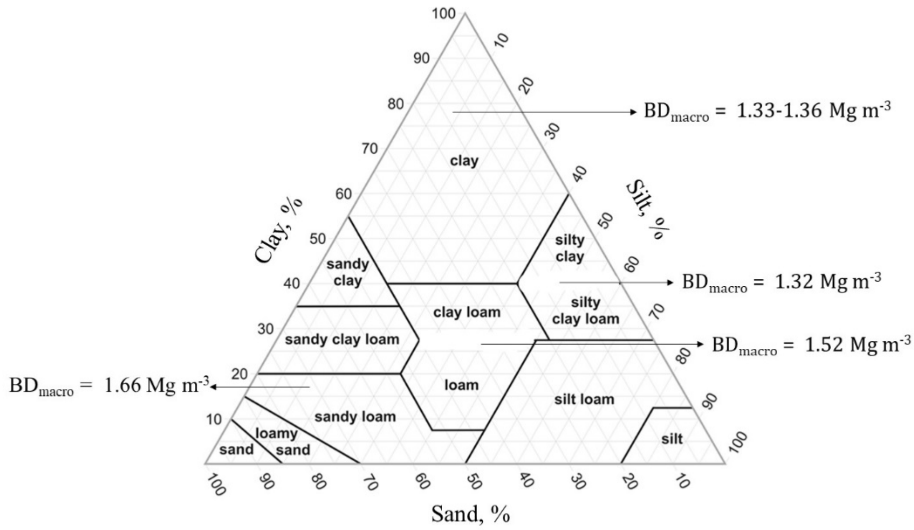


Figure 2. Textural triangle with values of BD_{macro} (critical bulk density corresponding to macroporosity of 0.10 m^3 m^{-3}).

In an experiment in pots, using Oxisols with different clay contents, a 50% reduction in soybean root growth occurred for bulk densities of 1.82, 1.75, 1.51, and 1.45 Mg m^{-3}, respectively, for a soil sandy loam, sandy clay loam, clay, and very clay [4]. In another study, also in the laboratory, the diameter of the corn stalk was reduced when the surface layer of the Latossolo Vermelho–Amarelo Distrófico, with texture class sandy clay, reached a bulk density of 1.7 Mg m^{-3}, while in the subsurface layer the reduction occurs in the bulk density of 1.5 Mg m^{-3}, a problem that can cause plant lodging [62]. In a field experiment in an Argissolo Vermelho with 150 g kg^{-1} clay and 730 g kg^{-1} sand in horizon A, cover crop roots grew normally to the bulk density of 1.75 Mg m^{-3}, while in the range of 1.75 to 1.85 Mg m^{-3} there was restriction with the deformation of the roots [36]. Generally, values from the literature are higher than that presented in Figure 2.

All managements of Argissolo Vermelho Distrófico arênico had a bulk density lower than the critical value (BD_{macro} = 1.66 Mg m^{-3}) or slightly higher in the 0.20 to 0.25 m layer, such as the Chisel management, while the macroporosity was lower than the critical value (0.10 m^3 m^{-3}) only for the NTC management and below the 0.10 m layer (Figure 3). With no physical restrictions on the topsoil, the root system of the soybean (and edible black bean for Chisel management) reached 0.15 m in depth.

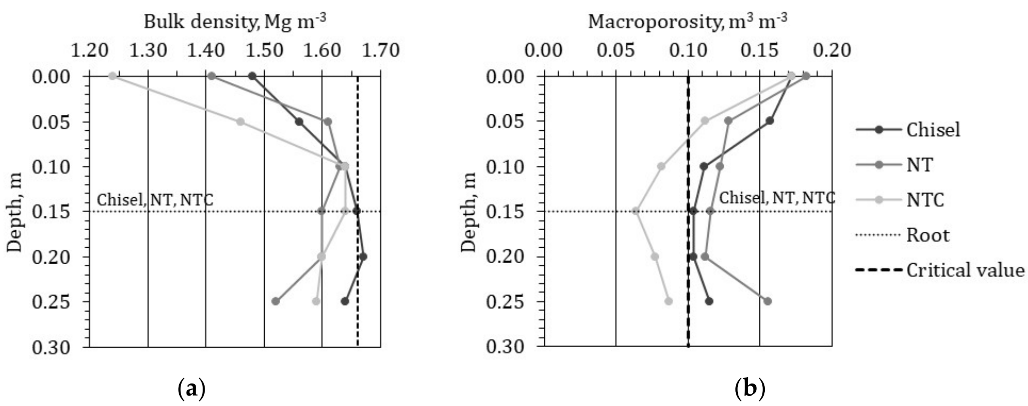
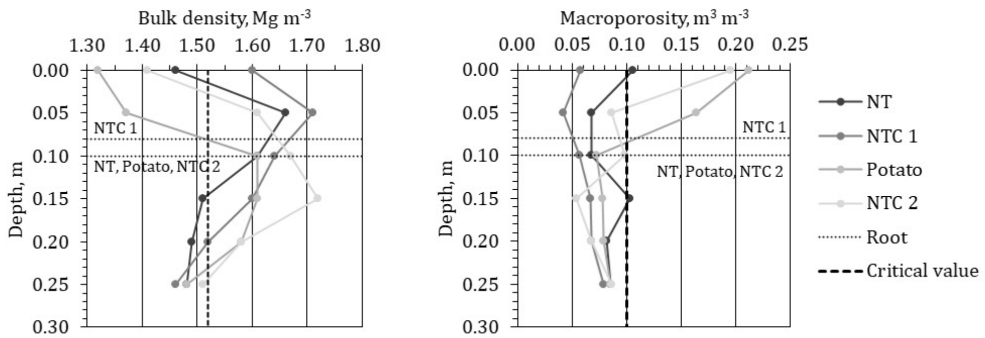


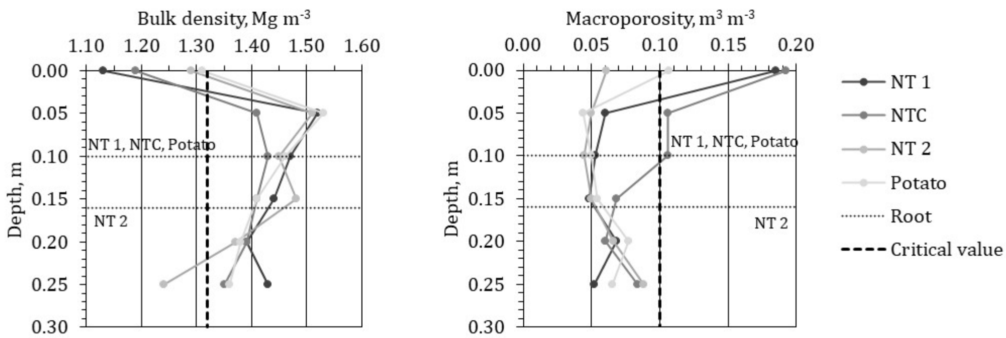
Figure 3. (**a**) Bulk density and (**b**) macroporosity average values, root system depth, bulk density (BD_{macro} = 1.66 Mg m^{-3}), and macroporosity (0.10 m^3 m^{-3}) critical values for the Argissolo Vermelho Distrófico arênico (Ultisol) and their respective managements under study.

All management systems for Argissolo Vermelho Distrófico latossólico (Figure 4), Argissolo Vermelho–Amarelo Alumínico típico (Figure 5), and Latossolo Vermelho Distrófico típico (Figure 6) presented bulk densities higher than the critical (BD_{macro} = 1.52 Mg m^{-3}, BD_{macro} = 1.32 Mg m^{-3}, and BD_{macro} = 1.33 Mg m^{-3}, respectively) and a macroporosity smaller than 0.10 m^3 m^{-3}. This occurred especially below the 0.05 m layer, limiting root growth to the layer and from 0.08 to 0.10 m for the Argissolo Vermelho Distrófico latossólico, and 0.10 m for the Argissolo Vermelho–Amarelo Alumínico típico, except the NT 2 that, even with the physical limitations of the soil, reached 0.16 m in depth.



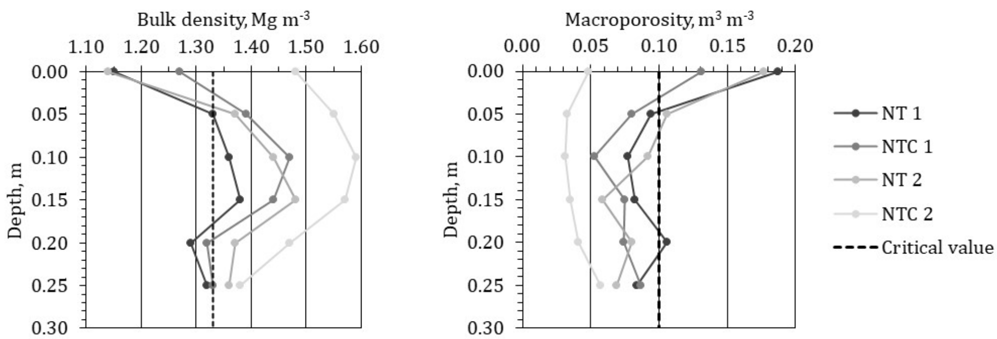
(**a**) (**b**)

Figure 4. (**a**) Bulk density and (**b**) macroporosity average values, root system depth, bulk density (BD_{macro} = 1.52 Mg m^{-3}), and macroporosity (0.10 m^3 m^{-3}) critical values for the Argissolo Vermelho Distrófico latossólico (Ultisol) and their respective managements under study.



