Influence of Biopreparations on Soil and Crop Residue Properties, Traction Force of Machines in Shallow Tillage

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Abstract: Solving traction force and energy consumption problem in crop production, the use of strategically selected bioproducts can change the physical properties of the soil and influence changes in the traction force during tillage technological operations. The aim of this work was to investigate the influence of different biopreparations on the physical properties of the soil, winter wheat residues and the machine traction force during shallow tillage. In spring, after the resumption of winter wheat vegetation, seven different biopreparations and their mixtures were used. In autumn, after the harvest, studies of plant residues and soil porosity and density were performed prior to shallow tillage. The traction force of the tractor when working the soil shallowly was determined at 3 driving velocities—8, 10 and 12 km h⁻¹. Research has shown a positive effect of biopreparations on the total porosity, density, and traction force of the machine. However, biopreparations did not significantly affect the cutting force of winter wheat residues. Biopreparations can reduce the traction force in shallow tillage due positive changes soil properties.

Keywords: density; porosity; wheat remains; pull

1. Introduction

Technological progress in agriculture has increased energy consumption per hectare several times, and agriculture has become a major energy consumer [1]. Energy in agriculture is directly used in fuel and electric machinery and equipment [2]. Energy consumption in agriculture is increasing due to intensifying and more complex mechanized operations [3,4]. Shallow tillage consumes about 9 liters less fuel per hectare than deep tillage [5,6]. An intensive effect of agricultural mechanization on soil compaction results in higher energy consumption [7]. Studies have shown that traction affects fuel consumption. During strip tillage, the traction force of the machine ranged from 1712 N to 5370 N, and fuel consumption ranged from 7.5 l h⁻¹ to 8.7 l h⁻¹ [8]. Tractor tire contact area with soil also has an influence for fuel consumption and traction force. Bigger effect of soil moisture content is significant on increasing fuel consumption because the tire slip [9]. However, tire contact area is not this research purpose.

Continuous tillage mechanically changes the soil, affecting its physical, biological, and chemical properties [10–12]. Energy consumption can be reduced by optimizing complex technological processes [13–16]. Other researchers have identified important and proper measures to reduce energy consumption [13,17,18] related to the level of mechanization and agricultural engineering processes, as well as utilization of soil nutrients [19,20].

Tillage changes the physical properties of the soil, the dynamics of nutrients, and the soil is more affected by erosion [21–23]. Tian et al. [24] state that, 40 days after cultivation of loamy sand soil, an increase in soil density was observed at a depth of 0–100 mm, while soil density remained unchanged at a depth of 100–150 mm. The traction force of the machine during tillage depends not only on the technological and structural parameters of...
the working parts, but also on the physical properties of the soil and the properties of plant residues remaining on the soil surface [25–27].

Working with notched disc working parts requires less traction than working with flat-blade discs or forged coulters [28,29]. Rahman and Chen [30] state that regardless of the dimensions of the working parts, increasing the working depth significantly increases the traction force, but no such trend has been observed with increasing driving velocity. Mouazen and Ramon [31] found that the gravitational force in sandy soils increases when increasing soil moisture, density, and tillage depth. Lower energy consumption is also influenced by soil structure, but this influence is smaller than the effects of mechanization [5].

Due to their physical-mechanical, biological and other properties, plant residues interfere with the quality of work of tillage machines [32]. Plant residues embedded in the soil are one of the disturbances when ensuring proper tillage and sowing technological process [33]. In addition, Tourn et al. [34] found that higher yields were obtained in soil in which plant residues were removed. Studies of the mechanical properties of plant residues are relevant to the quality of tillage and sowing technological processes, the production of agricultural machinery and the selection of their working parts [35]. Researchers in various countries have found that the force required to cut or break plant residues depends on the plant type, stem diameter, plant length, moisture, cell structure and elasticity, the time which the residue remains on the soil surface after harvest, and also on whether biopreparations are used to accelerate the mineralization of plant residues [35–38].

