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The Impact of Soil Tillage and Crop Residue Incorporation Systems on Agrophysical Soil Properties

Vaida Steponavičienė *, Aušra Rudinskienė, Giedrius Žiūraitis and Vaclovas Bogužas

Department of Agroecosystems and Soil Sciences, Vytautas Magnus University, K. Donelaičio Street 58, 44248 Kaunas, Lithuania; ausra.rudinskiene@vdu.lt (A.R.); giedrius.ziuraitis@gmail.com (G.Ž.); vaclovas.boguzas@vdu.lt (V.B.)

* Correspondence: vaida.steponaviciene@vdu.lt

Abstract: This study investigates the long-term impact of soil tillage systems and crop residue incorporation on agrophysical properties. A long-term field experiment has been conducted since 1999 at the Experimental Station of Vytautas Magnus University Agriculture Academy. According to the latest edition of the International Soil Classification System, the soil in the experimental field was classified as Planosol, with a silty medium loam texture at a depth of 0–20 cm and a silty light loam at a depth of 20–40 cm. This investigation aimed to assess the long-term impact of reduced tillage systems, straw, and green manure combinations on soil physical properties, including soil shear strength, and soil aggregate stability. Studies were carried out on winter wheat crops in 2014, 2017, and 2023. The treatments were arranged using a split-plot design. In a two-factor field experiment, one part of the experimental field had straw removed, while the other part had the entire straw yield chopped and spread at harvest (Factor A). The subplot factor (Factor B) included three different tillage systems: conventional deep ploughing, cover cropping for green manure with no-till, and no-tillage. Soil samples were analysed in the Laboratory of Agrobiology at Vytautas Magnus University Agriculture Academy. The findings indicate that long-term application of reduced tillage significantly increases soil shear strength. Shallower tillage depths lead to higher soil shear strength, while the effect of spreading plant residues is relatively lower. Long-term tillage of different intensities, spreading plant residues, and catch crop cultivation for green manure did not significantly affect soil structure. However, soil structural stability was found to be highly dependent on soil tillage. Cover cropping for green manure with no-till and no-tillage positively affected soil aggregate stability in the upper (0–10 cm) and 10–25 cm layers.

Keywords: long-term experiment; shear strength; soil aggregate stability; straw return; cover crop

1. Introduction

Preserving and enhancing soil functions are essential aspects of sustainable agricultural practices. The implementation of long-term crop rotation and tillage practices significantly influences the soil environment by introducing inputs and disturbances that impact soil quality. The long-term impact of tillage on agroecosystems have been widely acknowledged. Conservation tillage systems that minimize soil disturbance, such as reduced or no-tillage and residue retention or mulching, are often advocated to improve agricultural sustainability. Previous studies have demonstrated the positive impacts of reduced tillage on soil properties [1]. Conservation agriculture encompasses a set of principles aimed at implementing and developing sustainable technologies that ensure sufficient plant residues on the soil surface for erosion control, reduced water evaporation and surface runoff, optimised rainfall utilisation, and long-term enhancement of physical, chemical, and biological soil properties, leading to stable and sustained yields [2].

The importance of soil health has gained exponential awareness and interest over the last decade, with excessive tillage identified as a significant contributor to soil degradation, particularly

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erosion [3]. Soil physical properties of a long-term no-till system underwent drastic changes with subsequent tillage, rendering previously valid soil quality indicators invalid [4]. Conservation tillage systems have been shown to have positive impact on soil porosity and aggregate stability across various soil types and climates [5]. However, the beneficial influences of conservation tillage practices, including reduced soil disturbance, cover cropping, and residue retention, appear to be site-specific, influenced by the post-adoption period, climate conditions, properties of the previous management system, and choice of cover crop species [6].

Regarding soil structure, it has been observed that different tillage technologies do not significantly alter soil aggregate structure. The most substantial increases in soil aggregate stability at sizes above 1 mm (average increase of 74.3% and 96.3%) and above 0.25 mm (average increase of 14.6% and 20.3%) were observed in shallowly loosened or untilled soil (direct drilling) compared to conventionally ploughed soil at the beginning of the vegetation period. Similar trends were observed at the end of the vegetation period, although the impact of tillage diminished [7].

Soil hardness is another important determinant of soil quality. Smaller soil aggregates result in higher soil hardness. Soil hardness increases as soil density rises and moisture content decreases [8]. Direct drilling has been associated with higher soil hardness compared to deep and shallow ploughing. Immediately after sowing, the topsoil (0-10 cm) exhibited similar hardness in both shallow ploughing and deep ploughing treatments, while directly drilled soil showed 49-54% higher hardness [9].

Sustainable agricultural practices are crucial for the maintenance and improvement of soil functions. The long-term implementation of crop rotation and tillage influences the soil environment through inputs and disturbance of the soil, which, in turn, impacts soil quality. Tillage has long-term impacts on agroecosystems. Conservation tillage systems with minimal soil disturbance, including no- or reduced-tillage and residue retention or mulching, are often proposed to improve agricultural sustainability [10].