(**a**) (**b**)

Figure 5. (**a**) Bulk density and (**b**) macroporosity average values, root system depth, bulk density (BD_{macro} = 1.32 Mg m^{-3}), and macroporosity (0.10 m^3 m^{-3}) critical values for the Argissolo Vermelho-Amarelo Alumínico típico (Ultisol) and their respective managements under study.



(**a**) (**b**)

Figure 6. (**a**) Bulk density and (**b**) macroporosity average values, root system depth, bulk density (BD_{macro} = 1.33 Mg m^{-3}), and macroporosity (0.10 m^3 m^{-3}) critical values for the Latossolo Vermelho Distrófico típico (Oxisol) and their respective managements under study.

In the Latossolo Vermelho Aluminoférrico típico (Figure 7), soil bulk density (BD_{macro} = 1.36 Mg m^{-3}) and macroporosity (0.10 m^3 m^{-3}) critical values limited root growth, particularly in the NT 2. However, NT 1 and Pasture are noteworthy, in which, even with physical limitations from the 0.05 m layer onwards, the roots reached, respectively, 0.20 and 0.30 m in depth. To penetrate more resistant soil layers, the root increases its diameter, as long as this resistance is not so high as to bend or deflect the root, and thus they find paths of lesser resistance. On the other hand, in regions of the soil where resistance is higher and oxygen and nutrient availability are deficient, the roots grow less and the plant compensates this by growing more in the less resistant zones [81].

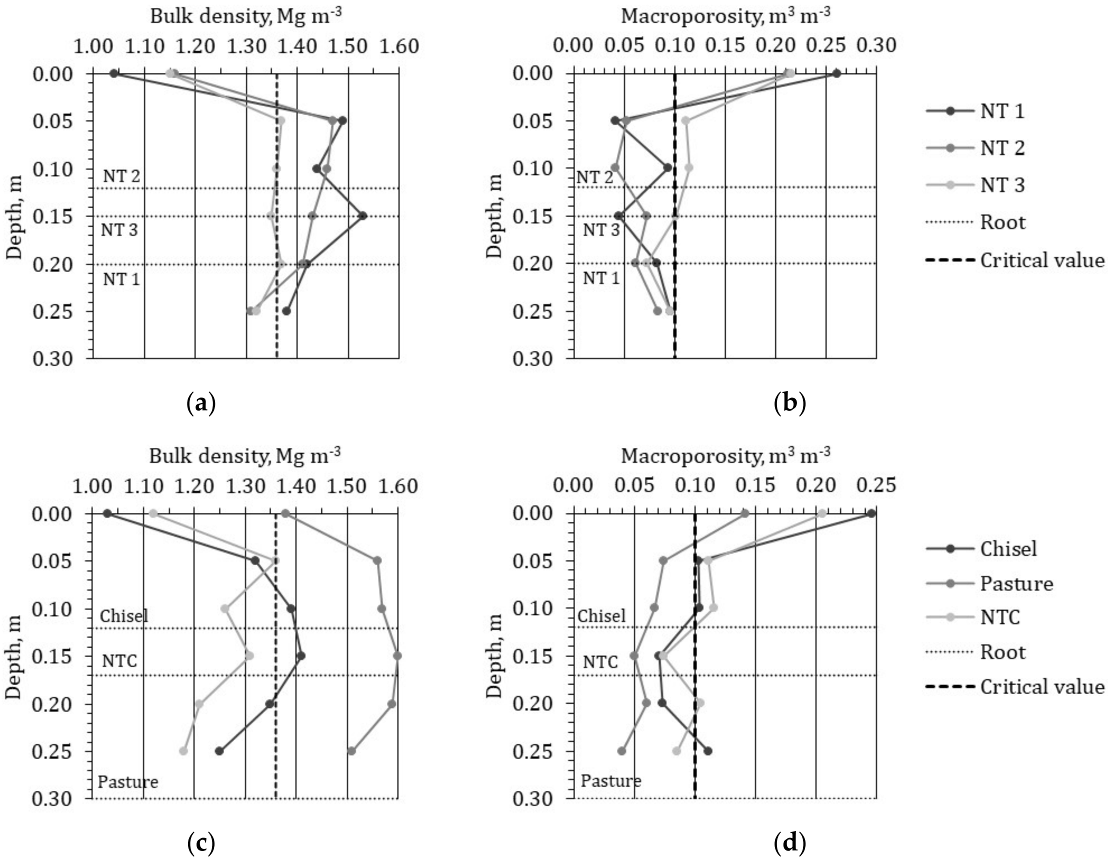


Figure 7. (**a**,**c**) Bulk density and (**b**,**d**) macroporosity average values, root system depth, bulk density (BD_{macro} = 1.36 Mg m^{-3}), and macroporosity (0.10 m^3 m^{-3}) critical values for the Latossolo Vermelho Aluminoférrico típico (Oxisol) and their respective managements under study.

Generally, the results indicate that the critical values of bulk density and macroporosity limit root growth for all soils in our study.

Assessing the spatial variability of penetration resistance in an experimental area of 0.2 ha with different sampling grids in an Oxisol in the south-central region of Paraná, the soil layer between 0.05 and 0.20 m was the one with the highest resistance values [58]. In a laboratory study on the influence of soil compaction on maize crops, Carneiro et al. [68] found that leaf mass was reduced regardless of the depth of the compacted layer; however, when it occurs in the surface layer, the problem is exacerbated due to the low availability of water and nutrients for the establishment of the plant, which requires a large amount of energy to develop its root system.

Using microporosity as a reference, obtained by applying a tension of 6 kPa, it is noted that the volumetric moisture at the time of assessing the soil mechanical resistance to penetration, in general, presented values lower or close to those obtained at a tension of 6 kPa (Figure 8). Knowledge of moisture and other physical properties when assessing penetration resistance is important, as soil mechanical resistance to penetration is related to soil moisture, bulk density, and texture [67–69]. For example, there was an increase in penetration resistance as the soil reduced moisture, and small differences in soil bulk density affected the penetration resistance as a function of moisture in different ways in a Latossolo Vermelho–Amarelo with 0.366 kg kg^{-1} clay [68].

