soil systems

MDPI

Article

Assessing Different Stubble Tillage Technologies on Covered and Uncovered Surfaces

Zoltán Kende [1,*], Norbert Egri [1,2], Márta Birkás [1,†], Márton Jolánkai [1], Viola Kunos [1], Boglárka Bozóki [1] and Ákos Tarnawa [1]

[1] Institute of Agronomy, Hungarian University of Agriculture and Life Sciences, Páter Károly u. 1., 2100 Gödöllő, Hungary
[2] Szarvasi Gallifarm Ltd., 5561 Békésszentandrás, Hungary
* Correspondence: kende.zoltan@uni-mate.hu
† Deceased.

Abstract: This study evaluates the impact of ten stubble tillage methods, cultivators, and disk harrows, on clay loam soil under uncovered and mulched conditions during a wetter-than-average (+20% precipitation) summer in 2020. Key parameters such as soil moisture, penetration resistance, soil structure, surface coverage, and earthworm abundance were assessed. Shallow tillage with the Lemken Rubin 9 disk preserved the highest soil moisture (27.65% at 15–30 cm depth) while reducing compaction. Mulched conditions with the Bird cultivator yielded the highest earthworm abundance, while uncovered treatments, such as Carrier deep, outperformed covered alternatives in some cases. The study underscores the role of stubble tillage in soil conservation, particularly under climate change scenarios, and aligns with the European Green Deal's emphasis on sustainable and resilient agricultural practices by contributing to the development of sustainable farming practices.

Keywords: soil conservation; mulching; agricultural machinery; climate adaptation; regenerative agriculture; green deal

check for updates

Academic Editor: Claudio Cocozza

Received: 12 September 2024
Revised: 31 January 2025
Accepted: 3 February 2025
Published: 7 February 2025

Citation: Kende, Z.; Egri, N.; Birkás, M.; Jolánkai, M.; Kunos, V.; Bozóki, B.; Tarnawa, Á. Assessing Different Stubble Tillage Technologies on Covered and Uncovered Surfaces. *Soil Syst.* **2025**, *9*, 13. https://doi.org/10.3390/soilsystems9010013

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Traditional systems of soil preparation, such as disk tillage, have been widely used for decades as part of conventional tillage practices. These methods typically involve significant soil disturbance to incorporate crop residues and prepare the seedbed, but they can lead to soil compaction, erosion, and loss of organic matter over time [1,2]. In response to these issues, conservation tillage systems, including no-till practices, have been developed to minimize soil disturbance and retain crop residues on the soil surface. These approaches aim to conserve soil moisture, reduce erosion, and enhance soil health by preserving organic matter, fostering biodiversity, improving soil structure, increasing organic carbon levels, and supporting diversity in soil biota [3–5].

Within the broader category of soil tillage, stubble tillage occupies a unique position as an intermediate tillage practice conducted between the harvesting of one crop and the planting of another. Unlike primary tillage, which often involves deeper soil inversion (e.g., moldboard plowing in conventional tillage), or conservation tillage systems, which minimize soil disturbance, stubble tillage focuses on shallow residue incorporation to maintain good soil conditions during the summer and control weed growth. This method is particularly effective in dryland systems where preserving surface cover is essential for moisture retention and erosion prevention [6]. Stubble tillage involves the partial incorporation of crop residues into the soil without complete removal, which helps to

manage soil surface conditions and retain moisture [7,8]. This practice plays a crucial role in preparing the soil for the next cropping season by maintaining soil structure, preventing soil compaction, and conserving soil moisture [9,10].

The shift towards integrating various tillage practices, including stubble tillage, is driven by the need for sustainable agricultural management. Conventional tillage encompasses a range of practices aimed at soil preparation, often involving significant soil disturbance, such as deep plowing to incorporate crop residues and prepare the seedbed. While effective for weed control and seedbed preparation, deep plowing has been shown to contribute to soil compaction and the loss of soil organic matter over time, particularly in the topsoil layer [11,12].

Conservation tillage systems, including no-till and reduced tillage, minimize soil disruption and retain residue to conserve moisture, improve soil health, and reduce erosion, while enhancing soil organic carbon and lowering compaction risk compared to conventional methods [13,14]. Stubble tillage offers flexibility for shallow residue incorporation and weed control, making it ideal for dryland farming by preserving soil moisture and structure. Studies show that it mitigates issues like compaction from deep plowing while supporting crop productivity [15]. By balancing soil conservation with residue management, stubble tillage provides a practical solution for optimizing soil conditions under varying environmental constraints [16,17]. The adoption of tillage practices varies globally, shaped by climate, soil, and economic factors, with some regions embracing them more easily while others face challenges like transition costs and equipment availability [18,19].

Soil quality refers to the capacity of soil to perform its essential functions, including sustaining plant and animal productivity, maintaining or enhancing water and air quality, and supporting human health and habitation. This concept encompasses the soil's physical, chemical, and biological properties, which together determine its ability to function within natural or managed ecosystems [20,21]. Evaluation of soil quality involves assessing key indicators such as organic matter content, bulk density, pH, microbial activity, and water retention capacity [22,23]. These indicators vary spatially and temporally, requiring region-specific parameters to effectively monitor and manage soil health [24,25].

Biologically, stubble tillage affects soil microbial communities by helping to maintain a diverse and active population of microorganisms [26]. This diversity is vital for processes such as nutrient cycling and organic matter decomposition, contributing to overall soil health [27–29]. The biological benefits of stubble tillage are critical for maintaining soil fertility and supporting sustainable agricultural systems [30].

In the context of climate change, stubble tillage offers significant benefits. It can help mitigate the adverse effects of climate variability by improving soil resilience and maintaining soil moisture levels [31,32]. By promoting higher levels of soil organic carbon (SOC) and enhancing moisture retention, stubble tillage serves as an important strategy for climate change adaptation [33]. The use of cover crops and organic amendments alongside stubble tillage can further improve soil health and crop resilience, particularly in regions facing increased drought and temperature extremes [34,35].

Nevertheless, implementing stubble tillage effectively requires addressing challenges such as weed management without excessive herbicide use, which can impact biodiversity [36,37]. Strategies like cover cropping and crop rotations can complement stubble tillage to maintain productivity while minimizing environmental damages [38]. Moreover, selecting suitable equipment and understanding local soil and climatic conditions are crucial for maximizing the benefits of stubble tillage [39].

Despite the extensive use of various tillage methods and mulching practices in agriculture, comprehensive studies comparing these techniques under diverse conditions, particularly between uncovered and mulched surfaces, remain scarce. Existing research of-

ten highlights benefits such as improved soil moisture retention and reduced erosion [6,40], but these findings are typically derived from limited geographic areas or idealized experimental setups [41–43]. The interactions between different tillage systems and mulching materials, such as straw versus plastic, and their combined effects on soil properties and crop performance across various soil types and climatic conditions have not been thoroughly explored [42]. This knowledge gap is particularly significant in the context of the European Green Deal (EGD), which emphasizes sustainable agricultural practices as a pathway to achieving climate neutrality and enhancing biodiversity [44,45].

This is especially critical considering the increasing climate variability, which exacerbates soil degradation and necessitates more tailored and adaptive soil management strategies [1,2]. While previous studies have demonstrated the potential of conservation tillage to mitigate erosion and improve soil health, limited attention has been given to intermediate practices like stubble tillage, which balances soil disturbance with residue management [6]. Thus, this study aims to evaluate the applicability of various stubble tillage tools, including cultivators, traditional round disks, and flat disks, both with and without rollers, on uncovered and mulched soil surfaces. It will assess the effects of these tools on critical soil parameters such as moisture retention, penetration resistance, soil structure, surface coverage, and the abundance of earthworms. The objective is to provide a comprehensive analysis of the suitability of different stubble tillage methods and to offer practical recommendations for optimizing cultivation practices. This study is especially relevant under the EGD that advocates for reduced environmental impact and enhanced soil conservation as essential components of sustainable agriculture. Understanding the most effective tillage and mulching practices will support the EGD's goals of reducing chemical inputs, improving soil health, and increasing biodiversity [45], thereby contributing to a more resilient agricultural system capable of adapting to the challenges posed by climate change.

2. Materials and Methods

2.1. Study Location

The experiment was set up on a 32-hectare winter wheat field in the administrative boundary of the municipality of Békésszentandrás, Hungary (46°50′11.5″ N 20°28′52.6″ E) in the summer of 2020, which was wetter than the long-term average with an extremely unevenly distributed and powerful events accompanied by storms. About 580–590 mm of precipitation felt in 2020, exceeding approximations by 20% of the average annual rainfall of 450–520 mm which is typical for the region.

2.2. Soil Analysis

Based on the soil analysis results, the soil of the experimental field was classified as a Dystric Clayic Humic Cambisol (IUSS WRB Working Group, 2022) [46]. The physical type of the soil was clay loam, with an average humus content of 2.47% (MSZ 21470-52:1983 [47]). The soil was weakly acidic (pH = 6.04; MSZ EN ISO 10390:2022 [48]). Nutrient analysis revealed that the soil was well supplied with phosphorus (P_2O_5 = 218 mg/kg; MSZ 20135:1999 [49]) and had a high potassium level (K_2O = 367 mg/kg; MSZ 20135:1999 [49]). Nutrient extraction was conducted using the ammonium-lactate (AL) method, and the potassium and phosphorus concentrations were quantified using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), ensuring precise and sensitive measurements. These characteristics align with the soil's clay-rich properties, which contribute to its high cation exchange capacity and nutrient retention capability.

2.3. Agrotechnology of the Experimental Field

The experimental field had not been plowed for more than 10 years, as conservation tillage practices were typically used for primary tillage in this area. Specifically, field management predominantly involved reduced tillage methods, such as tine tillage or subsoiling. These practices were performed using machine coupling systems that allowed for efficient soil disturbance while operating at a reduced number of revolutions to minimize soil compaction and preserve soil structure. This approach aligns with the principles of reduced tillage, emphasizing soil conservation, erosion reduction, and the retention of crop residues on the surface. No-till practices were not part of the standard management for this field. Sunflower was grown in the area in 2018, winter wheat in 2019, and winter wheat again in 2020. The latter received soil loosening to a depth of about 30 cm as primary tillage, followed by flat disk harrowing and seedbed preparation with a shallow tine cultivator. Due to the rainy season, the harvest was postponed until the 21st of July. The Hungarian wheat variety GK Békés yielded 5.4 t/ha. The experiment was set up on the 12th of August. The mulching material used for covered surfaces in this study consisted of straw residues from the preceding winter wheat crop, left on the soil surface after harvest. The straw was evenly distributed using the combine harvester straw chopping. The straw mulch was not incorporated into the soil prior to the stubble tillage treatments. This method preserved the stubble as a protective surface layer, aimed at enhancing soil moisture retention, reducing erosion, and supporting soil health. For the uncovered treatments, the straw was collected, baled, and removed from the field immediately after harvest, thus this process ensured minimal residual surface coverage.

2.4. Study Design

We created a total of 20 different plots with 10 different stubble tillage technologies with and without mulching, for which we used 5 different machines listed in Table 1, each working at the indicated depths. All tillage methods were used in parallel on the straw-covered and uncovered treatments. In the case of the control plots, no stubble tillage was carried out, so we tested 20 different stubble tillage technologies on the 32-hectare field. As a field experiment, we could not establish a random block design (RDB) in the experimental layout due to the operational nature of the experiment and the lack of space; however, the plots were separated into three different subplots, and the physical measurements and sampling for chemical soil analysis were performed in 3 repetitions per subplot (Figure 1 and Table 2). In total, we had 60 subplots, one subplot size was 50 m × 20 m which is 0.1 hectare.

Table 1. Presentation of the investigated tillage machines and stubble stripping technologies, the cultivation depths, and the layout of the treatments.

#	Machine and Working Depth	Manufacturer	Name of Treatments	Code *
1.	Undisturbed (0 cm)	-	Covered control	K
2.	Lemken Rubin 9 disk (5–10 cm)	Lemken, Germany	Covered Lemken shallow	Ls
3.	Lemken Rubin 9 disk (10–15 cm)	Lemken, Germany	Covered Lemken deep	Ld
4.	Rabe Profi Bird 4000 K cultivator (8–10 cm)	Rabe, Germany	Covered Bird cultivator	B
5.	Väderstad Carrier 925 disk (6–8 cm)	Väderstad, Sweden	Covered Carrier deep	Cd
6.	Väderstad Carrier 925 disk (2–4 cm)	Väderstad, Sweden	Covered Carrier shallow	Cs
7.	Rába IH 10-770 disk (6–8 cm)	Rába, Hungary	Covered IH shallow	IHs
8.	Rába IH 10-770 disk (6–8 cm) + Väderstad Rexius 1020 roller	Rába, Hungary and Väderstad, Sweden	Covered IH shallow + roller	IHsr

Table 1. *Cont.*

#	Machine and Working Depth	Manufacturer	Name of Treatments	Code *
9.	Rába IH 10-770 disk (10–12 cm) + Väderstad Rexius 1020 roller	Rába, Hungary and Väderstad, Sweden	Covered IH deep + roller	IHdr
10.	Rába IH 10-770 disk (10–12 cm)	Rába, Hungary	Covered IH deep	IHd
11.	Rába IH 10-770 disk (10–12 cm)	Rába, Hungary	Uncovered IH deep	IHd
12.	Rába IH 10-770 disk (10–12 cm) + Väderstad Rexius 1020 roller	Rába, Hungary and Väderstad, Sweden	Uncovered IH deep + roller	IHdr
13.	Rába IH 10-770 disk (6–8 cm) + Väderstad Rexius 1020 roller	Rába, Hungary and Väderstad, Sweden	Uncovered IH shallow + roller	IHsr
14.	Rába IH 10-770 disk (6–8 cm)	Rába, Hungary	Uncovered IH shallow	IHs
15.	Väderstad Carrier 925 disk (2–4 cm)	Väderstad, Sweden	Uncovered Carrier shallow	Cs
16.	Väderstad Carrier 925 disk (6–8 cm)	Väderstad, Sweden	Uncovered Carrier deep	Cd
17.	Rabe Profi Bird 4000 K cultivator (8–10 cm)	Rabe, Germany	Uncovered Bird cultivator	B
18.	Lemken Rubin 9 disk (10–15 cm)	Lemken, Germany	Uncovered Lemken deep	Ld
19.	Lemken Rubin 9 disk (5–10 cm)	Lemken, Germany	Uncovered Lemken shallow	Ls
20.	Undisturbed (0 cm)	-	Uncovered control	K

* Capital letters sign the manufacturer of the machine: L—Lemken; B—Rabe; C—Väderstad; IH—Rába IH; K—Control. Lowercase letters: s—shallow stubble tillage (<10 cm); d—deep stubble tillage (≥10 cm); r—surface closed with a roller.



