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Spatio-Temporal Dynamics of Soil Penetration Resistance Depending on Different Conservation Tillage Systems

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Abstract: As conservation tillage becomes one of the foundations of sustainable crop production, important questions arise about its value, which needs to be defined and evaluated. One of the most important indicators of soil compaction is penetration resistance (PR), which comes as a short-term response to the state of soil physics. The objective of this work is to compare different tillage treatments (TT) on soil compaction on silty clay loam Stagnosol and silt Gleysol in the continental part of Croatia. The research included three tillage treatments: ST—conventional tillage, CTD—deep conservation tillage, and CTS—shallow conservation tillage. PR was determined on each soil depth of 5 cm up to 80 cm, and measuring was provided on two measuring dates. The obtained results showed a higher influence of the year factor than TT. In the upper layers (up to 35 cm), PR values between TT were with significant differences, but in most cases below root-limiting critical values, while in deeper soil layers (35–80 cm), we found that penetration values on each tillage treatment begin to stabilize and smooth out in most cases, with similar dynamics on both soil types and measurement dates. In most of the cases, the highest PR was measured for conservation treatments in wetter soil conditions.

Keywords: tillage management; soil compaction; crop production; Stagnosol; Gleysol

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1. Introduction

Soil tillage is one of the most important agrotechnical measures, and the main demand is to provide optimal soil conditions for growing crops [1]. Its active role affects every aspect of soil quality, defining and changing soil properties (physical, chemical, and biological aspects) [2,3]. Conservation soil tillage (CST) is usually defined as a tillage method with soil surface covering at a minimum of 30%, with crop residues leaving as permanent cover after all tillage treatments and planting [4]. Along with crop residues, proper crop rotation and minimal soil disturbance represent a baseline for Conservation agriculture (CA) [5]. On a global scale, CA represents a platform that should replace existing conventional agriculture as a sustainable approach to prevent further soil degradation [6]. This requirement is more relevant as the problems of climate change [7] are becoming more severe (desertification, soil degradation, lack of water, etc.), and the need for adaptation and mitigation is increasing [8]. CST does not represent one unique technique. CST includes numerous different techniques and practices that exist as relevant, primarily depending on agroecological conditions and available mechanization [9].

The indicators of soil physics are most influenced by tillage, and they are usually placed as the most relevant before the chemical and biological complex of the soil. Soil compaction, as well as soil penetration resistance (PR), depends on the natural properties of the soil (soil texture), soil characteristics, and climatic conditions (dominantly soil water content) [10–12], but mostly on the type of soil tillage [13,14] and other soil trafficking [15]. Measurement of PR can be provided easily and rapidly, which means that it is possible to obtain a sufficient amount of data about soil compaction in a very short time [16,17]. These measurements can provide useful data along vegetation periods for analyzing different aspects of applied tillage techniques and other trafficking on soil compaction [17], root proliferation and development [18,19], and other types of soil degradation [20]. PR, which can impede root growth, plant development, and crop yield, is usually lined at 2.5 MPa [21], 3 MPa [22], or higher [23]. One of the largest and most highly expressed impacts on PR is soil water content [11,24]. Higher water content resulted in the creation of compacted, both upper and deeper layers [25,26] and led to further soil degradation and decreasing crop productivity [13,27–29].

CST, in comparison to conventional tillage (ST), is often a research topic in every aspect of crop production and soil compaction. From the scientific literature, it is very easy to conclude the persistence of correlations between different tillage methods with soil compaction as well as PR. These differences in PR are both between different tillage methods and between different soil depths [30]. The growing crops, respectively, in the way of soil preparation and trafficking, also have an important role and impact on soil compaction [17,31]. Based on information about soil compaction, farmers make decisions to adopt or reject specific tillage methods, sometimes without reason and wrongly [32]. Contrastory results regarding CST and its impact on PR can be found in the literature. Some results show that CST, compared to conventional tillage with plowing, increases soil compaction and, accordingly, PR, while other results indicate non-significant results [33].

Although there is no official data in Croatia, according to our free estimation, it is, at minimum, 30% of arable land under some type of CST and less than 50% under conventional tillage with plowing. Despite this information and the growing interest of farmers in the last two decades in adopting CST techniques, research on the impact of different CSTs on crop production on Stagnosol and Gleysol soil types is still very rare and insufficient [34]. Both soil types have low production capacity caused by periodic excessive water wetting. Gleysols have a high level of underground water and often unfavorable physical, chemical, and biological properties, and it is necessary to choose the appropriate agrotechnical practices. The production capacity of Stagnosols is low. They are usually used as such in agricultural production, but they give very variable yields, which largely depend on the amount and distribution of precipitation and the applied agricultural technology. Bogunović and Kisić [35] argue that perennial plowing should not be relied upon as the sole long-term soil management approach. Instead, supplementary methods such as controlled traffic and periodic soil loosening every 1–2 years should be applied to stagnant soils in Pannonian Croatia. Bašić et al. [36] researched the effects of soil erosion influenced by deep (30 cm) soil tillage practiced for deep-rooted row crops in comparison with other tillage methods on Stagnic Luvisols. Bašić et al. [37], in their study, argues that no-tillage (even with an up and down slope row orientation) and all-across-the-slope plowing and planting treatments achieved efficient soil conservation on the Stagnic Luvisols.

The main goal of this experiment, which also correlates with the main hypothesis, was to determine the intensity and dynamics of changes in soil tillage penetration resistance, especially under different tillage treatments. The main hypothesis is that in different agroecological conditions, and especially concerning different "starting positions" of the studied soils, there will be significant changes in the soil tillage penetration resistance on the conservation tillage treatments compared to conventional soil tillage.

2. Materials and Methods

2.1. Site Description and Treatments

The experiment was performed in 2020–2023 at two different locations in the most productive agricultural region of the continental part of Croatia but on two different soil types that are not usually recognized as the most productive soils due to lower productive properties [38]. The first experimental site (ES1) was set up on Stagnosol (location Cacinci) in the eastern part of Croatia, and the second one (ES2) in the western part of Croatia on a Gleysol (location Krizevci) soil-type [39]. The soil types determined on both experimental sites are hydromorphic with characteristic periodical excess wetting through the year. Excess water in the soil sometimes appears in part of the profile but mostly in the entire profile. The physical and chemical properties of both types of soil are relatively unfavorable, with a recommendation for the mandatory application of lime material in different quantities depending on soil type [40]. A detailed description of the mechanical, physical, and chemical properties of the experimental sites can be found in Table 1.