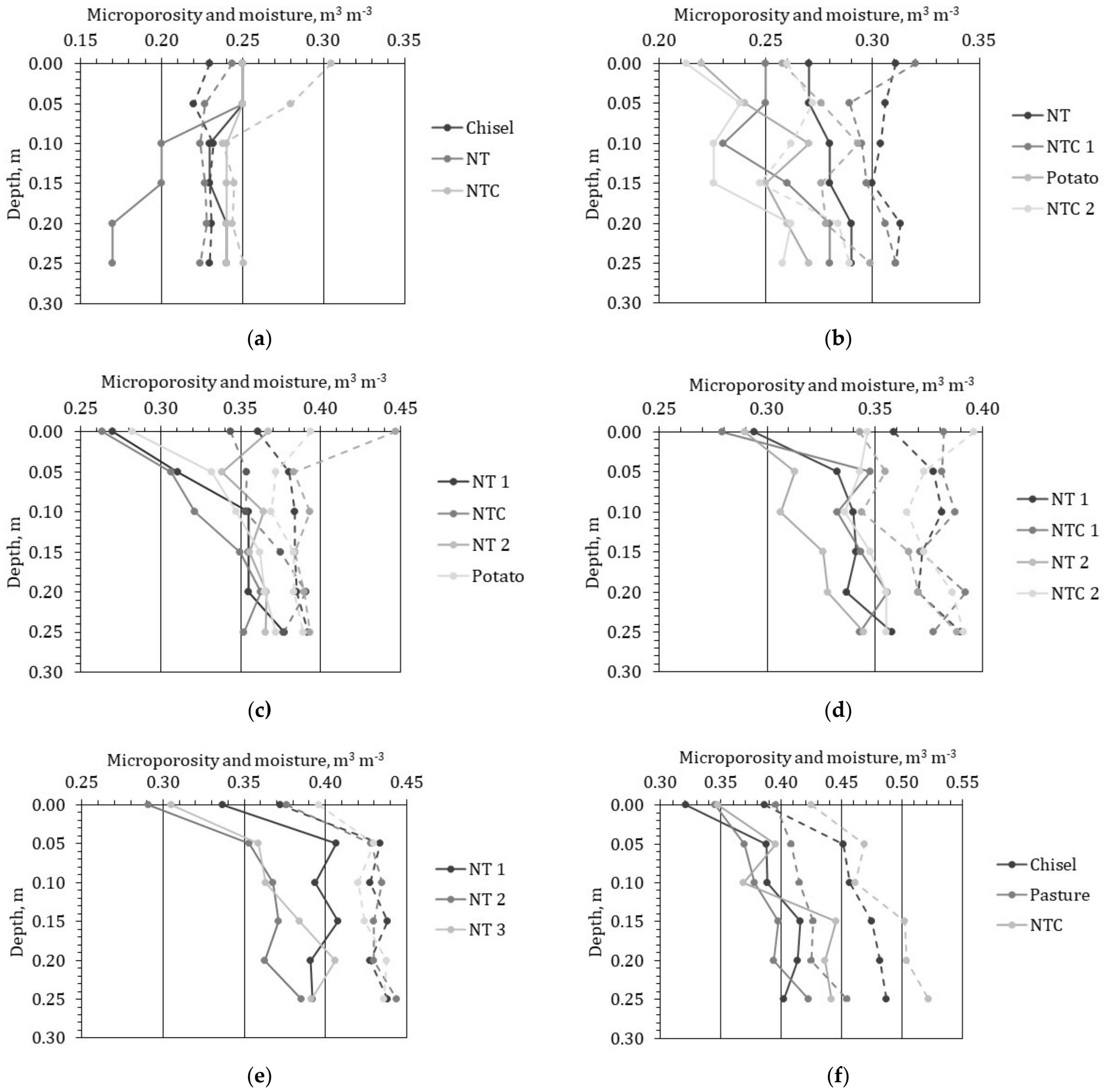


Figure 8. Average values of microporosity (dashed line) and volumetric moisture (solid line) at the time of evaluating the mechanical resistance of the soil to penetration of the (**a**) Argissolo Vermelho Distrófico arênico (Ultisol), (**b**) Argissolo Vermelho Distrófico latossólico (Ultisol), (**c**) Argissolo Vermelho–Amarelo Alumínico típico (Ultisol), (**d**) Latossolo Vermelho Distrófico típico (Oxisol), (**e**,**f**) Latossolo Vermelho Aluminoférrico típico (Oxisol), and respective managements.

Under high bulk density values, the increase in soil water content reduced penetration resistance, allowing soybean root growth to occur without restrictions in Oxisols with a clay content varying between 195.1 and 730.3 g kg^{-1} [4]. The authors found that, regardless of the soil textural class, the values of 2 and 3 MPa, considered limiting for root growth, had a small effect on soybean root growth when soil moisture was maintained at field capacity.

For the soils and managements under study, the soil's mechanical resistance to penetration presents variability in the profile, generally with lower values on the surface and increasing in depth (Figures 9–12). In an Argissolo Amarelo, the increase in resistance to penetration in depth was associated with the natural accommodation of clays, and the decrease in organic matter and microbiological activity at deeper layers in the soil profile [82].

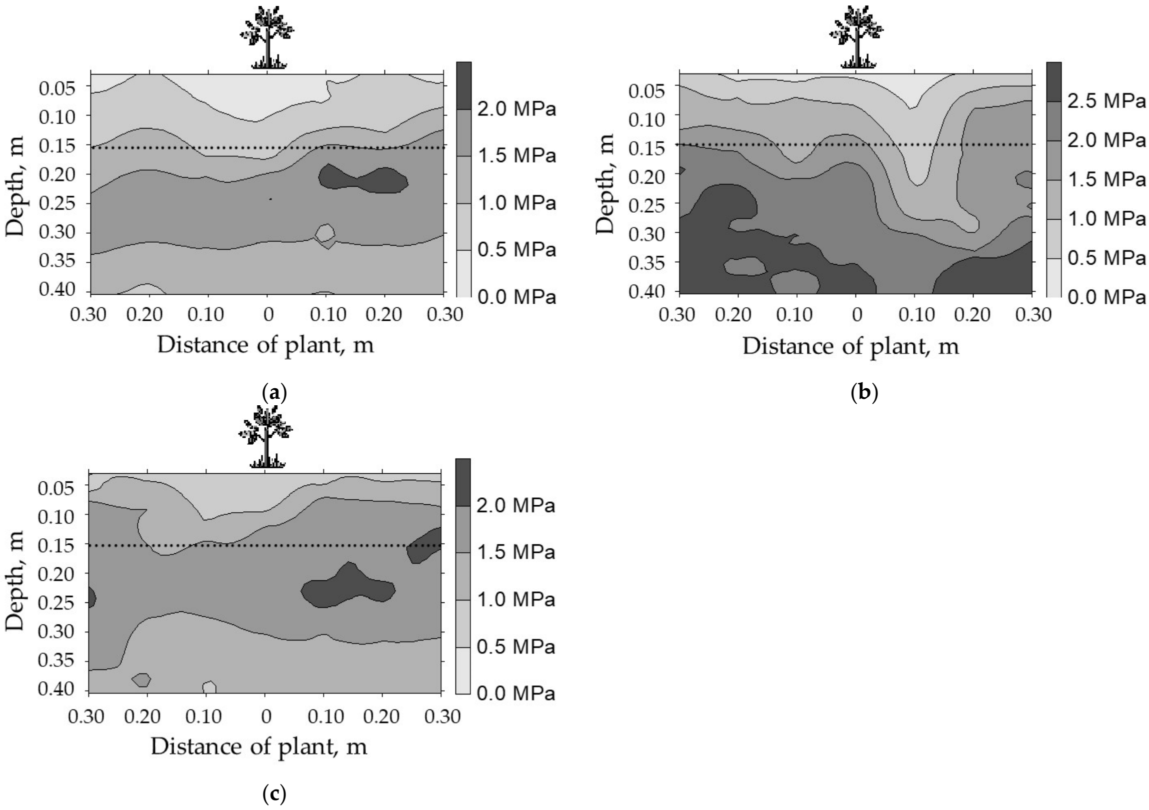


Figure 9. Profile of mechanical resistance to penetration of Argissolo Vermelho Distrófico arênico (Ultisol) in the managements (**a**) Chisel, (**b**) NT, and (**c**) NTC. ⋯⋯ root system depth.

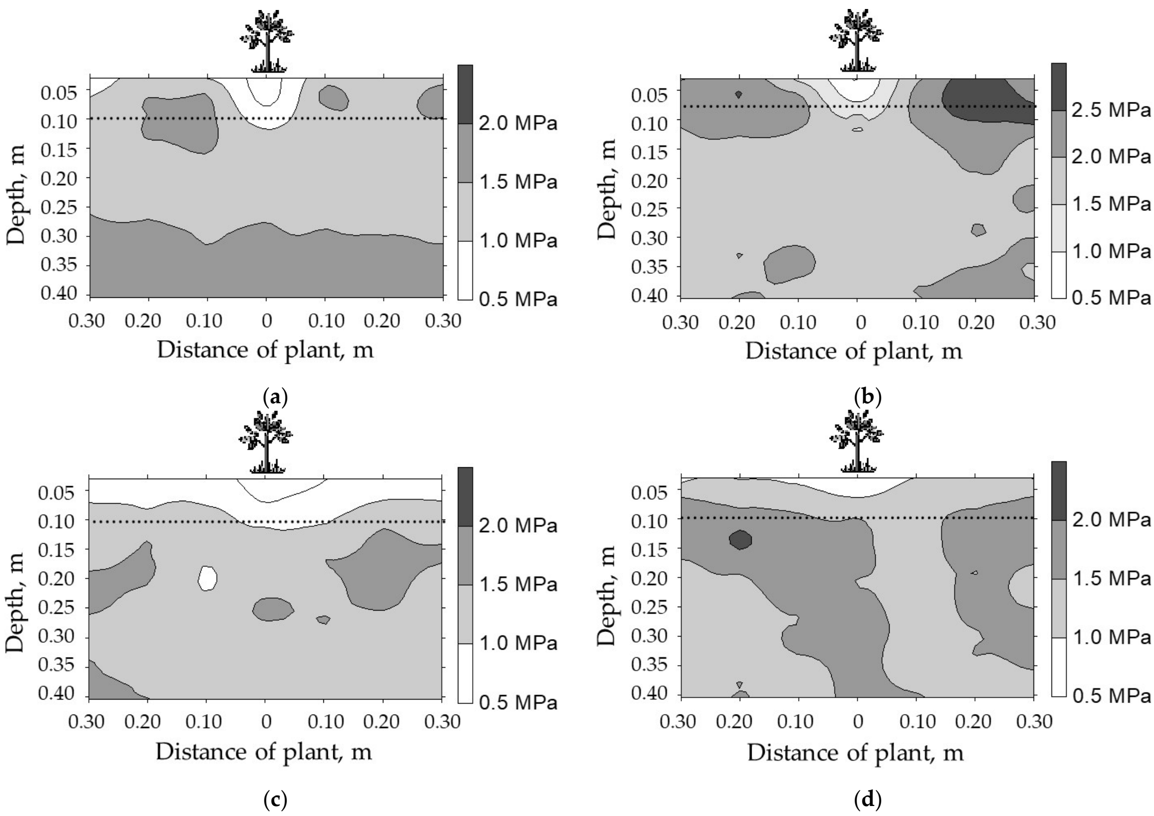


Figure 10. Profile of mechanical resistance to penetration of Argissolo Vermelho Distrófico latossólico (Ultisol) in the managements (**a**) NT, (**b**) NTC 1, (**c**) potato, and (**d**) NTC 2. ⋯⋯ root system depth.