Figure 1. Bird's-eye view of the experimental setup in the summer of 2020.

Table 2. Presentation of the experimental layout.

#		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Treatment replications	border	border																				border
		R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	R1	
		R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	R3	
		R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	R2	
		border																				
Treatments		K	Ls	Ld	B	Cd	Cs	IHs	IH sr	IHdr	IHd	IHd	IHdr	IH sr	IHs	Cs	Cd	B	Ld	Ls	K	

Note: Capital letters sign the manufacturer of the machine: L—Lemken; B—Rabe; C—Väderstad; IH—Rába IH; K—Control. Lowercase letters: s—shallow stubble tillage (<10 cm); d—deep stubble tillage (≥10 cm); r—surface closed with a roller. R1–3 shows the replication number per treatment.

The selected tillage equipment and methods presented in Table 1 mostly cover the practices and possibilities of the Hungarian farmers in the study region.

2.5. Measured Parameters

The measurements lasted 10 weeks in total. Soil penetration resistance, soil moisture content, soil structure, and earthworm abundance measurements were performed on 8 occasions, the surface coverage determination on 1 occasion, and the soil sampling on 2 occasions, between 12 August and 22 October 2020.

2.5.1. Soil Penetration Resistance (SPR)

Soil penetration resistance (SPR) was measured using an electronic cone penetrometer (Penetrologger, Eijkelkamp, The Netherlands) with a 1 cm^2 base area cone and a 50 cm stick probe. Four sampling points per plot were measured at each sampling date, and the data were expressed in megapascals (MPa) and grouped into 15 cm intervals to a depth of 45 cm.

2.5.2. Soil Moisture Content (SMC)

The soil moisture content (SMC) was also measured in the vicinity of each SPR measurement using a PT-I type instrument (Kapacitív Kft., Budapest, Hungary) at a depth of 0–45 cm in 15 cm increments which was expressed as a percentage (m/m%).

2.5.3. Examination of the Soil Structure

Soil structure measurements were performed according to the method described by [50]. Sampling was conducted at a depth of 0–20 cm, with 3 replicates per subplot in each sampling period. The soil samples were air-dried and sieved manually on an agronomic sieve to separate the different soil fractions, including clods (>10 mm), crumbs (2.5–10 mm), small crumbs (0.25–2.5 mm), and dust (<0.25 mm). These fractions were weighed to determine the soil structure ratio and to assess the impact of the tillage treatments on soil structure.

2.5.4. Counting the Earthworm Abundance

The earthworm abundance was determined using the hand-sorting method with the help of a spade probe described by [51]. In this method, soil samples were collected using a spade probe (25 × 25 cm, 30 cm deep) in all subplots, with 3 replicates per subplot and we calculated the number of earthworms by hand in every sample. The sampling locations were chosen randomly. The earthworm abundance was expressed in several individuals per spade probe.

2.5.5. Estimation of Surface Coverage

Immediately after stubble tillage, the surface coverage of the straw mulch was determined in every plot using a modified version of the rapid coenologycal visual assessment technique [52,53]. A wooden bracket as a quadrat with a surface area of 0.25 m^2 (50 cm × 50 cm) was placed in each treatment at random distances in 3 replications. Each quadrat was examined, and coverage of mulch was defined as the fraction of the total quadrat area that is obscured by straw particles when viewed from directly above.

2.5.6. Measurement of the Soil Chemical Parameters

After the harvest, a composite soil sample was collected from the 0–15 cm layer of the entire area to characterize the initial state of the study. Toward the end of the growing season, soil sampling was repeated for each plot, resulting in a total of 60 soil samples analyzed for their agrochemical composition. The analyses were conducted in an accredited

laboratory following Hungarian standards. The pH was measured using the potentiometric method (KCl and H_2O extracts) according to MSZ EN ISO 10390:2022 [48]. The Arany-type plasticity index was also determined following the same standard. The humus content was measured spectrophotometrically according to MSZ-08-0210:1977 [54]. The nitrate and nitrite nitrogen (NO_{3-} + NO_{2-}) levels were determined by FIA spectrophotometry using a KCl extract, and phosphorus (P_2O_5) and potassium (K_2O) contents were analyzed by ICP-OES after AL extraction, all following MSZ 20135:1999 [49]. This comprehensive soil analysis provided detailed insight into the chemical properties of the soil before and after treatment.

2.6. Statistical Analysis

For the descriptive statistics with associated test statistics, we used the IBM SPSS Statistics V27 software [55]. Further analyses were conducted in R (R Core Team, 2022 [56]) with the 'agricolae' package [57] to perform the one-way analysis of variance (ANOVA) with the associated Tukey HSD post hoc test. For data manipulation, we used the 'dplyr' [58] and 'tidyr' [59] packages. The absolute ranking was performed based on identifying the best treatment with the highest or lowest value by measured parameter. In the last step, we summarized the results to be able to make a total performance ranking of the treatments. All figures were produced using the 'ggplot2' [60] and 'pheatmap' [61] packages. The type I error rate (α) was set at 0.05 for all statistical tests. Kolmogorov–Smirnov and Shapiro–Wilk tests were conducted which resulted in the collected dataset being normally distributed.

3. Results

3.1. Results of Moisture Content

3.1.1. Moisture Content of Uncovered Plots

A one-way between-subjects ANOVA was conducted to compare the effect of uncovered surfaces on SMC in 20 treatments in total. There was a significant effect of uncovering the plot surface on SMC values at the $p < 0.05$ level [$F(9,20) = 17.675$, $p = 0.001$].

Post hoc comparisons using the Tukey HSD test indicated that in the case of uncovered plots, the method of stubble tillage had a statistically verifiable effect on the change in moisture content of the upper 15 cm soil layer (Figure 2). The mean values of Uncovered IH deep treatment (21.01 ± 0.36%) differed significantly from the mean values of Uncovered Carrier deep (26.11 ± 0.32%), Uncovered Carrier shallow (25.91 ± 0.45%), Uncovered Bird (25.3 ± 0.18%), and Uncovered Lemken shallow (24.74 ± 0.48%) treatments. According to the results, the lowest moisture content was on deeply tilled soil with the IH disk (21.01 ± 0.36%). In the case of the Uncovered IH deep + roller plot, although the closure reduced moisture loss somewhat (22.82 ± 0.34%), it still differed significantly from Carrier shallow (25.93 ± 0.46%) and Carrier deep (26.11 ± 0.33%) treatments, and the most recently mentioned treatment also retained the highest moisture level in the soil. Due to the shallower operation of more modern stubble tillage devices on uncovered soils, the moisture content in the upper 0–15 cm soil layer is statistically proven to be preserved. The wetter-than-average summer of 2020 significantly influenced soil moisture retention across treatments. During the study period, cumulative rainfall exceeded the long-term average by approximately 20%, with particularly heavy precipitation in July and August. This elevated moisture level in the soil likely minimized the differences in moisture retention typically observed between covered and uncovered plots. These conditions highlight the importance of considering annual climatic variations when interpreting results, as such variations can amplify or dampen the effects of stubble tillage methods on soil moisture.

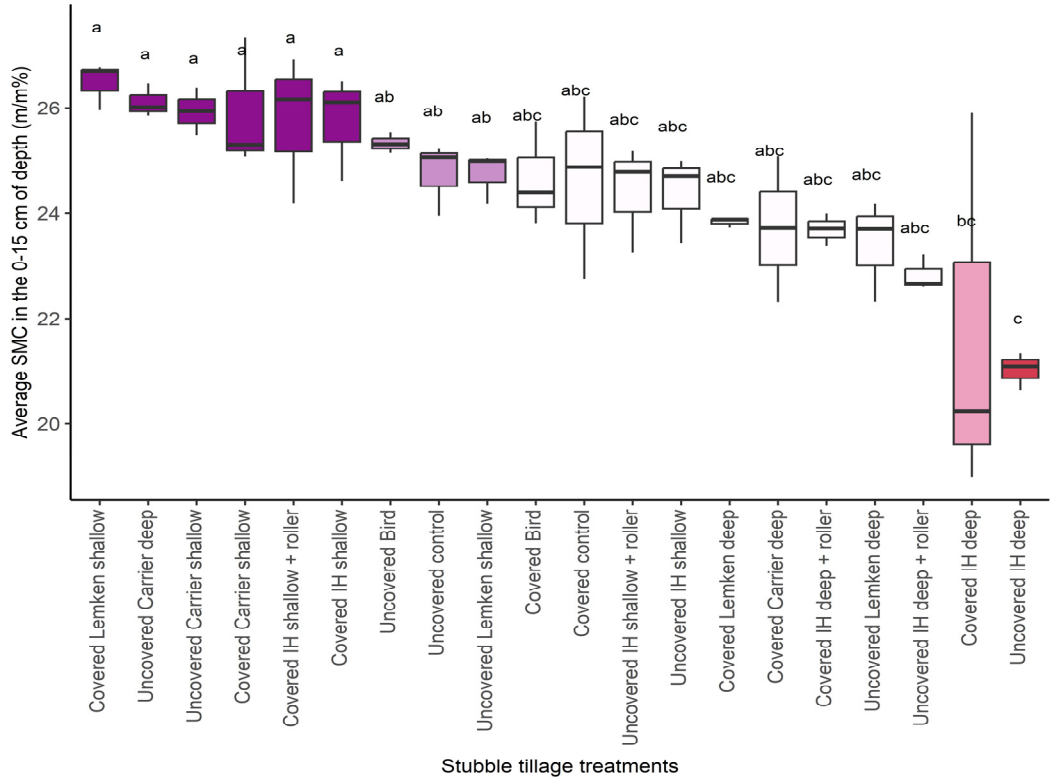


Figure 2. The impact of various stubble tillage methods on soil moisture content at 0–15 cm depth in the case of covered and uncovered surfaces. Results from a Tukey HSD analysis are shown as letters over the boxplots. Treatments sharing the same letter and color are not significantly different from each other at $p > 0.05$ level.

In the case of moisture values measured in the soil layer of 15–30 cm, similar to the upper layer, we found statistically significant results [F(9,20) = 4.682, $p = 0.002$]. Based on the post hoc comparison, the Carrier deep treatment (27.63 ± 0.21%) was significantly different from the Uncovered Bird (27.19 ± 0.17%) and the Uncovered Control (27.11 ± 0.09%), with the last one also having different results than the Uncovered Carrier shallow (27.65 ± 0.09%) treatment. The lowest moisture content was caused by the Uncovered Control plot (27.11 ± 0.09%), while the highest was detected in the case of the Uncovered Carrier deep (27.65 ± 0.21%) plot. The various tillage overall shows no outliers at this depth. In the deepest layer of soil (30–45 cm), we cannot register significant differences in the moisture content [F(9,20) = 0.69, $p = 0.710$].

3.1.2. Moisture Content of Covered Plots

For the covered treatments, the ANOVA results indicated a significant difference in the means of the SMC in 0–15 cm depth [F(9,20) = 2.523, $p = 0.041$]. However, based on the Tukey HSD, only the Covered Lemken shallow (26.48 ± 0.45%) and the Covered IH deep + roller (23.69 ± 0.31%) plots were significantly different in the moisture content of the 0–15 cm soil layer.

There were also differences in the moisture content of the soil layer with a depth of 15–30 cm [F(9,20) = 5.667, $p = 0.001$]. The moisture content of the Covered IH deep plot (26.92 ± 0.30%) was different from the values Covered Control (28.02 ± 0.35%), Lemken shallow (28.33 ± 0.16%), and Carrier shallow (28.04 ± 0.29%) treatments.

In the case of the covered treatments, there was a noticeable difference in moisture content at the 30–45 cm soil layer as well [F(9,20) = 13.514, $p = 0.001$]. The post hoc test showed that the Covered Control (29.13 ± 0.24%) at this depth was significantly different from the Covered Bird (28.40 ± 0.19%), the Carrier deep (28.23 ± 0.12%), the IH shallow (28.49 ± 0.14%),

the IH shallow + roller (28.43 ± 0.22%), the IH deep + roller (28.46 ± 0.28%) and the IH deep (27.82 ± 0.41%) treatments. Also, the Covered Lemken shallow (29.12 ± 0.16%) treatment had unique results compared to the Covered Bird (28.40 ± 0.19%), Carrier deep (28.23 ± 0.12%), IH Shallow (28.49 ± 0.14%), IH shallow + roller (28.43 ± 0.22%), IH deep + roller (28.46 ± 0.28%), and IH deep (27.82 ± 0.41%) treatments.

Overall, the results indicate that both the method of stubble tillage and the presence of surface coverage significantly influence soil moisture content across various soil depths. Shallow tillage methods, particularly with modern machinery, generally preserved more moisture in the upper layers, especially on uncovered surfaces. The use of rollers, such as in the IH deep + roller treatment, demonstrated some moisture retention benefits, though these were less pronounced compared to other treatments like the Carrier deep and shallow. In covered treatments, the variability in moisture content across different tillage methods was more nuanced, suggesting that surface coverage may play a critical role in modulating the effects of tillage on soil moisture retention. These findings highlight the importance of selecting appropriate tillage practices and considering surface coverage to optimize soil moisture conservation, which is vital for sustainable soil management and agricultural productivity. The impact of the wetter-than-average summer of 2020 provides additional context to the results of this study. Elevated rainfall likely contributed to the generally high soil moisture levels observed, particularly in uncovered plots, where treatments like the Carrier deep retained higher moisture in the upper layers. While such conditions may reduce the typical advantages of surface mulching, they underscore the importance of adaptive tillage practices. The results demonstrate that shallow and modern stubble tillage tools are effective under varying climatic conditions, making them suitable for broader application in regions experiencing increasingly unpredictable rainfall patterns due to climate change.