The combined practices of tillage and rotation profoundly impact soil quality, crop performance, and the overall sustainability of cropping systems. Conservation tillage, recognized as one of the most effective soil management practices, offers mutual benefits in terms of erosion control, carbon sequestration, and reduced input of energy and labour [11]. Excessive compaction of untilled topsoil, leading to decreased soil physical quality, is considered a primary cause of yield reductions [12]. This issue is particularly problematic on weakly structured soils in humid temperate climates [13,14].

These recent findings further underscore the importance of implementing sustainable agricultural practices, such as conservation tillage systems, to enhance soil quality, improve crop productivity, and ensure the long-term sustainability of agricultural systems [15].

The research aimed to assess how different long-term tillage systems impact soil shear strength. Tillage practices can vary from conventional ploughing, where the soil is deeply turned over, to reduced tillage or no-tillage systems, where soil disturbance is minimized or eliminated. Each tillage system can lead to distinct impact on soil structure, organic matter distribution, and soil compaction, ultimately influencing soil shear strength.

2. Results and discussion

2.1. Soil shear strength

When direct drilling was implemented, it induced changes in closely related soil characteristics, wherein alterations in one characteristic led to corresponding changes in others [16].

The research results in 2014, 2017 and 2023 might have been significantly influenced by warmer-than-usual climatic conditions and a shortage of humidity. This might have exerted a significant effect on the critical threshold of soil shear strength. In 2014, at the beginning of winter wheat vegetation, the effect of tillage systems on the soil shear strength was significant both in the upper (0–10 cm) and the bottom (10–25 cm) layers (Figure 1). Compared with conventional ploughing, rest of the no-till systems significantly increased soil shear strength.

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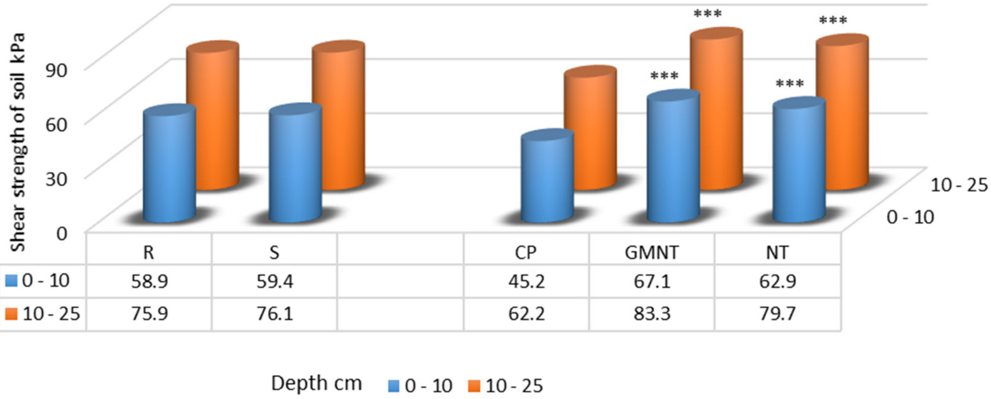

	R	S		CP	GMNT	NT
0 - 10	58.9	59.4		45.2	67.1	62.9
10 - 25	75.9	76.1		62.2	83.3	79.7

Figure 1. Shear strength of soil in spring 2014**.** Notes. Significant differences at *** P ≤ 0.001; Fisher LSD test vs. control.. Factor A: R - straw removed (control), S – straw chopped and spread. Factor B: CP - conventional deep ploughing (control), GMNT – cover cropping for green manure with no-till, NT - no-tillage, direct drilling.

In line with these findings, recent research has shed further light on the diverse impact of various tillage methods on soil strength and structure. Their study compared different tillage practices to conventional ploughing and revealed that all other tillage systems significantly increased soil shear strength [17].

Moreover conducted a comprehensive study focusing on the impact of tillage systems on soil shear strength. Their results were in line with the findings of [17,18] showing that all alternative tillage methods led to a significant increase in soil shear strength compared to conventional ploughing.

Furthermore, a meta-analysis conducted by provided additional evidence supporting the effectiveness of alternative tillage practices in enhancing both soil shear strength and sustainability. The meta-analysis synthesized data from multiple studies and reinforced the notion that adopting innovative tillage techniques can positively influence soil properties and contribute to improved agricultural practices [19].

Overall, the growing body of research emphasizes the importance of considering different tillage strategies and their impact on soil shear strength and structure. These findings play a crucial role in promoting sustainable agricultural practices and soil management strategies, ensuring long-term soil health and productivity. As researchers continue to explore the complexities of soil-tillage interactions, farmers and land managers can make informed decisions to preserve and improve soil quality, contributing to a more resilient and sustainable agricultural system.