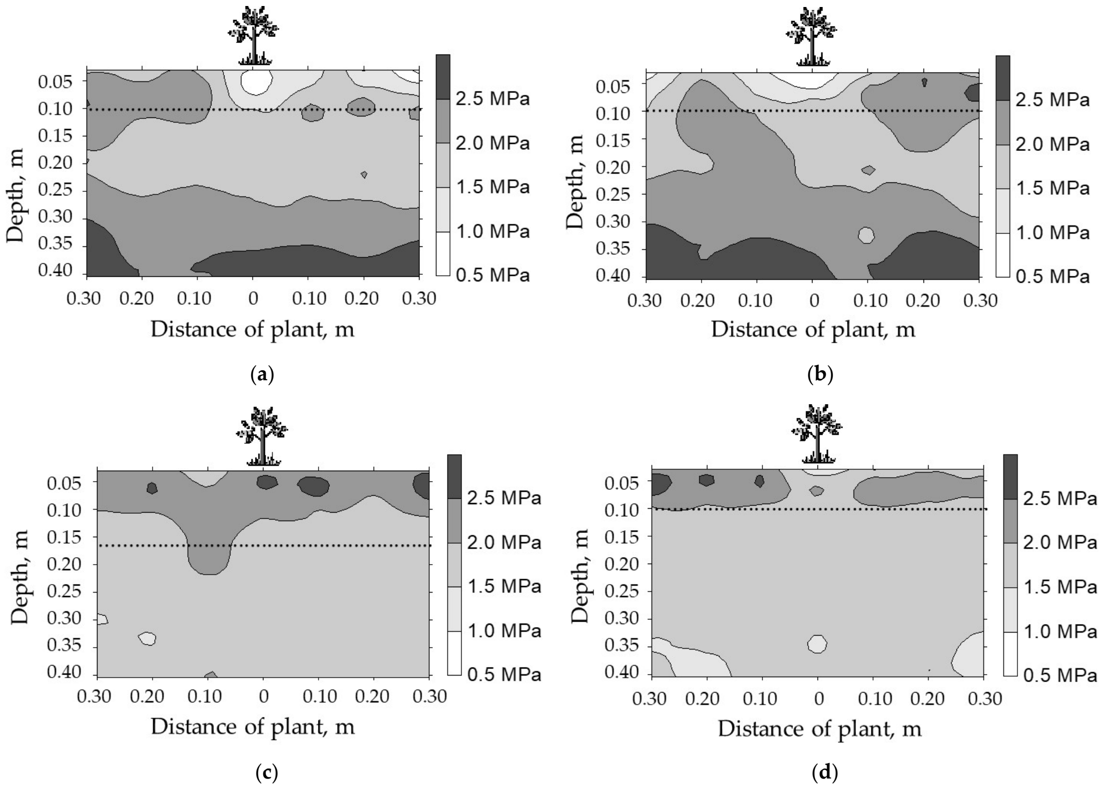


Figure 11. Profile of mechanical resistance to penetration of Argissolo Vermelho–Amarelo Alumínico típico (Ultisol) in the managements (**a**) NT 1, (**b**) NTC, (**c**) NT 2, and (**d**) potato. ⋯ ⋯ root system depth.

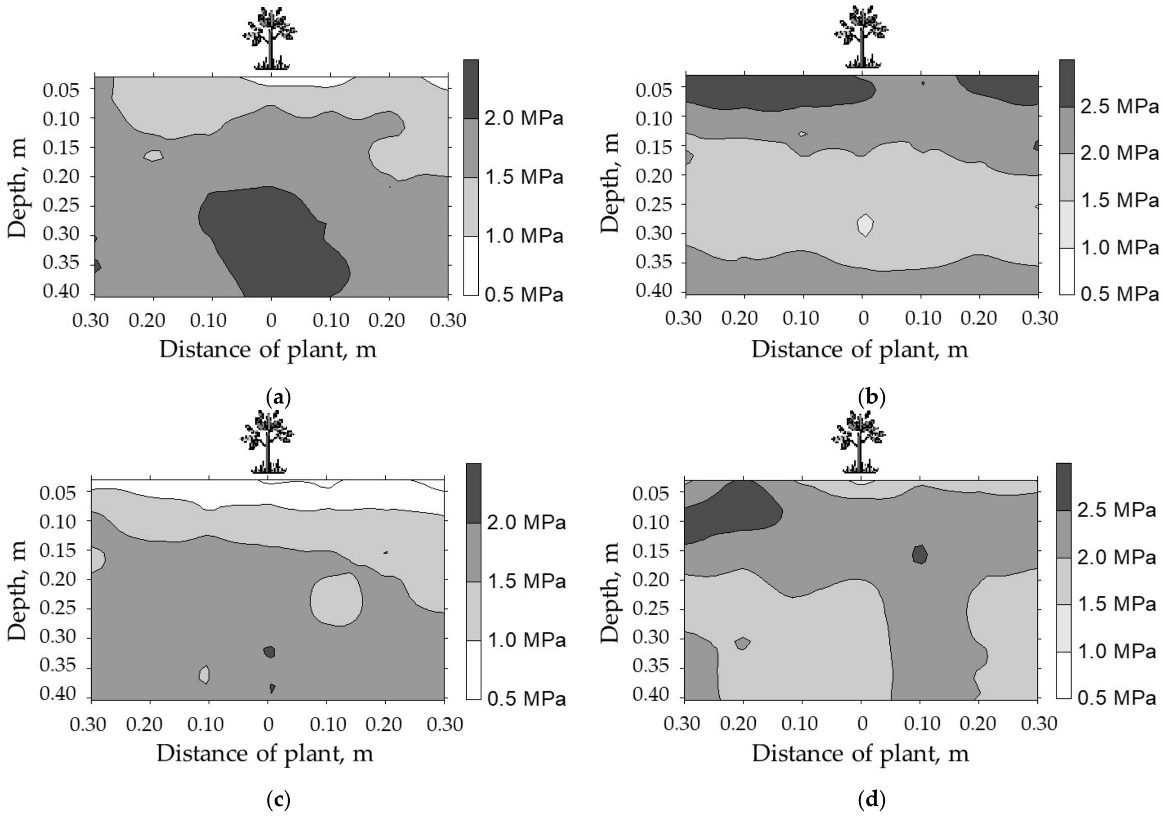


Figure 12. Profile of mechanical resistance to penetration of Latossolo Vermelho Distrófico típico (Oxisol) in the managements (**a**) NT 1, (**b**) NTC 1, (**c**) NT 2, and (**d**) NTC 2. The depth of the root system was not evaluated.

In general, soil layers with a resistance of <2 MPa may have limited root system growth, with 1.5 to 2 MPa for the Argissolo Vermelho Distrófico arênico and Argissolo Vermelho–Amarelo Alumínico, 1 to 1.5 MPa for the Argissolo Vermelho Distrófico latossólico (Figures 9–11), and between 2 and 3.5 MPa for the Latossolo Vermelho Aluminoférrico típico (Figure 13). In the Latossolo Vermelho Aluminoférrico típico, pasture management demands special attention, because the soybean roots grew up to 0.30 m, even passing through the most resistant layer, which may be associated with the presence of biopores, allowing for preferential root penetration.