Biopreparations are most commonly used as nutrients for soil and plants. Plants sprayed with the biopreparation solution absorb mineral substances much better, grow more intensively, and their productivity increases [39,40]. Biopreparations determine the stability of agroecosystems and their resistance to abiotic environmental factors and stress [41]. They help to create a distinctive agricultural culture and ensure long-term and stable yields of field crops while maintaining clean environment without harming humans [41,42]. Biopreparations may contain strain nitrogen-fixing bacteria and biologically active substances that affect the structure of plant residues. As a result, the mineralization of plant residues in the topsoil is activated and living nitrogen-fixing bacteria simultaneously perform the function of accelerating the processes of decomposition of plant residues and deterioration of mechanical properties [42,43]. The use of a biological preparation with nitrogen-fixing bacteria significantly reduces the content of cellulose, hemicellulose, and lignin in wheat straw [44]. Vaitauskienė [38], Ahmadi [42], and Holtze et al. [43] state that it is recommended to spray the plant residues remaining on the soil surface with the solution of the biopreparation, because not only the mineralization of plant residues is accelerated, but the nutrients in plant residues are released faster and soil aeration is improved.

The use of mineral fertilizers also accelerates the mineralization of organic matter but can disturb the balance of natural processes in the soil. The change of interrelated natural and anthropogenic factors in the agrosystem is caused by using developed chemicals to increase production, thus reducing natural self-regulatory processes in the soil and increasing environmental pollution [45,46]. The use of biopreparations and modification of organic waste can maintain or increase the amount of organic carbon in the soil [47], increase porosity, and reduce energy consumption for tillage, as well. Therefore, it is very important to know how different biopreparations and their mixtures can increase the traction force reduction efficiency of tillage technological processes and improve the management of energy consumption in tillage systems. The aim of this work is to investigate the effect of different formulations of biopreparations on the properties of soil porosity and density, mechanical properties of plant residues, and traction force of tillage machines in shallow work.

2. Materials and Methods
2.1. Site Description and Experimental Design

Experimental field research was carried out at the Experimental Station of Vytautas Magnus University Agriculture Academy (54°53′N; 23°50′E), Kaunas district, Lithuania,
in 2016 and in 2017. The field site was located the southwest side of Kaunas city, on the left side of the Nemunas river. It is characterized by a slightly wavy plain, and the soil that has formed in the area represents bottom moraine or bottom glacial deposits that are covered with limnoglacial sediments and deeply lukewarm soaked soil (Endohypogleyic-Eutric Planosol—PLe-gln-w). The average soil pH was 6.5–7.2, total nitrogen 1.47–1.59%, humus 2.2–3.0%, mobile phosphorus 173–235 mg kg\(^{-1}\), mobile potassium 115–189 mg kg\(^{-1}\), and mobile sulfur 5.6–26.4 mg kg\(^{-1}\). The research was carried out under meteorological conditions of central Lithuania: the annual amount of precipitation was 844 mm in 2016. Precipitation was particularly high in July (162.9 mm) and August (114.9 mm), when shallow tillage was carried out after the harvest. In 2017, the annual precipitation was 522 mm (79.6 mm in July, 55.0 mm in August). The average temperature in 2016 was 7.7 °C (17.9 °C in July, 16.9 °C in August), and in 2017—8.7 °C (16.8 °C in July, 17.5 °C in August).

The area of the experimental field studies of 19200 m\(^2\) was divided into 8 experimental treatments, each of which had an area of 2400 m\(^2\) (length of 200 m and width of 12 m) (Figure 1). There were 4 replicates in each treatment.

![Figure 1](image_url)  
Figure 1. Experimental design of field research: 1, 2, 3, 4—repetitions; 5—accounting field; 6—protection zone.

In spring, after the resumption of plant vegetation, winter wheat “Famulus” in 2016 and winter oilseed rape “Cult” in 2017 were sprayed with 4 different biopreparations and their mixtures using “Amazone” sprayer (model UF-901) manufactured in Austria company “Josef Duben KG” (Sitzendorf an der Schmida, Austria). The rate ranged from 1.0 to 4.0 l ha\(^{-1}\). Biopreparations were mixed with water at 200 l ha\(^{-1}\). The composition of the biological preparations are provided in Table 1.