Results of the studies that the soil shear strength in the upper (0–10 cm) soil layer was significantly (11.6%) higher when straw was present compared to the soil without straw. Similarly, in the deeper soil layer of 10–25 cm, the shear strength was 11.1% higher with straw (Figure 2). These findings highlight shear strength the beneficial impact of incorporating straw into the soil [20].

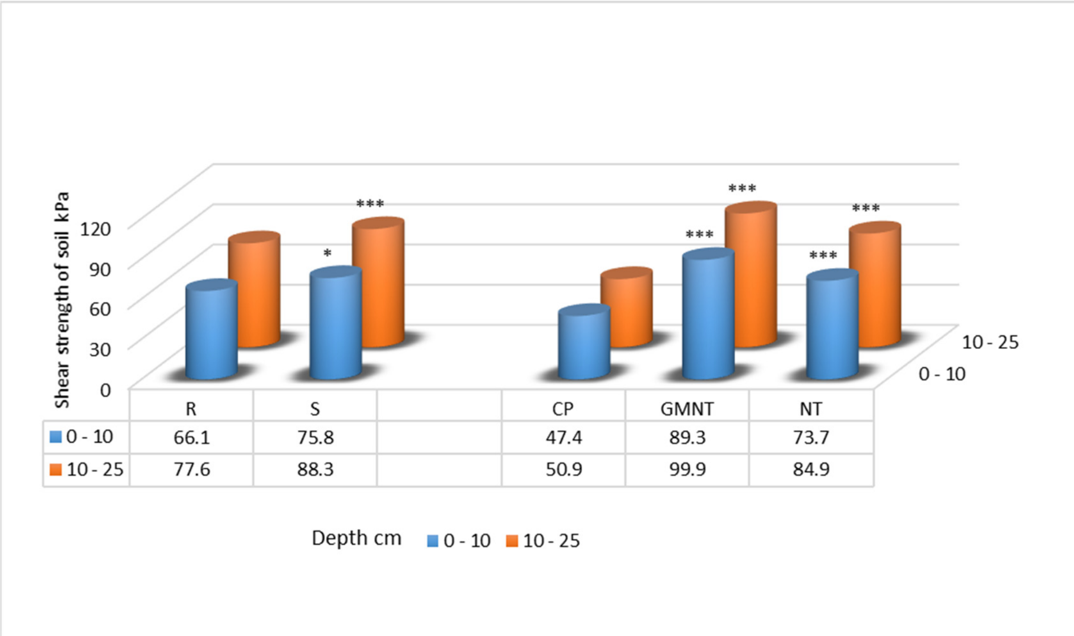

Figure 2. Shear strength of soil in spring 2017. Notes. Significant differences at *P ≤0.05>0.01; *** P ≤ 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

Furthermore, the study also investigated the effect of different tillage systems on soil shear strength. It was observed that the tillage systems had a significant influence in both the 0–10 cm and 10–25 cm soil layers. In the upper (0–10 cm) layer, the shear strength increased from 14.6% to 64.5% across different tillage systems, while in the deeper (10–25 cm) layer, the increase ranged from 49.8% to 71.7%.

These findings align with other recent research emphasizing the positive impact of straw incorporation and alternative tillage practices on overall soil health [21,22].

In 2023, the study faced challenges in measuring the soil shear strength beyond the upper (0–10 cm) layer due to lower-than-usual precipitation in May, resulting in excessively hard soil conditions (Figure 3). The scarcity of moisture in the soil made it difficult to conduct further measurements, and only the upper layer was evaluated.

