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COMPARISON OF PLOUGHING VS. PLOUGHLESS CULTIVATION IN TERMS OF ENERGY EXPENDITURE AND TREATMENT QUALITY

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Abstract

The article discusses the basic soil cultivation technologies and analyses the effectiveness of ploughless cultivation machines manufactured in Poland. The study also describes the design of a prototype of an innovative MultiCat 6HD aggregated tillage unit and presents the research methodology for examining the aggregated unit and machines for traditional plough tillage. The following parameters were determined: fuel consumption, theoretical and effective field capacity, depth at which plant residues are incorporated into the soil, and the indicator of crop residue embedding. The conducted analyses revealed that ploughless cultivation required approximately 30% less fuel than traditional plough tillage. Plant material was also more favourably distributed within the soil profile and crop residues were nearly identically embedded as in plough tillage. The study demonstrated that ploughless cultivation involving the MultiCat 6HD aggregated unit can increase the competitiveness of agricultural farms.

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Introduction

One of the goals of agricultural policy is to improve the competitiveness of agricultural farms. To achieve this goal, agricultural farms and enterprises can rely on European funds for innovative projects (GORYŃSKA-GOLDMANN, WOJCIESZAK 2017). Most farms improve their competitive edge by introducing innovative production technologies and dedicated machinery. The introduced technologies improve a farm's economic performance and quality indicators by decreasing fuel consumption and energy inputs, improving fertiliser mixing with soil and the incorporation of crop residues.

Tillage, namely a series of agronomic treatments which aim to provide crops with optimal sowing and growth conditions, is one of the most common agricultural operations. Classical tillage involves ploughing and soil preparation before sowing, usually with an aggregated tillage unit (PRZYBYŁ et al. 2009). These treatments may be preceded by post-harvest tillage (PIEKARCZYK 2006). The ploughing treatment itself requires considerable energy inputs in the range of 115.4 to 198.1 kJ·m^2, and pre-sowing tillage consumes 57.6 to 75.3 kJ·m^2 of energy (SĘK, PRZYBYŁ 1993). During ploughing, approximately 150 Mg of soil is lifted and inverted per each centimetre of working depth per 10,000 m^2, and fuel consumption accounts for 30-60% of fuel inputs in the entire crop production process (KUŚ 2007).

Changes in the soil cultivation technology should reduce energy inputs and improve efficiency without deteriorating growth conditions (GOLKA, PTASZYŃSKI 2014). The following alternative tillage technologies have been promoted for many years (SMAGACZ 2013):

– simplified tillage (which reduces the number of cultivation or decreases cultivation depth);

– conservation tillage (comprising ploughless cultivation and zero tillage).

Ploughless cultivation and zero tillage systems considerably reduce the energy inputs in the cultivation process. In ploughless cultivation, ploughing is replaced by treatments that loosen the soil without inverting it (FISZER et al. 2006). In turn, zero tillage eliminates separate soil-loosening treatments from the cultivation process (SMAGACZ 2013).

Conservation tillage is most widely applied in South America (60% of land under cultivation). In Europe, conservation tillage covers only 2.8% of agricultural land, and this technology is likely to attract growing interest in the years to come (KASSAM et al. 2015).

Zero tillage requires significantly more spending on plant protection products which have an adverse effect on the environment. Therefore, ploughless cultivation is a more desirable solution which offers the following benefits (GOLKA, PTASZYŃSKI 2014, SMAGACZ 2013):

– smaller loss of soil organic matter,
– increased organic carbon sequestration in the soil,
– enhanced soil infiltration,
– smaller loss of unproductive water from soil,
– reduced runoff and leaching of fertiliser components,
– improved livestock housing conditions (KOSEWSKA 2018, TOPA 2020),
– lower cultivation costs and greenhouse gas emissions.

The disadvantages of this technology include the risk of weed development and higher incidence of plant diseases and pests (JAKUBOWSKA, MAJCHRZAK 2013). The risk is particularly high when the design of aggregated tillage units does not ensure sufficiently deep incorporation of crop residues covering the soil surface.