Table 1. Basic description of the mechanical, physical, and chemical properties of the experimental sites.

Parameter	ES1 [1]	ES2
Location	17°86′36″ E 45°61′32″ N 111 m a. s. l.	16°33′32″ E 46°01′38″ N 141 m a. s. l.
	Mechanical properties	
Soil type	Stagnosol	Gleysol
Soil texture	Silty clay loam	Silt
Soil particles (%) [4]	Depth [2] 0–32 cm: Silt = 60.84 Clay = 29.35 Sand = 9.81 Depth 32–65 cm: Silt = 57.61 Clay = 34.08 Sand = 8.31 Depth 65–200 cm: Silt = 58.92 Clay = 30.29 Sand = 10.79	Depth 0–36 cm: Silt = 82.95 Clay = 9.61 Sand = 7.44 Depth 36–97 cm: Silt = 80.41 Clay = 14.08 Sand = 5.52 Depth 97–175 cm: Silt = 78.96 Clay = 14.90 Sand = 6.15
	Physical properties	
Field capacity—FC (vol.%)	D1 [3]: 43.04 D2: 42.58 D3: 40.13	D4: 42.44 D5: 37.69 D6: 36.31
Particle density—ρ_b (g cm^{-3})	D1: 2.65 D2: 2.74 D3: 2.71	D4: 2.69 D5: 2.73 D6: 2.78
Packing density—PD (g cm^{-3})	D1: 1.76 D2: 1.87 D3: 1.83	D4: 1.51 D5: 1.73 D6: 1.79
Total porosity—ε (%)	D1: 43.50 D2: 42.97 D3: 40.65	D4: 47.21 D5: 41.39 D6: 39.91
	Chemical properties	
pH(KCl)	D1: 3.92 D2: 4.23 D3: 4.39	D4: 5.22 D5: 5.73 D6: 5.68
pH(H_2O)	D1: 5.12 D2: 6.16 D3: 5.92	D4: 6.65 D5: 7.44 D6: 7.50
Hidrolitic acidity—Hy (cmol(+) kg^{-1})	D1: 7.48 D2: 4.07 D3: 3.15	D4: 2.47 D5: – D6: –

Table 1. *Cont.*

Parameter	ES1 [1]	ES2
P_2O_5 (AL), mg kg^{-1} soil	D1: 75 D2: 20 D3: 18	D4: 154 D5: 26 D6: 32
K_2O (AL), mg kg^{-1} soil	D1: 111 D2: 107 D3: 114	D4: 75 D5: 52 D6: 48
Soil Organic Matter—SOM (%)	D1: 2.83 D2: 0.83 D3: 0.48	D4: 1.64 D5: 0.52 D6: 0.41

[1] ES1—experimental site on Stagnosol (location Cacinci); ES2—experimental site on Gleysol (location Krizevci); [2] Soil depths are defined according to genetic horizons from soil profiles; [3] D1—depth on stagnosol (0–32 cm), D2—depth on Stagnosol (32–65 cm), D3—depth on Stagnosol (65–200 cm), D4—depth on Gleysol (0–36 cm), D5—depth on Gleysol (36–97 cm), D6—depth on Gleysol (97–175 cm); [4] Sand—(2–0.05 mm), Silt—(0.05–0.002 mm), Clay—(<0.002 mm).

Both experimental sites belong to the region characterized by typical moderate continental climate conditions with hot summers and cold winters. Patterns of average precipitation show a decrease from west to east (from ES2 to ES1) and average temperatures in the opposite direction. The average amount of precipitation on ES1 varies from 690 to 730 mm with average air temperatures ranging from 10.7 to 11.1 °C, and on ES2 from 870 to 890 mm with air temperature variation from 10.1 to 10.6 °C, according to Meteorological and Hydrological Service of Croatia. The average growing season with daily temperatures of 5 °C or more lasts from 250 to 270 days.

The comparison of the observed period with the 40-year average (1984–2023) is characterized by a large variation of both parameters, the amount of precipitation as well as the average temperature (Table 2).

Table 2. Monthly and 40-year (1984–2023) average precipitation (mm) and air temperature (°C) on both experimental sites.

Site	Year	Month							
		April	May	June	July	August	September	Tvp [1]	Avp [2]
Precipitation (mm)									
ES1	2021	41	20	34	135	52	29	311	
	2022	1	60	69	19	62	217	427	
	2023	101	239	56	70	31	71	568	
	LTA	63	75	95	69	70	77	449	
ES2	2021	55	17	4	56	60	35	227	
	2022	0	70	57	12	18	168	325	
	2023	64	11	119	47	12	1	254	
	LTA [3]	53	70	81	70	78	93	445	
Air temperature (°C)									
ES1	2021	10.7	14.7	22.1	23.4	20.8	16.9		18.1
	2022	13.7	17.8	22.5	23.3	22.8	16.4		19.4
	2023	10.3	15.9	21.0	23.8	22.7	20.1		18.9
	LTA	11.6	16.3	19.7	21.8	21.1	16.4		17.8
ES2	2021	11.0	13.9	21.5	22.2	19.6	15.2		17.2
	2022	10.0	16.9	21.5	22.0	21.5	15.5		17.9
	2023	9.2	14.9	19.6	21.9	20.8	18.0		17.4
	LTA	11.2	15.8	19.2	21.0	20.3	15.5		17.2

ES1—experimental site on Stagnosol (location Cacinci); ES2—experimental site on on Gleysol (location Krizevci); [1] Tvp—Total vegetation period; [2] Avp—Average vegetation period; [3] LTA—long term average (1984–2023).

The experiment was started on both sites in the autumn of 2020 and last (data presented in this paper) up to the summer of 2023. The stationary experiment was set up as a complete randomized block design (RCBD) with three different soil tillage treatments in three replications. Tillage treatments are the same on both experimental sites and included ST-Standard/Conventional tillage (based on plowing up to 30 cm); CTD-deep conservation tillage (soil loosening up to 30 cm) with a minimum soil surface coverage of 30% of crop residues; CTS-shallow conservation tillage (soil loosening up to 10 cm in depth) with a minimum soil surface coverage of 50% of crop residues. Additional secondary tillage treatments, the number of tillage passes, and slight variations in tillage depth vary depending on the growing cultivars. The basic experimental plot for each individual tillage treatment was 640 m^2.