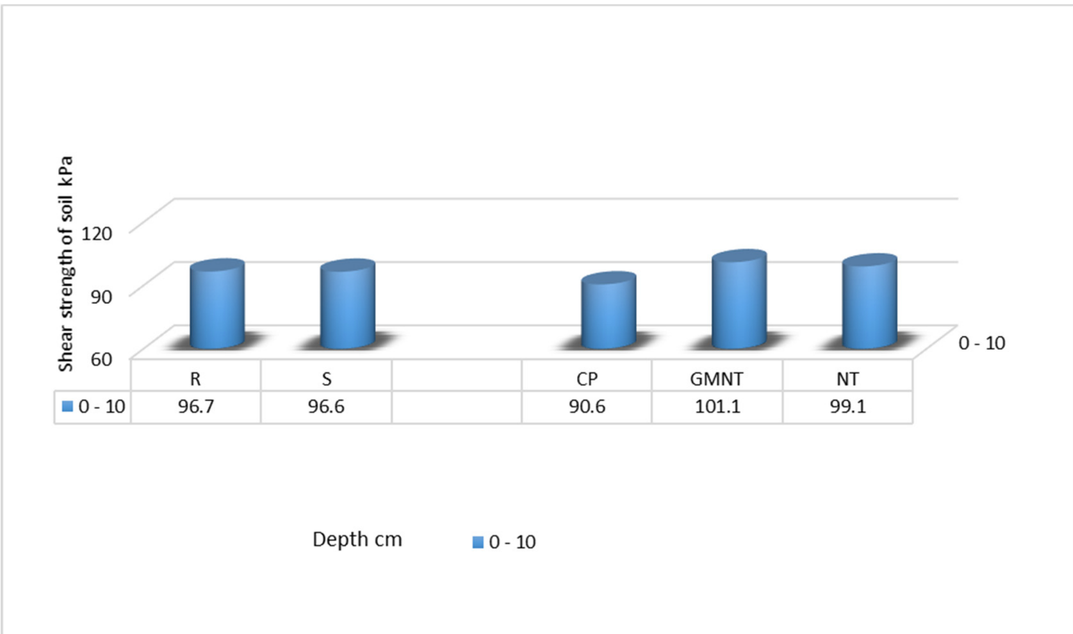

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Figure 3. Shear strength of soil in spring 2023. Notes. No significant differences at P > 0.05; Fisher LSD test vs. control. Other explanations as in Figure 1.

Despite the limited measurements, the study yielded notable insights. It was found that different tillage practices had a considerable impact on soil shear strength in the upper (0–10 cm) layer. Among the tillage methods, the direct drilling approach exhibited an 11.3% increase in shear strength compared to conventional ploughing, suggesting that this method could be particularly advantageous in drought-prone or low-moisture conditions

These findings show the importance of considering moisture levels and selecting the right tillage practices to effectively manage soil shear strength. The study highlights that soil moisture content can significantly influence soil shear strength, and, in dry conditions, certain tillage methods may be more suitable to maintain soil integrity.

The research conducted further reinforces the impact of tillage systems on various soil properties. These studies emphasize the need for context-specific approaches in soil management, taking into account regional climate patterns, soil types, and crop requirements. By tailoring tillage practices to local conditions, farmers and land managers can optimise soil health and productivity, contributing to sustainable and resilient agricultural systems [23].

In conclusion, the 2023 studys findings shed light on the significance of moisture levels in influencing soil shear strength, with direct drilling showing promise in drought conditions. Incorporating knowledge from previous research further emphasises the importance of adopting tailored tillage practices to improve soil properties and support sustainable agricultural practices [24].

Taken together, the three years of experimental data show a significant increase in soil shear strength over time with reduced tillage. It should be noted that the lower the tillage depth, the greater the increase in soil shear strength.

The influence of straw spreading on soil penetration and shear strength was assessed specifically in drier and hotter years. It is under these climatic conditions that the impact of straw spreading on soil penetration and shear strength were examined, revealing valuable insights into its impact on soil properties. These findings are in line with prior research which also highlight the beneficial impact of reduced tillage practices on soil strength and the importance of considering specific climatic conditions when managing agricultural systems [25,26].

2.2. Soil aggregate stability

Soil aggregate stability is a vital factor that influences crop yield, especially when coupled with good tillage practices [27]. The research conducted that conventional tillage practices reduced the macroaggregate fraction at a depth of 0–20 cm. This reduction in >0.25 mm aggregate fraction was attributed to the mechanical disruption of soil structure macroaggregates caused by frequent tillage operations, resulting in reduced aggregate stability.

The type of soil plays a significant role in determining the best tillage practices. Reduced tillage methods are particularly beneficial as they help minimise moisture loss and maintain optimal soil temperature, which is crucial for creating an ideal seedbed. However, soil structure can be degraded due to various factors, including mechanical, physical, biological, or chemical ones. Cultivation, driving over the soil, and heavy precipitation can mechanically dismantle the soil structure, while the leaching of calcium from the upper soil layers and a decrease in humus content can contribute to soil degradation. As a result, soil-stable aggregates lose their adhesive properties and begin to decompose. To combat soil degradation, it is crucial to control factors leading to soil structure deterioration and make efforts to enrich the soil with organic matter [28,29].

The results of specific research carried out since 2014 show that soil aggregate stability in the 0–10 cm soil layer was significantly higher with measures such as direct drilling compared to conventional ploughing. The increase ranged from 1.8 to 2 times (Figure 4). In the 10–25 cm soil layer, a similar significant increase in soil aggregate stability was observed, with the treatments resulting

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in 1.4 times greater stability compared to conventional ploughing. It should be noted that straw spreading did not have a significant influence on soil aggregate stability in this study.

