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FUEL CONSUMPTION AND TILLAGE EFFICIENCY DURING CULTIVATION OF FIELDS OF DIFFERENT AREAS

Summary

Fuel consumption and hourly tillage efficiency have been compared using a 7-furrow reversible plow coupled with a John Deere 8330 tractor during cultivation of fields of different areas (26.00, 12.74 and 3.22 ha). A reduction of efficiency has been observed as the area of the field decreased by – 2.35, 2.23 and 1.64 ha·h^{-1} along with an increase in the fuel consumption – 14.7, 15.0 and 18.0 dm^3·ha^{-1}. The proportions of the fuel consumption have also been changed when cultivating smaller fields - the share of fuel consumption during accompanying activities in the total fuel consumption grew by – 1.9, 2.4 and 6.5 dm^3·ha^{-1}.
***Key words**: tillage, fuel consumption, efficiency*

ZUŻYCIE PALIWA I WYDAJNOŚĆ ORKI PRZY UPRAWIE PÓL O RÓŻNEJ POWIERZCHNI

Streszczenie

Porównano zużycie paliwa i godzinową wydajność orki wykonywanej obracalnym, siedmioskibowym pługiem sprzężonym z ciągnikiem John Deere 8330, przy uprawie pól o różnej powierzchni (26,00, 12,74 i 3,22 ha). Stwierdzono obniżanie się wydajności wraz z uprawą mniejszych pól - 2,35, 2,23 i 1,64 ha·h^{-1} oraz wzrost zużycia paliwa - 14,7, 15,0 i 18,0 dm^3·ha^{-1}. Zmianie ulegały też proporcje w zużyciu paliwa - przy uprawie mniejszych pól, w całkowitym zużyciu paliwa wzrastał udział paliwa zużytego na czynności towarzyszące orce - 1,9, 2,4 i 6,5 dm^3·ha^{-1}.
***Słowa kluczowe**: orka, zużycie paliwa, wydajność*

1. Introduction

For many years, in agriculture, there has been a trend to obtain the highest efficiency and reduce the number of people and equipment involved. This is achieved by the application of efficient agricultural tools and machines characterized by large operating widths, thus large size and weight. A similar effect is obtained using multi tasking equipment performing several tasks at a single run. In most cases the source of propulsion of these machines are high-power farm tractors. When these sorts of aggregates are used, a variety of scientific problems related to proper operation appear such as appropriate selection of the gear ratios or the influence of size and shape of fields on the operating indexes, let alone the machinery environmental performance [2, 11, 13, 14].

The tractor driver, when performing agrotechnical activities aims at obtaining appropriate engine power in order to maintain the right speed, even if the motion resistance changes [4, 17], while the engine load depends on the realized tasks, applied tools and conditions of operation. It is noteworthy that the driving technique heavily depends on the driver's psychomotoric characteristics and his driving style. The driver changes the gear ratios following only his own experience and such a choice is not always optimum in terms of low unit fuel consumption (many speeds in the transmission) [2]. The use of a reducer and torque multiplier multiplies the number of possible settings in the transmission. Hence, to some extent, the experience and driving style of the tractor operator influence the fuel tractor efficiency.

Another important issue, particularly for large agricultural aggregates, is related to the relation between the size and shape of the cultivated fields and the organizational and economic parameters of a given task e.g. the range of tractor power used during a task, fuel economy or efficiency. It is generally acknowledged that these parameters are worse when smaller or less regular fields are cultivated compared to large and regular ones. Nevertheless, literature does not provide quantitative information in this matter, which is why the aim of the research was a comparison of the fuel consumption by an engine of a farm tractor and its hourly tillage efficiency when cultivating fields of different areas using a 7-furrow reversible plow.

2. Research methodology

The object of the research was an aggregate composed of a John Deere 8330 farm tractor (of the power output of 230 kW) coupled with a EuroDiamant plow by Lemken. This was a semi-mounted reversible plow fitted with 7 furrows with full moldboards. The research was carried out during tillage (on fields after harvesting with post-harvest activities performed). During the cultivation, the plow worked with the roller. The research was performed in 2012, in the fields of the Bralęcin Co-op (Spółdzielcza Agrofirma Witkowo near Stargard Szczeciński).

The measurements were made during cultivation of three fields that differed in size and shape (Fig. 1). Fields 1 and 2 were regular in shape but the area of field 1 was twice as large compared to field 2. Field 3 was characterized by the smallest area (approx. 8 and 4 times smaller than fields