Crop rotation is applied equally on both sites and includes crops in the following sequence: 2021—maize, 2022—soybean, and 2022/2023—winter wheat. Before establishing experimental sites, the previous crop on Stagnosol was winter wheat, and on Gleysol, it was a meadow (previously grown for 15 years).

Mineral fertilizers (NPK) were calculated with the ALRxp computer program for fertilizer recommendations [41] and applied uniformly for all tillage treatments and with the same distribution dynamics. Fertilizer amounts varied depending on location and crop type. Except for the soil tillage, all the other crop growing practices sequences, e.g., sowing (no-till seed drill machine), harvesting, pests' control, machinery, and equipment, were used identically on both experimental sites and in all the tillage treatments.

2.2. Measurement Methods

Soil tillage penetration resistance measurements were carried out two times per vegetation each year, mostly at the beginning of intensive vegetation growth and at the end of vegetation (Table 3).

Table 3. Dates of sowing, harvesting, and penetration resistance measurements on both experimental sites.

Season	Crop	Site	Sowing Date	Harvest Date	Penetration Resistance Measurement	
					GS	Date [2]
2020/2021	Maize	ES1 [1]	6 May 2021 [2]	22 September 2021	V3	4 June 2021
					R5	23 September 2021
		ES2	10 May 2021	25 September 2021	V3	5 June 2021
					R5	25 September 2021
2021/2022	Soybean	ES1 [1]	14 January 2022	29 September 2022	V3	27 May 2022
					R8	17 October 2022
		ES2	29 April 2022	3 October 2022	V3	3 June 2022
					R8	17 October 2022
2022/2023	Winter wheat	ES1 [1]	20 October 2022	6 July 2023	Feekes 6	10 April 2023
					Feekes 11	10 April 2023
		ES2	21 October 2022	12 July 2023	Feekes 6	1 June 2023
					Feekes 11	1 June 2023

[1] ES1—experimental site on Stagnosol (location Cacinci), ES2—experimental site on Gleysol (location Krizevci), GS—Growth stage; [2] Date creation: day/month/year.

Soil tillage penetration resistance measurement was provided with an electronic penetrometer, "Eijkelkamp Penetrologger SN" using a cone tip with a base area of 1 cm^2 and an angle of 60°, up to 80 cm (maximum length of cone-rod). Penetrologger automatically records readings on each 1 cm of depth, with mean velocity 1 cm s^{-1}. Penetration resistance was automatically recorded. After the experiment was established and before the first soil resistance measurement, a GPS-located network was created to more precisely determine the location of the following measurements. Each point on the grid was 2 m in diameter.

The number of measurements per each basic tillage plot was 8 (×3 repetitions = 24 measurements per treatment); in total, all tillage treatments in one sampling date and one location were made 72 measurements. Soil water content was determined according to ISO 11461:2001 [42].

2.3. Data Analysis

All collected data were statistically processed by the statistical package TIBCO Data Science Workbench 14.1.0.8 [43]. Soil penetration readings from each single centimeter are grouped by 5 cm up to a depth of 80 cm for further analysis. The influence of different soil tillage treatments and soil depth on penetration resistance in three different production years (two measurements per year) on two types of soil was tested using a factorial ANOVA design (factors: soil tillage and soil depth). In cases where ANOVA showed significant differences at $p < 0.05$, a Fisher LSD test was applied. In the interpretation of the results of the analysis of the two-factorial experiment, where a joint dependent effect of tillage and depth was determined, only the results of their interaction were interpreted, while in the case where no interaction was recorded (the factors acted independently), the effect of the main factors (tillage and depth) was interpreted. The assumption of homogeneity of variance for all parameters was conducted by Levene's test; the normality of the distribution of results was examined by the Kolmogorov-Smirnov test. The assumption of independence was secured by the design of the study (randomized complete block design). The descriptive statistic was performed in Microsoft Excel and applied to analyze the differences in soil moisture content between soil tillage treatments in all experimental years, measuring dates and soil types.

3. Results

During all studied periods, PR (1st and 2nd measurements) on Stagnosol was significantly influenced by tillage and depth. An interaction between tillage and depth during 1st measurement was identified during all studied periods, but during 2nd measurement, it was identified only in 2022 (Table 4).

Table 4. ANOVA values for penetration resistance for both sites.

	d.f.	2021		2022		2023	
		1st	2nd	1st	2nd	1st	2nd
Stagnosol							
Tillage (T)	2	*	*	*	*	*	*
Depth (D)	15	*	*	*	*	*	*
T × D	30	*	ns	*	*	*	ns
Gleysol							
Tillage (T)	2	*	*	*	*	*	*
Depth (D)	15	*	*	*	*	*	*
T × D	30	*	*	*	ns	*	ns

* $p < 0.05$; ns—not significant.

Significant differences were observed during 1st measurement in 2021, 2022, and 2023 between all tillage treatments and between almost all depths (up to 45 cm). Through the entire studied soil profile (0–80 cm), the highest PR in all investigated years was measured on the CTS treatment at a depth of 5–10 cm (in 2021 = 2.32 MPa; 2022 = 3.89 MPa and 2023 = 3.96 MPa, respectively (Figure 1).

During the second measurement (in 2021), the highest PR was measured at CTS (5.58 MPa) and 35–40 cm depth (6.47 MPa). PR on CTS was statistically higher compared to ST, while the difference in PR compared with CTD was statistically unjustified. All differences in PR by depth in 2021 and their statistical significance are shown in Table 5.

Table 5. LSD [1] test for penetration resistance (MPa) on different depths (Stagnosol 2021—2nd measurement).