3.2. Results of the Penetration Resistance

3.2.1. Soil Resistance of Uncovered Treatments

In the case of uncovered plots, the SPR results showed significant differences based on the ANOVA analysis [F(9,20) = 5.711, p = 0.001] at the depth of 0–15 cm (Figure 3). The post hoc comparison showed that the IH deep treatment resulted in a significantly lower SPR (0.99 ± 0.5 MPa) compared to the IH shallow + roller (1.47 ± 0.4 MPa), the Uncovered Carrier shallow (1.41 ± 0.16 MPa), and the Uncovered Control (1.44 ± 0.8 MPa) treatments. We also found significant differences between the SPR values at the layer of 15–30 cm [F(9,20) = 4.262, p = 0.003]. Here, also the Uncovered IH deep treatment had a lower significant result (1.40 ± 0.6 MPa) compared to the IH shallow + roller (1.81 ± 0.11 MPa) plot. We could not detect a statistically verifiable difference in SPR values at the depth of 30–45 cm [F(9,20) = 1.326, p = 0.285] in the case of the uncovered treatments.

3.2.2. Soil Penetration Resistance of Covered Treatments

In the case of the surface-covered treatments at the layer 0–15 cm, we found significant differences based on the ANOVA analysis [F(9,20) = 6851, p = 0.001]. The Tukey HSD multiple comparisons showed that the Covered Control plot (1.60 ± 0.25 MPa) had a significantly higher SPR result compared to the Covered Lemken shallow (1.10 ± 0.19 MPa), the Covered Carrier shallow (1.16 ± 0.17 MPa), the Covered IH shallow (0.89 ± 0.11 MPa), the Covered IH deep (0.94 ± 0.22 MPa), the Covered IH shallow + roller (0.88 ± 0.12 MPa), and the covered IH deep + roller (0.88 ± 0.04 MPa); the latterly mentioned treatment also had the lowest penetration resistance at this depth in the case of the cover treatments.

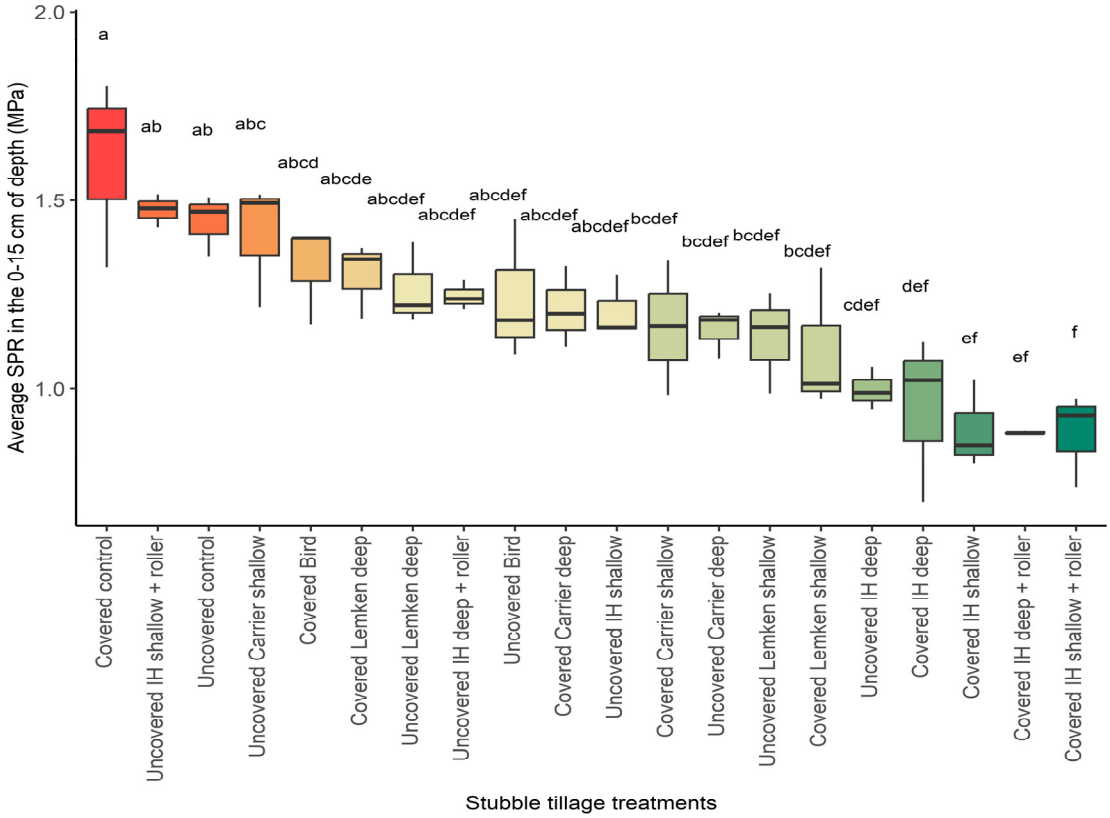


Figure 3. The impact of various stubble tillage methods on soil penetration resistance at 0–15 cm of depth in the case of covered and uncovered surfaces. Results from a Tukey HSD analysis are shown as letters over the boxplots. Treatments sharing the same letter and color are not significantly different from each other at $p > 0.05$ level.

At a depth of 15–30 cm [F(9,20) = 6.637, $p = 0.001$] there were significant differences between the treatments; the Covered Control plot (1.87 ± 0.8 MPa) showed significantly higher SPR result compared to the Lemken shallow (1.27 ± 0.17 MPa), Covered IH shallow + roller (1.32 ± 0.20 MPa), the Lemken deep (1.48 ± 10 MPa), the Carrier shallow (1.38 ± 0.13 MPa), the Covered IH shallow (1.25 ± 0.11 MPa), and the IH deep + roller (1.32 ± 0.20 MPa). In the depth of 30–45 cm soil layer [F(9,20) = 1.758, $p = 0.141$] we were not able to detect any statistically relevant differences between the covered treatments.

The soil penetration resistance (SPR) analysis revealed significant differences across different stubble tillage methods and depths for both uncovered and covered plots. In uncovered plots, the IH deep treatment consistently resulted in significantly lower SPR values at both 0–15 cm and 15–30 cm depths, indicating less soil compaction compared to other treatments such as the IH shallow + roller and Carrier shallow. However, no significant differences were observed in the 30–45 cm depth layer, suggesting that tillage effects diminish with soil depth. For covered plots, significant variations in SPR were also evident, with the covered control plot exhibiting the highest resistance across most depths, indicating more compacted soil. The Covered IH shallow + roller and IH deep + roller treatments demonstrated the lowest SPR values, highlighting their effectiveness in maintaining lower soil compaction. Similarly to the uncovered plots, no significant differences in SPR were detected at the 30–45 cm depth. These findings underscore the influence of both tillage method and surface coverage on soil compaction, with implications for selecting appropriate agricultural practices to manage soil structure and health.

3.3. Surface Cover Measurement Results

Regarding the surface coverage (Figure 4), there is a clear difference between covered and uncovered soils. It is important to note that the "not covered" or "uncovered" surface formed after harvest with baling, which does not mean there was a completely uncovered soil surface, some stubble residues were left on the surface.

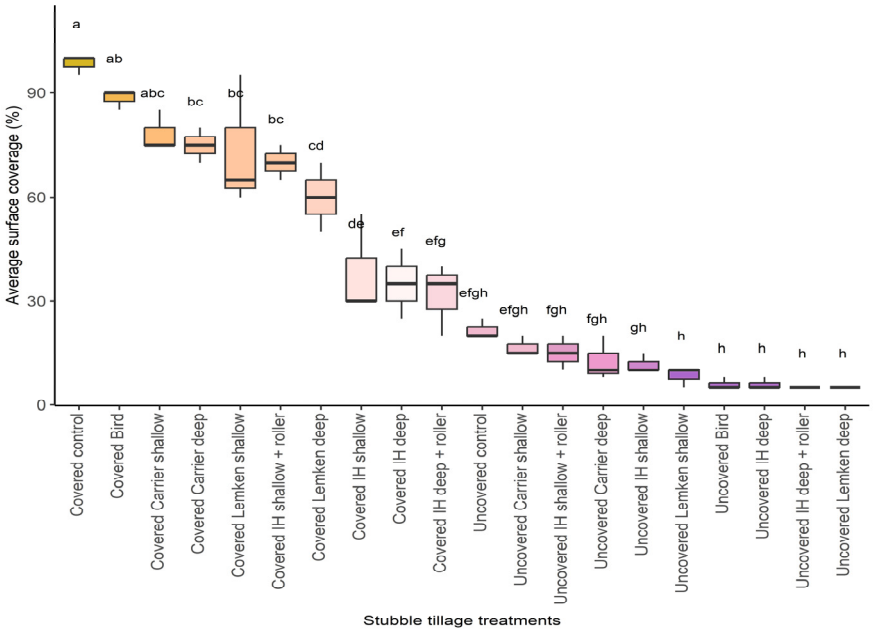


Figure 4. The impact of various stubble tillage methods on soil surface coverage in the case of covered and uncovered surfaces. Results from a Tukey HSD analysis are shown as letters over the boxplots. Treatments sharing the same letter and color are not significantly different from each other at $p > 0.05$ level.

The surface coverage with stubble residues of the uncovered treatments showed significant differences [$F(9,20) = 16.324$, $p = 0.001$]. For example, the Uncovered Control treatment (21.67 ± 2.88%) had the highest surface coverage with stubble residues, which was statistically different from the Uncovered IH deep (6.00 ± 1.73%), the IH deep + roller (5.00 ± 0.01%), the IH shallow + roller (15.00 ± 5.00), the IH shallow (11.67 ± 2.88%), the Lemken deep (5.00 ± 0.02%), the Bird (6.00 ± 1.73%), and the Lemken shallow (8.33 ± 2.88%) treatments. However, it is important to note that the Carrier shallow (16.67 ± 2.87%) and the Carrier deep (12.68 ± 6.43%) treatments did not show significant differences compared to the Uncovered Control.

In the case of the covered areas with stubble residues, different tillage technologies have had a significant impact on surface coverage [$F(9,20) = 9.269$, $p = 0.001$]. The surface coverage of the Covered Control plot (98.33 ± 2.88%) differed significantly compared to the Covered Lemken deep (60.00 ± 10.00%), and the IH shallow (38.33 ± 14.43%) treatments which differ from each other as well.

The analysis of surface coverage with stubble residues demonstrated significant differences between covered and uncovered treatments. The Uncovered Control treatment exhibited the highest surface coverage (21.67 ± 2.88%), significantly differing from other uncovered treatments such as IH deep, IH deep + roller, IH shallow, and others. Notably, the Carrier shallow and Carrier deep treatments did not significantly differ from the Uncovered Control in terms of residue coverage. In contrast, for covered plots, surface coverage varied significantly among the different tillage technologies. The Covered Control plot had almost complete surface coverage (98.33 ± 2.88%), which was substantially higher than

treatments like the Covered Lemken deep and IH shallow, indicating different efficiencies in residue management.

3.4. Differences in Earthworm Abundance

We examined the earthworm abundance (Figure 5) via spade probes where we express the result of the earthworms/spade probe (ew/sp). We found statistically significant differences between the treatments in the case of the uncovered treatments [$F(9,20) = 8.205$, $p = 0.001$]. The Tukey HSD post hoc comparison showed that only the Uncovered Bird cultivator treatment (3.05 ± 0.41 ew/sp) showed higher earthworm abundance compared to the other nine uncovered treatments where the Uncovered Control (0.61 ± 0.34 ew/sp), Carrier deep (0.70 ± 0.26 ew/sp), IH deep (0.92 ± 0.88 ew/sp), IH deep + roller, IH shallow (1.05 ± 0.41 ew/sp), IH shallow + roller (0.89 ± 0.19 ew/sp), the Lemken shallow (1.39 ± 0.34 ew/sp), and the Carrier shallow (1.72 ± 0.25 ew/sp) treatments showed a moderate earthworm abundance per spade probe.

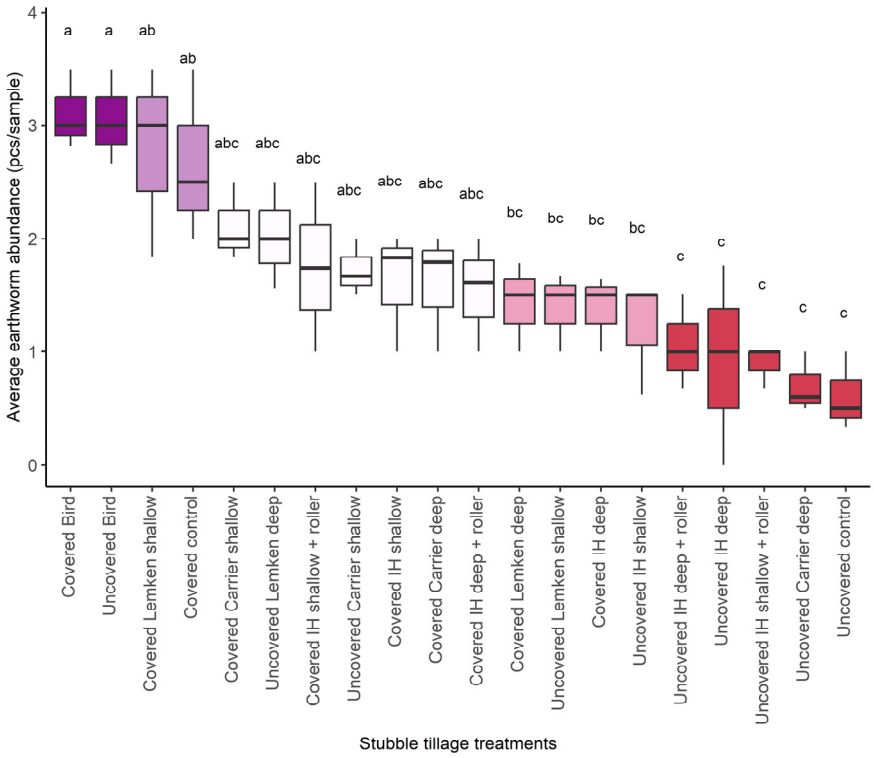


Figure 5. The impact of various stubble tillage methods on earthworm abundance in the case of covered and uncovered surfaces. Results from a Tukey HSD analysis are shown as letters over the boxplots. Treatments sharing the same letter and color are not significantly different from each other at $p > 0.05$ level.

The covered treatments showed similar results; thus, we found significant differences between the treatments [$F(9,20) = 3.745$, $p = 0.007$]; however, the post hoc comparison showed less spectacular results. The highest earthworm abundance was registered in the Bird cultivator treatment (3.10 ± 0.35 ew/sp), which was higher than the Covered Lemken deep (1.42 ± 0.39 ew/sp) and the IH deep (1.38 ± 0.33 ew/sp) treatment. The other treatments achieved similar results in relation to each other.

