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Precision tillage operations: Analyzing the efficiency of conventional and robotic systems

Egidijus Šarauskis[1], Simas Sokas[1], Indrė Bručienė[1], Sidona Buragienė[1], Marius Kazlauskas[1], Vilma Naujokienė[1], Abdul M. Mouazen[1,2]

[1]Vytautas Magnus University, Agriculture Academy, Faculty of Engineering, Department of Agricultural Engineering and Safety, Lithuania

[2]Ghent University, Faculty of Bioscience Engineering, Department of Environment, Belgium

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Abstract

Soil tillage is one of the most expensive and polluting technological processes; therefore, modern automated and precision technologies that are applied according to soil variability can help to reduce economic costs and environmental pollution. This study evaluated the effects of variable-depth tillage (VDT) at different depths using two combinations of equipment: a conventional tractor and multifunctional cultivator, and an autonomous robot and tine cultivator. The effects on fuel consumption, engine power, soil, environmental and economic characteristics were compared with those of uniform-depth tillage (UDT). Two experimental studies were conducted in two fields. Initial soil characteristics, such as apparent electrical conductivity (ECa), bulk density, moisture and total porosity, were examined. Based on these characteristics, especially ECa, five different field zones (F1–F5) were formed in each field. One field received VDT with a conventional tractor and multifunctional cultivator at a depth of 9 to 21 cm. The other field received VDT with an autonomous robot and tine cultivator at a variable depth of 6 to 18 cm. During the technological operation, telemetric data on the working speed, engine power requirement and fuel consumption of both machines was collected. After tillage, the soil characteristics were re-examined in the same field areas using a method similar to the initial soil tests. We analysed the technological operation data to identify dependencies in technological, energy, economic and environmental aspects. Experimental studies have shown that both UDT and VDT changed the physical properties of the soil, depending on the field zone. However, they usually increased density, reduced total porosity, and caused uneven moisture changes. In lighter soil zones, VDT resulted in lower fuel consumption, CO_2 emissions and fuel costs, while in heavier soil zones, the engine power requirement increased. The effect of comparing VDT with UDT depends on the size of the field zones; larger areas of lighter soil zones may provide stronger advantages for VDT. Similar results were obtained when using both the conventional tractor and multifunctional cultivator, as well as the robot and tine cultivator systems.

Keywords

Variable-depth tillage, autonomous robot, soil properties, diesel fuel, CO_2 emissions, economy

Introduction

The selection of tillage depth depends on decisions made based on soil characteristics such as texture, bulk density, penetration resistance, moisture and apparent electrical conductivity (ECa) (Whattoff et al., 2017; Azevedo et al., 2022; Al-Dosary et al., 2022; Šarauskis et al., 2024). It is crucial to understand the impact of soil texture and ECa on the performance of variable-depth tillage in order to optimise soil management and crop productivity in modern agriculture (Sokas et al., 2026; Mirzakhaninafchi et al., 2026). The transition to variable-depth tillage (VDT) focuses on problematic soil layers while preserving non-problematic areas. Higher bulk density and penetration resistance indicate the presence of compacted layers, justifying targeted deep passes. Deeper loosening is often necessary where denser soil horizons are present. However, deeper loosening may not be necessary for looser topsoil (Azevedo et al., 2022; Kim et al., 2022; Šarauskis et al., 2024).

The correlation between soil texture and ECa is one of the most important factors in precision agriculture, soil mapping and the definition of management zones (Corwin and Scudiero, 2020). Soil texture, which is defined by the proportions of sand, silt, and clay, influences soil moisture, salinity, and nutrient retention. These properties influence ECa measurements (Hossain et al., 2020). Understanding this relationship enables more efficient management and allocation of agricultural resources to specific locations. Soil texture and ECa are generally positively correlated, particularly in clay- and silt-dominated fields, meaning ECa can be used to define management zones and site-specific management (Corwin and Scudiero, 2020; Serrano et al., 2023). ECa-controlled tillage can help to adjust tillage in real time. Site-specific tillage based on ECa and soil texture improves energy efficiency. Previous studies (Mirzakhanian et al., 2026; Al-Sager et al., 2024; Sokas et al., 2026) have shown that using variable-tillage depths based on ECa and soil texture can reduce the need for deep tillage, thereby reducing fuel consumption and associated CO_2 emissions without compromising critical soil properties or crop yields. Reduced fuel combustion has been shown to reduce environmental impacts by approximately 14% (Sokas et al., 2026).