| No. | The Composition of the Biopreparates |
|-----|-------------------------------------|
| 1   | Essential oils of plants; 40 species of various herb extracts; marine algae extracts; mineral oils. |
| 2   | \textit{Azospirillum} sp. (N), bacterial colony count—1 \times 109/mL; \textit{Frateria aurentia} (K), bacterial colony count—1 \times 109/mL; \textit{Bacillus megaterium} (P), bacterial colony count—1 \times 109/mL; seaweed extract—10% by volume. |
| 3   | \textit{Azotobacter chroococcum}, 1 \times 109/mL—non-membrane, nitrogen-fixing bacteria; \textit{Azospirillum brasilense}, 1 \times 109/mL—non-membrane, nitrogen-fixing bacteria; \textit{Phosphorus P} (P\textsubscript{2}O\textsubscript{5})—7.5%; Potassium K (K\textsubscript{2}O)—7.5%; seaweed extract—10% by volume. |
| 4   | \textit{Azotobacter vinelandii} 1 \times 109 mL; 5% of solids; 4.5% of humic acids; 0.5% gibberellic acid; 0.01% copper (Cu); 0.01% zinc (Zn); 0.01% manganese (Mn); 0.01% iron (Fe); 0.01% calcium (Ca); 0.005% sodium molybdate (Na\textsubscript{2}MoO\textsubscript{4}). |

Figure 2 shows the plan of experimental research, indicating the technological operations of plant cultivation, the place of spraying of biological preparations in the sequence of these operations, the place of determination of plant residues, soil properties, and traction forces of tillage machines in the plan.
Prior to tillage, soil density and porosity were sampled using a soil drill. For each treatment, 5 soil samples were taken from each soil layer at a depth of 0–250 mm in each replicate. Experimental sampling was random on both sides of the tramlines. Soil properties studies were performed in 5 replicates. Total soil porosity was determined using an Air Pycnometer.

2.2. Investigation of Traction Force during the Tillage

After the harvest, the tractor’s traction force measurements were performed during shallow tillage in 3 repetitions. The tests were performed according to a globally recognized methodology (The OECD Standard Codes for the Official Testing of Agricultural and Forestry Tractors, 2016) and the requirements of the USA Standard S296.2 from the American Society of Agricultural and Biological Engineers (ASABE).

This analysis used the following equipment: a mobile loader AW400 tractor, Australia—New Zealand region, company “A.M.D.S.” (Wagga Wagga, Australia), a data link scanner for tractor control modules with computer software, speed, voltage, and motor sensors and a “SKRT–21 Lite” data recorder with a timer. The average values were calculated, and the saving period was programmed for 5 s. Motor sensors captured voltage, which was then converted into traction force. (Figure 3).
For shallow tillage, a 4.0 m wide disc harrow was used with the notched disc. The average tillage depth was shallow 100 ± 20 mm. The disc harrow was pulled by a tractor “Zetor 10540” (Brno, Czech Republic, company “ZETOR”) in which engine 4.2 l, 4 cylinder, in-line, liquid-cooled, turbocharged diesel, rated speed was 1600 min⁻¹. Three different tillage velocities were selected for the experimental research: 8.0 ± 0.15 km h⁻¹, 10.0 ± 0.17 km h⁻¹, and 12.0 ± 0.20 km h⁻¹.

2.3. Cutting Characteristics of Plant Residues

It has been established that the disc working parts of machines can cut or pressed plant residues into the soil [28,37]. A force-mechanical property testing machine “Instron 5960” (Riedlingen, Germany, company Form+test Seidner & Co. Gmbh) (Figure 4) with computer data processing software “Bluehill” was used to determine the cutting force characteristics of winter wheat crop residues.

![Figure 4. Device for determining the mechanical properties of plant residues “Instron 5960”: 1—upper stroller; 2—frame; 3—control panel; 4—grabs of knife; 5—tube of air supply to grabs; 6—60° angled knife; 7—box with the soil.]

Residues of winter wheat with a length of 100 ± 5 mm and a moisture content of 7.0 ± 1.0% were taken from eight different experimental study fields two weeks after the harvest. Residue incision studies were performed in 5 replicates. In order to improve the cutting quality of the crop residues, it is important to use notched disc working parts [38], so the cutting tests were performed with the knife built at an angle of 60°, during which the cutting of plant residues in the notched disc working parts was simulated. Knife blade thickness was 0.4 mm, length—4 mm, and sink depth—up to 100 mm. Knife blade was sharpened at an angle of 30°. In order to ensure the most natural conditions for the experimental research, the research on the cutting of plant residues was performed in interaction with the soil. Light loam soil with a moisture content of 15.0 ± 1.3% and a hardness of 1.0 ± 0.06 MPa was used for the research.