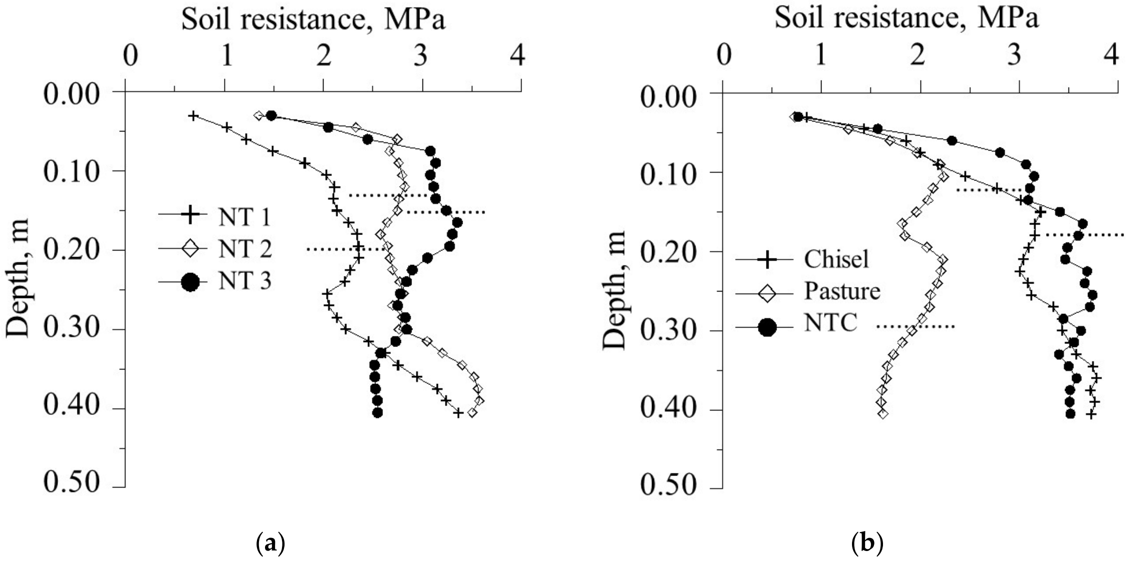


Figure 13. Mechanical resistance to penetration of Latossolo Vermelho Aluminoférrico típico (Oxisol) in the managements (**a**) NT 1, NT 2, and NT 3; (**b**) Chisel, Pasture, and NTC. ⋯⋯ root system depth.

Although horizontal layers with similar resistance occur, in some cases there is discontinuity of these layers with zones of smaller resistance, which allows the roots to use these zones of lesser resistance to deepen the profile. According to Queiroz-Voltan et al. [83], as compaction does not present itself as a continuous mass in the field, the roots search for free spaces in the soil to develop. From isolines maps of penetration resistance, it is possible to identify the depth of action of agricultural implements and compacted soil layers [82]. Even with the increase in bulk density and soil resistance to penetration and the decrease of macroporosity, the area and root length of corn were not affected in the Latossolo Vermelho Distrófico and a Latossolo Vermelho eutroférrico [84]. According to the authors, root growth can be inhibited with penetration resistance values below 1 MPa in dry soils; however, with enough moisture, growth can occur with a resistance to penetration ranging from 4 to 5 MPa.

Between the rows of the crop, in general, there was greater resistance to penetration, since the cutting disc or seeder rod ruptures the layer of greater resistance in the row (Figures 9–12), allowing root growth in the first centimeters of the soil (Figures 9–11). The furrower mechanisms may mobilize 30% of the soil surface area to a depth of 0.05 cm in winter crops with 0.17 m spacings [38]. Therefore, when the sowing for soybeans is added in succession, in a short time the entire surface layer is mobilized. Unger and Kaspar [85] state that soils are not uniformly compacted by machine traffic. Because the traffic direction for many field operations is parallel to the planting row, traffic tends to be concentrated in the rows, and some rows are compacted while others are not. As a result, traffic can cause significant differences in soil physical conditions between trafficked and non-trafficked rows, as studied in detail by Reichert et al. [86] for various soil properties.

The depth reached by the root system (soybean and edible black bean in the Argissolo Vermelho Distrófico arênico—Chisel) in the soils and managements under study was affected by soil properties, such as bulk density and soil resistance to penetration. Reichert et al. [61] comment that the root system perceives and integrates all soil conditions in space and time, similarly to the aerial part of plants, which is exposed to constant changes in the environment, clearly indicating that stresses in the aerial part and root system are equally important.

Crop yield is a function of several factors, such as physical, chemical, and biological soil properties, management given to the crop, in addition to climatic factors. Some soils may have unsuitable conditions, but proper climatic and rainfall conditions can minimize these effects. In the constant climatic adversities, a soil in a good condition allows the farmer to plan, as variations in yield are less fluctuating. For example, the effects of compaction in a clayey soil can be mitigated over time as a function of biopores formed by predecessor crops, especially cover crops, combined with the natural wetting and drying cycles of the soil [71]. Similarly, in a sandy loam soil, the use of cover crops reduced soil resistance to penetration by 25% compared to the value of 2 MPa after two crop rotation cycles, and 32% after three cycles [72]. These authors also verified that plant roots need approximately 4 to 6 years to decompose and produce biopores through the compacted soil layer.

To facilitate decision making on soil management considering the critical bulk density (BD_{macro}) corresponding to a macroporosity of 0.10 m^3 m^{-3}, the relative soil bulk density was calculated through the relationship between the current bulk density of the soil and the BD_{macro} for each soil class (Table 4).

Table 4. Average values of relative bulk density for the different soils and their respective managements under study.

Layer, m	**Management**					
	Argissolo Vermelho Distrófico arênico (Ultisol) (BD_{macro} = 1.66 Mg m^{-3})					
	Chisel	NT	NTC			
0–0.05	89.2	84.9	74.7			
0.05–0.10	94.0	97.0	88.0			
0.10–0.15	98.8	98.2	98.8			
0.15–0.20	100.0	96.4	98.8			
0.20–0.25	100.6	96.4	96.4			
0.25–0.30	98.8	91.6	95.8			
	Argissolo Vermelho Distrófico latossólico (Ultisol) (BD_{macro} = 1.52 Mg m^{-3})					
	NT	NTC 1	Potato	NTC 2		
0–0.05	96.1	105.3	86.8	92.8		
0.05–0.10	109.2	112.5	90.1	105.9		
0.10–0.15	105.9	107.9	105.9	109.9		
0.15–0.20	99.3	105.3	105.9	113.2		
0.20–0.25	98.0	100.0	103.9	103.9		
0.25–0.30	97.4	96.1	97.4	99.3		
	Argissolo Vermelho-Amarelo Alumínico típico (Ultisol) (BD_{macro} = 1.32 Mg m^{-3})					
	NT 1	NTC	NT 2	Potato		
0–0.05	85.6	90.2	97.7	99.2		
0.05–0.10	115.2	106.8	114.4	115.9		
0.10–0.15	111.4	108.3	109.8	110.6		
0.15–0.20	109.1	106.8	112.1	106.8		
0.20–0.25	105.3	105.3	103.8	104.5		
0.25–0.30	108.3	102.3	93.9	103.0		
	Latossolo Vermelho Distrófico típico (Oxisol) (BD_{macro} = 1.33 Mg m^{-3})					
	NT 1	NTC 1	NT 2	NTC 2		
0–0.05	86.5	95.5	85.7	111.3		
0.05–0.10	100.0	104.5	103.0	116.5		
0.10–0.15	102.3	110.5	108.3	119.5		
0.15–0.20	103.8	108.3	111.3	118.0		
0.20–0.25	97.0	99.2	103.0	110.5		
0.25–0.30	99.2	100.0	102.3	103.8		
	Latossolo Vermelho Aluminoférrico típico (Oxisol) (BD_{macro} = 1.36 Mg m^{-3})					
	NT 1	Chisel	Pasture	NT 2	NT 3	NTC
0–0.05	76.5	75.7	101.5	85.3	84.6	82.4
0.05–0.10	109.6	97.1	114.7	108.1	100.7	100.0
0.10–0.15	105.9	102.2	115.4	107.4	100.0	92.6
0.15–0.20	112.5	103.7	117.6	105.1	99.3	96.3
0.20–0.25	104.4	99.3	116.9	103.7	100.7	89.0
0.25–0.30	101.5	91.9	111.0	96.3	97.1	86.8

These relative bulk density values represent how close the actual soil bulk density is in relation to the critical bulk density. For example, relative bulk density values greater than 100% indicate that the soil bulk density is greater than critical, while values smaller than 100% mean that the bulk density is smaller than critical. Furthermore, it is possible to define, according to the percentage of relative bulk density, some action that should be taken to prevent the bulk density from being close to the critical one, namely mechanical soil management such as chiseling or vegetative management through cover crops with a root system that improves the soil physics properties. Bulk density values greater than 85% could thus be defined as an alert for decision making in relation to soil management.

4. Conclusions

From the evaluation of some physical properties associated with the compaction of Ultisols and Oxisols subjected to different management systems, it is concluded that with the increasing of soil bulk density there is a decrease in its macroporosity, and the variation in the content of sand, silt, and clay of soil is related to bulk density and porosity.