Depth [3] MPa	1 2.08	2 4.00	3 4.93	4 4.96	5 5.08	6 5.74	7 6.35	8 6.47	9 6.29	10 6.12	11 5.99	12 5.90	13 5.75	14 5.54	15 5.28	16 5.08
1		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2	* [2]		*	*	*	*	*	*	*	*	*	*	*	*	*	*
3	*	*		ns	ns	*	*	*	*	*	*	*	*	*	*	ns
4	*	*	ns		ns	*	*	*	*	*	*	*	*	*	ns	ns
5	*	*	ns	ns		*	*	*	*	*	*	*	*	*	ns	ns
6	*	*	*	*	*		*	*	*	*	ns	ns	ns	ns	*	*
7	*	*	*	*	*	*		ns	ns	ns	*	*	*	*	*	*
8	*	*	*	*	*	*	ns		ns	*	*	*	*	*	*	*
9	*	*	*	*	*	*	ns	ns		ns	ns	*	*	*	*	*
10	*	*	*	*	*	*	ns	*	ns		ns	ns	*	*	*	*
11	*	*	*	*	*	ns	*	*	ns	ns		ns	ns	*	*	*
12	*	*	*	*	*	ns	*	*	*	ns	ns		ns	*	*	*
13	*	*	*	*	*	ns	*	*	*	*	ns	ns		ns	*	*
14	*	*	*	*	*	ns	*	*	*	*	*	*	ns		ns	*
15	*	*	*	ns	ns	*	*	*	*	*	*	*	*	ns		ns
16	*	*	ns	ns	ns	*	*	*	*	*	*	*	*	*	ns	

[1] LSD test-Probabilities for Post Hoc Tests; Error: Between MS = 0.28422, df = 240; [2] * $p < 0.05$; ns—not significant; [3] Depth (cm): 1 (0–5), 2 (5–10), 3 (10–15), 4 (15–20), 5 (20–25), 6 (25–30), 7 (30–35), 8 (35–40), 9 (40–45), 10 (45–50), 11 (50–55), 12 (55–60), 13 (60–65), 14 (65–70), 15 (70–75), 16 (75–80).

On Stagnosol in 2022 (2nd measurement), the highest PR was recorded at the soil depth from 35 to 80 cm, ranging from 1.8 to 2.2 MPa. All differences in PR between tillage × depth on 35–80 cm were not statistically significant. In the upper part of the soil profile (up to 35 cm), the highest PR value was recorded on CTD treatment (2.0 MPa) and was statistically significantly higher compared to ST and CTS (Figure 1), while the difference between ST (1.75 MPa) and CTS (1.70 MPa) was non-significant. All differences and statistical significance in PR are visible in Figure 1.