The Department of Vehicle and Machinery Construction and Operation of the University of Warmia and Mazury in Olsztyn analysed agricultural machines manufactured by 75 domestic companies (as at 2016) to select aggregated units that are best suited for ploughless cultivation. The analysis revealed that ploughless cultivation units with the following design characteristics are not manufactured in Poland:

– a disc section with hydraulic overload protection devices;
– teeth for deep loosening with a hydraulic overload protection device (hydraulic protection systems facilitate the rapid return of an operating part to its nominal working position, which improves soil cultivation quality);
– a three-point suspension system with positioning control (working segments that require the additional weight of the unit's frame can be freely ganged);
– a disc section preceding the tooth section;
– soil loosening to a depth of 0.4 m with the use of machines ganged with high-power tractors (over 300 kW).

The MultiCat 6HD prototype of an aggregated unit for ploughless cultivation was designed and developed by a domestic manufacturer based on the above requirements. The machine is an innovative solution on the domestic market.

The MultiCat 6HD aggregated tillage unit has a working width of 6 m, and it is designed for ganging with tractors with the minimum engine power of 310 kW (Fig. 1). The unit was designed as a trailing implement, and it features four working sections. The first two sections are permanently attached to the load bearing frame supported with rubber tyre ground wheels. A coupling system is attached to the front part of the frame, and a three-point suspension system for aggregating sections 3 and 4 with an independent load bearing frame is attached to the rear part of the frame. MultiCat 6HD is multi-functional tillage unit. The four sections prepare soil for sowing without plough tillage. The first section comprises two rows of toothed discs with a diameter of 0.68 m. The discs are grouped into four segments, with two segments per row. Each segment has a shared, self-aligning beam to which seven discs are attached with brackets.

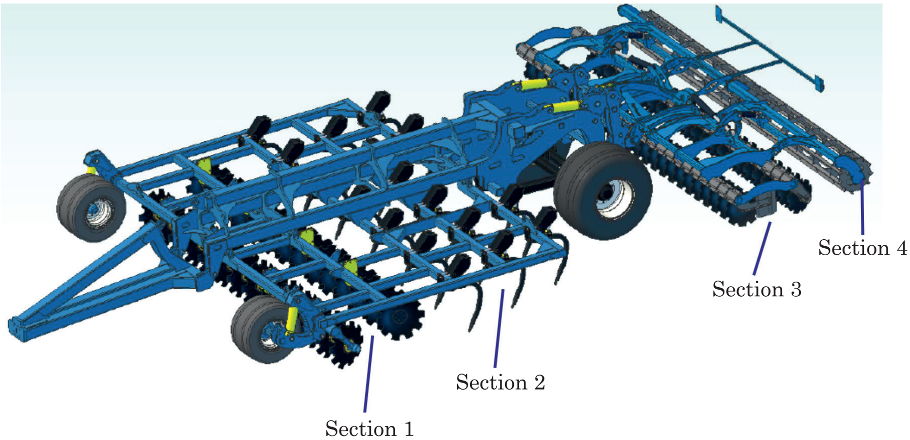


Fig. 1. A view of the MultiCat 6HD aggregated tillage unit in a working position

This type of disc assembly produces a constant rake angle of 17°. Each of the four segments is equipped with a hydraulic overload protection device. The first section cuts the field surface and crop residues, incorporates and mixes crop residues with soil, and cuts roots. The first section has a maximum working depth of 0.2 m, and it can also loosen the soil to decrease the working resistance of the second section and minimise clogging. The second section comprises four rows of teeth for deep soil loosening. This arrangement effectively prevents crop residues from clogging the second section (teeth have a spacing of 0.365 m). Each tooth is equipped with a hydraulic overload protection device. The second section loosens subsoil and combines it with the top soil layer. It has a maximum working depth of 0.4 m.

The third section comprises two rows of toothed discs with a diameter of 0.51 m. A total of 48 discs are attached to two rigid beams that are divided into two segments with supports and brackets. This type of disc assembly produces a constant rake angle of 17°. Each disc has an independent rubber shock absorber mounted in the support. The third section cuts crop residues, incorporates them into the soil and levels out the deformations in the surface of the field caused by the second section. The third section has a maximum working depth of 0.15 m. The spacing between discs is 0.25 m to prevent clogging with plant material.