From a regression analysis between bulk density and macroporosity for each soil class, the bulk density (BD_{macro}) corresponding to a macroporosity of 0.10 $m^3\ m^{-3}$, considered critical for plant growth, was defined, according to the textural class, as: sandy loam—BD_{macro} = 1.66 Mg m^{-3}; loam and clay loam—BD_{macro} = 1.52 Mg m^{-3}; silty clay loam and silty clay—BD_{macro} = 1.32 Mg m^{-3}; and clay—BD_{macro} = 1.33 to 1.36 Mg m^{-3}.

Soil's mechanical resistance to penetration presents variability in the profile, generally with lower values on the surface and increasing in depth, in response to soil management. Although there are horizontal layers in the soil profile with similar resistance, in some cases there is discontinuity of these layers with zones of smaller resistance, which allows the roots to use these zones to deepen into the profile.

Penetration resistance values that limited the root growth of the soybean and edible black bean (in the Argissolo Vermelho Distrófico arênico—Chisel) were from 1.5 to 2 MPa for the Argissolo Vermelho Distrófico arênico (Ultisol) (of the textural class "sandy loam") and Argissolo Vermelho–Amarelo Alumínico (Ultisol) (of the textural classes "silty clay loam" and "silty clay"), 1 to 1.5 MPa to the Argissolo Vermelho Distrófico latossólico (Ultisol) (of the textural class "loam"), and 2 to 3.5 MPa to the Latossolo Vermelho Aluminoférrico típico (Oxisol) (of the textural class "clay").

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References

1. Silva, P.L.F. Compactação e seus efeitos sobre o funcionamento do solo e a absorção de nutrientes pelas plantas: Uma revisão bibliográfica. *Meio Ambiente* **2021**, *3*, 24–33.
2. Lima, C.L.R.; Reinert, D.J.; Reichert, J.M.; Suzuki, L.E.A.S.; Gubiani, P.I. Qualidade físico-hídrica e rendimento de soja (*Glycine max* L.) e feijão (*Phaseolus vulgaris* L.) de um Argissolo Vermelho Distrófico sob diferentes sistemas de manejo. *Ciência Rural* **2006**, *36*, 1172–1178. [CrossRef]

3. Suzuki, L.E.A.S.; Reichert, J.M.; Reinert, D.J. Degree of compactness, soil physical properties and yield of soybean in six soils under no-tillage. *Soil Res.* **2013**, *51*, 311–321. [CrossRef]
4. Sato, M.K.; Lima, H.V.; Oliveira, P.D.; Rodrigues, S. Critical soil bulk density for soybean growth in Oxisols. *Int. Agrophysics* **2015**, *29*, 441–447. [CrossRef]
5. Cecagno, D.; de Andrade Costa, S.E.V.G.; Anghinoni, I.; Kunrath, T.R.; Martins, A.P.; Reichert, J.M.; Gubiani, P.I.; Balerini, F.; Fink, J.R.; de Faccio Carvalho, P.C. Least limiting water range and soybean yield in a long-term, no-till, integrated crop-livestock system under different grazing intensities. *Soil Tillage Res.* **2016**, *156*, 54–62. [CrossRef]
6. Mentges, M.I.; Reichert, J.M.; Rodrigues, M.F.; Awe, G.O.; Mentges, L.R. Capacity and intensity soil aeration properties affected by granulometry, moisture, and structure in no-tillage soils. *Geoderma* **2016**, *263*, 47–59. [CrossRef]
7. Reichert, J.M.; Mentges, M.I.; Rodrigues, M.F.; Cavalli, J.P.; Awe, G.O.; Mentges, L.R. Compressibility and elasticity of subtropical no-till soils varying in granulometry organic matter, bulk density and moisture. *Catena* **2018**, *165*, 345–357. [CrossRef]
8. Veiga, M.; Reinert, D.J.; Reichert, J.M. Tillage systems and nutrient sources affecting soil cover, temperature and moisture in a clayey oxisol under corn. *Rev. Bras. Ciênc. Solo* **2010**, *34*, 2011–2020. [CrossRef]
9. Gubiani, P.I.; Goulart, R.Z.; Reichert, J.M.; Reinert, D.J. Crescimento e produção de milho associados com o intervalo hídrico ótimo. *Rev. Bras. Ciênc. Solo* **2013**, *37*, 1502–1511. [CrossRef]
10. Reichert, J.M.; Brandt, A.A.; Rodrigues, M.F.; Reinert, D.J.; Braida, J.A. Load dissipation by corn residue on tilled soil in laboratory and field-wheeling conditions: Lab and field load dissipation by soil surface mulch. *J. Sci. Food Agric.* **2016**, *96*, 2705–2714. [CrossRef]
11. Moraes, M.; Debiasi, H.; Franchini, J.C.; Bonetti, J.A.; Levien, R.; Schnepf, A.; Leitner, D. Mechanical and hydric stress effects on maize root system development at different soil compaction levels. *Front. Plant Sci.* **2019**, *10*, 1358. [CrossRef] [PubMed]
12. Goulart, R.Z.; Reichert, J.M.; Rodrigues, M.F.; Chaiben Neto, M.; Ebling, E.D. Comparing tillage methods for growing lowland soybean and corn during wetter-than-normal cropping seasons. *Paddy Water Environ.* **2021**, *19*, 401–415. [CrossRef]
13. Abreu, S.L.; Reichert, J.M.; Silva, V.R.; Reinert, D.J.; Blume, E. Variabilidade espacial de propriedades físico-hídricas do solo, da produtividade e da qualidade de grãos de trigo em Argissolo franco arenoso sob plantio direto. *Ciênc. Rural* **2003**, *33*, 275–282. [CrossRef]
14. Collares, G.L.; Reinert, D.J.; Reichert, J.M.; Kaiser, D.R. Compactação de um latossolo induzida pelo tráfego de máquinas e sua relação com o crescimento e produtividade de feijão e trigo. *Rev. Bras. Ciênc. Solo* **2008**, *32*, 933–942. [CrossRef]
15. Secco, D.; Reinert, D.J.; Reichert, J.M.; da Silva, V.R. Atributos físicos e rendimento de grãos de trigo, soja e milho em dois Latossolos compactados e escarificados. *Ciênc. Rural* **2009**, *39*, 58–64. [CrossRef]
16. Bonini, A.K.; Secco, D.; Santos, R.F.; Reinert, D.J.; Reichert, J.M. Atributos físico-hidricos e produtividade de trigo em um Latossolo sob estados de compactação. *Ciênc. Rural* **2011**, *41*, 1543–1548. [CrossRef]
17. Collares, G.L.; Reinert, D.J.; Reichert, J.M.; Kaiser, D.R. Qualidade física do solo na produtividade da cultura do feijoeiro num Argissolo. *Pesqui. Agropecu. Bras.* **2006**, *41*, 1663–1674. [CrossRef]
18. Kaiser, D.R.; Reinert, D.J.; Reichert, J.M.; Collares, G.L.; Kunz, M. Intervalo hídrico ótimo no perfil explorado pelas raízes de feijoeiro em um latossolo sob diferentes níveis de compactação. *Rev. Bras. Ciênc. Solo* **2009**, *33*, 845–855. [CrossRef]
19. Reichert, J.M.; Suzuki, L.E.A.S.; Reinert, D.J.; Horn, R.; Håkansson, I. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil Tillage Res.* **2009**, *102*, 242–254. [CrossRef]
20. Reichert, J.M.; Rodrigues, M.F.; Awe, G.O.; Riquelme, U.F.B.; Kaiser, D.R.; Reinert, D.J. Common bean in highly variable weather conditions, on sandy soils, and food security in a subtropical environment. *Food Energy Secur.* **2015**, *4*, 219–237. [CrossRef]
21. Reichert, J.M.; Brandt, A.A.; Rodrigues, M.F.; da Veiga, M.; Reinert, D.J. Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? *Geoderma* **2017**, *301*, 72–79. [CrossRef]
22. Reichert, J.M.; da Silva, V.R.; Awe, G.O.; Wendroth, O.O.; Srinivasan, R. Defining tillage need for edible bean production under no-tillage: Classical and time series analyses. *Soil Tillage Res.* **2020**, *202*, 10467. [CrossRef]
23. Gubiani, P.I.; Reichert, J.M.; Reinert, D.J. Interação entre disponibilidade de água e compactação do solo no crescimento e na produção de feijoeiro. *Rev. Bras. Ciênc. Solo* **2014**, *38*, 765–773. [CrossRef]
24. Ferraz, L.L.; Silva, A.C.; Rocha, L.V.F.; Oliveira, T.M.S.; Silva, J.O. Influência da compactação do solo no desenvolvimento do sistema radicular do feijão (*Phaseolus vulgaris* L.). *Agrar. Acad.* **2017**, *4*, 166–174. [CrossRef]
25. Mentges, M.I.; Reichert, J.M.; Gubiani, P.I.; Reinert, D.J.; Xavier, A. Alterações estruturais e mecânicas de solo de várzea cultivado com arroz irrigado por inundação. *Rev. Bras. Ciênc. Solo* **2013**, *37*, 221–231. [CrossRef]
26. Goulart, R.Z.; Reichert, J.M.; Rodrigues, M.F. Cropping poorly-drained lowland soils: Alternatives to rice monoculture, their challenges and management strategies. *Agric. Syst.* **2020**, *177*, 102715. [CrossRef]
27. Fasinmirin, J.T.; Reichert, J.M. Conservation tillage for cassava (*Manihot esculenta crantz*) production in the tropics. *Soil Tillage Res.* **2011**, *113*, 1–10. [CrossRef]
28. Reichert, J.M.; Rodrigues, M.F.; Bervald, C.M.P.; Brunetto, G.; Kato, O.R.; Schumacher, M.V. Fragmentation, fiber separation, decomposition, and nutrient release of secondary-forest biomass, mechanically chopped-and-mulched, and cassava production in the Amazon. *Agric. Ecosyst. Environ.* **2015**, *204*, 8–16. [CrossRef]
29. Reichert, J.M.; Rodrigues, M.F.; Bervald, C.M.P.; Kato, O.R. Fire-free fallow management by mechanized chopping of biomass for sustainable agriculture in eastern amazon: Effects on soil compactness, porosity, and water retention and availability. *Land Degrad. Dev.* **2016**, *27*, 1403–1412. [CrossRef]