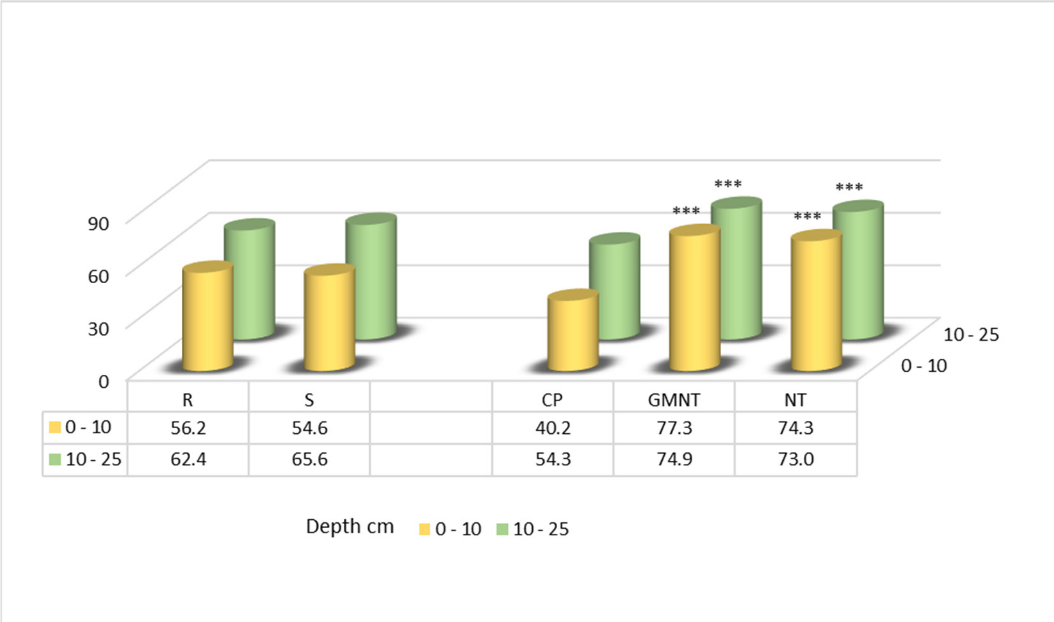

Figure 4. Soil aggregate stability in spring 2014. Notes. Significant differences at *** P ≤ 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

These findings are in line with other research which also highlight the importance of good tillage practices and their impact on soil aggregate stability [30].

Data from 2017 showed significantly higher soil aggregate stability in the 0–10 cm layer in the treatments (Figure 5) direct drilling of plant residues and direct drilling, compared with conventional ploughing by 37 and 34 percentage points, respectively.

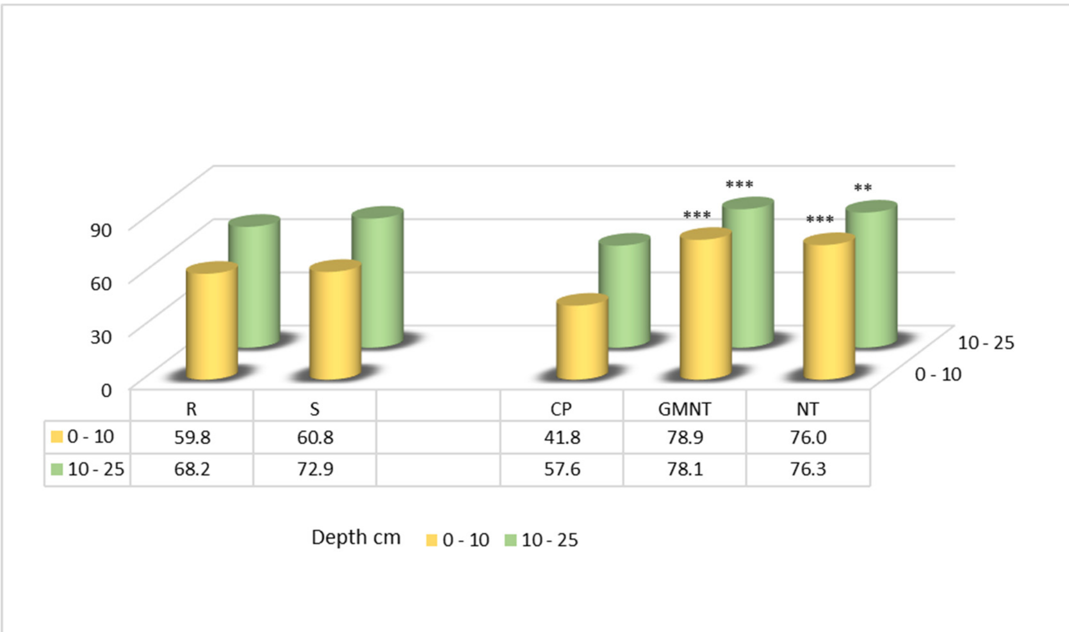

Figure 5. Soil aggregate stability in spring 2017. Notes. Significant differences at **P ≤ 0.010 > 0.001 ;*** P ≤ 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

These findings highlight the dynamic nature of soil response to different tillage practices and reinforce the notion that good tillage methods can significantly influence soil properties. The substantial improvements in soil aggregate stability observed with the specified treatments underscore their potential to contribute to enhanced soil structure, reduced erosion risks, and improved water infiltration, similar to the results of research obtained by other authors [30,31].

The study emphasizes the importance of considering year-to-year variations in the impact of tillage practices on soil aggregate stability. Soil health and stability are influenced by various factors, including weather conditions, cropping patterns, and management practices, making it essential to evaluate data across multiple years to gain a comprehensive understanding of soil responses.