The fourth section features a string roller with a diameter of 0.61 m, divided into two segments. The fourth section lightly compacts the soil and crushes lumps of soil. The string roller forms a loose and pulverised soil layer underlain by a lightly compacted soil layer.

The aim of this study was to compare the energy and quality indicators calculated based the performance of the MultiCat 6HD aggregated tillage unit prototype (ploughless cultivation) and a conventional plough and disc harrow (traditional cultivation).

Materials and Methods

A passive experiment was conducted in 2016. The parameters of the work process were set by the owner of an agricultural farm owner where the experiment was conducted. The aim of the study was to calculate energy and quality indicators based on empirical data (changes in cultivation technology without the involvement of external agents). The experiment was conducted on a hilly plot with an estimated area of $20 \cdot 10^4$ m^2 and varied soil structure. Spring wheat had been combine-harvested three weeks before the experiment. The harvested wheat straw was cut, pulverised and evenly distributed across the field. The plot was moderately infested with weeds, some areas were periodically water logged, and the plot featured tree and shrub clusters. The weather during the field experiment was sunny and partly cloudy, without any rainfall, and daytime temperature ranged from 20°C to 25°C. Ploughless cultivation was performed by the MultiCat 6HD tillage unit ganged with a New Holland T9.670 tractor with twinned wheels (Fig. 2).

Fig. 2. A view of the MultiCat 6HD tillage unit ganged with a New Holland T9.670 tractor

The second analysed agricultural treatment was plough tillage which was performed in two stages. In the first stage, soil was ploughed by a tractor-pulled aggregated unit comprising the New Holland T8050 tractor and the Rabe Werk Marabu-Avant 180C plough. In the second stage, soil was prepared for spring sowing using a disc harrow ganged with the New Holland T8050 tractor. The disc harrow was disconnected from the MultiCat 6HD unit for ploughless cultivation (sections 3 and 4).

The percentage of crop residues that were embedded in the surface layer of soil was analysed in three locations in each experimental plot. Crop residues were collected from the frame with an area of 1 m^2, and were weighed.

This operation was carried out twice, before and after tillage. The percentage of crop residues embedded in the surface layer of soil was determined by calculating the arithmetic mean of three measurements. The indicator of residue surface embedding R_r, expressed in %, was calculated using the following formula:

$$R_r = \frac{(m_{p-m_k})}{m_p} \cdot 100 \text{ [\%]} \tag{1}$$

where:

m_p – weight of plant residues collected from an area of 1 m^2 before cultivation [kg],

m_k – weight of plant residues collected from an area of 1 m^2 after cultivation [kg].

The collected plant material was weighed on the STEINBERG SYSTEMS SBS-LW-7500A LCD electronic scale with an accuracy of 0.001 kg.

The depth to which crop residues were incorporated into the soil was determined by measuring uncovered portions of loosened soil after tillage. The depth at which crop residues were placed in soil was measured using a measuring ruler with an accuracy of 0.01 m and measuring instruments. A fragment of uncovered soil measuring 0.3×0.3×0.3 m was selected and three layers were removed from it (0-0.1 m, 0.1-0.2 m, and 0.2-0.3 m). Plant material was separated from each layer using a sieve and were weighed. Crop residues were weighed on the STEINBERG SYSTEMS SBS-LW-7500A LCD electronic scale with an accuracy of 0.001 kg.

Fuel consumption measurements began with a full tank. The fuel tank was completely filled before tillage at the test site. During each refuelling, the tank was vented and the machine was levelled. After refuelling, at least $2.8 \cdot 10^4$ m^2 of plot area was tilled by the tractor-pulled aggregated unit. After tillage, the fuel tank was filled to the level determined before the treatment on the same assumptions. Fuel consumption was measured using a graded glass cylinder with an accuracy of 0.002 dm^3. Fuel consumption measurements were performed with the use of a system for monitoring the operating parameters of tractor-pulled aggregated tillage units designed and developed by the Department of Vehicle and Machinery Construction and Operation of the University of Warmia and Mazury in Olsztyn. The system relies on GPS technology to determine the duration of the work process, machine status (main and auxiliary operations) and the cultivated area under.