The study on earthworm abundance revealed significant differences across various tillage treatments, both in uncovered and covered plots. In uncovered soils, the Bird cultivator treatment had the highest earthworm density, markedly higher than other treatments like the Uncovered Control and IH deep. Other treatments showed moderate levels of earthworm presence. In covered plots, a similar trend was observed, with the Bird culti-

vator again leading in earthworm abundance, while treatments like the Covered Lemken deep and IH deep recorded lower numbers. These results suggest that both the choice of tillage method and the presence of surface cover can significantly influence earthworm populations, underscoring the impact of different agricultural practices on soil health and biodiversity.

3.5. Changes in the Soil Structure

In the evaluation of the agronomic structure results, it should be taken into account that the measurements were made during a wetter-than-average summer. Regarding the uncovered treatments, the Carrier shallow (clod: 40.0%, crumb: 42.2%, small crumb: 17.4%, dust: 0.4%), Carrier deep (clod: 41.2%, crumb: 41.3%, tiny crumb: 17.0%, dust: 0.5%), Bird cultivator (clod: 41.2%, crumb: 41.7%, small crumb: 16.8%, dust: 0.3%), and IH shallow + roller (clod: 43.7%, crumb: 37.1%, small crumb: 18.3%, dust: 0.9%) treatments were considered optimal based on [50,62], while the IH shallow treatment became the least appropriate with the highest clod (65.89%) and the lowest small crumb (8.21%) and crumb (25.5%) content (Figure 6). Due to the wet summer, the proportion of the dust fraction was generally lower than 1%, while the proportion of the clod fraction was at least 40% in every uncovered treatment. During the stubble tillage of uncovered areas, the dust fraction increased the most by 0.2–0.9%. The Bird cultivator treatment produced the least dust (+0.2%), while the plots shallowly tilled with the IH disk and rolled in separate threads produced the most (+0.9%).

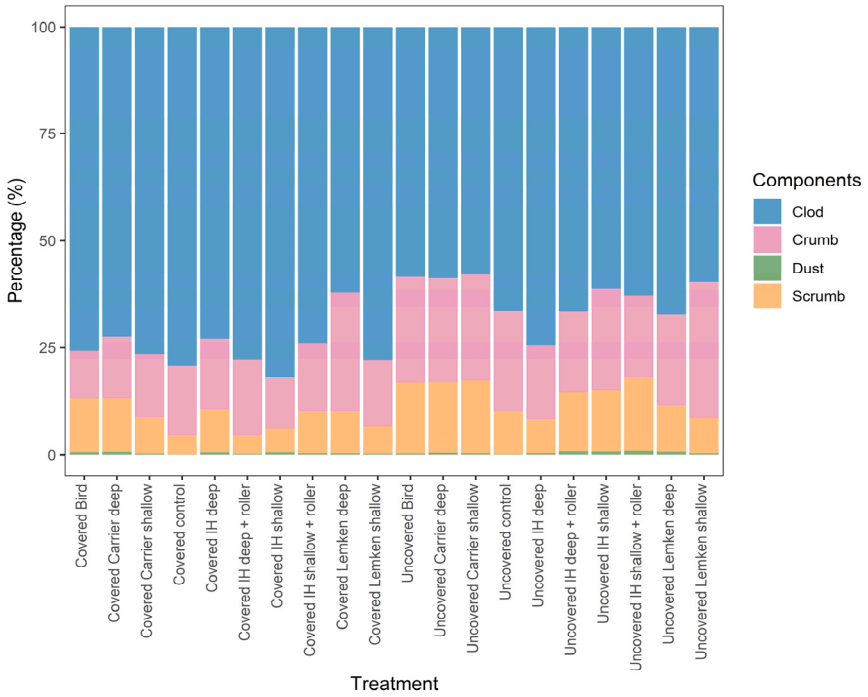


Figure 6. The average impact of various stubble tillage methods on soil structure in the case of covered and uncovered surfaces.

Due to the high average clod ratio in the straw-covered areas, the crumb and small crumb fractions together could only occur in less than 50% of the samples. However, it is important to note that in all cases, the proportion of dust fraction under mulching was lower compared to uncovered areas. In the case of the covered treatments, after any type of stubble tillage, the structure of the treatment had been improved compared to the Covered Control treatment (clod: 74.8%, crumb: 20.8%, small crumb: 4.5%, dust: 0.05%), which was valid in the case of the least appropriate treatment the IH deep (clod: 61.6%, crumb: 27.2%,

small crumb: 10.7%, dust: 0.5%). The most favorable structure was considered in the case of the Lemken deep (clod: 51.6%, crumb: 37.9%, small crumb: 10.2%, dust: 0.3%) treatment. The exceptionally high clod fraction rate of the covered control plot was mainly caused by the fact that the sampling happened immediately after harvesting, thus the soil was extremely compacted due to the soil compaction effect of the combined thrashers.

After the stubble tillage of the plots covered with straw, the magnitude of the clod formation was negligible. The least dust fraction changes were seen in the structure of the Covered IH deep + roller (+0.4%) and the Covered Lemken shallow (+0.15%) treatments, while the most dust was formed in the case of the Carrier deep (+0.65%) and the Covered Bird cultivator (+0.55%) treatments.

The evaluation of agronomic structure during a wetter-than-average summer revealed key differences between treatments. In uncovered plots, treatments like Carrier shallow, Carrier deep, Bird cultivator, and IH shallow + roller were considered optimal, displaying balanced proportions of clods, crumbs, and small crumbs, with minimal dust formation. The IH deep treatment; however, was the least good, having the highest clod and lowest small crumb and crumb content. The wet conditions resulted in a generally low dust fraction across all treatments.

For covered plots, the structure improved compared to the Covered Control, with treatments like Lemken deep showing the most favorable structure. The Covered Control plot had a high clod fraction due to compaction from harvesting. Clod formation was minimal in straw-covered plots, with the least dust fraction changes observed in Covered IH deep + roller and Covered Lemken shallow treatments. The Covered Bird cultivator and Carrier deep treatments produced slightly more dust. Overall, the presence of straw cover generally resulted in a lower dust fraction and a more stable soil structure.

3.6. Changes in Soil Chemistry

A sample was taken from the experimental field before the experiment was set up (alpha-control test) and then at the end of the experiment to compare how certain soil chemical characteristics of the area changed. The results of the control study were as follows:

- Humus = 3.43%
- NO_3—N + NO_2--N = 27.9 mg/kg
- P_2O_5 = 218 mg/kg
- K_2O= 470 mg/kg.

3.6.1. Changes in Nitrogen Content

The nitrogen content of the soil decreased across all treatments compared to the baseline (Figure 7), with reductions observed in both covered and uncovered plots. In the covered treatments, the largest nitrogen reductions occurred for Covered IH shallow (−94.23%) and Covered Lemken shallow (−93.66%), while the smallest reductions were seen for Covered Carrier shallow (−71.18%) and Covered IH deep (−73.76%). Asterisks in the graph indicate significant differences between the pre- and post-treatment nitrogen content (** $p < 0.01$ for all treatments), confirming the substantial nitrogen losses across treatments. These reductions suggest the rapid decomposition of straw by soil microorganisms, which utilize nitrogen as a nutrient source, particularly in covered plots where straw is well-incorporated.

In the uncovered treatments, the nitrogen losses were less severe compared to their covered counterparts. The largest reductions were measured in the Uncovered IH shallow + roller (−61.29%) and Uncovered IH deep (−59.14%), whereas the smallest reduction occurred in the Uncovered Control (−39.43%). The uncovered plots, particularly the Uncovered Control, exhibited less nitrogen depletion due to lower levels of microbial activity

and reduced straw incorporation. Interestingly, the Uncovered IH shallow (+17.05 ppm) had the highest nitrogen content among all treatments, indicating that minimal mixing or disturbance can retain more nitrogen in certain scenarios.

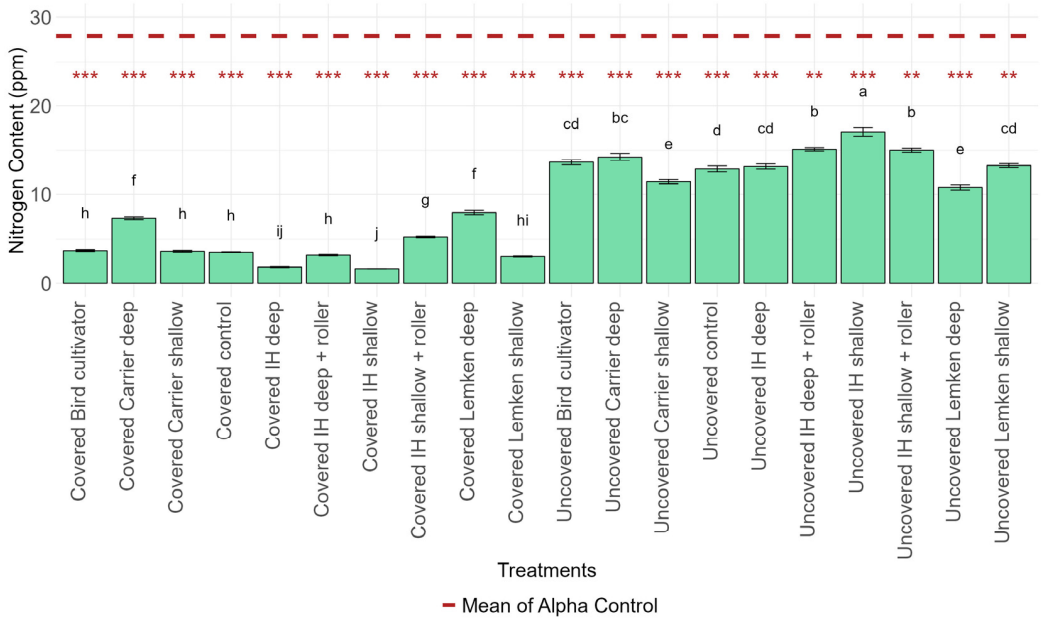


Figure 7. Changes in nitrogen content (mean ± SD) across 20 soil stubble tillage technologies compared to the baseline (red dashed line). Red asterisks indicate significant differences between pre- and post-treatment nitrogen content (** $p < 0.01$; *** $p < 0.001$), while treatments sharing the same letters do not significantly differ from each other at the $p < 0.05$ level at the end of the experiment, as determined by Tukey HSD. Treatments are categorized by covered and uncovered conditions, with reductions reflecting the influence of microbial activity, straw decomposition, tillage depth, and surface coverage on nitrogen dynamics.

The ANOVA results confirmed significant differences among treatments [$F(19,40) = 494.6$, $p < 0.001$], and Tukey HSD comparisons categorized treatments into distinct statistical groups. The highest nitrogen levels were observed in the Uncovered IH shallow (17.05 ppm, group "a"), followed by Uncovered IH deep + roller (15.10 ppm, group "b"), and Uncovered IH shallow + roller (15.00 ppm, group "b"). The lowest levels were found in Covered IH shallow (1.61 ppm, group "j") and Covered IH deep (1.79 ppm, group "ij"). These results highlight the impact of straw incorporation, tillage depth, and surface coverage on nitrogen dynamics. Covered plots demonstrated the most substantial nitrogen losses due to active microbial decomposition, while uncovered plots showed greater nitrogen retention, albeit with some variability depending on the treatment. These findings underscore the role of microbial activity and environmental conditions in determining nitrogen availability in the soil.

3.6.2. Change in Phosphorus Content

The phosphorus content of the soil displayed significant variability among treatments, with a general downward trend observed across most plots (Figure 8). The reductions were likely influenced by heavy rainfall during the summer, which may have washed phosphorus out of the soil despite its limited mobility. Covered treatments tended to stabilize phosphorus levels better, with minor decreases observed in the Covered Bird (−1.83%) and Covered IH shallow (−1.23%). In contrast, significant increases were recorded for the Covered IH deep (+15.60%) and Covered Carrier deep (+7.70%), reflecting the benefits of surface coverage in minimizing nutrient loss. Asterisks on the graph highlight treat-

ments where pre- and post-treatment phosphorus content significantly differed (* $p < 0.05$, ** $p < 0.01$), such as the Covered Bird cultivator ($p = 0.00722$) and Covered IH deep + roller ($p = 0.00107$).

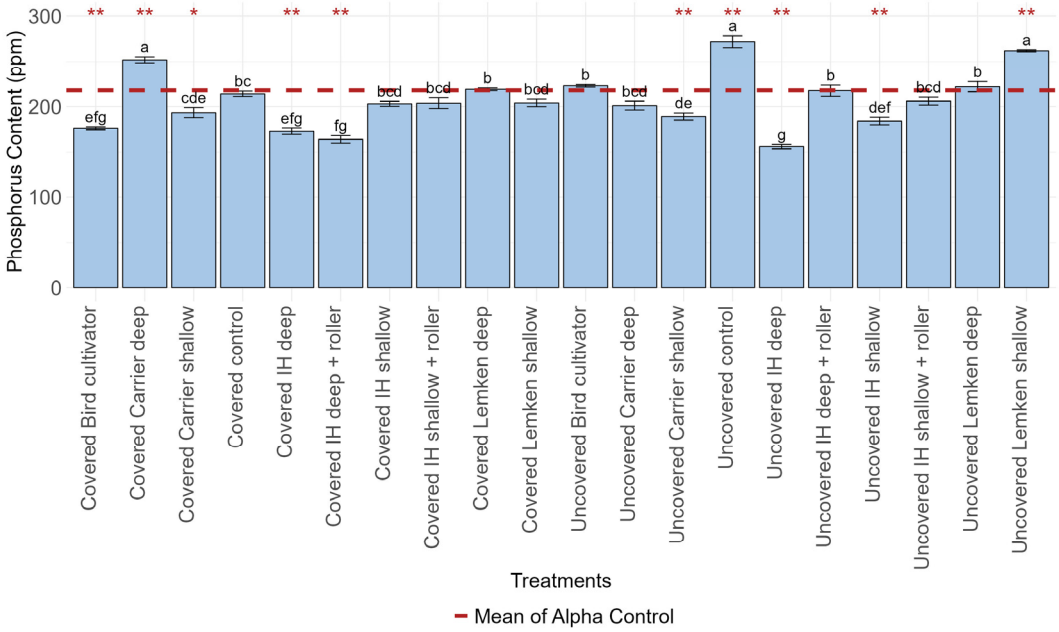


Figure 8. Changes in phosphorus content (mean ± SD) across 20 soil stubble tillage technologies compared to the baseline (red dashed line). Red asterisks indicate significant differences between pre- and post-treatment phosphorus content (* $p < 0.05$, ** $p < 0.01$), while treatments sharing the same letters do not significantly differ from each other at the $p < 0.05$ level at the end of the experiment, as determined by Tukey HSD. Treatments are categorized by covered and uncovered conditions, with variability reflecting the influence of rainfall, tillage depth, implement type, and surface coverage on phosphorus availability.