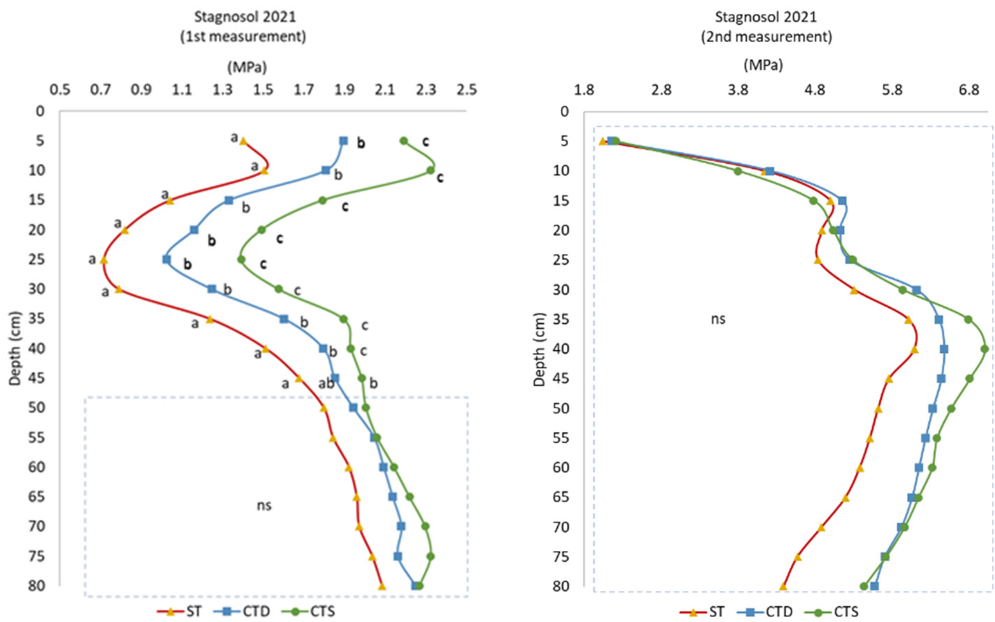

Figure 1. *Cont.*

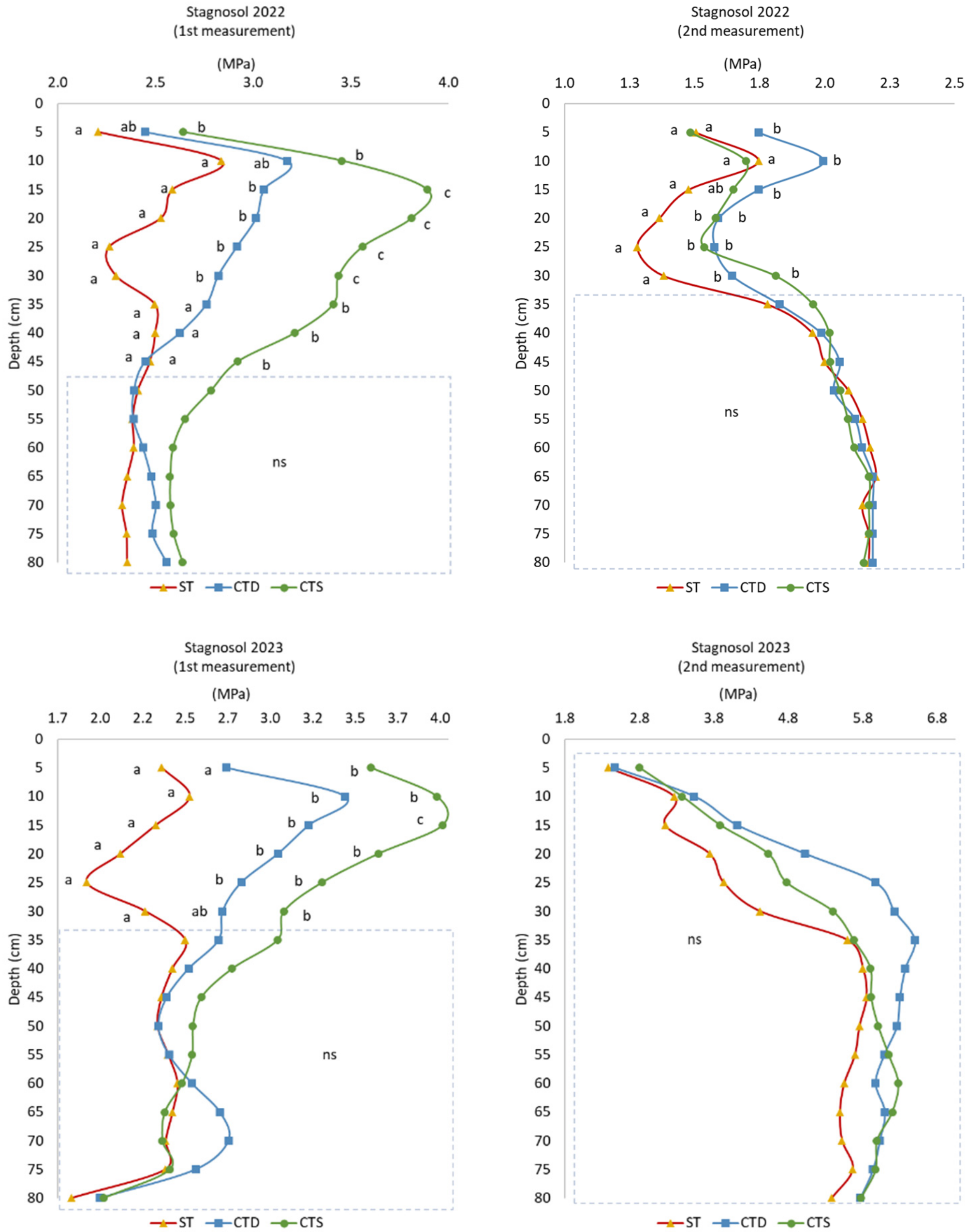

Figure 1. Penetration resistance under ST, CTD, and CTS at 0–5; 5–10; 10–15; 15–20; 20–25; 25–30; 30–35; 35–40; 40–45; 45–50; 50–55; 55–60; 60–65; 65–70; 70–75; 75–80 cm depth. Different letters for each depth indicate significant differences at $p < 0.05$ among the treatments, and ns-not significant at $p < 0.05$.

PR in 2023 (2nd measurement) was significantly lower on ST (4.77 MPa) than on CTD (5.49 MPa) and CTS (5.24 MPa), between which there were no statistically significant differences. Also, the highest PR was recorded at 35–40 cm (5.98 MPa). Significant differences in PR were found at almost all depths of 0–30 cm, as well as concerning depths greater than 30 cm. Differences in PR at depths of 30–80 cm were not statistically significant (Table 6).

Table 6. LSD [1] test for penetration resistance (MPa) on different depths (Stagnosol 2023—2nd measurement).

Depth [3] MPa	1 2.50	2 3.34	3 3.66	4 4.38	5 4.84	6 5.30	7 5.87	8 5.98	9 5.97	10 5.96	11 5.93	12 5.88	13 5.88	14 5.80	15 5.81	16 5.59
1		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2	* [2]		ns	*	*	*	*	*	*	*	*	*	*	*	*	*
3	*	ns		ns	*	*	*	*	*	*	*	*	*	*	*	*
4	*	*	ns		ns	*	*	*	*	*	*	*	*	*	*	*
5	*	*	*	ns		ns	*	*	*	*	*	*	*	*	*	*
6	*	*	*	*	ns		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
7	*	*	*	*	*	ns		ns	ns	ns	ns	ns	ns	ns	ns	ns
8	*	*	*	*	*	*	ns		ns	ns	ns	ns	ns	ns	ns	ns
9	*	*	*	*	*	*	ns	ns		ns	ns	ns	ns	ns	ns	ns
10	*	*	*	*	*	*	ns	ns	ns		ns	ns	ns	ns	ns	ns
11	*	*	*	*	*	*	ns	ns	ns	ns		ns	ns	ns	ns	ns
12	*	*	*	*	*	*	ns	ns	ns	ns	ns		ns	ns	ns	ns
13	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns		ns	ns	ns
14	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns	ns		ns	ns
15	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns	ns	ns		ns
16	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	

[1] LSD test-Probabilities for Post Hoc Tests; Error: Between MS = 1.2830, df = 240; [2] * $p < 0.05$; ns—not significant; [3] Depth (cm): 1 (0–5), 2 (5–10), 3 (10–15), 4 (15–20), 5 (20–25), 6 (25–30), 7 (30–35), 8 (35–40), 9 (40–45), 10 (45–50), 11 (50–55), 12 (55–60), 13 (60–65), 14 (65–70), 15 (70–75), 16 (75–80).

On Gleysol, PR in 1st and 2nd measurements were affected by tillage and depth during 2021, 2022, and 2023, respectively. Interaction between tillage × depth was identified for 1st measurement during all studied periods, while 2nd measurement was observed only in 2021 (Figure 2).

Significant differences were observed during the 1st measurement in 2021, 2022, and 2023 between tillage × deep tillage (Figure 2). Penetration resistance in 2021 was highest at CTD at depths of 40–80 cm (values ranged from 2.77 to 2.83) without any statistical significance between depths (from 40 to 80 cm) at the same tillage treatment, but with established statistically significant differences between other tillage treatments (Figure 2). In 2022 and 2023, the highest value of soil PR was measured at CTD treatment at 50–55 cm (3.79 MPa and 2.70 MPa). Significant differences in PR were found between tillage × depth treatments, which are shown in Figure 2.

During the 2nd measurement (in 2021), the highest PR was measured at ST at 60–65 cm (9.17 MPa), and all statistically significant differences in PR are shown in Figure 2. In 2022 and 2023, the measured resistances were significantly influenced by tillage and depth, which acted independently, i.e., their interaction was not determined. The highest PR (in 2002) was recorded on ST (3.76 MPa) and on the depth 75–80 cm (5.95 MPa). ST and CTD (3.60 MPa) treatments had a significantly higher PR than CTS (3.23 MPa). Differences in soil PR between ST and CTD were not statistically significant. The differences in PR between the observed depths are shown in Table 7.

In 2023, the highest PR was measured on ST (2.77 MPa) and 60–65 cm (3.41 MPa). CTS (2.37 MPa) and CTD (2.22 MPa) had a significantly lower PR than ST. Differences in soil PR between CTS and CTD were not statistically significant. The differences in PR between the observed depths are shown in Table 8, while the average soil moisture content is presented in Table 9.