30. Reichert, J.M.; Fontanela, E.; Awe, G.O.; Fasinmirin, J.T. Is cassava yield affected by inverting tillage, chiseling or additional compaction of no-till sandy-loam soil? *Rev. Bras. Ciênc. Solo* **2021**, *45*, e0200134. [CrossRef]
31. Reichert, J.M.; Morales, C.A.S.; Lima, E.M.; de Bastos, F.; Sampietro, J.A.; Cavalli, J.P.; de Araújo, E.F.; Srinivasan, R. Best tillage practices for early-growth of clonal eucalyptus in soils with distinct granulometry, drainage and profile depth. *Soil Tillage Res.* **2021**, *212*, 105038. [CrossRef]
32. Reichert, J.M.; Corcini, A.L.; Awe, G.O.; Reinert, D.J.; Albuquerque, J.A.; García Gallarreta, C.C.; Docampo, R. Onion-forage cropping systems on a Vertic Argiudoll in Uruguay: Onion yield and soil organic matter, aggregation, porosity and permeability. *Soil Tillage Res.* **2022**, *216*, 105229. [CrossRef]
33. Marins, A.C.; Reichert, J.M.; Secco, D.; Rosa, H.A.; Veloso, G. Crambe grain yield and oil content affected by spatial variability in soil physical properties. *Renew. Sustain. Energy Rev.* **2018**, *81*, 464–472. [CrossRef]
34. Awe, G.O.; Reichert, J.M.; Timm, L.C.; Wendroth, O.O. Temporal processes of soil water status in a sugarcane field under residue management. *Plant Soil* **2015**, *387*, 395–411. [CrossRef]
35. Awe, G.O.; Reichert, J.M.; Fontanela, E. Sugarcane production in the subtropics: Seasonal changes in soil properties and crop yield in no-tillage, inverting and minimum tillage. *Soil Tillage Res.* **2020**, *196*, e104447. [CrossRef]
36. Reichert, J.M.; Pellegrini, A.; Rodrigues, M.F. Tobacco growth, yield and quality affected by soil constraints on steeplands. *Ind. Crops Prod.* **2019**, *128*, 512–526. [CrossRef]
37. Reinert, D.J.; Albuquerque, J.A.; Reichert, J.M.; Aita, C.; Andrada, M.M.C. Limites críticos de densidade do solo para o crescimento de raízes de plantas de cobertura em Argissolo Vermelho. *Rev. Bras. Ciênc. Solo* **2008**, *32*, 1805–1816. [CrossRef]
38. Genro, S.A., Jr.; Reinert, D.J.; Reichert, J.M.; Albuquerque, J.A. Atributos físicos de um Latossolo Vermelho e produtividade de culturas cultivadas em sucessão e rotação. *Ciênc. Rural* **2009**, *39*, 65–73. [CrossRef]
39. Gomar Capurro, E.P.; Reichert, J.M.; Reinert, D.J.; García, F. Atributos do solo e biomassa radicular após quatro anos de semeadura direta de forrageiras de estação fria em campo natural dessecado com herbicidas. *Rev. Bras. Ciênc. Solo* **2002**, *26*, 211–223. [CrossRef]
40. Collares, G.L.; Reinert, D.J.; Reichert, J.M.; Kaiser, D.R. Compactação superficial de Latossolos sob integração lavoura: Pecuária de leite no noroeste do Rio Grande do Sul. *Ciênc. Rural* **2011**, *41*, 246–250. [CrossRef]
41. Kunz, M.; Gonçalves, A.D.M.A.; Reichert, J.M.; Guimarães, R.M.L.; Reinert, D.J.; Rodrigues, M.F. Compactação do solo na integração soja-pecuária de leite em Latossolo argiloso com semeadura direta e escarificação. *Rev. Bras. Ciênc. Solo* **2013**, *37*, 1699–1708. [CrossRef]
42. Gomar Capurro, E.P.G.; Secco, D.; Reichert, J.M.; Reinert, D.J. Compressibilidade e elasticidade de um Vertissolo afetado pela intensidade de pastejo bovino. *Ciênc. Rural* **2014**, *44*, 283–288. [CrossRef]
43. Ambus, J.V.; Reichert, J.M.; Gubiani, P.I.; de Faccio Carvalho, P.C. Changes in composition and functional soil properties in long-term no-till integrated crop-livestock system. *Geoderma* **2018**, *330*, 232–243. [CrossRef]
44. Holthusen, D.; Brandt, A.A.; Reichert, J.M.; Horn, R. Soil porosity, permeability and static and dynamic strength parameters under native forest/grassland compared to no-tillage cropping. *Soil Tillage Res.* **2018**, *177*, 113–124. [CrossRef]
45. Holthusen, D.; Brandt, A.A.; Reichert, J.M.; Horn, R.; Fleige, H.; Zink, A. Soil functions and in situ stress distribution in subtropical soils as affected by land use, vehicle type, tire inflation pressure and plant residue removal. *Soil Tillage Res.* **2018**, *184*, 78–92. [CrossRef]
46. Reichert, J.M.; Bervald, C.M.P.; Rodrigues, M.F.; Kato, O.R.; Reinert, D.J. Mechanized land preparation in eastern Amazon in fire-free forest-based fallow systems as alternatives to slash-and-burn practices: Hydraulic and mechanical soil properties. *Agric. Ecosyst. Environ.* **2014**, *192*, 47–60. [CrossRef]
47. Reichert, J.M.; Cechin, N.F.; Reinert, D.J.; Rodrigues, M.F.; Suzuki, L.E.A.S. Ground-based harvesting operations of Pinus taeda affects structure and pore functioning of clay and sandy clay soils. *Geoderma* **2018**, *331*, 38–49. [CrossRef]
48. Reichert, J.M.; Morales, C.A.S.; de Bastos, F.; Sampietro, J.A.; Cavalli, J.P.; Araújo, E.F.; Srinivasan, R. Tillage recommendation for commercial forest production: Should tillage be based on soil penetrability, bulk density or more complex, integrative properties? *Geoderma Reg.* **2021**, *25*, e00381. [CrossRef]
49. Sampietro, J.A.; Lopes, E.D.S.; Reichert, J.M. Compactação causada pelo tráfego de feller buncher e skidder em um Neossolo Regolítico sob distintas umidades. *Ciênc. Florest.* **2015**, *25*, 239–248. [CrossRef]
50. Suzuki, L.E.A.S.; Reichert, J.M.; Reinert, D.J.; de Lima, C.L.R. Degree of compactness and mechanical properties of a subtropical Alfisol with eucalyptus, native forest, and grazed pasture. *For. Sci.* **2015**, *61*, 716–722. [CrossRef]
51. França, J.S.; Reichert, J.M.; Holthusen, D.; Rodrigues, M.F.; de Araújo, E.F. Subsoiling and mechanical hole-drilling tillage effects on soil physical properties and initial growth of eucalyptus after eucalyptus on steeplands. *Soil Tillage Res.* **2021**, *207*, 104860. [CrossRef]
52. Wang, X.; Shen, J.; Hedden, P.; Phillips, A.L.; Thomas, S.G.; Ge, Y.; Ashton, R.W.; Whalley, W.R. Wheat growth responses to soil mechanical impedance are dependent on phosphorus supply. *Soil Tillage Res.* **2021**, *205*, 104754. [CrossRef]
53. FAO. *Voluntary Guidelines for Sustainable Soil Management*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017; 16p, Available online: http://www.fao.org/3/bl813e/bl813e.pdf (accessed on 9 July 2021).
54. Silva, S.M.A.; Locatelli, M.; Nunes, A.C.S.; Oliveira, C.P.; Sampaio, F.A.R.; Mandu, T.S.; Silva, C.A. Resistência mecânica do solo à penetração associado à umidade, densidade, granulometria e macronutrientes em Ji-Paraná-RO. *Braz. J. Dev.* **2021**, *7*, 5629–5647. [CrossRef]