Uncovered treatments demonstrated greater variability, with both substantial increases and significant decreases observed. The Uncovered Lemken shallow treatment showed the highest increase in phosphorus content (+24.77%), while the Uncovered Lemken deep (+20.18%) and Uncovered IH deep + roller (+17.35%) also exhibited notable gains. On the other hand, the largest reductions in phosphorus were recorded for the Uncovered Bird cultivator (−28.44%) and Uncovered Carrier shallow (−23.45%), demonstrating the impact of leaving the soil uncovered on phosphorus leaching. Interestingly, the Uncovered Control treatment achieved the highest overall phosphorus content (272.00 ± 11.22 ppm), potentially due to the absence of additional straw or disturbances, but it still experienced a moderate decrease compared to the baseline.

The ANOVA results confirmed a significant effect of treatments on phosphorus content [$F(19,40) = 53.74$, $p < 0.001$], with Tukey HSD comparisons categorizing treatments into distinct statistical groups. The highest phosphorus levels were observed in the Uncovered Control (272.00 ± 11.22 ppm) and Uncovered Lemken shallow (262.00 ± 2.07 ppm), both placed in group “a”. Conversely, the lowest phosphorus levels were recorded for the Uncovered IH deep (156.00 ± 4.21 ppm), assigned to group “g”. These results emphasize the importance of surface coverage and management practices in influencing phosphorus availability. Covered treatments generally reduced the extent of phosphorus loss, while uncovered treatments displayed higher variability, with both the largest gains and losses. This highlights the critical role of tillage practices and environmental conditions, such as rainfall, in shaping phosphorus dynamics in the soil.

3.6.3. Change in Potassium Content

The experiment revealed significant variability in potassium content changes across the tested soil stubble tillage technologies, with the initial potassium content (Mean of Alpha control: 505.83 ± 16.72 ppm) serving as the baseline (Figure 9). The results indicated that potassium content increased in most covered treatments, with significant growth observed in the Covered Carrier shallow (+18.72%), Covered IH shallow (+17.45%), and Covered Lemken deep (+15.71%) treatments. Similarly, the Covered Control (+15.45%) also showed a substantial increase, reflecting the stabilizing effect of surface coverage. Asterisks on the graph indicate significant differences between the pre- and post-treatment potassium content (* $p < 0.05$, ** $p < 0.01$), highlighting treatments that significantly altered potassium levels compared to the baseline. Conversely, minor increases were observed in treatments such as the Covered IH deep + roller (+10.91%), suggesting that the addition of a roller may influence potassium retention in covered plots.

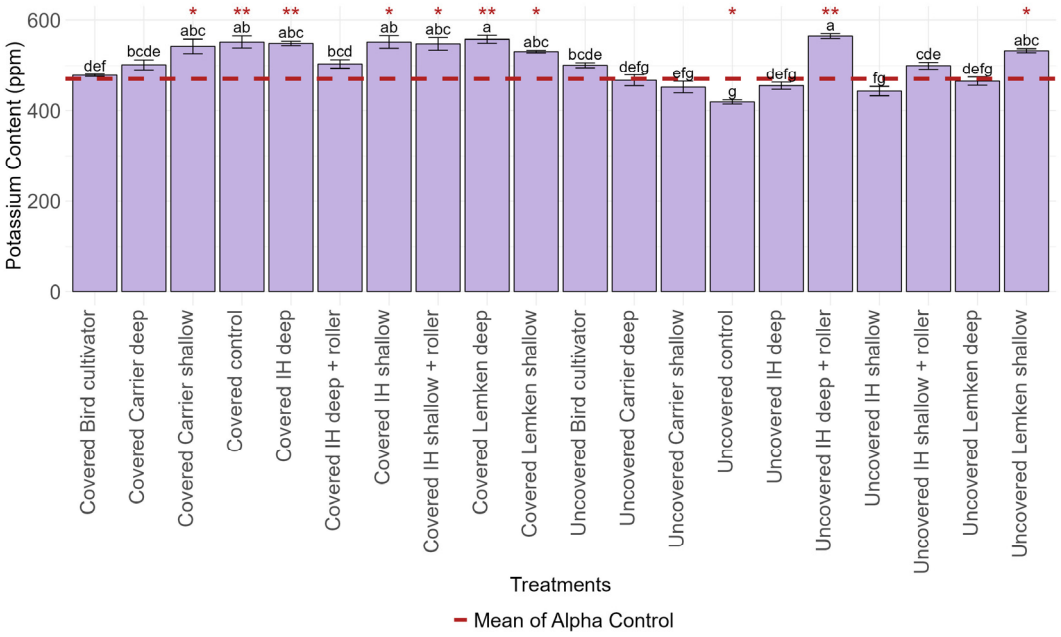


Figure 9. Changes in potassium content (mean ± SD) across 20 soil stubble tillage technologies compared to the baseline (red dashed line). Red asterisks indicate significant differences between pre- and post-treatment potassium content (* $p < 0.05$, ** $p < 0.01$), while treatments sharing the same letters do not significantly differ from each other at the $p < 0.05$ level at the end of the experiment, as determined by Tukey HSD. Treatments are categorized by covered and uncovered conditions, with variability reflecting the influence of tillage depth, implement type, and roller usage.

In uncovered treatments, potassium dynamics were more variable, with both notable increases and decreases observed. Among the uncovered treatments, the Uncovered Carrier deep (+20.21%) achieved the highest potassium content increase, highlighting its potential effectiveness. However, significant reductions in potassium content were recorded for the Uncovered Lemken shallow (−10.85%) and the Uncovered Control (−5.74%), demonstrating that the absence of surface coverage may lead to nutrient losses. Interestingly, the Uncovered IH deep + roller (+13.21%) exhibited one of the highest potassium contents among all treatments, suggesting that the use of rollers in uncovered plots can mitigate potassium depletion and enhance retention.

The ANOVA results confirmed a significant treatment effect on potassium content [$F(19,40) = 21.39$, $p < 0.001$], with Tukey HSD comparisons grouping treatments into distinct categories. Treatments sharing the same letters do not significantly differ at the $p < 0.05$ level, as indicated by the Tukey HSD results. The highest potassium content was

observed in Uncovered IH deep + roller (565.00 ± 9.35 ppm) and Covered Lemken deep (558.00 ± 15.15 ppm), both categorized in group "a". In contrast, the lowest potassium levels were recorded for the Uncovered Control (419.00 ± 8.37 ppm), placed in group "g". These findings emphasize the importance of surface coverage and roller usage in influencing potassium dynamics. Covered treatments generally led to consistent increases in potassium content, while uncovered treatments displayed greater variability, with both the largest gains and losses. These results underscore the critical role of tillage practices in soil potassium management, warranting further investigation into their long-term effects on soil fertility.

3.6.4. Change in Humus Content

The experiment revealed considerable variability in humus content changes across the tested soil stubble tillage technologies, with the initial humus content (Mean of Alpha control: 3.35 ± 0.15 ppm) serving as the baseline (Figure 10). Significant differences were identified through *t*-tests (* $p < 0.05$, ** $p < 0.01$), highlighting the distinct impacts of different treatments. Among the uncovered treatments, the Uncovered IH shallow + roller exhibited the highest humus content (3.80 ± 0.20 ppm, +13.43%), while the Uncovered Lemken shallow treatment recorded the lowest (2.70 ± 0.07 ppm, −19.40%). Significant decreases were also observed for the Uncovered Lemken deep (−21.28%) and Uncovered IH shallow + roller (−20.12%) treatments. In contrast, notable gains were achieved in uncovered treatments such as the Carrier shallow (+11.66%) and Carrier deep (+7.58%). These findings highlight the variability in humus dynamics among uncovered treatments, which tended to show both the most substantial gains and losses. Covered treatments generally showed smaller changes in humus content, with some modest increases. The Covered Control (3.12 ± 0.14 ppm, +6.12%) and Covered Lemken shallow (3.10 ± 0.11 ppm, +6.71%) exhibited slight improvements, while the Covered Carrier deep (3.27 ± 0.11 ppm, −9.62%) and Covered Bird cultivator (3.64 ± 0.16 ppm, −8.75%) displayed notable decreases.

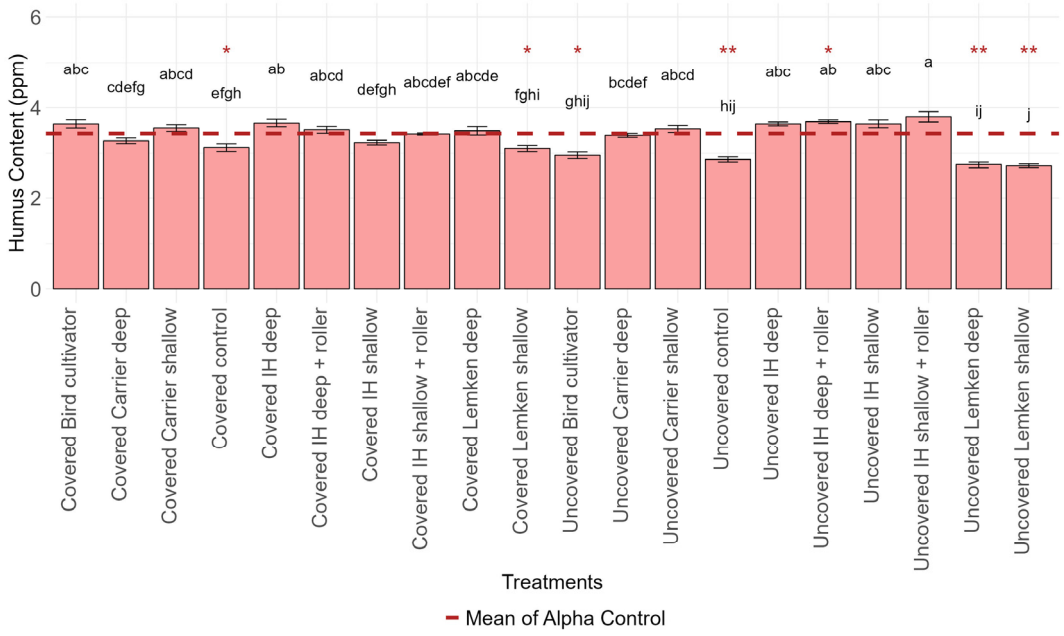


Figure 10. Changes in humus content (mean ± SD) across 20 soil stubble tillage technologies compared to the baseline (red dashed line). Red asterisks indicate significant differences between pre- and post-treatment humus content (* $p < 0.05$, ** $p < 0.01$), while treatments sharing the same letters do not significantly differ from each other at the $p < 0.05$ level at the end of the experiment, as determined by Tukey HSD. Treatments are categorized by covered and uncovered conditions, with variability reflecting the influence of tillage depth, implement type, and roller usage.

The ANOVA results confirmed a significant treatment effect on humus content [$F(19,40) = 22.11$, $p < 0.001$], with Tukey HSD comparisons grouping treatments based on statistical similarities. Treatments such as the Covered IH deep (3.66 ± 0.14 ppm, −4.29%) and Covered Bird cultivator showed better retention of humus than other covered treatments but did not achieve significant gains. These results suggest that the effects of surface coverage, while stabilizing humus content, may depend on the specific tillage method employed.

The variability in humus changes underscores the importance of treatment-specific factors such as tillage depth, implement type, and roller usage. Treatments incorporating rollers, such as the Uncovered IH deep + roller (3.69 ± 0.07 ppm, +10.15%), showed improved humus retention compared to their counterparts without rollers. However, the uncovered treatments tended to be more dynamic, with both the largest losses and gains in humus content. While short-term changes in humus levels were evident, these results suggest that the long-term effects of these tillage practices on soil health and nutrient dynamics require further study. Optimizing cultivation practices for improved humus retention and sustainable soil management will likely necessitate continued evaluation under varying environmental and management conditions.

3.6.5. Cluster Analysis of the Nutrient Changes

The heatmap (Figure 11) showcases changes in soil nutrients across 20 stubble tillage treatments, which were clustered into two distinct groups based on performance and nutrient dynamics. This clustering effectively highlights the contrasting behavior of covered and uncovered treatments, with covered plots forming one group and uncovered plots forming the other. The separation underscores the significant role of surface coverage in influencing nutrient retention and soil quality.

Nitrogen (N) levels showed substantial reductions across all treatments, with the highest losses observed in covered plots. For example, Covered IH shallow and Covered Lemken shallow recorded extreme nitrogen declines of −94.23% and −93.57%, respectively. In uncovered plots, the losses were notably less severe, with Uncovered Control showing the smallest reduction at −38.90%. Phosphorus (P) displayed mixed trends, with covered treatments such as Covered Carrier deep (+15.60%) and Covered IH deep (+7.70%) exhibiting gains, while uncovered treatments like Uncovered Lemken shallow (+24.77%) and Uncovered Lemken deep (+20.18%) also showed significant increases. Conversely, uncovered treatments such as Uncovered Bird cultivator (−28.44%) and Uncovered Carrier shallow (−23.45%) experienced the most phosphorus loss.

Potassium (K) levels increased in most treatments, with Covered Carrier shallow (+18.72%) and Covered IH shallow (+17.45%) achieving the highest gains among covered treatments, while Uncovered Carrier deep (+20.21%) led the uncovered treatments. However, uncovered plots such as Uncovered Lemken shallow (−10.85%) and Uncovered Control (−5.74%) exhibited notable potassium reductions. Humus content showed similar variability, with covered treatments like Covered Lemken shallow (+6.71%) showing moderate improvements, while uncovered treatments like Uncovered IH shallow + roller (+13.40%) outperformed in humus retention. Meanwhile, significant humus losses were recorded for Uncovered Lemken shallow (−19.40%) and Uncovered Lemken deep (−21.28%).

The clustering emphasizes that covered treatments generally stabilized nutrient levels and improved retention, particularly for potassium and humus, while uncovered treatments displayed a broader range of outcomes. These findings highlight the critical role of surface coverage, tillage depth, and mechanical treatment in managing soil nutrient dynamics and ensuring sustainable soil management practices.