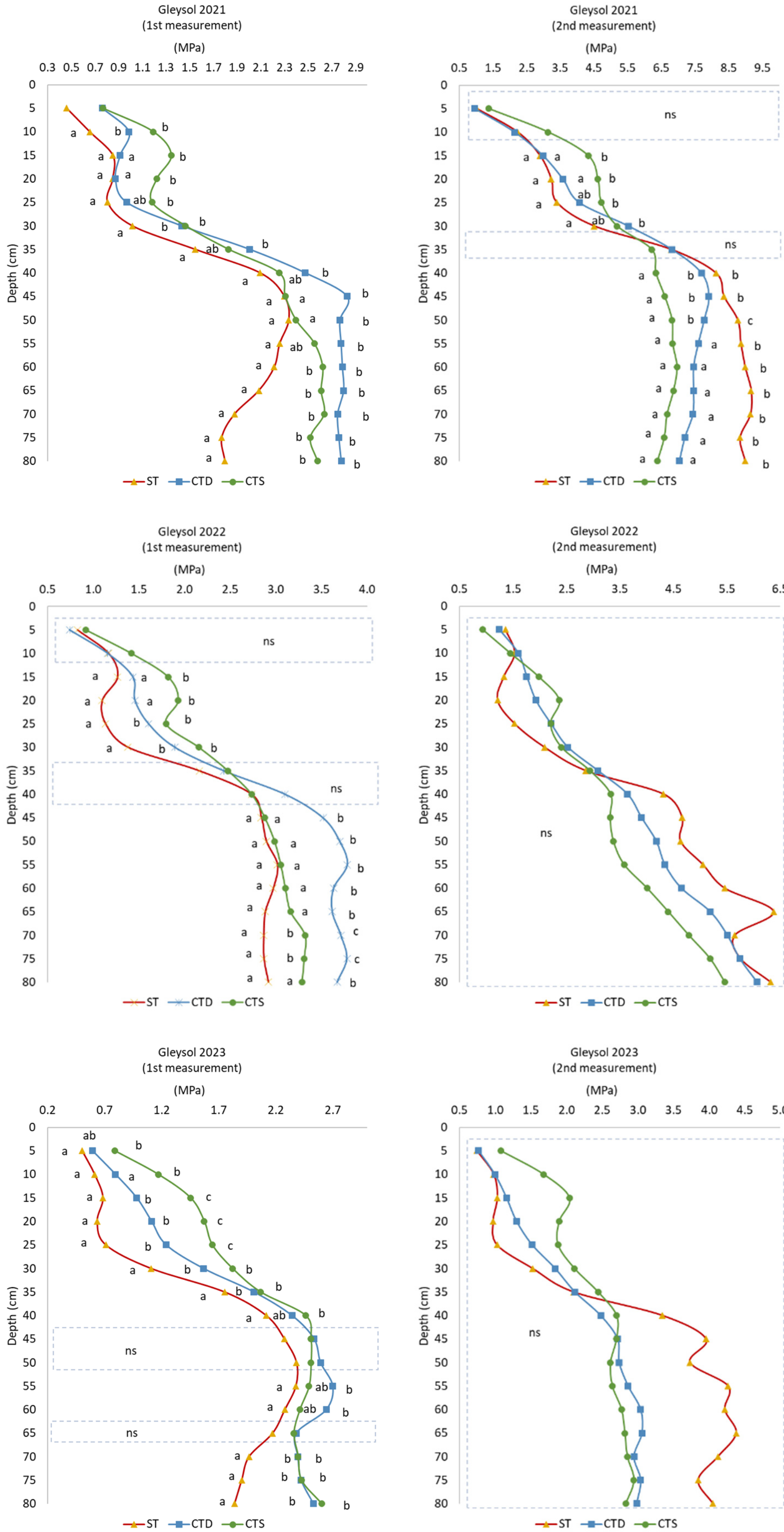

Figure 2. Penetration resistance under ST, CTD, and CTS at 0–5; 5–10; 10–15; 15–20; 20–25; 25–30; 30–35; 35–40; 40–45; 45–50; 50–55; 55–60; 60–65; 65–70; 70–75; 75–80 cm depth. Different letters for each depth indicate significant differences at $p < 0.05$ among the treatments, ns-not significant at $p < 0.05$.

Table 7. LSD [1] test for penetration resistance (MPa) on different depths (Gleysol 2022—2nd measurement).

Depth [3]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
MPa	1.18	1.53	1.69	1.83	1.98	2.34	2.96	3.76	3.96	4.06	4.32	4.70	5.32	5.31	5.56	5.95
1		ns	ns	ns	*	*	*	*	*	*	*	*	*	*	*	*
2	ns [2]		ns	ns	ns	*	*	*	*	*	*	*	*	*	*	*
3	ns	ns		ns	ns	ns	*	*	*	*	*	*	*	*	*	*
4	ns	ns	ns		ns	ns	*	*	*	*	*	*	*	*	*	*
5	*	ns	ns	ns		ns	*	*	*	*	*	*	*	*	*	*
6	*	*	ns	ns	ns		ns	*	*	*	*	*	*	*	*	*
7	*	*	*	*	*	ns		*	*	*	*	*	*	*	*	*
8	*	*	*	*	*	*	*		ns	ns	ns	*	*	*	*	*
9	*	*	*	*	*	*	*	ns		ns	ns	*	*	*	*	*
10	*	*	*	*	*	*	*	ns	ns		ns	ns	*	*	*	*
11	*	*	*	*	*	*	*	ns	ns	ns		ns	*	*	*	*
12	*	*	*	*	*	*	*	*	*	ns	ns		ns	ns	*	*
13	*	*	*	*	*	*	*	*	*	*	*	ns		ns	ns	ns
14	*	*	*	*	*	*	*	*	*	*	*	ns	ns		ns	ns
15	*	*	*	*	*	*	*	*	*	*	*	*	ns	ns		ns
16	*	*	*	*	*	*	*	*	*	*	*	*	ns	ns	ns	

[1] LSD test-Probabilities for Post Hoc Tests; Error: Between MS = 1.1460, df = 240; [2] * $p < 0.05$; ns—not significant; [3] Depth (cm): 1 (0–5), 2 (5–10), 3 (10–15), 4 (15–20), 5 (20–25), 6 (25–30), 7 (30–35), 8 (35–40), 9 (40–45), 10 (45–50), 11 (50–55), 12 (55–60), 13 (60–65), 14 (65–70), 15 (70–75), 16 (75–80).