In summary, the 2017 data reinforce the positive impact of specific tillage practices, such as direct drilling of plant residues, and direct drilling, on soil aggregate stability in the 0–10 cm soil layer. These findings further support the significance of adopting sustainable tillage strategies to maintain and improve soil health, providing valuable insights for informed decision-making in agricultural land management.

According to the results of the 2023 research, a significant increase in soil aggregate stability was observed in in both layers of the soil (Figure 6) with two specific treatments. The treatment involving direct drilling of plant residues showed a 20 and 20 percentage point increase in stability, while direct drilling alone resulted in an 21 and 22 percentage point increase in stability, both compared to conventional ploughing.

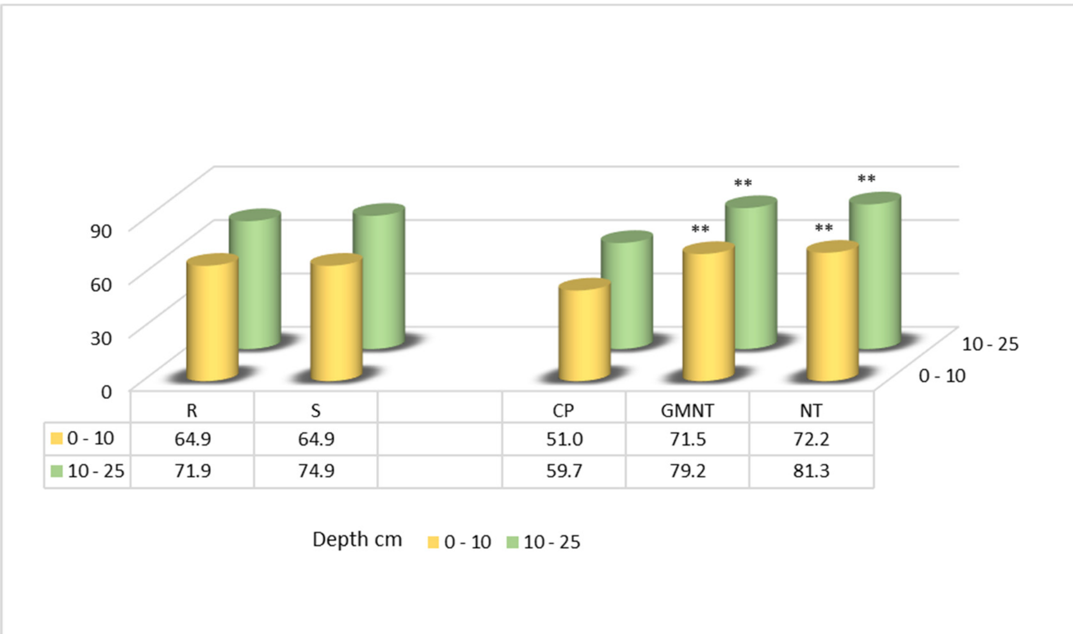

Figure 6. Soil aggregate stability in spring 2023. Notes. Significant differences at **P ≤ 0.010 > 0.001; Fisher LSD test vs. control. Other explanations as in Figure 1.

Moreover, the study revealed that soil aggregate stability was lowest when the soil was ploughed deeply or shallowly each year. However, the incorporation of straw residues tended to increase aggregate stability. These trends are in line with similar research conducted highlighting the consistent impact of different tillage practices on soil aggregate stability [32,33].

Additionally, the positive effect of direct drilling on soil structure was evident, as it significantly reduced the number of small aggregates and increased the number of stable aggregates not only in the upper (0–10 cm) soil layer but also in the (10–25 cm) soil layer. This finding is found that the increase in large aggregates in no-till soils is associated with the presence of a high level of crop residues on the soil surface and minimal soil disturbance, promoting soil structural stability [34].

In summary, the research reveals the influence of tillage practices, in particular direct drilling and straw incorporation, on soil aggregate stability in different soil layers. These findings highlight the potential of adopting conservation tillage practices to improve soil structure and promote sustainable soil management. However, the study also revealed that the impact of specific tillage practices may vary across different research periods and study conditions. It is important to acknowledge the complexities of soil-tillage interactions and the need for context-specific approaches in agricultural land management.

In conclusion, the results of these studies provide valuable insights for farmers and land managers to make informed decisions regarding good tillage practices that promote soil health, stability, and sustainable land use. Further research and understanding of soil response to different tillage strategies will contribute to the development of resilient agricultural systems that protect and enhance soil resources for future generations.

3. Material and methods

3.1. Site description

The research was conducted at the Experimental Station of Vytautas Magnus University Agriculture Academy (54º52′50″ N latitude and 23º49′41″ E longitude) as a long-term field experiment established in 1999. The study took place in 2014, 2017 and 2023. The soil at the experimental site was classified as Planosol. The long-term experiment was carried out using a split-plot design with four replications, resulting in a total of 24 plots. Initially, each plot had a size of 102 m^2 (6 m x 17 m), and the harvested area measured 30 m^2 (15 m x 2 m).