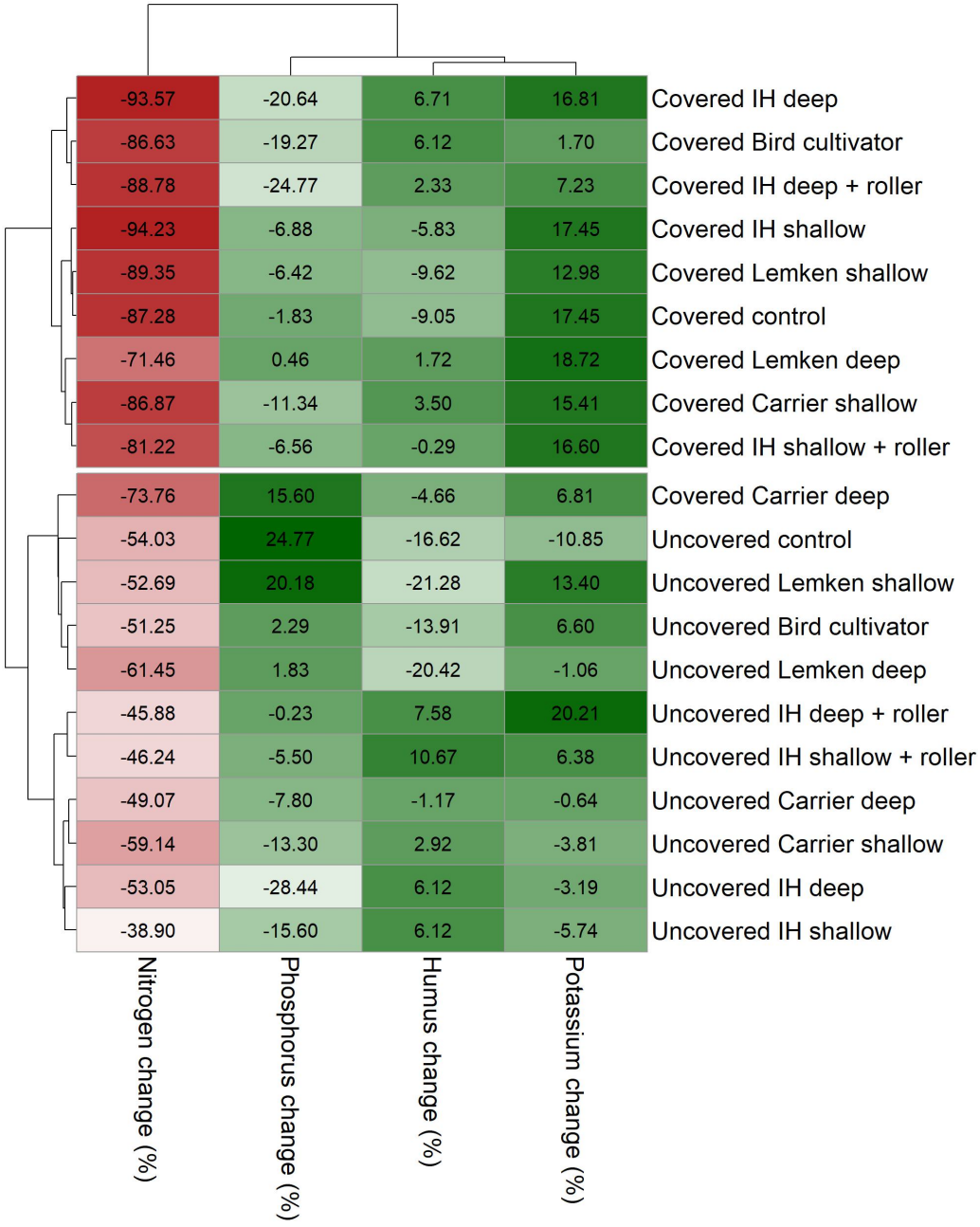


Figure 11. Clustered heatmap of the percentage changes in nitrogen (N), phosphorus (P), potassium (K), and humus content across 20 stubble tillage treatments, showing changes between the beginning and the end of the experiment. The colors in the heatmap represent the magnitude and direction of nutrient changes.

3.7. Ranking of Stubble Tillage Treatments

From the measured parameters of the treatments, we determined the performance ranking separately for both covered and uncovered treatments based on [63]. The results of each parameter were sorted and numbered, where the smallest number indicated the most advantageous, and the largest indicated the most unfavorable result for the given parameter. At the end of the process, we combined the results which gave us the complex effect of the treatments.

In the case of uncovered surfaces (Figure 12), the most favorable complex stubble tillage quality was developed for the Lemken shallow (1), the Bird cultivator (2), and Carrier deep (3) treatments. By using these three devices according to a specific setting, you can create approximately the same state when mulching is not available.

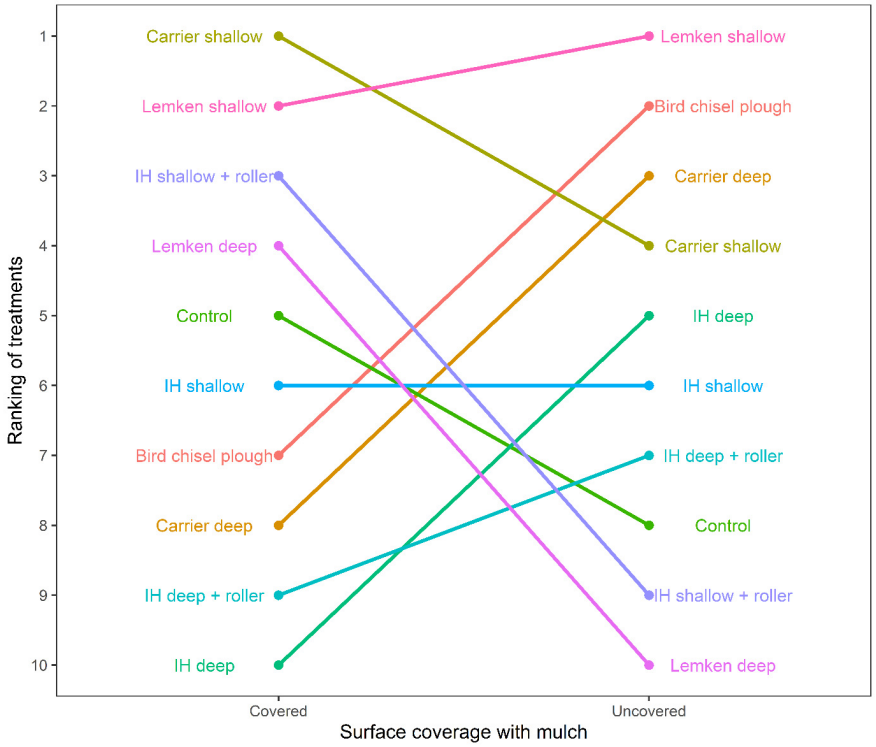


Figure 12. The results of the performance ranking (1–10) of the treatments in the case of the covered and uncovered surfaces. Comparison between the treatments shows the effect of mulching as well. Treatments closer to 1 are better, and those closer to 10 are less favorable.

For straw-covered plots, the most favorable result in the overall ranking by parameters was obtained by devices operated at a shallow setting in the following order: Carrier shallow (1), Lemken shallow (2), and IH shallow + roller (3) treatments.

If we compare the covered and uncovered treatments on Figure 12, it can be stated that the leftover mulch on the soil surface has a huge effect on soil quality. Most of the treatments slipped back in the ranking if we removed the straw from the surface. The biggest setback was registered in the case of the IH shallow + roller and the Lemken deep treatments 6-6 position, respectively. The Bird cultivator worked better without mulching; it ranked higher with five positions without surface coverage, just like the Carrier deep treatment. Overall, the best stubble tillage quality was reached with the Lemken shallow treatment, which was ranked second place in the case of surface coverage and first place in the case of uncovered surfaces.

Finally, we prepared the overall ranking of the 20 treatments (Figure 13), in which we combined the plots covered with mulch and uncovered surfaces. Based on this, it can be said that the best results were achieved by the Uncovered Lemken shallow treatment (1), followed by the Uncovered Bird cultivator treatment (2), followed by the Uncovered Carrier deep (3), Covered Lemken shallow (3), and Covered Carrier shallow (3) treatments, all of which are in third place. It is important to note again that the experiment was set up in a rainier-than-average summer, which is why there are so many uncovered treatments in the top three. The last three places where the Covered IH deep + roller (16), Uncovered Lemken deep (17), and Covered IH deep (18) treatments.

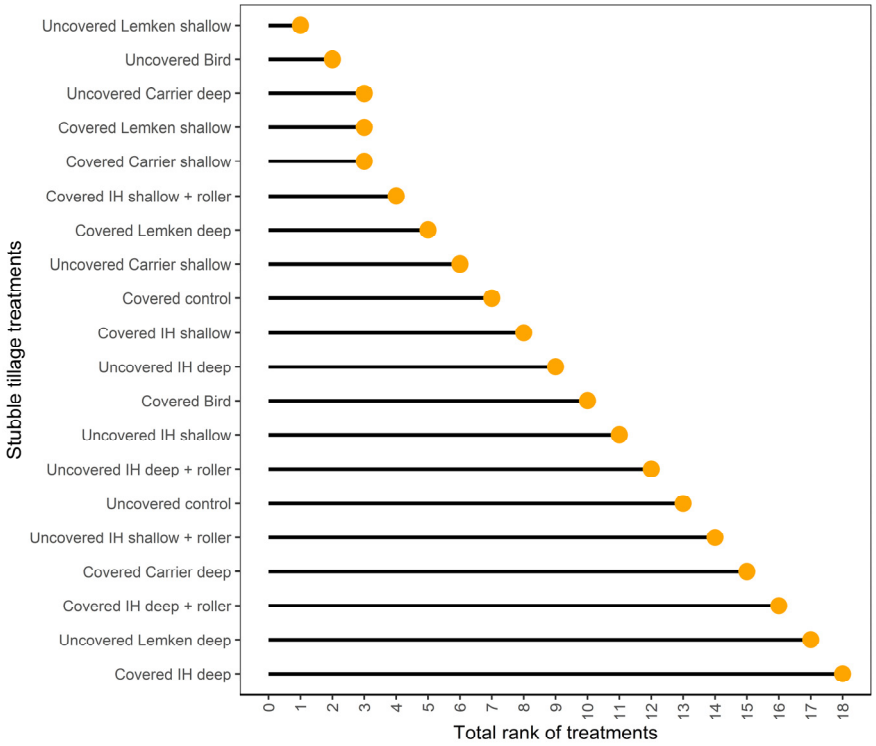


Figure 13. The results of the performance ranking (1–20) of the treatments. Comparison between the treatments shows the effect of mulching as well. Treatments closer to 1 are better, and those closer to 20 are less favorable.

4. Discussion

The objective of this study was to investigate the impact of various soil tillage machines on several soil parameters, including soil moisture, penetration resistance, soil structure, surface coverage, and earthworm abundance. We evaluated a total of 20 different treatments, and our findings are consistent with earlier research [6,24,64] while also providing new insights into the effects of tillage methods under different conditions.

Our results demonstrated that in the 15–30 cm soil layer, treatments like the Carrier deep retained higher moisture levels compared to the uncovered control plots. This was similarly observed in previous studies [65,66], indicating that insulating layers can be effectively established either by applying a covering material or through shallow stubble tillage. These findings are further supported by recent work emphasizing the benefits of maintaining soil moisture through minimal disturbance and appropriate coverage.

For the IH shallow + roller treatment, uncovered plots exhibited increased soil compaction, whereas covered plots showed reduced resistance in the 0–30 cm layer. This suggests that stubble tillage under cover can lower soil resistance, even if it involves minor moisture loss, aligning with [67], who noted that conservation tillage has a limited impact on soil moisture and soil mineral nitrogen under temperate conditions. This variability can be attributed to annual differences and interaction effects, as discussed by [68,69]. Additionally, recent studies have indicated that soil moisture dynamics are crucially affected by the timing and method of tillage, especially the residual cover left on the soil surface [70,71].

Our study also examined surface coverage and earthworm abundance. We found that coverage values were generally lower in treated areas, particularly with treatments like IH deep and Bird cultivator. Interestingly, while there was no significant difference in earthworm abundance between cultivated and non-cultivated plots, covered soils tended to support higher populations of earthworms. This observation is consistent with findings from previous research [29,72], and it highlights the role of soil cover in creating a more

favorable microenvironment for soil fauna. The role of surface coverage was also evident in nutrient retention, where covered plots demonstrated better preservation of humus and potassium, as well as enhanced phosphorus availability in certain treatments. These chemical improvements, combined with the higher earthworm abundance, suggest that soil cover contributes to both biological and chemical soil quality improvements. This is corroborated by recent studies that suggest that the presence of mulch can enhance soil biodiversity and microbial diversity.

The Väderstad Carrier 925 disk treatment showed one of the highest soil moisture contents in the upper 15 cm layer among the covered treatments. For straw-covered plots, the moisture content in the 0–15 cm soil layer did not differ significantly among treatments, underscoring the critical importance of appropriate tool selection, particularly for uncultivated plots [73]. Despite the lack of significant differences in soil resistance across treatments, deeper settings in covered plots resulted in more compacted upper soil layers. This observation aligns with the general understanding that deeper tillage can lead to increased soil compaction, which may hinder root growth and water infiltration [5].

Shallowly tilled plots with the "Lemken Rubin type 9" disk generally produced the best quality results, particularly in covered areas. This suggests that deeper cultivation should be avoided in uncovered plots due to its overall unfavorable impact, as indicated by previous studies [74,75]. Moreover, the "Rába IH 10-770" disk retained more moisture in the upper 15 cm layer compared to other treatments, even after rolling, which partially mitigated moisture loss. Similarly, this treatment demonstrated better humus and phosphorus retention, further emphasizing its role in improving both physical and chemical soil properties. The combination of shallow tillage and rolling appears to optimize both soil structure and nutrient dynamics, particularly in covered treatments. The implications of these findings are significant, suggesting that the choice of machinery and depth settings must be carefully considered to optimize soil moisture retention and reduce compaction. The results from Figure 12 reveal that uncovered treatments outperformed their covered counterparts in several cases, particularly the Uncovered Carrier deep treatment, which ranked third overall in the performance analysis. This finding highlights the complex interplay between tillage depth, soil coverage, and environmental conditions. The superior performance of uncovered treatments may be attributed to the wetter-than-average summer during the study, which likely reduced the benefits typically associated with mulching, such as moisture retention. Furthermore, the deeper tillage with the Carrier deep treatment may have enhanced subsurface soil structure and moisture distribution, compensating for the lack of surface coverage. These results align with findings by [76–78], which showed that deep tillage can be advantageous in mitigating compaction and improving moisture availability under specific conditions. However, this outcome also underscores the need for site-specific tillage strategies, as climatic variability and soil type can significantly alter the effectiveness of tillage practices.