During experimental cutting research, the blade movement velocity was 50 mm min⁻¹. After each test of cutting crop residues, the soil was thickened, and its surface hardness and moisture were measured with an Eijkelkamp electronic penetrometer (Giesbeek, The Netherlands, company Eijkelkamp Soil & Water) in 3 replicates in order to ensure uniform physical-mechanical soil properties and experimental conditions.

2.4. Statistical Analysis

For statistical evaluation of the research results, ANOVA tool of Microsoft Excel software was used, which performed one-factor data variance analysis. Comparative evaluation of data between different treatments was performed using the HSD05 (Honest Significant Difference) method at the 95% probability level [48]. The same letters in the tables and figures indicate that there was no significant difference between the treatments. Arithmetic averages, standard deviations, and their confidence intervals were determined at the $p < 0.05$ probability level [49].
3. Results and Discussion
3.1. The Influence of Biological Preparations and Tillage Velocity on Traction Force

In 2016, experimental research showed that at a minimum tillage velocity of 8 km h\(^{-1}\), all treatments treated with biopreparations had significantly lower traction force compared to the control treatment in which no biopreparation was used (Figure 5). When the driving velocity was increased to 10 km h\(^{-1}\) and 12 km h\(^{-1}\), a significant difference in traction force compared to the control was observed in all treatments except for Treatment 5, where the soil was sprayed with biopreparations. Biopreparations containing *Azotobacter vinelandii* bacteria were used in this treatment. A similar trend was observed in 2017. At all driving velocities tested, the traction force was significantly lower in all treatments compared to the control, except for the same Treatment 5 at 8 km h\(^{-1}\). It is very important to determine the main reasons why most biopreparations or their mixtures allowed reducing the traction force of the soil by tillaging shallowly. Based on our results and the results of other researchers, it can be assumed that biopreparations may have increased the organic carbon content of the soil, leading to a decrease in soil density and an increase in total soil porosity, which may have contributed to a reduction in tillage energy costs [47, 50, 51].

Comparison of the years with different meteorological conditions revealed that, in drier years, namely 2017, in all cases where the soil was exposed to biopreparations, shallow tillage required between 11% and 20% less traction force compared to the more humid year 2016 (Figure 6). The largest reduction in traction (20%) was found in Treatment 1, Treatment 2, and Treatment 5 at the velocities of 10 km h\(^{-1}\) and 12 km h\(^{-1}\), and the smallest (11%)—in Treatment 5 and Treatment 7, when the driving velocity was 8 km h\(^{-1}\).

Comparison of the results obtained in this research with previous research of other authors revealed that the traction force of the machine can be reduced by optimizing the technological processes of agricultural machines [13, 15], as well as by changing the physical properties of the soil, such as moisture, hardness, density, and porosity [24, 52]. Naujokienė et al. [51] found that, by acting on the physical properties of the soil, biopreparations allow reducing the traction force and the energy consumption in conventional deep tillage with a plough. Our results provide opportunities to supplement previous research that biopreparations also have an important positive effect on the traction force of machines and on shallow tillage. Conventional tillage uses a lot of traction force and diesel fuel [53–56]. Shallow tillage, however, not only reduces the tillage depth and the need for traction force and fuel consumption associated with it, but greenhouse gas emissions, as well [8, 9], thus contributing to a cleaner environment. Krauss et al. [57] argued that using less mechanized processes in tillage makes it more sensitive to power, energy, labor, and time costs in terms of soil moisture and environmental pollution.