Table 1 shows the soil characteristics of the experimental plots (16) at a depth of 0–25 cm. The average values for sand, clay, silt, pH_{KCl}, soil organic carbon (SOC), available phosphorus (PAL), and available potassium (KAL) are provided [14].

Table 1. Soil characteristics of the experimental plot (0–25 cm).

Index	Average value
Sand %	35.6
Clay %	19.0
Silt %	45.4
pH_{KCl}	7.7
Soil organic carbon (SOC) g kg $^{-1}$	16.6
Available PAL mg kg^{-1}	116.0
Available KAL mg kg^{-1}	111.0

3.2. Experimental design and agricultural practices

Agroecosystems of the most popular crops grown in Lithuania – winter oilseed rape (Brassica napus L.), winter wheat (Triticum aestivum L.), and spring barley (Hordeum vulgare L.) – were chosen as the research objects. In a two-factor field experiment, a straw (Factor A) was removed (R) from one part of the experimental field, and in the other part of the field, the entire straw yield was chopped and spread (S) at harvest. Three different tillage systems (Factor B) were investigated as subplots: conventional deep ploughing (CP) in autumn at a depth of 23–25 cm, cover cropping for green manure with no-till (GMNT) and no-tillage (NT). White mustard (Sinapis Alba L.) was sown as a cover crop for green manure on stubble only in GMNT plots right after winter wheat and spring barley harvest.

In 2014 and 2017, the crops were sown with a Väderstad pneumatic no-tillage machine, and in 2022 autum with no-tillage machine a Agrisem SLY BOSS. After harvesting the pre-crop (except for winter rape), the straw was removed for one-half of the experiment (R), while for the other half the straw was chopped and spread (S). All the tillage systems were tested in both halves of the experiment with and without the straw. The design of the experiment and the farming practices are presented in our previous articles [35].

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3.3. Meteorological conditions

In 2014, during the vegetation period, the average monthly temperatures were lower than the long-term averages. This indicates that it was relatively cooler during that year, potentially impacting the growth and development of cultivated plants. Furthermore, the precipitation during this period was unevenly distributed. This means that the amount and timing of precipitation might have varied, which could have had an impact on water availability and moisture conditions for plant growth.

In 2017, the temperatures at the beginning and the end of the vegetation period were higher than the long-term averages. This suggests that there were periods of relatively higher temperatures, which might have influenced the growth and development of crops. However, a particularly dry period was observed in June and August, indicating lower-than-average precipitation during these months. This dry period could have hurt the growth of the cultivated plants, as water availability is crucial for plant growth and development.

During the 2023 vegetation period, average monthly temperatures were very similar to long-term averages. This implies that temperatures in that year were within the normal range compared to long-term climatic patterns. However, it is worth noting that precipitation over the entire vegetation period decreased less than the long-term average. This suggests that, although there might have been some variations in precipitation, overall, precipitation in that year was relatively constant compared to the long-term average. This could have contributed to more favourable water conditions for plant growth during the 2022 vegetation period.

Considering these meteorological conditions together with the precipitation data provides a more comprehensive understanding of the environmental factors that might have influenced the growth and productivity of cultivated plants in that particular year. Furthermore, it was observed that in all the years studied the precipitation was lower than the sum of the long-term averages. This suggests a general trend towards lower precipitation during the vegetation period compared to the long-term average conditions. Below-average precipitation can have important consequences for soil moisture availability, water resources, and plant water stress. These conditions can impact the growth, yield potential, and overall health of cultivated plants.

In summary, the climatic parameters during the three-year vegetation periods differed from each other and deviated from the long-term average conditions since 1974. This highlights the variability in meteorological conditions and the potential impact on agricultural systems. It is important to consider these climatic variations and their relationship with the agrophysical and hydrophysical soil properties. The interaction between meteorological conditions and soil properties is crucial for understanding the overall dynamics of agricultural systems and their response to changing climatic patterns.

Table 2. Average temperature (°C) and the sum of active temperatures (SAT) during the vegetation period in 2014, 2017, and 2022, Kaunas Meteorological Station.

Year/Month	04	05	06	07	08	SAT
2014	6.1	12.3	15.6	17.6	16.6	1675.6
2017	7.1	11.4	15.4	17.4	20.3	1800.2
2023	9.1	13.0	19.8	17.1		1918.5
Long-term average 1974–2023	6.9	13.2	16.1	18.7		-

SAT = sum of active temperatures (≥ 10 °C).

Table 3. Precipitation (mm) during the vegetation period in 2014, 2017, and 2022, Kaunas Meteorological Station.