Fuel consumption Q_p per unit of performed work was determined using the following formula:

$$Q_p = \frac{10000 \cdot Q_t}{s_e \cdot a} \text{ [dm}^3 \cdot 10^{-4} \cdot \text{m}^{-2}\text{]} \tag{2}$$

where:

Q_t – fuel consumption during cultivation [dm^3],
s_e – effective distance (when soil is cut by the implement) [m],
a – the machine's working width [m].

Hourly fuel consumption Q_g was determined using the following equation:

$$Q_g = \frac{Q_t}{t} \text{ [dm}^3\cdot\text{h}^{-1}\text{]} \tag{3}$$

where:

Q_t – fuel consumption during cultivation [dm^3],
t – duration of tillage [h].

The experimental design is presented in Table 1.

Table 1

Experimental design

Item	Soil condition	Conducted tests	
1	before tillage	measurement of soil volumetric moisture content (VMC) – 5 measurements	
2		stage 1	determination of the percentage of crop residues that were effectively embedded in the surface layer of soil – 6 measurements
3	after ploughless cultivation*	stage 2	determination of the percentage of crop residues that were effectively embedded in the surface layer of soil – 3 measurements
4		measurement of fuel consumption, beginning with a full tank – 1 measurement	
5		measurement of the depth at which crop residues were incorporated into the soil– 1 test pit	
6	after traditional tillage**	stage 2	determination of the percentage of crop residues that were effectively embedded in the surface layer of soil – 3 measurements
7		measurement of fuel consumption, beginning with a full tank – 1 measurement	
8		measurement of the depth at which crop residues were incorporated into the soil – 1 test pit	

* – tillage involving the MultiCat 6HD aggregated tillage unit
** – two-stage tillage involving a plough and a disc harrow

Results and Discussion

The results of the measurements and the percentage of crop residues that were embedded in the surface layer of soil are presented in Table 2.

The percentage of crop residues that are effectively embedded in the surface layer of soil has a considerable impact on the spread of plant diseases. When infected, non-decomposed residues cover the cultivated soil, pathogens are more likely to be transferred from the residues to the emerging crops, which decreases yields and increasing spending on plant protection products. The MultiCat 6HD aggregated tillage unit embedded 94.87% of crop residues in soil surface, which is a highly satisfactory result. The above can be attributed to the arched shape of the teeth that dig out soil from deeper layers, as well as disc section No. 3 which evenly distributes the extracted material across the entire field. Ploughless

Table 2

Depth at which crop residues were embedded in the surface layer of soil

Measurement	Before tillage	After tillage	Measurement and calculation results	Average value
No. 1*			m_p = 1.251 kg m_k = 0.052 kg R_r = 95.84%	R_r = 94.87%
No. 2*			m_p = 1.376 kg m_k = 0.057 kg R_r = 95.85%	
No. 3*			m_p = 0.863 kg m_k = 0.058 kg R_r = 93.27%	
No. 1**			m_p = 1.421 kg m_k = 0.014 kg R_r = 99.01%	R_r = 99.25%
No. 2**			m_p = 1.155 kg m_k = 0.005 kg R_r = 99.56%	
No. 3**			m_p = 0.988 kg m_k = 0.008 kg R_r = 99.19%	