Summaries of previously published sources show that this topic is highly relevant to precision agriculture. However, the results of applying it to shallow tillage with cultivators in individual regions are still quite fragmentary. The aim of this study was therefore to investigate the influence of two machine systems (a tractor and a robot) on the main physical characteristics of a specific location, and to assess changes in fuel consumption and the associated CO_2 emissions and costs in different field management zones.

Materials and methods

Experimental sites

In September and October 2025, experimental field studies were conducted in two commercial fields located in the Jurbarkas and Kaunas districts of Lithuania. The end of summer and beginning of autumn that year were very rainy, making it difficult for agricultural machinery to enter the fields. In the Jurbarkas field, the studies were conducted in Faba bean stubble using a traditional tractor and multifunctional cultivator. In the Kaunas field, the studies were conducted in winter wheat stubble using a robot and tine cultivator system.

Experiment design

Before the research was conducted, both fields were scanned using an EM38-MK2 electrical conductivity measuring device, and soil apparent electrical conductivity (ECa) maps were created. According to the ECa of the soil, each field was divided into five zones (F1–F5), with F1 having the lowest ECa and F5 having the highest. Soil samples were taken in each zone before tillage, and the soil density, moisture content, and total porosity were determined in the 0–10 cm and 10–20 cm depth layers. Based on soil variability, a different tillage depth was selected for each zone.

In the tractor system, the tillage depths varied from 9 cm in zone F1 to 21 cm in zone F5, with a step of 3 cm. Due to the limited power of the robot, the tillage depths in the robot system varied from 6 to 18 cm with a step of 3 cm. The tillage depth was 15 cm with the tractor system using uniform-depth tillage (UDT) and 12 cm with the robot system. To ensure accuracy, every second pass was made using the variable-depth tillage (VDT) system (Fig. 1).

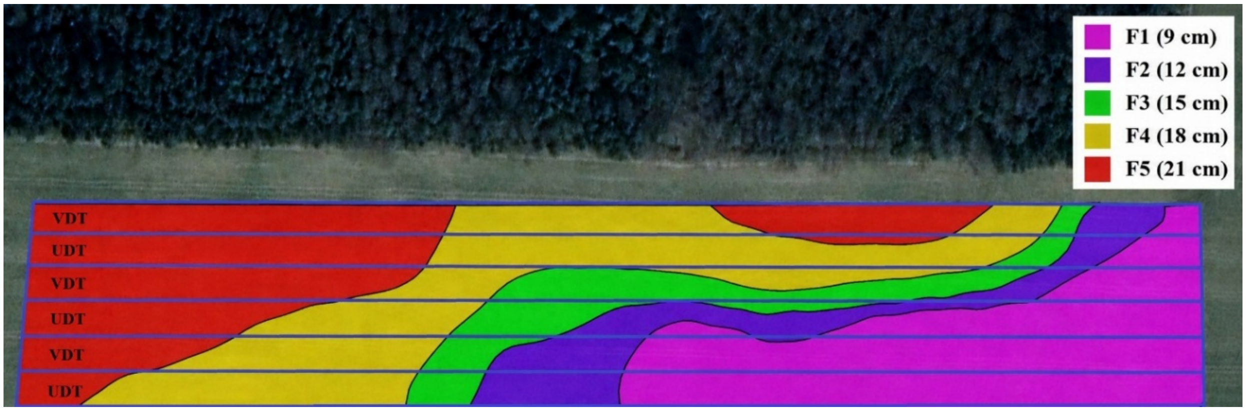

Fig. 1. Map of variable ECa and tillage depths of field zones: Tractor and multifunctional cultivator system, when tillage depth varied from 9 cm (F1) to 21 cm (F5); Robot and tine cultivator system – from 6 cm (F1) to 18 cm (F5).

Soil samples were immediately taken again from the same field zones after the tillage process. The soil density, moisture content and total porosity characteristics were then determined in the laboratories of the Department of Agricultural Engineering and Safety at Vytautas Magnus University. Measurements were performed in five replicates in each zone and each soil layer.

Agricultural machinery and the assessment of their work efficiency

Traditional experimental field studies were carried out using a John Deere 8R 410 tractor with 302 kW of power and a 5-metre-wide multifunctional cultivator (Väderstad TopDown 500). The robotic system used a 3-metre-wide tine cultivator Bednar FENIX FN 3000L mounted on a tracked chassis robot AgXeed 5.115T2.

During the tillage process, the main technological parameters of the machinery, such as driving speed, engine power requirements and fuel consumption, were recorded. These data were then used to evaluate the energy, environmental and economic efficiency of the tillage technologies. The technological data were collected and the necessary calculations were performed for each field zone separately. CO_2 emissions were calculated using the following formula (Wang and Mouazen, 2025; Sokas et al. 2026):

$$CO_2 \text{ emissions (kg ha}^{-1}) = FC \times 2.68 \tag{1}$$

where FC = fuel consumption (L ha^{-1}), 2.68 = emission factor representing the amount of CO_2 produced per litre of diesel fuel.