Table 8. LSD [1] test for penetration resistance (MPa) on different depths (Gleysol 2023—2nd measurement).

Depth [3]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
MPa	0.87	1.22	1.41	1.39	1.48	1.83	2.22	2.84	3.12	3.03	3.26	3.34	3.42	3.31	3.28	3.29
1		ns	ns	ns	ns	*	*	*	*	*	*	*	*	*	*	*
2	ns [2]		ns	ns	ns	ns	*	*	*	*	*	*	*	*	*	*
3	ns	ns		ns	ns	ns	ns	*	*	*	*	*	*	*	*	*
4	ns	ns	ns		ns	ns	ns	*	*	*	*	*	*	*	*	*
5	ns	ns	ns	ns		ns	ns	*	*	*	*	*	*	*	*	*
6	*	ns	ns	ns	ns		ns	*	*	*	*	*	*	*	*	*
7	*	*	ns	ns	ns	ns		ns	*	ns	*	*	*	*	*	*
8	*	*	*	*	*	*	ns		ns	ns	ns	ns	ns	ns	ns	ns
9	*	*	*	*	*	*	*	ns		ns	ns	ns	ns	ns	ns	ns
10	*	*	*	*	*	*	ns	ns	ns		ns	ns	ns	ns	ns	ns
11	*	*	*	*	*	*	*	ns	ns	ns		ns	ns	ns	ns	ns
12	*	*	*	*	*	*	*	ns	ns	ns	ns		ns	ns	ns	ns
13	*	*	*	*	*	*	*	ns	ns	ns	ns	ns		ns	ns	ns
14	*	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns		ns	ns
15	*	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns	ns		ns
16	*	*	*	*	*	*	*	ns	ns	ns	ns	ns	ns	ns	ns	

[1] LSD test-Probabilities for Post Hoc Tests; Error: Between MS = 1.8008, df = 240; [2] * $p < 0.05$; ns—not significant; [3] Depth (cm): 1 (0–5), 2 (5–10), 3 (10–15), 4 (15–20), 5 (20–25), 6 (25–30), 7 (30–35), 8 (35–40), 9 (40–45), 10 (45–50), 11 (50–55), 12 (55–60), 13 (60–65), 14 (65–70), 15 (70–75), 16 (75–80).

Table 9. Average soil moisture content (%, vol.) on both experimental sites.

Year	Depth (cm)	Stagnosol						Gleysol					
		Measuring 1			Measuring 2			Measuring 1			Measuring 2		
		ST	CTD	CTS	ST	CTD	CTS	ST	CTD	CTS	ST	CTD	CTS
2021	0–20	33.1	37.2	35.9	27.2	16.4	19.7	39.6	36.6	39.7	24.5	28.2	27.3
	20–40	41.3	41.3	42.0	25.4	14.3	19.0	40.3	37.4	42.6	13.8	20.1	18.7
	40–60	36.1	37.2	36.9	21.0	16.4	18.8	39.9	40.9	37.0	16.2	15.7	19.4
	60–80	44.5	41.4	37.8	21.4	17.9	18.1	42.1	40.0	38.7	16.6	16.2	15.6

Table 9. *Cont.*

Year	Depth (cm)	Stagnosol						Gleysol					
		Measuring 1			Measuring 2			Measuring 1			Measuring 2		
		ST	CTD	CTS	ST	CTD	CTS	ST	CTD	CTS	ST	CTD	CTS
2022	0–20	36.1	37.2	34.7	34.7	38.9	34.0	31.3	35.2	35.9	34.7	38.0	31.0
	20–40	40.9	38.7	36.9	35.9	40.4	40.0	34.1	39.6	40.7	35.9	42.3	38.9
	40–60	37.7	33.1	35.2	41.6	40.6	40.2	36.8	34.1	35.2	39.6	42.7	40.1
	60–80	42.8	37.3	40.6	40.3	39.4	39.3	32.7	36.9	38.6	40.4	38.8	39.6
2023	0–20	44.3	44.5	42.3	40.0	42.1	41.4	43.2	43.1	43.9	43.1	43.0	46.0
	20–40	43.2	42.9	41.6	41.1	41.8	42.4	42.9	41.4	44.2	40.1	42.7	43.8
	40–60	45.7	44.2	44.7	41.2	42.7	42.2	41.1	43.2	42.5	39.6	40.5	44.1
	60–80	43.6	42.7	42.8	39.8	42.1	42.5	41.6	42.1	41.4	42.9	43.6	41.9
	average	40.8	39.8	39.3	34.1	32.8	33.1	38.8	39.2	40.0	32.3	34.3	33.9
	min	33.1	33.1	34.7	21.0	14.3	18.1	31.3	34.1	35.2	13.8	15.7	15.6
	max	45.7	44.5	44.7	41.6	42.7	42.5	43.2	43.2	44.2	43.2	43.6	46.0
	Me	42.0	40.0	39.2	37.9	39.9	39.7	40.1	39.8	40.2	37.8	39.7	39.3
	SD	4.0	3.5	3.4	8.1	12.3	10.8	4.1	3.1	3.0	11.2	11.1	11.0
	CV	9.9	8.8	8.7	23.7	37.4	32.5	10.6	7.9	7.6	34.8	32.3	32.6

4. Discussion

Penetration resistance is one of the most important soil indicators, and it is in line with the level and intensity of soil compaction. PR values appear as the results of various factors and processes, such as soil texture, soil water content, type of tillage, etc., and each of them is closely interconnected on many levels with different significations that ultimately influence crop yields.

A compacted soil layer often develops in the topsoil during long-term reduced tillage, resulting from soil settling, field traffic compaction, and less effective loosening compared to conventional tillage [34,44,45]. Stagnosols are a type of soil characterized by poor drainage, leading to periodic water saturation. This waterlogging occurs due to a dense, compacted subsoil layer, often rich in clay, that impedes water movement. In our research on Stagnosol, the highest soil penetration resistances in all investigated years were measured on CTS treatment at a depth of 10–15 cm (1st measurement). Higher peaks of PR that were measured on Stagnosol soil type, mostly from 10 to 15 cm on each tillage treatment in each experimental year and in both measurement dates (except in 2023 in 2nd measurement), are the result of repeated passages in secondary tillage and other soil trafficking (e.g., application of pesticides and top dressing). This is related to the results presented by Upadhyay and Rahman [46] and Soane and van Ouwerkerk [22], who compared the different effects of multiple tillage passes on soil compaction at a depth of 10–20 cm. Also, a study conducted in Argentina found that no-till increased soil resistance compared to conventional tillage, with the increase being more pronounced in the shallow layers than in the deeper layers [30].