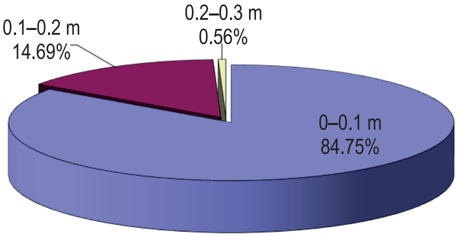
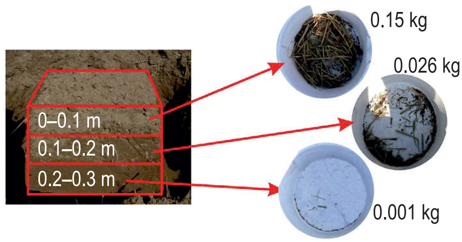
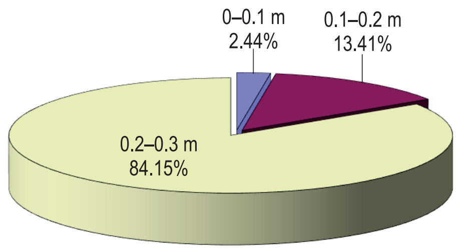
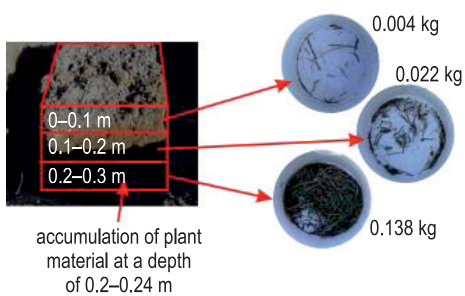
* – tillage involving the MultiCat 6HD aggregated tillage unit,
** – two-stage tillage involving a plough and a disc harrow

cultivation and plough tillage produced similar results that differed by only 4.38%, which indicates that soil tillage with the MultiCat 6HD aggregated tillage unit does not differ significantly from plough tillage and creates safe conditions for the growth of crops (by decreasing the risk of pathogen infections).

The depth at which crop residues were incorporated into the soil in the compared cultivation techniques is presented in Table 3. The accumulation

Table 3

Depth at which crop residues were incorporated with soil

Tillage	Soil layer	Weight	Distribution of plant material
Ploughless cultivation	0-0.1 m	0.15 kg	
	0.1-0.2 m	0.026 kg	
	0.2-0.3 m	0.001 kg	
	material evenly distributed across the entire working width. Plant material evenly mixed with soil		
Plough tillage	0-0.1 m	0.004 kg	
	0.1-0.2 m	0.022 kg	
	0.2-0.3 m	0.138 kg	
	material distributed in strips. Material accumulated at a depth of 0.2-0.24 m		

of plant material in the top soil layer delivers several benefits: it increases the biological activity of soil, promotes the growth of soil-dwelling microorganisms, decreases the loss of soil organic matter, minimizes water and wind erosion, increases soil porosity, reduces soil crusting, and enhances the buffering capacity of soil (SMAGACZ 2013). The conducted analyses demonstrated that plant biomass was accumulated in the top soil layer (0-0.1 m) only in ploughless cultivation. As much as 84.75% of total biomass was evenly distributed in the top soil layer. In contrast, only 2.44% of crop residues were embedded in the top layer (0-0.1 m) as a result of plough tillage, and up to 84.15% of biomass was

Table 4

Results of fuel consumption analysis

Parameter	Ploughless cultivation	Plough tillage	
		Ploughing	Pre-sowing tillage
Duration of tillage	1.3275 h	1.3816 h	0.6132 h
Duration of main operations	1.0938 h	1.1878 h	0.5610 h
Duration of auxiliary operations	0.2337 h	0.1938 h	0.0522 h
Engine crankshaft speed	1,730 rpm	1,730 rpm	1,730 rpm
Transmission ratio	Gear #7	Gear #10	Gear #10
Driving speed	8 km·h^{-1}	8.8 km·h^{-1}	8.8 km·h^{-1}
Average driving speed	7.501 km·h^{-1}	7.57 km·h^{-1}	8.52 km·h^{-1}
Average driving speed during the performance of main operations	7.508 km·h^{-1}	8.03 km·h^{-1}	8.49 km·h^{-1}
Average driving speed during the performance of auxiliary operations	7.46 km·h^{-1}	4.73 km·h^{-1}	8.75 km·h^{-1}
Working width	6 m	3 m	6 m
Working depth	0.4 m	0.22 m	0.12 m
Distance covered	9,958 m	10,466 m	5,225 m
Effective distance	8,213 m	9,548 m	4,768 m
Effective surface area P_e	4.9278 m^2	2.8644 m^2	2.8608 m^2
Effective field capacity W_1	4.5095 [10^4·m^2·h^{-1}]	2.4115 [10^4·m^2·h^{-1}]	5.0994 [10^4·m^2·h^{-1}]
Operational efficiency W_{02}	3.712 [10^4·m^2·h^{-1}]	2.235 [10^4·m^2·h^{-1}]	4.665 [10^4·m^2·h^{-1}]
Fuel consumption during cultivation Q_t	84 dm^3	49.24 m^3	20.53 dm^3
Specific fuel consumption Q_p	17.046 dm^3·10^{-4}·m^{-2}	17.192 dm^3·10^{-4}·m^{-2}	7.176 dm^3·10^{-4}·m^{-2}
Hourly fuel consumption Q_e	63.276 dm^3·h^{-1}	35.639 dm^3·h^{-1}	33.480 dm^3·h^{-1}
Number of passages	27	24	12
Average length of the cultivated plot	304.2 m	397.8 m	397.3 m