Year/Month	04	05	06	07	08	Sum
2014	56.5	63.8	45.9	118.5	67.2	351.9
2017	46.0	43.8	16.4	72.4	6.9	185.5
2022	0.6	29.9	49.4	60.1		208.2
Long-term average 1974–2023	41.3	61.7	76.9	96.6		365.4

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3.4. Methods and analysis

Soil sampling and soil aggregate stability analysis methods were carried out to assess soil properties and determine soil aggregate stability. The following procedures were followed:

In the experimental years 2014, 2017, and 2023, soil samples were collected from the experimental site at two depths in the plough layer: 0–10 cm and 10–25 cm. Ten spots were sampled within each plot to ensure representative soil samples. These individual samples were then combined (250 g per sample) to form a composite sample for each depth, representing the characteristics of the plot.

The collected soil samples were air-dried to remove excess moisture. Subsequently, the soil was sieved using a Retsch sieve shaker (Retsch GmbH, Germany) to separate it into eight fractions according to diameter: <0.25, 0.25-0.5, 0.5-1.0, 1.0-2.0, 2.0-4.0, 4.0-5.6, 5.6-8.0, and >8.0 mm. A wet sieving apparatus (Eijkelkamp Agrisearch Equipment, The Netherlands) was used to assess the soil aggregate stability. Specifically, air-dried soil aggregates of 1–2 mm in size were subjected to wet sieving in distilled water. Stable aggregates were retained, while unstable aggregates were destroyed by treating them with a 0.2% $(NaPO_3)_6$ solution. The stable aggregates were then oven-dried at 105°C for 24 hours and weighed. These methods allowed us to determine the soil aggregate stability at both 0–10 cm and 10–25 cm depth in the plough layer. The analysis provided valuable information on the ability of soil aggregates to resist breakdown under wet conditions, offering insights into structural soil stability.

The procedures described here are consistent with the approach outlined which provides standardized and reliable measurements of soil aggregate stability [36].

Soil shear strength was assessed using a penetrometer Geonor 72410 (Eijkelkamp) at two depths in the plough layer: 0–10 cm and 10–25 cm. The measurements were conducted after sowing or after the resumption of winter wheat vegetation at ten different locations within each plot. The penetrometer was used to determine the resistance encountered when applying a controlled force to the soil. These measurements provided insights into the soil's mechanical strength and its ability to resist shear forces, which are essential for understanding soil stability and its response to different tillage practices and crop management techniques.

3.5. Statistical analysis

Experimental data were analysed using a two-factor analysis of variance (ANOVA) based on the methodology [37] using the statistical software package SYSTAT, version 12 (SPSS Inc., USA). The significance of differences among the treatments was determined using the least significant difference (LSD) test. The probability levels indicating significant differences between specific treatments and the control treatment are denoted as follows: * – when $P \leq 0.050 > 0.010$ (significant at the 95% probability level), ** – when $P \leq 0.010 > 0.001$ (significant at the 99% probability level), *** – when $P \leq 0.001$ (significant at the 99.99% probability level).

4. Conclusions

Long-term field experiments conducted over 24 years (1999-2023) provide valuable insights into the changes in soil physical state resulting from different tillage practices and crop residue incorporation. The findings highlight a significant impact of reduced tillage on soil shear strength and soil aggregate stability.

The study revealed that long-term application of reduced tillage substantially increased n soil shear strength. This indicates that reduced tillage practices contribute to improved soil strength and compaction resistance over time. Additionally, the results showed that the depth of tillage played a crucial role, with shallower tillage associated with higher soil penetration resistance and shear strength. This finding shows that it is important to consider the depth of tillage when evaluating its impact on soil's physical properties. In contrast, the effect of straw retention on soil shear strength was relatively smaller. Although straw incorporation may have some influence, it is not as pronounced as the impact of reduced tillage.

An important aspect of the soil's physical condition is soil aggregate stability. The study demonstrated that soil aggregate stability was highly dependent on the tillage practices employed. Direct drilling (no-tillage) had a positive effect, increasing soil aggregate stability by up to 1.9 times compared to deep ploughing. These findings emphasize the benefits of reduced tillage practices and the incorporation of specific plant residues in enhancing soil aggregate stability.

The study further revealed that soil aggregate stability was lowest when the soil was deeply ploughed every year. This indicates that frequent ploughing can negatively impact soil aggregate stability. However, the incorporation of plant residues tended to increase soil aggregate stability, suggesting that residue retention can help mitigate the negative impact of ploughing. Additionally, reduced tillage and direct drilling showed positive impact on soil aggregate stability in the upper (0–10 cm) and 10–25 cm soil layers. This highlights the potential of reduced tillage practices in promoting soil aggregation and stability in the topsoil.

However, it is important to acknowledge that the results of this study are based on specific experimental conditions and may not be directly applicable to all soil types, climates, and crops. Further research is needed to validate these findings across different agroecosystems and to establish more comprehensive guidelines for the implementation of reduced tillage practices and crop residue incorporation in diverse agricultural contexts.

Author Contributions: V.S, and V.B. designed the research framework and contributed to the application of the study methodology and the analysis of the results. V.S, A.R. and G.Ž played an active role in writing, reviewing, and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

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