1 and 2) and a triangular shape. The fields under research were cultivated by the same tractor operator. This is important in terms of the methodology as all the results obtained during the investigations were equally influenced by the driver's technique. The operating conditions have been presented in table 1. The methods of measurement of individual quantities given in table 1 have been discussed in [10]. The tillage was performed on sandy soils. According to the data shown in the agricultural map covering the investigated area [12] these were heavy loamy silty sand, light loamy sand and heavy loamy sand (tab. 1). Table 1 presents the granulometric parameters of the soil performed for collective soil samples, distinguishing fractions in use by Polskie Towarzystwo Gleboznawcze (Polish Society of Soil Science) since 2008. Soils of such granulometric composition are currently classified as loamy sand and fine sandy loam. These are light and medium soils in terms of agrotechncial weight [5]. The humidity of the soil varied in a small range from 13.1 to 15.0%. Volumetric density, compactness and shearing tension were characteristic of the soil after harvesting and in field 3 these parameters were mostly a bit higher than in fields 2 and 1. The depth of the tillage in field 2 was approx. 3 cm smaller than in fields 1 and 3. The plow speed and its operating width varied from 2.53 to 2.61 $m \cdot s^{-1}$ and from 3.27 to 3.36 m respectively. Despite certain differences during the cultivation of individual fields it can be assumed that the tillage conditions were comparable.

The investigations were based on the EDM 1404.01 system (fitted in the John Deere 8330) applied to monitor the engine and tractor operation. It recorded the engine operating time, engine speed, volumetric fuel consumption, GPS position, covered distance and speed. During the tractor operation these parameters were recorded with the resolution of 1 Hz (After over 18 hours of work 67450 measurement points were collected used in the analysis) [6].

The hourly efficiency of the tillage was calculated based on the cultivation time of individual fields. The cultivation time was determined based on the data collected by EDM 1404.01, while the information on the areas of the fields was obtained from the field owner and verified with the data contained in relevant maps.

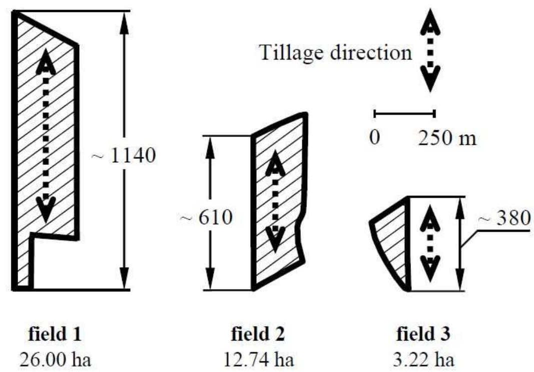

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Fig. 1. Size and shape of the cultivated fields
Rys. 1. Wielkość i kształt uprawianych pól

Table 1. Characteristics of the tillage conditions
Tab. 1. Charakterystyka warunków orki

Size		Soil layer	Value					
			Field number					
			1		2		3	
Share of individual soil types * in the top soil, %	shls	Top soil	40.9		68.5		100	
	lls		52.8		-		-	
	hls		-		31.5		-	
	sls		4.5		-		-	
	slls		1.8		-		-	
granulometry**, %	2 ≥ d >1		2.7	lfs	1.5	fsl	1.7	fsl
	1 ≥ d > 0.5		7.9		6.2		6.4	
	0.5 ≥ d > 0.25		15.1		11.0		12.5	
	0.25 ≥ d > 0.1		33.2		31.6		31.1	
	0.1≥ d > 0.05		17.1		17.7		19.3	
	0.05 ≥ d > 0.02		8		14		10	
	0.02 ≥ d > 0.002		11		13		14	
	d ≤ 0.002		5		5		5	
Soil humus, %			2.1		1.9		2.0	
Soil current weighted humidity, %		0 - 10 cm	15.0 s=2.0		13.7 s=1.0		13.3 s=1.3	
Soil volumetric density, $g \cdot cm^{-3}$		0 - 10 cm	1.35 s=0.10		1.31 s=0.15		1.44 s=0.15	
Soil compactness, kPa		0 - 10 cm	538 s=258		535 s=192		758 s=439	
Shearing tension, kPa		0 - 10 cm	24 s=10		18 s=6		18 s=4	
Plowing speed, $m \cdot s^{-1}$			2.53 s=0.23		2.58 s=0.46		2.61 s=0.48	
Plow operating depth, cm			25 s=2		22 s=2		25 s=3	
Plow operating width, m			3.34 s=0.05		3.36 s=0.04		3.27 s=0.03	

**- according to the above classification of Polish Society of Soil Science, **- as per the PTG (Polish Society of Soil Science) standards adopted in 2008: shls– silty heavy loamy sand, lls – light loamy sand, hls – heavy loamy sand, sls – slightly loamy sand, slls– silty light loamy sand, fls– fine loamy sand, fsl– fine sandy loam, , s – standard deviation*

**- zgodnie z wcześniejszą klasyfikacją Polskiego Towarzystwa Gleboznawczego, **- według ustaleń przyjętych przez PTG w 2008 r., pgmp - piasek gliniasty mocny pylasty, pgl - piasek gliniasty lekki, pgm - piasek gliniasty mocny, ps - piasek słabogliniasty, pglp - piasek gliniasty lekki pylasty, pgdr - piasek gliniasty drobnoziarnisty, gpdr - glina drobnopiaszczysta, s - odchylenie standardowe*

Source: own work / Źródło: opracowanie własne

While determining the indexes related to fuel consumption one needs to know the value of torque on the engine shaft. EDM 1404.01 unfortunately does not record this parameter, because a direct measurement of torque would require fitting a torque meter, which would require a modification of the engine. It is noteworthy that the identification of the engine torque and speed allows distinguishing of the engine work states directly corresponding to the performed tillage, u-turns, and other fieldwork activities. The above allows determining of the time share of these states when cultivating field of different areas and shapes and attributing relevant fuel consumption to these states as recorded by EDM 1404.01.