accumulated at a depth of 0.2-0.3 m. Crop residues were distributed in strips at a depth of 0.2-0.24 m is involved. These results suggest that only ploughless cultivation ensures effective distribution of crop residues within the soil profile.

The results of fuel consumption analysis are presented in Table 4. The route travelled by the tillage unit is presented in Figure 3.

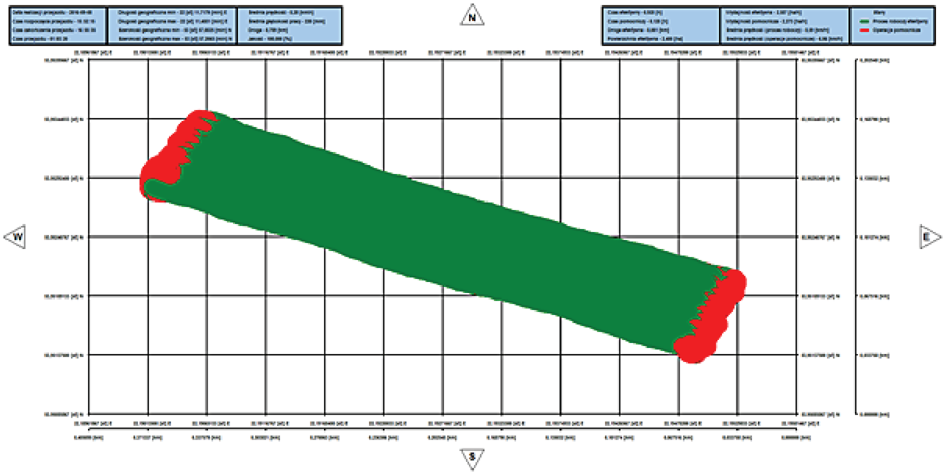


Fig. 3. Map of tillage operations performed by the MultiCat 6HD aggregated tillage unit (green colour – field operation, red colour – returns)

Specific fuel consumption in ploughless cultivation was 17.046 $dm^3 \cdot 10^{-4} \cdot m^{-2}$, which is somewhat lower than that noted during conventional ploughing. These results indicate that simplified tillage with the MultiCat 6HD aggregated tillage unit is more economical than conventional tillage. Additional treatments are required after ploughing to prepare soil for the spring sowing and planting; therefore, specific fuel consumption during plough tillage was determined at 24.36 $dm^3 \cdot 10^{-4} \cdot m^{-2}$. A comparison of the examined technologies indicates that specific fuel consumption was 30.04% lower in ploughless cultivation than in ploughing. At the same time, the efficiency of simplified tillage involving the MultiCat 6HD aggregated tillage unit was nearly three times higher. The working speed during ploughing and soil preparation for spring sowing was higher than the working speed of the MultiCat 6HD aggregated tillage unit. The above increased fuel consumption, but due to the small length of the test plot (average of 304.2 m), the proportion of the distance covered during ploughless cultivation was less favourable at 17.52% in comparison with only 8% in ploughing and pre-sowing tillage. These differences compensated for increased fuel consumption because tractor-pulled aggregated units moved at a higher speed during plough tillage. It should be noted that fuel consumption is highly influenced by the rotational speed of the engine crankshaft which was determined at 1,730 rpm in all cases. The same driving speed could not be set at the same rotational speed and at different transmission ratios in the tractors. In conclusion, simplified tillage involving the MultiCat 6HD aggregated tillage unit is far more economical and efficient than plough tillage.