Experimental studies of the traction force showed that the reduction of the it was achieved when the soil was treated with biopreparations. Therefore, in order to justify the results of this research, other experimental studies were performed in parallel to determine changes in soil density, total porosity, and mechanical properties of plant residues when using biopreparations.
Figure 5. The impact of different biopreparations and driving velocities on the traction force of a shallow tillage machine: Treatment 1—composition of the biopreparation No. 1; Treatment 2—No. 1 and No. 2 mixture; Treatment 3—composition of the biopreparation No. 2; Treatment 4—No. 1 and No. 3 mixture; Treatment 5—composition of the biopreparation No. 4; Treatment 6—No. 1 and No. 4 mixture; Treatment 7—composition of the biopreparation No. 3. Letters with the same color indicate no significant difference between different variants the same year.
3.2. Soil Density and Total Porosity

Experimental research has shown that continuous treatment of the same soil with biopreparations for two years on average increased the total porosity of the soil in 2017 by about 6.49% compared to 2016, except for Treatment 7 (Table 2). It was found that, after exposure to different biopreparations and their mixtures, in the first year after the whole vegetation period, the total porosity of the soil increased by, on average, 0.30 to 12.20%, and in the second year—by 4.20–8.40% compared to the control. A higher average increase in total soil porosity was observed in the second year (approximately 7.60%) compared to the first year (5.37%) of the research. Comparing the results of 2016 and 2017 between the same treatments it has been established that an increase in the total soil porosity was significantly higher in Treatment 1, Treatment 2, Treatment 4, and Treatment 6 in 2017. Other researchers also claim that an exposure of soil to biopreparations has a positive effect on soil physical properties and observe an increased in soil porosity [50,58]. Improving the physical properties of the soil has a positive impact not only on one technological operation, but on the successful management of the whole agriculture, as well [22].

Our analysis of the experimental research results showed that the soil density decreased on average by 0.09 g cm$^{-3}$ in 2017 compared to 2016. A decrease in soil density from 0.04 to 0.19 g cm$^{-3}$ was observed in all treatments with biopreparations in the first year, and from 0.01 to 0.15 g cm$^{-3}$ in the second year of the experimental research, compared to the control treatment without biopreparations. Comparison of soil density between the same treatments in different years revealed a significant decrease in soil density in 2017 in all treatments except for Treatment 7. Soil density was especially small (approximately 1085 g cm$^{-3}$) in 2017 in a Treatment 1 and Treatment 2. In addition to the effect of biopreparations on soil density, different precipitation rates in July and August before shallow tillage may also have had an influence. Other researchers have reported that water content in soil affects soil density [24,59,60].
Table 2. Total soil porosity and soil density before the tillage.

| Soil Properties | Control (A) | Treatment 1 (B) | Treatment 2 (C) | Treatment 3 (D) | Treatment 4 (E) | Treatment 5 (F) | Treatment 6 (G) | Treatment 7 (H) |
|-----------------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Total porosity (%) | 48.60 ± 5.75 a | 48.90 ± 3.68 a | 53.00 ± 3.04 b | 52.90 ± 7.19 b | 53.00 ± 3.07 b | 52.00 ± 3.20 b | 60.80 ± 6.94 c |                  |
| Soil density (g cm⁻³) | 1.42 ± 0.21 a | 1.37 ± 0.09 a | 1.26 ± 0.11 b | 1.29 ± 0.21 b | 1.38 ± 0.06 b | 1.28 ± 0.04 b | 1.41 ± 0.18 c | 1.23 ± 0.15 c |

2017 y.

| Soil Properties | Control (A) | Treatment 1 (B) | Treatment 2 (C) | Treatment 3 (D) | Treatment 4 (E) | Treatment 5 (F) | Treatment 6 (G) | Treatment 7 (H) |
|-----------------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Total porosity (%) | 50.60 ± 2.85 a | 54.80 ± 3.21 a | 59.00 ± 6.08 b | 56.40 ± 5.16 b | 57.80 ± 2.83 b | 56.60 ± 3.98 b | 58.00 ± 2.32 c | 57.40 ± 3.11 c |
| Soil density (g cm⁻³) | 1.23 ± 0.14 a | 1.09 ± 0.07 a | 1.08 ± 0.08 b | 1.19 ± 0.15 b | 1.14 ± 0.12 b | 1.15 ± 0.02 b | 1.21 ± 0.14 c | 1.22 ± 0.08 c |

Porosity HSD₉₅ R(A) = 4.65 R(B) = 3.87 R(C) = 5.15 R(D) = 5.02 R(E) = 4.87 R(F) = 4.79 R(G) = 5.05 R(H) = 5.84 a
Density HSD₉₅ R(A) = 0.14 R(B) = 0.18 R(C) = 0.10 R(D) = 0.09 R(E) = 0.15 R(F) = 0.12 R(G) = 0.19 R(H) = 0.12 a

Summarizing the results of soil density and total soil porosity, it can be concluded that, in spring, when plant vegetation is renewed, the use of biopreparations can strongly affect these soil properties, having a positive effect on the reduction of machine traction force during shallow tillage. Previous researchers have also found that biopreparations not only affect plant productivity and improve soil microbiological status but alter soil physical and chemical properties, as well [61,62]. Exposure of soil to nutrient-based biopreparations can increase the content of organic carbon in the soil and affect soil structure, porosity, and density. Changes in organic waste can maintain or increase the content of soil organic carbon, soil porosity, and decrease soil density [50,63].