Additionally, the study highlighted the favorable impact of using cultivators, particularly those equipped with knives, for both uncovered and covered plots. These tools enhanced soil structure and supported higher numbers of earthworms [24]. Our findings align with the notion that mechanical soil management can be tailored to promote soil health and biodiversity, as recent literature also suggests [79]. The use of rollers generally improved outcomes in covered areas regardless of working depth, as noted by [80]. This aspect of soil management is crucial for maintaining soil structure and preventing erosion, particularly in changing climatic conditions.

Overall, our findings, together with previous studies [7,9,30,64,81] suggest that the choice of tillage equipment and operational depth significantly affects soil quality and, in addition to mulching, plays a critical role in preserving soil moisture and structure. The

integration of soil chemical analyses into this study further highlights how tillage practices influence nutrient availability, with covered treatments showing greater retention of humus and potassium, and uncovered treatments occasionally outperforming nitrogen retention due to reduced microbial activity. These findings provide a comprehensive understanding of how mechanical and chemical soil properties interact under varying tillage methods.

This study underscores the critical role of tailored stubble tillage practices in addressing challenges posed by climate change. For instance, the uncovered Carrier deep treatment's superior performance demonstrates the potential of deep tillage to maintain soil structure and moisture under wetter conditions, which may become more frequent with shifting rainfall patterns. Moreover, the observed benefits of mulching, such as enhanced earthworm abundance and soil biodiversity, align with strategies to build soil organic carbon and improve water infiltration, both crucial for climate resilience. These results are particularly relevant in the context of climate change adaptation, as soil management practices that conserve moisture and reduce compaction can mitigate the impacts of extreme weather events, such as droughts or heavy rains. These results are particularly relevant to the European Green Deal's objectives of fostering sustainable and climate-neutral farming practices. Shallow tillage combined with mulching contributes to improving soil organic carbon levels and retaining moisture, which aligns with the Green Deal's goals of enhancing soil health and resilience [45]. By minimizing soil disturbance, these practices reduce greenhouse gas emissions associated with excessive tillage and improve the soil's ability to sequester carbon. Furthermore, mulching supports biodiversity by creating a favorable environment for soil biota, such as earthworms, which play a critical role in nutrient cycling. These findings emphasize that adopting such practices not only improves agricultural productivity but also aids in achieving long-term environmental sustainability, particularly under the pressures of climate change.

The clustering analysis of nutrient changes distinctly separated the treatments into two groups based on surface coverage, with covered treatments demonstrating enhanced nutrient retention and uncovered treatments exhibiting greater variability. By enhancing soil health and stability, such practices contribute to sustainable agriculture, aligning with global initiatives like the European Green Deal, which advocates for climate-neutral farming systems. These results underline the importance of tailored tillage practices to optimize soil conservation and productivity, especially under varying climatic conditions. As recent studies indicate, the integration of advanced soil management practices is essential for sustainable agriculture and for mitigating the adverse effects of climate change [82].

Given that this study was conducted during a wetter-than-average summer, the findings may reflect specific conditions that differ from typical growing seasons. To validate the observed results and enhance their generalizability, future research should include multi-year studies under a range of climatic conditions. This approach will help to confirm the effects of stubble tillage technologies across diverse environmental scenarios. This study contributes to a broader understanding of stubble tillage and its implications for sustainable agriculture, offering valuable insights for both researchers and practitioners. The implications for practical applications are significant, emphasizing the need for careful consideration of local environmental conditions and soil characteristics when planning tillage operations.

5. Conclusions

This study provides valuable insights into the performance of various stubble tillage methods under specific conditions, emphasizing the impact of tillage practices on both physical and chemical soil properties. Our findings demonstrate that covered treatments, such as Covered Control and Covered Lemken shallow, were effective in preserving humus

and potassium content, while uncovered treatments, like Uncovered IH shallow + roller, exhibited higher nitrogen retention and phosphorus gains. This highlights the importance of considering nutrient dynamics alongside traditional soil parameters when evaluating tillage methods. The clustering analysis revealed a clear distinction between covered and uncovered treatments, with covered treatments generally promoting better nutrient retention and uncovered treatments showing greater variability in nutrient changes. The wetter-than-average summer during the study highlights the need for additional multi-year research to assess the consistency and broader applicability of these findings. Extending the study across multiple seasons and varying climatic conditions will provide a more comprehensive understanding of the long-term impacts of these tillage practices on soil health and crop productivity. Among the treatments, the Uncovered Lemken shallow, Uncovered Bird cultivator, and Uncovered Carrier deep treatments ranked highest in overall performance based on combined soil parameters, including soil moisture retention, penetration resistance, surface coverage, and earthworm abundance. These results highlight that shallow tillage, such as with the Lemken Rubin 9 disk, offers significant benefits for both covered and uncovered soils, particularly in retaining soil moisture while minimizing compaction. Furthermore, the superior potassium retention in the Covered Carrier shallow and phosphorus gains in the Covered IH deep treatments emphasize the role of surface coverage and appropriate tool selection in enhancing soil nutrient availability.

The findings also reveal the nuanced interplay between tillage depth and mulching. While covered treatments generally promoted higher earthworm populations and reduced compaction, the Uncovered Carrier deep treatment demonstrated superior moisture retention, challenging the assumption that covered methods always outperform uncovered ones. This variability emphasizes the need for site-specific tillage strategies tailored to local environmental and climatic conditions. The integration of soil chemical and physical properties into the evaluation framework underscores the complexity of soil-tillage interactions, offering a holistic approach to sustainable soil management.

These results underscore the critical role of tool selection and operational depth in optimizing soil health and resilience. They also highlight the potential of stubble tillage to mitigate the impacts of climate variability, contributing to the development of sustainable agricultural practices in alignment with the European Green Deal. The findings from this study provide a clear pathway for implementing agricultural practices that align with the EGD sustainability targets. Shallow tillage and mulching have proven effective in enhancing soil health, promoting nutrient retention, and fostering biodiversity, which are key components of sustainable farming systems. These practices reduce reliance on synthetic inputs and support climate adaptation by improving soil resilience to extreme weather events. To facilitate broader adoption, policymakers should consider offering incentives or subsidies to support farmers in transitioning to these practices. By integrating these methods into agricultural strategies, farmers can contribute to climate-neutral farming while maintaining soil productivity and sustainability. Future research should explore long-term impacts across diverse climates and soil types to further refine these strategies.

Author Contributions: Conceptualization, Z.K. and N.E.; methodology, M.B.; software, Z.K.; formal analysis, Z.K. and Á.T.; investigation, N.E.; writing—original draft preparation, Z.K. and N.E.; writing—review and editing, B.B., M.J. and V.K.; supervision, M.B. All authors have read and agreed to the published version of the manuscript.

Funding: We would like to thank the owners, the management, and all the machine operators of Gallifarm Ltd., Hungary, who provided the on-site inspection and the machines and tools necessary for the preparation of the experimental plots and supported our work.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: On request, the data are available from the corresponding author.

Acknowledgments: We would like to thank the support of the Research Excellence Program of the Hungarian University of Agricultural and Life Sciences.

Conflicts of Interest: Author Norbert Egri was employed by the company Gallifarm Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Rusu, T. Energy Efficiency and Soil Conservation in Conventional, Minimum Tillage and No-Tillage. *Int. Soil Water Conserv. Res.* **2014**, *2*, 42–49. [CrossRef]
2. Carretta, L.; Tarolli, P.; Cardinali, A.; Nasta, P.; Romano, N.; Masin, R. Evaluation of Runoff and Soil Erosion under Conventional Tillage and No-till Management: A Case Study in Northeast Italy. *Catena* **2021**, *197*, 104972. [CrossRef]
3. Birkás, M.; Dekemati, I.; Kende, Z.; Pósa, B. Review of Soil Tillage History and New Challenges in Hungary. *Hung. Geogr. Bull.* **2017**, *66*, 55–64. [CrossRef]
4. Subbulakshmi, S.; Saravanan, N.; Subbian, P. Conventional Tillage vs Conservation Tillage-a Review. *Agric. Rev.* **2009**, *30*, 56–63.
5. Nichols, V.; Verhulst, N.; Cox, R.; Govaerts, B. Weed Dynamics and Conservation Agriculture Principles: A Review. *Field Crops Res.* **2015**, *183*, 56–68. [CrossRef]
6. Kalmár, T.; Bottlik, L.; Kisic, I.; Gyuricza, C.; Birkás, M. Soil Protecting Effect of the Surface Cover in Extreme Summer Periods. *Plant Soil Environ.* **2013**, *59*, 404–409. [CrossRef]
7. Damanauskas, V.; Velykis, A.; Satkus, A. Efficiency of Disc Harrow Adjustment for Stubble Tillage Quality and Fuel Consumption. *Soil Tillage Res.* **2019**, *194*, 104311. [CrossRef]
8. Du, C.L.; Li, L.L.; Effah, Z.; Xu, J.; Xie, J.H.; Luo, Z.Z.; Wang, L.L.; Zhang, J.; Kang, Y.Q. Different Tillage and Stubble Management Practices Affect Root Growth and Wheat Production in a Semi-Arid Area. *Plant Soil* **2024**, *502*, 211–225. [CrossRef]
9. Boström, U.; Hansson, M.; Fogelfors, H. Weeds and Yields of Spring Cereals as Influenced by Stubble-Cultivation and Reduced Doses of Herbicides in Five Long-Term Trials. *J. Agric. Sci.* **2000**, *134*, 237–244. [CrossRef]
10. Hati, K.M.; Jha, P.; Dalal, R.C.; Jayaraman, S.; Dang, Y.P.; Kopittke, P.M.; Kirchhof, G.; Menzies, N.W. 50 Years of Continuous No-Tillage, Stubble Retention and Nitrogen Fertilization Enhanced Macro-Aggregate Formation and Stabilisation in a Vertisol. *Soil Tillage Res.* **2021**, *214*, 105163. [CrossRef]
11. Alamouti, M.Y.; Navabzadeh, M. Investigation of Plowing Depth Effect on Some Soil Physical Properties. *Pak. J. Biol. Sci.* **2007**, *10*, 4510–4514. [CrossRef]
12. Alcántara, V.; Don, A.; Well, R.; Nieder, R. Deep Ploughing Increases Agricultural Soil Organic Matter Stocks. *Glob. Change Biol.* **2016**, *22*, 2939–2956. [CrossRef]
13. Xue, L.; Khan, S.; Sun, M.; Anwar, S.; Ren, A.; Gao, Z.; Lin, W.; Xue, J.; Yang, Z.; Deng, Y. Effects of Tillage Practices on Water Consumption and Grain Yield of Dryland Winter Wheat under Different Precipitation Distribution in the Loess Plateau of China. *Soil Tillage Res.* **2019**, *191*, 66–74. [CrossRef]
14. Défossez, P.; Richard, G.; Keller, T.; Adamiade, V.; Govind, A.; Mary, B. Modelling the Impact of Declining Soil Organic Carbon on Soil Compaction: Application to a Cultivated Eutric Cambisol with Massive Straw Exportation for Energy Production in Northern France. *Soil Tillage Res.* **2014**, *141*, 44–54. [CrossRef]
15. Botta, G.F.; Jorajuria, D.; Balbuena, R.; Ressia, M.; Ferrero, C.; Rosatto, H.; Tourn, M. Deep Tillage and Traffic Effects on Subsoil Compaction and Sunflower (*Helianthus annus* L.) Yields. *Soil Tillage Res.* **2006**, *91*, 164–172. [CrossRef]
16. Derpsch, R.; Friedrich, T.; Kassam, A.; Hongwen, L. Current Status of Adoption of No-till Farming in the World and Some of Its Main Benefits. *Int. J. Agric. Biol. Eng.* **2010**, *3*, 1–25. [CrossRef]
17. Reicosky, D. Conservation Agriculture Systems: Soil Health and Landscape Management. In *Advances in Conservation Agriculture*; Burleigh Dodds Science Publishing: Cambridge, UK, 2020; pp. 87–154.
18. Chen, Y.; Wylde, J. Transition from Conventional to No Tillage in a Poorly Drained Clay Soil. In Proceedings of the 2007 ASAE Annual Meeting, Minneapolis, MN, USA, 17–20 June 2007; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2007.
19. Karayel, D.; Sarauskis, E. Environmental Impact of the No-Tillage Farming. *Environ. Res. Eng. Manag.* **2019**, *75*, 7–12. [CrossRef]
20. Karlen, D.L.; Ditzler, C.A.; Andrews, S.S. Soil Quality: Why and How? *Geoderma* **2003**, *114*, 145–156. [CrossRef]
21. Herrick, J.E. Soil Quality: An Indicator of Sustainable Land Management? *Appl. Soil Ecol.* **2000**, *15*, 75–83. [CrossRef]
22. Novák, P.; Vopravil, J.; Lagová, J. Assessment of the Soil Quality as a Complex of Productive and Environmental Soil Function Potentials. *Soil Water Res.* **2010**, *5*, 113–119. [CrossRef]