Specific fuel consumption during the field experiment is presented in Figure 4.

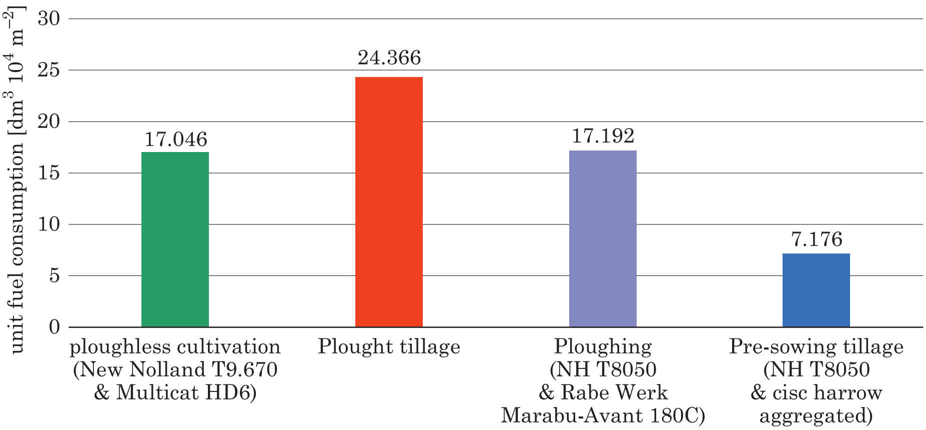


Fig. 4. Specific fuel consumption determined during the field experiment

The average absolute soil moisture content during the field experiment was 15.3% (based on five measurements).

The percentage of crop residues that are effectively embedded in the surface layer of soil was also examined in other studies (ZBYTEK 2010). This parameter was determined at 68% during the cultivation of a stubble field with a tooth-harrow plough (subsoiler, cultivator, discs, string and ring roller), and it ranged from 54% to 81% in ploughless cultivation with an aggregated unit (subsoiler, cultivator, leveller, string roller). These results indicate that the MultiCat 6HD aggregated unit is characterised by superior performance. The depth to which crop residues were embedded in soil by a tooth-harrow plough was identical, but fuel consumption was more than 25% higher in comparison with the MultiCat 6HD aggregated unit.

MOITZI et al. (2006) determined the fuel consumption of a heavy cultivator during ploughless cultivation. Fuel consumption reached 21.55 $dm^3 \cdot 10^{-4} \cdot m^2$ at a working depth of only 0.15 m, which is 26% higher than in the MultiCat 6HD aggregated unit.

JASKULSKI and JASKULSKA (2016) measured fuel consumption during ploughless cultivation (grubbing, pre-sowing tillage with an aggregated unit), and the cited values were more than 30% higher on average in comparison with the MultiCat 6HD aggregated unit.

Summary

Ploughless cultivation is a highly promising technology that will gradually replace traditional plough tillage on account of lower energy requirements. Ploughless cultivation and soil loosening to a depth of 0.4 m effectively prevent the formation of a plough pan. The percentage of crop residues that are embedded in the top soil level is similar during ploughless cultivation involving the MultiCat 6HD aggregated tillage unit and traditional plough tillage, which minimizes the risk of pathogen infections in the early stages of plant growth. The above can be attributed to the design of teeth which dig out soil from deeper layers, and the distribution of the excavated material across the entire field by section No. 3 (disc harrow). Crop residues were more favourably distributed within the soil profile by means of ploughless cultivation (84.15% to a depth of up to 0.1 m) which reduces the loss of soil organic matter, minimises water and wind erosion, increases soil porosity, reduces soil crusting, and enhances the buffering capacity of soil. The operating parts of the MultiCat 6HD aggregated tillage unit were not clogged with plant material because biomass was effectively pulverised by a disc section mounted in the front of the tooth section. Simplified tillage involving the MultiCat 6HD aggregated tillage unit reduced fuel consumption by 30% and increased effective field capacity by 63%. The improvement in performance indicators resulting from the application of a new cultivation technology will increase the competitiveness of agricultural farms.

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