The average price of diesel fuel in Lithuania between 22 and 29 September 2025 was used to conduct the economic assessment: 1.48 EUR per litre (Lithuanian Energy Agency, 2025).

Results and discussion

Soil characteristics

Appropriate soil properties play an important role in seed germination and plant growth. After determining the field soil zones according to ECa and conducting soil property tests, it was found that soil properties varied between different field zones. Soil tests conducted before tillage showed that the soil bulk density in the upper soil layer (0–10 cm) varied from 1.30 to 1.52 g cm^{-3}, the soil moisture varied from 22.66 to 28.47%, and the soil total porosity varied from 44.00 to 59.00% (Table 1). Similar studies in the deeper 10–20 cm layer before tillage indicated that soil bulk density ranged from 1.27 to 1.52 g cm^{-3}, soil moisture from 21.15 to 32.08%, and total soil porosity from 42.83 to 61.67%.

Table 1. Soil characteristics in different field zones when using a tractor with a multifunctional cultivator system.

Characteristics			VDT					UDT				
			F1	F2	F3	F4	F5	F1	F2	F3	F4	F5
Soil bulk density, g cm^{-3}	Before tillage	0–10 cm	1.42 ±0.16	1.49 ±0.04	1.42 ±0.06	1.39 ±0.10	1.30 ±0.04	1.35 ±0.09	1.52 ±0.15	1.33 ±0.01	1.44 ±0.04	1.41 ±0.09
		10–20 cm	1.37 ±0.01	1.34 ±0.14	1.39 ±0.07	1.44 ±0.13	1.38 ±0.20	1.42 ±0.08	1.52 ±0.15	1.29 ±0.15	1.27 ±0.05	1.41 ±0.06
	After tillage	0–10 cm	1.41 ±0.03	1.50 ±0.05	1.34 ±0.01	1.36 ±0.17	1.41 ±0.12	1.49 ±0.02	1.42 ±0.18	1.25 ±0.04	1.45 ±0.09	1.51 ±0.10
		10–20 cm	1.46 ±0.10	1.56 ±0.04	1.48 ±0.05	1.35 ±0.07	1.42 ±0.10	1.50 ±0.12	1.56 ±0.09	1.41 ±0.14	1.62 ±0.09	1.56 ±0.19
Soil moisture, %	Before tillage	0–10 cm	25.13 ±6.08	22.66 ±4.27	27.47 ±2.36	24.49 ±6.13	27.30 ±3.56	28.47 ±2.44	23.28 ±5.89	26.28 ±3.53	27.90 ±0.27	26.29 ±4.63
		10–20 cm	26.13 ±0.84	32.08 ±2.10	27.74 ±6.21	22.80 ±3.28	26.79 ±2.87	27.57 ±4.69	21.15 ±6.41	27.65 ±2.74	27.59 ±0.99	26.95 ±2.31
	After tillage	0–10 cm	28.02 ±4.63	24.63 ±3.01	26.44 ±4.29	20.00 ±7.39	24.08 ±6.49	23.99 ±3.92	25.98 ±3.25	30.34 ±3.33	25.67 ±1.83	21.99 ±4.54
		10–20 cm	26.45 ±5.75	26.33 ±3.84	27.75 ±5.24	22.13 ±5.10	25.64 ±0.47	22.77 ±6.96	20.59 ±3.30	29.41 ±5.38	17.53 ±0.89	23.92 ±4.58
Soil total porosity, %	Before tillage	0–10 cm	59.00 ±2.48	49.00 ±12.42	51.83 ±3.13	50.17 ±6.13	52.67 ±0.72	50.33 ±1.43	51.83 ±5.02	44.00 ±2.48	51.00 ±4.97	50.33 ±1.43
		10–20 cm	49.67 ±3.79	54.67 ±7.59	61.67 ±14.34	52.67 ±6.25	52.00 ±2.48	48.83 ±3.13	43.83 ±9.96	42.83 ±0.72	48.00 ±2.48	49.67 ±1.43
	After tillage	0–10 cm	47.00 ±7.45	49.67 ±6.25	51.50 ±3.73	50.00 ±2.48	40.67 ±12.25	41.33 ±1.43	48.00 ±2.48	47.67 ±3.79	43.33 ±1.43	41.67 ±1.43
		10–20 cm	44.67 ±7.17	45.67 ±5.17	51.67 ±10.34	52.50 ±6.21	42.00 ±2.48	45.67 ±10.04	47.00 ±2.48	50.33 ±6.25	48.00 ±2.48	39.00 ±2.48

Note: VDT – variable-depth tillage; UDT – uniform-depth tillage; F1 – lowest ECa, F5 – highest ECa.