23. Doran, J.W.; Zeiss, M.R. Soil Health and Sustainability: Managing the Biotic Component of Soil Quality. *Appl. Soil Ecol.* **2000**, *15*, 3–11. [CrossRef]
24. Dekemati, I.; Simon, B.; Vinogradov, S.; Birkás, M. The Effects of Various Tillage Treatments on Soil Physical Properties, Earthworm Abundance and Crop Yield in Hungary. *Soil Tillage Res.* **2019**, *194*, 104334. [CrossRef]
25. Maurya, S.; Abraham, J.S.; Somasundaram, S.; Toteja, R.; Gupta, R.; Makhija, S. Indicators for Assessment of Soil Quality: A Mini-Review. *Environ. Monit. Assess.* **2020**, *192*, 604. [CrossRef]
26. Das, A.; Babu, S.; Singh, R.; Kumar, S.; Rathore, S.S.; Singh, V.K.; Datta, M.; Yadav, S.K.; Wani, O.A.; Yadav, D. Impact of Live Mulch-Based Conservation Tillage on Soil Properties and Productivity of Summer Maize in Indian Himalayas. *Sustainability* **2022**, *14*, 12078. [CrossRef]
27. Borie, F.; Rubio, R.; Rouanet, J.L.; Morales, A.; Borie, G.; Rojas, C. Effects of Tillage Systems on Soil Characteristics, Glomalin and Mycorrhizal Propagules in a Chilean Ultisol. *Soil Tillage Res.* **2006**, *88*, 253–261. [CrossRef]
28. Dorr de Quadros, P.; Zhalnina, K.; Davis-Richardson, A.; Fagen, J.R.; Drew, J.; Bayer, C.; Camargo, F.A.O.; Triplett, E.W. The Effect of Tillage System and Crop Rotation on Soil Microbial Diversity and Composition in a Subtropical Acrisol. *Diversity* **2012**, *4*, 375–395. [CrossRef]
29. Ernst, G.; Emmerling, C. Impact of Five Different Tillage Systems on Soil Organic Carbon Content and the Density, Biomass, and Community Composition of Earthworms after a Ten Year Period. *Eur. J. Soil Biol.* **2009**, *45*, 247–251. [CrossRef]
30. Radics, Z.A.; Dekemati, I.; Gyuricza, C.; Simon, B.; Ibrahim, H.; Vinogradov, S.; Birkás, M. Effects of Irrigation and Organic Mulchingon the Abundance and Biomass of Earthworms. *Pol. J. Environ. Stud.* **2022**, *31*, 2811–2821. [CrossRef]
31. O'Leary, G.J.; Connor, D.J. Stubble Retention and Tillage in a Semi-Arid Environment: 1. Soil Water Accumulation during Fallow. *Field Crops Res.* **1997**, *52*, 209–219. [CrossRef]
32. Murphy, B.W.; Packer, I.J.; Cowie, A.L.; Singh, B.P. Tillage and Crop Stubble Management and Soil Health in a Changing Climate. In *Soil Health and Climate Change*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 181–206.
33. Lobell, D.B.; Bala, G.; Duffy, P.B. Biogeophysical Impacts of Cropland Management Changes on Climate. *Geophys. Res. Lett.* **2006**, *33*, L06708. [CrossRef]
34. Handayani, I.P.; Folz, N. Adaptive Land Management for Climate-Smart Agriculture. In Proceedings of the 2021 IEEE International Conference on Health, Instrumentation & Measurement, and Natural Sciences (InHeNce), Medan, Indonesia, 14–16 July 2021; pp. 1–7.
35. Cooper, H.V.; Sjögersten, S.; Lark, R.M.; Mooney, S.J. To till or Not to till in a Temperate Ecosystem? Implications for Climate Change Mitigation. *Environ. Res. Lett.* **2021**, *16*, 054022. [CrossRef]
36. Birkás, M.; Kisic, I.; Mesic, M.; Jug, D.; Kende, Z. Climate Induced Soil Deterioration and Methods for Mitigation. *Agric. Conspec. Sci.* **2015**, *80*, 17–24.
37. Kende, Z.; Sallai, A.; Kassai, M.K.; Mikó, P.P.; Percze, A.; Birkás, M. The Effects of Tillage-Induced Soil Disturbance on Weed Infestation of Winter Wheat. *Pol. J. Environ. Stud.* **2017**, *26*, 1131–1138. [CrossRef]
38. Vincent-Caboud, L.; Casagrande, M.; David, C.; Ryan, M.R.; Silva, E.M.; Peigne, J. Using Mulch from Cover Crops to Facilitate Organic No-till Soybean and Maize Production. A Review. *Agron. Sustain. Dev.* **2019**, *39*, 45. [CrossRef]
39. Davis, A.S.; Hill, J.D.; Chase, C.A.; Johanns, A.M.; Liebman, M. Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. *PLoS ONE* **2012**, *7*, e47149. [CrossRef]
40. Bottlik, L.; Csorba, S.; Gyuricza, C.; Kende, Z.; Birkás, M. Climate Challenges and Solutions in Soil Tillage. *Appl. Ecol. Environ. Res.* **2014**, *12*, 13–23. [CrossRef]
41. Sharma, P.; Abrol, V.; Sharma, R.K. Impact of Tillage and Mulch Management on Economics, Energy Requirement and Crop Performance in Maize–Wheat Rotation in Rainfed Subhumid Inceptisols, India. *Eur. J. Agron.* **2011**, *34*, 46–51. [CrossRef]
42. Gatea Al-Shammary, A.A.; Lahmod, N.R.; Fernández-Gálvez, J.; Caballero-Calvo, A. Effect of Tillage Systems Combined with Plastic Film Mulches and Fertilizers on Soil Physical Properties in a Wheat-Agricultural Site in Southern Iraq. *Cuad. Investig. Geogr.* **2023**, *49*, 51–63. [CrossRef]
43. Chen, B.; Cui, J.; Man, X.; Dong, W.; Yan, C.; Mei, X. The Climate Cost of Saving Water by Different Plastic Mulching Patterns. *J. Clean. Prod.* **2022**, *359*, 132011. [CrossRef]
44. Bálint, C.; Bernas, J.; Dezsényi, Z.; Encarnação, M.; Farkas, T.; Goda, P.; Grand, A.; Horstink, L.; Jancsovszka, P.; Klenkhart, L.; et al. *Background Report for Agroecological Vocational Training*; Bálint, C., Ujj, A., Eds.; NAIK Agrárgazdasági Kutatóintézet: Budapest, Hungary, 2020.
45. Montanarella, L. Soils and the European Green Deal. *Ital. J. Agron.* **2020**, *15*, 1761. [CrossRef]
46. IUSS Working Group WRB. *World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed.; International Union of Soil Sciences (IUSS): Vienna, Austria, 2022.
47. *MSZ 21470-52:1983*; Environmental Protection. Testing of Soils. Determination of Organic Matter. Hungarian Standard Association: Budapest, Hungary, 1983. (In Hungarian)

48. *MSZ EN ISO 10390:2022*; Soil, Treated Biowaste and Sludge. Determination of PH (ISO 10390:2021). Hungarian Standard Association: Budapest, Hungary, 2022. (In Hungarian)
49. *MSZ 20135:1999*; Determination of the Soluble Nutrient Element Content of the Soil. Hungarian Standard Association: Budapest, Hungary, 1999. (In Hungarian)
50. Dane, J.H.; Topp, G.C. *Methods of Soil Analysis*; Dane, J.H., Topp, G.C., Eds.; Soil Science Society of America: Madison, WI, USA, 2002.
51. Kautenburger, R. Genetic Structure among Earthworms (*Lumbricus terrestris* L.) from Different Sampling Sites in Western Germany Based on Random Amplified Polymorphic DNA. *Pedobiologia* **2006**, *50*, 257–266. [CrossRef]
52. Braun-Blanquet, J. Einleitung. In *Pflanzensoziologie*; Springer: Vienna, Austria, 1951; pp. 1–5.
53. Braun-Blanquet, J. *Pflanzensoziologie*; Springer: Vienna, Austria, 1951.
54. *MSZ-08-0210:1977*; Testing Organic Carbon Content in Soils. Hungarian Standard Association: Budapest, Hungary, 1977. (In Hungarian)
55. IBM Corp. *IBM SPSS Statistics for Windows*; IBM Corp.: Somers, NY, USA, 2020.
56. R Core Team. *R: A Language and Environment for Statistical Computing*; R Core Team: Vienna, Austria, 2022.
57. De Mendiburu, F.; Simon, R. Agricolae—Ten Years of an Open Source Statistical Tool for Experiments in Breeding, Agriculture and Biology. *PeerJ* **2015**, *3*, e1404v1. [CrossRef]
58. Wickham, H.; François, R.; Henry, L.; Müller, K.; Vaughan, D. Dplyr: A Grammar of Data Manipulation. 2023. Available online: https://dplyr.tidyverse.org/ (accessed on 31 January 2025).
59. Wickham, H.; Vaughan, D.; Girlich, M. Tidyr: Tidy Messy Data. 2024. Available online: https://tidyr.tidyverse.org (accessed on 31 January 2025).
60. Wickham, H. Programming with Ggplot2. In *Use R!* Springer International Publishing: Cham, Switzerland, 2016; pp. 241–253.
61. Kolde, R. Pheatmap: Pretty Heatmaps. R Package Version 1.0. 12. 2019. Available online: https://search.hsl.med.nyu.edu/discovery/openurl?institution=01NYU_HS&vid=01NYU_HS:HSL&date=2019&aulast=Kolde&genre=article&title=&atitle=pheatmap:%20Pretty%20Heatmaps.%20R%20package%20version%201.0.12&sid=oup:orr (accessed on 31 January 2025).
62. Dekemati, I.; Simon, B.; Bogunovic, I.; Kisic, I.; Kassai, M.K.; Kende, Z.; Birkás, M. Long Term Effects of Ploughing and Conservation Tillage Methods on Earthworm Abundance and Crumb Ratio. *Agronomy* **2020**, *10*, 1552. [CrossRef]
63. Wittink, D.R.; Bergestuen, T. Forecasting with Conjoint Analysis. In *International Series in Operations Research & Management Science*; Springer: New York, NY, USA, 2001; pp. 147–167.
64. Ringselle, B.; Bergkvist, G.; Aronsson, H.; Andersson, L. Importance of Timing and Repetition of Stubble Cultivation for Post-Harvest Control of iElymus Repens/i. *Weed Res.* **2015**, *56*, 41–49. [CrossRef]
65. Liu, S.; Li, J.; Zhang, X. Simulations of Soil Water and Heat Processes for No Tillage and Conventional Tillage Systems in Mollisols of China. *Land* **2022**, *11*, 417. [CrossRef]
66. Tagar, A.A.; Gujjar, M.A.; Adamowski, J.; Leghari, N.; Soomro, A. Assessment of Implement Efficiency and Soil Structure under Different Conventional Tillage Implements and Soil Moisture Contents in a Silty Loam Soil. *Catena* **2017**, *158*, 413–420. [CrossRef]
67. Gruber, S.; Möhring, J.; Claupein, W. On the Way towards Conservation Tillage-Soil Moisture and Mineral Nitrogen in a Long-Term Field Experiment in Germany. *Soil Tillage Res.* **2011**, *115–116*, 80–87. [CrossRef]
68. Faye, B.; Webber, H.; Gaiser, T.; Müller, C.; Zhang, Y.; Stella, T.; Latka, C.; Reckling, M.; Heckelei, T.; Helming, K.; et al. Climate Change Impacts on European Arable Crop Yields: Sensitivity to Assumptions about Rotations and Residue Management. *Eur. J. Agron.* **2023**, *142*, 126670. [CrossRef]
69. Barati, A.A.; Zhoolideh, M.; Azadi, H.; Lee, J.H.; Scheffran, J. Interactions of Land-Use Cover and Climate Change at Global Level: How to Mitigate the Environmental Risks and Warming Effects. *Ecol. Indic.* **2023**, *146*, 109829. [CrossRef]
70. Wei, L.; Zhang, B.; Wang, M. Effects of Antecedent Soil Moisture on Runoff and Soil Erosion in Alley Cropping Systems. *Agric. Water Manag.* **2007**, *94*, 54–62. [CrossRef]
71. Acharya, B.S.; Dodla, S.; Gaston, L.A.; Darapuneni, M.; Wang, J.J.; Sepat, S.; Bohara, H. Winter Cover Crops Effect on Soil Moisture and Soybean Growth and Yield under Different Tillage Systems. *Soil Tillage Res.* **2019**, *195*, 104430. [CrossRef]
72. Roger-Estrade, J.; Anger, C.; Bertrand, M.; Richard, G. Tillage and Soil Ecology: Partners for Sustainable Agriculture. *Soil Tillage Res.* **2010**, *111*, 33–40. [CrossRef]
73. Torotwa, I.; Ding, Q.; Makange, N.R.; Liang, L.; He, R. Performance Evaluation of a Biomimetically Designed Disc for Dense-Straw Mulched Conservation Tillage. *Soil Tillage Res.* **2021**, *212*, 105068. [CrossRef]
74. Cook, H.F.; Valdes, G.S.B.; Lee, H.C. Mulch Effects on Rainfall Interception, Soil Physical Characteristics and Temperature under *Zea mays* L. *Soil Tillage Res.* **2006**, *91*, 227–235. [CrossRef]
75. Lv, L.; Gao, Z.; Liao, K.; Zhu, Q.; Zhu, J. Impact of Conservation Tillage on the Distribution of Soil Nutrients with Depth. *Soil Tillage Res.* **2023**, *225*, 105527. [CrossRef]
76. Yang, Y.; Wu, J.; Zhao, S.; Mao, Y.; Zhang, J.; Pan, X.; He, F.; van der Ploeg, M. Impact of Long-term Sub-soiling Tillage on Soil Porosity and Soil Physical Properties in the Soil Profile. *Land Degrad. Dev.* **2021**, *32*, 2892–2905. [CrossRef]

77. Shukla, S.K.; Yadav, R.L.; Gupta, R.; Singh, A.K.; Awasthi, S.K.; Gaur, A. Deep Tillage, Soil Moisture Regime, and Optimizing N Nutrition for Sustaining Soil Health and Sugarcane Yield in Subtropical India. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 444–462. [CrossRef]
78. Schneider, F.; Don, A.; Hennings, I.; Schmittmann, O.; Seidel, S.J. The Effect of Deep Tillage on Crop Yield—What Do We Really Know? *Soil Tillage Res.* **2017**, *174*, 193–204. [CrossRef]
79. Yu, Q.; Wang, H.; Wen, P.; Wang, S.; Li, J.; Wang, R.; Wang, X. A Suitable Rotational Conservation Tillage System Ameliorates Soil Physical Properties and Wheat Yield: An 11-Year in-Situ Study in a Semi-Arid Agroecosystem. *Soil Tillage Res.* **2020**, *199*, 104600. [CrossRef]
80. Ogieriakhi, M.O.; Woodward, R.T. Understanding Why Farmers Adopt Soil Conservation Tillage: A Systematic Review. *Soil Secur.* **2022**, *9*, 100077. [CrossRef]
81. Cai, W.; Gu, X.; Du, Y.; Chang, T.; Lu, S.; Zheng, X.; Bai, D.; Song, H.; Sun, S.; Cai, H. Effects of Mulching on Water Saving, Yield Increase and Emission Reduction for Maize in China. *Agric. Water Manag.* **2022**, *274*, 107954. [CrossRef]
82. Lal, R. Soil Carbon Sequestration to Mitigate Climate Change. *Geoderma* **2004**, *123*, 1–22. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.