3.3. Cutting Force of Winter Wheat Residues

Experimental studies have shown that the cutting force of winter wheat residues varies from 22 N to 34 N (Figure 7). Comparison of the control treatment with the treatments, where the soil and the plants were exposed to different biopreparations and their mixtures in spring, revealed a significant difference in the cutting force of winter wheat residues only between the control treatment and Treatment 7. In Treatment 7, the cutting force of winter wheat residues was 11 N higher than in the control. The results showed that the biopreparations and their mixtures did not have a significant effect on the force required to cut plant residues in almost all cases. Jakienė and Liakas [40] state that biopreparations are more important for increasing plant productivity. In our research, biopreparations were applied to growing plants in spring, and several months passed before the harvest, so the effect on the cutting force was not significant. However, treatment of plant residues with biopreparation after the harvest and keeping them on the soil surface for two weeks resulted in a significant decrease in cutting force [38]. This was influenced by the intensified process of decomposition of plant residues, which depends on the type of plant residues, chemical composition, carbon-nitrogen ratio, lignin concentration, and other factors [64,65]. Our research showed that winter wheat residues, regardless of treatment, were cut at a similar depth (Figure 7). The cutting depth varied from 16 mm to 20 mm, and no significant difference was observed.

Summarizing the results of this type of experimental research, when the soil is tilled up to 100 mm with disc working parts, plant residues, regardless of the treatment, had the possibility to be cut in the top layer of soil. Plant residues are not only inserted, but also cut at the depth of cultivation, when the stresses of plant residues are lower than the penetration resistance of the disc part into the soil [38].
Figure 7. The impact of different biopreparations on winter wheat cutting force and cutting depth: Treatment 1—composition of the biopreparation No. 1; Treatment 2—No. 1 and No. 2 mixture; Treatment 3—composition of the biopreparation No. 2; Treatment 4—No. 1 and No. 3 mixture; Treatment 5—composition of the biopreparation No. 4; Treatment 6—No. 1 and No. 4 mixture; Treatment 7—composition of the biopreparation No. 3. The same letters indicate no significant difference.

Looking to future research, it would be important to identify the frequency and the exact timing of biopreparations that would have the greatest impact on the physical properties of soil and the mechanical properties of plant residues, as well as on the traction force and diesel fuel consumption of tillage machines and the reduction of greenhouse gas emissions.

4. Conclusions

Reduced tillage is becoming more popular every year. Therefore, research that can improve the quality of shallow tillage with disc implements, as well as reduce traction force and energy consumption, is very important. Biopreparations can be one of the useful tools that have a positive impact on the physical properties of the soil and the technical parameters of tillage machines.

Experimental research showed that the use of different biopreparations for shallow tillage (100 ± 20 mm) with disc harrows resulted in a reduction of the machine traction force by up to 20% at all investigated velocities (8 ± 0.15 km h⁻¹, 10 ± 0.17 km h⁻¹ and 12 ± 0.20 km h⁻¹).

Continuous treatment of the same soil with biopreparations for two years significantly reduced the soil density by about 0.09 g cm⁻³ and increased the total soil porosity by about 6.49%. It had a significant effect on the reduction of the machine’s traction force during shallow tillage.

Research has shown that biopreparations sprayed after the resumption of plant vegetation in spring did not significantly affect the cutting force of winter wheat residues, and the force required to cut one straw varied from 22 to 34 N. Plant residues were cut at a depth of 16–20 mm, regardless of the composition of the biological preparation.

The results of this research allow recommending the use of biopreparations in agricultural production, improvement of soil physical properties, and reduction of the traction force required for tillage, while saving fuel and the cost of all winter wheat production.

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