55. Queiroz, G.C.M.; Silva, F.W.A.; Portela, J.C.; Oliveira, V.N.S.; Santos, M.V. Densidade e resistência do solo à penetração de raízes em agroecossistemas no semiárido brasileiro. *Rev. Verde* **2019**, *14*, 497–505. [CrossRef]
56. Siqueira, P.G.S.; Ferro, M.G.F.; Santos, V.R.; Santos, M.A.L.; Silva, T.S.S.; Santos, C.G. Avaliação da resistência à penetração em um argissolo vermelho Distrófico. *Rev. Ambient.* **2019**, *10*, 1–15. [CrossRef]
57. Spliethoff, J.; Rampim, L.; Pott, C.A.; Lustosa, S.B.C. Implicação de grades amostrais na determinação da resistência do solo à penetração e indicação de manejo. *Res. Soc. Dev.* **2020**, *9*, e790997871. [CrossRef]
58. Andrade, A.D.; Faria, R.O.; Alonso, D.J.C.; Ferraz, G.A.S.; Herrera, M.A.D.; Silva, F.M. Spatial variability of soil penetration resistance in coffee growing. *Coffee Sci.* **2018**, *13*, 341–348. Available online: http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/1456 (accessed on 9 July 2021). [CrossRef]
59. De Maria, I.C.; Castro, O.M.; Dias, H.S. Atributos físicos do solo e crescimento radicular de soja em Latossolo Roxo sob diferentes métodos de preparo do solo. *Rev. Bras. Ciênc. Solo* **1999**, *23*, 703–709. [CrossRef]
60. Reichert, J.M.; Reinert, D.J.; Braida, J.A. Qualidade dos solos e sustentabilidade de sistemas agrícolas. *Ciênc. Ambiente* **2003**, *27*, 29–48.
61. Reichert, J.M.; Kaiser, D.R.; Reinert, D.J.; Riquelme, U.F.B. Variação temporal de propriedades físicas do solo e crescimento radicular de feijoeiro em quatro sistemas de manejo. *Pesqui. Agropecu. Bras.* **2009**, *44*, 310–319. [CrossRef]
62. Carneiro, K.A.A.; Oliveira, F.P.; Araujo, M.C.S.P.; Fernandes, L.F.; Abrantes, E.G.; Vendruscolo, J. Influência da compactação do solo no crescimento de milho (*Zea mays* L.) em Latossolo Vermelho-Amarelo. *Colloq. Agrar.* **2018**, *14*, 88–98. [CrossRef]
63. Taylor, H.M.; Roberson, G.M.; Parker, J.J., Jr. Soil strength-root penetration relations for medium to coarse-textured soil materials. *Soil Sci.* **1966**, *102*, 18–22. [CrossRef]
64. Canarache, A. Penetr—A generalized semi-empirical model estimating soil resistance to penetration. *Soil Tillage Res.* **1990**, *16*, 51–70. [CrossRef]
65. Beutler, A.N.; Centurion, J.F. Compactação do solo no desenvolvimento radicular e na produtividade da soja. *Pesqui. Agropecu. Bras.* **2004**, *39*, 581–588.
66. Beutler, A.N.; Centurion, J.F.; Centurion, M.A.P.C.; Silva, A.P. Efeito da compactação na produtividade de cultivares de soja em Latossolo Vermelho. *Rev. Bras. Ciênc. Solo* **2006**, *30*, 787–794. [CrossRef]
67. Vaz, C.M.P.; Manieri, J.M.; Maria, I.C.; van Genuchten, M.T. Scaling the dependency of soil penetration resistance on water content and bulk density of different soils. *Soil Sci. Soc. Am. J.* **2013**, *77*, 1488–1495. [CrossRef]
68. Silva, W.M.; Bianchini, A.; Cunha, C.A. Modelling and correction of soil penetration resistance for variations in soil moisture and soil bulk density. *Eng. Agric.* **2016**, *36*, 449–459. [CrossRef]
69. Jiang, Q.; Cao, M.; Wang, Y.; Wang, J. Estimating soil penetration resistance of paddy soils in the plastic state using physical properties. *Agronomy* **2020**, *10*, 1914. [CrossRef]
70. Abreu, S.L.; Reichert, J.M.; Reinert, D.J. Escarificação mecânica e biológica para a redução da compactação em argissolo franco-arenoso sob plantio direto. *Rev. Bras. Ciênc. Solo* **2004**, *28*, 519–531. [CrossRef]
71. Bertollo, A.M.; Moraes, M.T.; Franchini, J.C.; Soltangheisi, A.; Balbinot, A.A., Jr.; Levien, R.; Debiasi, H. Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil. *Soil Tillage Res.* **2021**, *206*, 104820. [CrossRef]
72. Jabro, J.D.; Allen, B.L.; Rand, T.; Dangi, S.R.; Campbell, J.W. Effect of previous crop roots on soil compaction in 2 yr rotations under a no-tillage system. *Land* **2021**, *10*, 202. [CrossRef]
73. Santos, H.G.; Jacomine, P.K.T.; Anjos, L.H.; Oliveira, V.A.; Lumbreras, J.F.; Coelho, M.R.; Almeida, J.A.; Araujo Filho, J.C.; Oliveira, J.B.; Cunha, T.J.F. *Sistema Brasileiro de Classificação de Solos*, 5th ed.; rev. e ampl.; Embrapa: Brasília, Brazil, 2018; 356p.
74. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; USDA-Natural Resources Conservation Service: Washington, DC, USA, 2014. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/taxonomy/?cid=nrcs142p2_053580 (accessed on 8 December 2021).
75. Wrege, M.S.; Steinmetz, S.; Reisser, C., Jr.; Almeida, I.R. (Eds.) *Atlas Climático da Região Sul do Brasil: Estados do Paraná, Santa Catarina e Rio Grande do Sul*, 2nd ed.; Embrapa: Brasília, Brazil, 2012.
76. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. (Eds.) *Manual de Métodos de Análise de Solo*, 3rd ed.; rev. e ampl.; Embrapa: Brasília, Brazil, 2017; 574p.
77. Suzuki, L.E.A.S.; Reichert, J.M.; Albuquerque, J.A.; Reinert, D.J.; Kaiser, D.R. Dispersion and flocculation of Vertisols, Alfisols and Oxisols in Southern Brazil. *Geoderma Reg.* **2015**, *5*, 64–70. [CrossRef]
78. National Resource Conservation Service-NRCS/United States Department of Agriculture-USDA. Soil Texture Calculator. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/?cid=nrcs142p2_054167 (accessed on 8 August 2020).
79. Baver, L.D. Practical values from physical analyses of soils. *Soil Sci.* **1949**, *68*, 1–14. [CrossRef]
80. Grable, A.R.; Siemer, E.G. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potential and elongation of corn roots. *Soil Sci. Soc. Am. Proc.* **1968**, *32*, 180–186. [CrossRef]
81. Correa, J.; Postma, J.A.; Watt, M.; Wojciechowski, T. Soil compaction and the architectural plasticity of root systems. *J. Exp. Bot.* **2019**, *70*, 6019–6034. [CrossRef]
82. Nagahama, H.J.; Cortez, J.W.; Pimenta, W.A.; Patrocinio Filho, A.P.; Souza, E.B. Resistência do solo à penetração em sistemas de preparo e velocidades de deslocamento do trator. *Comun. Sci.* **2016**, *7*, 56–65. [CrossRef]
83. Queiroz-Voltan, R.B.; Nogueira, S.S.S.; de Miranda, M.A.C. Aspectos da estrutura da raiz e do desenvolvimento de plantas de soja em solos compactados. *Pesqui. Agropecu. Bras.* **2000**, *35*, 929–938. [CrossRef]

84. Rossetti, K.V.; Centurion, J.F. Indicadores de qualidade em Latossolos compactados e suas relações com o crescimento do sistema radicular do milho. *Rev. Agro@Mbiente Online* **2017**, *11*, 181–190. [CrossRef]
85. Unger, P.W.; Kaspar, T.C. Soil compaction and root growth: A review. *Agron. J.* **1994**, *86*, 759–766. [CrossRef]
86. Reichert, J.M.; da Rosa, V.T.; Vogelmann, E.S.; da Rosa, D.P.; Horn, R.; Reinert, D.J.; Sattler, A.; Denardin, J.E. Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. *Soil Tillage Res.* **2016**, *158*, 123–136. [CrossRef]