After tillage at a uniform depth of 15 cm in all field zones and at variable depths ranging from 9 cm (F1, the lightest soil) to 21 cm (F5, the heaviest soil), the same soil characteristics were determined in the same places. It was found that the soil bulk density increased in most field zones, both in the upper soil layer and in the deeper soil layer, thanks to the roller in the multifunctional cultivator design. Soil moisture depends on environmental conditions. Since the experimental studies were carried out in autumn, the weather conditions were colder. Therefore, after tillage at variable depths, soil moisture in the upper layer increased slightly in four out of five zones. Meanwhile, soil moisture decreased in the lighter soil and increased in the heaviest soil (F5) when working at the uniform depth. Total soil porosity is strongly related to other soil properties; therefore, in those field zones where soil bulk density increased, total soil porosity decreased. However, when these physical soil properties are considered in general, it can be concluded that the soil bulk density in almost all field zones and in both layers met the regional norm of 1.2–1.6 g cm^{-3}. The same can be said for soil total porosity, which should be at least 50%. Only soil moisture was too high in individual cases (exceeding 25%) due to the previous rainy period.

Experimental studies conducted in a second field in Kaunas using a robot and tine cultivator system showed that, after VDT tillage, soil bulk density decreased in all zones in the upper soil layer (0–10 cm), while it increased in four out of five zones in the deeper soil layer (Table 2). Evaluating the soil moisture and total porosity characteristics indicated a decrease in these properties in more zones compared to before tillage.

Table 2. Soil characteristics in different field zones when using a robot and a tine cultivator system.

Characteristics			VDT					UDT				
			F1	F2	F3	F4	F5	F1	F2	F3	F4	F5
Soil bulk density, g cm^{-3}	Before tillage	0–10 cm	1.48 ±0.31	1.49 ±0.01	1.44 ±0.05	1.52 ±0.04	1.35 ±0.21	1.45 ±0.10	1.53 ±0.10	1.46 ±0.06	1.52 ±0.05	1.40 ±0.08
		10–20 cm	1.36 ±0.19	1.44 ±0.10	1.52 ±0.03	1.46 ±0.07	1.27 ±0.04	1.37 ±0.03	1.52 ±0.04	1.46 ±0.11	1.54 ±0.11	1.39 ±0.12
	After tillage	0–10 cm	1.46 ±0.03	1.39 ±0.00	1.39 ±0.07	1.51 ±0.01	1.28 ±0.03	1.36 ±0.09	1.43 ±0.03	1.42 ±0.12	1.53 ±0.00	1.37 ±0.06
		10–20 cm	1.50 ±0.04	1.46 ±0.08	1.45 ±0.10	1.54 ±0.07	1.35 ±0.05	1.42 ±0.10	1.44 ±0.04	1.43 ±0.04	1.57 ±0.11	1.36 ±0.08
Soil moisture, %	Before tillage	0–10 cm	29.16 ±5.88	25.27 ±2.27	25.45 ±1.33	21.26 ±1.21	25.80 ±1.78	25.73 ±5.72	22.47 ±9.99	24.59 ±1.47	22.66 ±2.09	24.71 ±4.22
		10–20 cm	29.14 ±6.60	24.47 ±4.35	22.21 ±0.40	21.45 ±7.81	25.16 ±8.41	25.08 ±6.93	22.34 ±1.49	22.80 ±2.64	20.94 ±4.74	24.52 ±8.39
	After tillage	0–10 cm	23.96 ±2.79	29.21 ±3.19	24.53 ±3.61	21.00 ±1.11	25.72 ±1.08	23.98 ±3.73	20.04 ±0.71	23.26 ±9.78	22.69 ±2.14	22.54 ±0.45
		10–20 cm	22.56 ±2.77	24.72 ±3.72	22.19 ±5.28	19.36 ±3.92	23.89 ±1.48	21.16 ±4.71	23.19 ±4.29	21.15 ±4.66	22.94 ±7.90	22.26 ±3.56
Soil total porosity, %	Before tillage	0–10 cm	48.50 ±2.48	45.25 ±0.62	46.33 ±6.84	43.00 ±2.15	49.00 ±6.21	48.00 ±9.38	49.83 ±0.72	47.50 ±4.30	46.00 ±4.30	46.33 ±4.36
		10–20 cm	46.17 ±6.37	46.17 ±2.59	50.75 ±0.62	46.33 ±1.90	49.00 ±11.98	46.83 ±9.40	44.17 ±0.72	45.67 ±3.79	42.50 ±4.97	46.50 ±4.48
	After tillage	0–10 cm	43.00 ±1.24	48.75 ±3.11	44.17 ±1.43	42.67 ±3.79	49.33 ±3.13	55.83 ±4.70	47.17 ±2.59	40.50 ±12.23	43.00 ±4.48	46.83 ±3.13
		10–20 cm	40.67 ±1.90	44.17 ±2.59	46.00 ±1.24	41.33 ±4.36	45.33 ±1.90	43.17 ±3.99	50.75 ±10.56	41.67 ±5.17	43.00 ±13.14	51.00 ±6.21