During the second measurement in 2021, the highest PR was recorded at CTS, which was statistically higher than ST, while the difference in resistances compared with CTD was statistically non-significant. Our results are probably due to the presence of an impermeable (compacted) layer characteristic of the Stagnosol at that depth that was not "loosened" by the conservation tillage (CTD and CTS treatments). Increased PR at a depth of 35–40 cm is a typical phenomenon on Stagnosol, which is characterized by the presence of an impermeable layer that is formed due to intense eluvial-illuvial processes in the solum [47]. This statement is supported by the fact that, on average, for all tillage treatments, the highest PR was measured at a depth of 35–40 cm (6.47 MPa). Numerous studies [44,45,48] reported that many soils under conservation treatment can show greater PR, suggesting that this parameter may not be able to provide information on soil functionality like other parameters. At the same time, the obtained results are not in accordance with the research of Birkas et al. [10] and Kovacs et al. [49], which state in their research that soil compaction at a depth of 30–40 cm was greater in conventional tillage than in no-tillage. The authors attribute this to the formation of a tillage-induced hardpan ("plow pan") under the conventional tillage treatment, which they report as a consequence of long-term plowing at a consistent depth.

In 2022, during the second measurement on Stagnosol, the highest PR was observed at a depth of 35 to 80 cm, ranging from 1.8 to 2.2 MPa, and in the soil layer above 35 cm, the highest PR was recorded in the CTD treatment (2.0 MPa). Bogunović et al. [34] mentions that a PR value of 2.0 MPa is the threshold for normal root development, as established by Taylor and Gardner [50]. According to Håkansson and Lipiec [51] and Birkas et al. [52], the critical limit for PR should be between 2.8 and 3.2 MPa.

Gleysols are soil types characterized by subsurface horizons with prominent redoximorphic features formed by intermittent to long-term anoxia (as a consequence of water saturation) [53]. In our research in Gleysol in 1st measurement, PR values ranged from 0.46 to 3.79 MPa. Bengough et al. [54] and Moraes et al. [26] state that PR values between 2.0 and 3.5 MPa are suitable for crop production, while higher values are the main limitation for root development. They also note that these critical limit values may vary primarily due to soil water content.

The highest resistance in 2021 (1st measurement) was measured on the CTD at a depth of 40–45 cm and did not change significantly up to 80 cm. The assumption is that stronger soil compaction at depths below 40 cm is the result of the formation of a more compact soil layer due to the periodic alternation of wet and dry periods, as found in our research (Tables 2 and 9). In 2022 and 2023, the highest value of soil PR was measured at CTD treatment at 50–55 cm. These results follow the expectations of periodic alternation of dry and over-wet hydrological conditions, especially if it is taken into account that higher compaction values, and therefore PR, can be expected on wetter soils [55]. Throughout all the years of research, during the first measurement, at all researched depths, PR at ST was the smallest and ranged from 0.46 to 2.38 MPa. The obtained results are probably due to the increase in the volume of the soil by ST, whereby the soil dries more easily and becomes looser, i.e., more porosity [2]. During the 2nd measurement, PR increased to ST treatment at depths from 40 cm with a relatively high value from 8.12 to 9.17 MPa. These results are probably due to stronger drying of the soil in the period preceding the PR measurement. In dry periods, conservation tillage enables better conservation of soil moisture [7].

In 2022 and 2023, the highest PR was recorded on ST at depths 75–80 and 60–65 cm, respectively. Conservation tillage treatments had a significantly lower PR than ST, while differences in soil PR between CTS and CTD were not statistically significant. In our research, PR in upper layers up to 35 cm in most cases was under the root-limiting critical value [26,52,54] on both experimental sites and in both measurement dates. However, PR values above these major limited values for most of the cropping season, in most cases, were found in deeper layers (from 35 to 80 cm) with a higher frequency on Gleysol soil type (Figures 1 and 2).

5. Conclusions

In a comparison of the average penetration resistance values at both experimental sites in the cross-section of all experimental years, it is quite clearly visible that the Stagnosol soil type is more compact than Gleysol, but only in the 1st measurement, while in the 2nd measurement, results are reversed.

Penetration resistance is more strongly influenced by weather conditions than by different tillage systems. In wetter conditions, higher penetration resistance was measured on conservation soil tillage treatments, while in drier conditions, the highest values of penetration resistance were recorded on conventional soil tillage treatment.

In the upper layers (up to 35 cm), penetration resistance values were, in most cases, below the root-limiting critical value (3.5 MPa) at both experimental sites and on both measurement dates. By increasing the depth of Stagnosol in the 1st measurement, the values decreased, while in the 2nd measurement, they increased. On Gleysol, penetration resistance values also increased with increasing depth. By increasing the depth, the penetration resistance values at each tillage treatment began to stabilize and smooth out, with similar dynamics on both soil types and measurement dates.

On Stagnosol, during all investigated years in 1st and 2nd measurements, the highest penetration values were measured at the conservation tillage treatments. On Gleysol, during 1st measurement throughout all three years of research, the highest penetration resistance was measured for conservation tillage treatments, while during the 2nd measurement, the highest penetration resistance was on conventional tillage.

Due to the different start positions of experimental sites (before the experiment started, the Stagnosol has applied very intensive conventional tillage, and on Gleysol, a meadow that was previously grown for 15 years), the results are in line with expectations. Compared to conventional soil tillage, both conservation soil tillage types showed, after three years of experiments, a significant overall reduction in PR values on both soil types, especially on the Gleysol soil type. This trend indicates first an increase in PR in conventional tillage systems and then a stagnation or decrease in PR in conservation tillage treatments. The achieved results indicate the potential of replacing conventional tillage with conservation tillage treatments that ensure better and more efficient rooting of crops and, consequently, higher yields. Penetration resistance measurement provides valuable results on soil compaction and can be a very useful tool in short-term response.

We suggest additional research on the response of conservation tillage treatments on Stagnosols and Gleysols soil types.

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