Note: VDT – variable-depth tillage; UDT – uniform-depth tillage; F1 – lowest ECa, F5 – highest ECa.

Fuel consumption and impact on environment

In this study, the tractor and multifunctional cultivator system were operated at a constant working speed. Depending on the field zone, this ranged from 11.25 km h^{-1} in heavier soil (F5) to 11.34 km^{-1} in lighter soil (F1). Using VDT resulted in varying engine power requirements (from 184.6 kW in F1 to 344.5 kW in F5) and fuel consumption (from 7.1 to 11.6 l ha^{-1}). CO_2 emissions and economic efficiency were only calculated by assessing fuel consumption in each field zone. It was found that, as ECa increased and the soil became heavier, CO_2 emissions increased from 19.1 kg CO_2eq ha^{-1} (F1) to 30.5 kg CO_2eq ha^{-1} (F5) and fuel costs increased from 10.5 to 16.83 Eur ha^{-1}. Singh et al. (2024) found that an increase in tillage depth was accompanied by an increase in dependent parameters such as torque demand and fuel consumption. A study by Al-Sager et al. (2024) concluded that practical and useful advice on agricultural production can be obtained through the optimisation of fuel consumption by selecting the correct operating parameters, such as operating speed, working width and working depth.

Analogue experimental studies involving a robot and a tine cultivator revealed that working speeds ranged from 7.4 km h^{-1} (F5) to 8.95 km h^{-1} (F1), engine power requirements ranged from 82.3 kW (F1) to 103.0 kW (F5), and fuel consumption ranged from 7.1 l ha^{-1} (F1) to 11.4 l ha^{-1} (F5). CO_2 emissions ranged from 19.1 kg CO_2eq ha^{-1} (F1) to 30.5 kg CO_2eq ha^{-1} (F5).

When comparing VDT with UDT for the entire field in terms of fuel consumption, environmental impact, and economic costs, the area of each zone must be assessed. If a larger part of the field consists of lighter soil, VDT will show very positive results. However, if a larger part of the field consists of heavier soils, UDT may be more advantageous.

Conclusions

The Conclusion or Summary section restates the major findings and suggests further research. It is the last main heading before the references.

Studies involving a tractor and a multifunctional cultivator showed that the physical properties of the soil varied depending on the field area and tillage intensity when both uniform-depth tillage (UDT) and variable-depth tillage (VDT) were applied. Soil density increased in most areas, while total porosity decreased accordingly; this was related to the roller incorporated into the multifunctional cultivator's design. Changes in soil moisture were inconsistent and depended more on environmental conditions and soil type. Despite these differences, most soil parameters met regional norms. Experimental studies using a robot and a tine cultivator system revealed that, after VDT tillage, soil density decreased in the upper (0–10 cm) soil layer but increased in the deeper layer in most areas. It was also found that soil moisture and total porosity decreased in most areas after tillage compared to the initial state.

When using the VDT system, an increase in soil heaviness leads to a significant rise in energy demand, fuel consumption, CO_2 emissions and economic costs. Therefore, the efficiency of the system depends directly on the initial soil conditions. A comparative analysis of VDT and UDT technologies showed that their respective advantages depend on the apparent electrical conductivity of the soil in the field and its associated physical characteristics. VDT is more effective in lighter soils, while UDT may be superior in heavier soils. Therefore, when evaluating the systems, it is necessary to consider the heterogeneity of the entire field.

Looking to the future, variable-depth tillage could play a significant role in precision agriculture by enabling real-time adaptation to variations in soil properties within a field. This would provide opportunities to improve technological, energy and environmental parameters while optimising plant growth conditions. As smart sensor and automated control system technologies improve, VDT could be further integrated into autonomous agricultural machinery to enable more sustainable farming.

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