The engine torque M_o was determined indirectly using the hourly fuel consumption and engine speed recorded by EDM 1404.01. Based on these values the torque was calculated from relation (1):

$$M_o = a \cdot g_{1000}^3 + b \cdot g_{1000}^2 + c \cdot g_{1000} + d \,. \qquad (1)$$

In which g_{1000} is described with an equation (2):

$$g_{1000} = \frac{V_{pal}}{n_s} \cdot 1000 \;\; g_{1000} = \frac{V_{pal}}{n_s} \cdot 1000 \,, \qquad (2)$$

where:

a, b, c, d – coefficient characteristic of a given engine type dependent on the engine speed,
g_{1000} – fuel consumption per 1000 revolutions [dm^3],
V_{pal} – volumetric fuel consumption [dm^3·min^{-1}],
n_s – engine speed [rev·min^{-1}].

The development of relation (1) has been described in [9]. The efficiency and correctness of this method of torque determination are confirmed by earlier investigations [7, 8, 15, 16]. Values of coefficients a, b, c, d occurring in relation (1) for the presented investigations have been given in table 2. It is noteworthy that the values of these coefficients are elated to the engine speed. Hence, in order to simplify the calculations, the procedure of determination of the above coefficients described in [9] was performed for five adopted engine speed ranges n_s: to 950, 951-1250, 1251-1550, 1551-1850, 1851-2150 and above 2151 rev·min^{-1}.

Eventually, using relation (1) with V_{pal} and n_s given, the values of torque M_o were calculated, which is how the set of all engine work points (n_s, M_o) occurring during the tractor operation in the field was obtained. This is a set of points in the engine power supply field that were divided into elementary fields of the dimensions Δn_s=100 rev·min^{-1} and ΔM_o=50 Nm. Then, according to relation (3) [3], for each elementary field, the engine operating time was determined in the area of these parameters in relation to the total operating time:

$$WC_{(i,j)} = \frac{t_{(i,j)}}{t_c} \,, \qquad (3)$$

where:
$WC_{(i,j)}$ – relative operating time of the engine in elementary power supply field,
$t_{(i,j)}$ – engine operating time in elementary power supply field [s],
t_c – total engine operating time [s].

In this way, two-dimensional distributions of relative engine operating time in individual elementary power supply fields were obtained when cultivating individual fields. The analysis and comparison of the obtained distributions is difficult. In order to obtain the fuel consumption indexes (fuel consumption differs during tillage, u-turns and other field activities) for the obtained work points (n_s, M_o) a cluster analysis was performed using Statistica software. Applying this statistical method, the engine work points, treated as objects, were distributed into groups to make their relations with the same group as close as possible and minimize the relations with other groups. When generating the clusters, the measure of distance between the objects was the actual geometrical distance in the n_s - M_o coordinate system. The grouping of objects was done with the method of complete linkage. This method well applies when objects form natural separate agglomerates, as is in the case of the operation of a tractor engine, which, during the agricultural activities, produces characteristic ranges of loads and engine speeds at individual stages of fieldwork. In the method of complete linkage, k-averages variant was applied with which v-fold cross validation was performed enabling automatic determination of the number of clusters [1].

Eventually, sets of engine work points were obtained, determining its states during individual cultivation activities performed by the tractor-plow aggregate. Then, based on the hourly fuel consumption (occurring in the attributed points of work) and duration of these states recorded EDM 1404.01, the fuel consumption during tillage of fields of different areas was ascertained, which was referred to the cultivation area (tillage and accompanying activities separated).

3. Analysis of results

For each of the cultivated fields four characteristic clusters of engine operating states were obtained, automatically distributed by the statistics software (Fig. 2). The clusters were characterized by n_s and M_o coordinates and their relative time share compared to the total engine operating time (tab. 3).

Table 2. Coefficients a, b, c, d for the engine of the tested tractor
Tab. 2. Wartości współczynników a, b, c, d dla silnika badanego ciągnika

Engine speed ranges n_s [rev·min^{-1}]	Values of the coefficients			
	a	*b*	*c*	*d*
Below 950	-7·10^{-6}	0.0042	1.3992	-1.1506
950÷1250	-6·10^{-6}	0.004	1.3193	14.087
1250÷1550	-8·10^{-6}	0.0063	0.8354	37.374
1550÷1850	-1·10^{-5}	0.007	0.9304	20.479
1850÷2150	-1·10^{-5}	0.0094	0.3923	50.361
Above 2150	-7·10^{-6}	0.0068	0.5357	59.126

Source: own work / Źródło: opracowanie własne

For fields 1 and 2 the coordinates of two clusters were similar (Fig. 2, tab. 3). The speed and torque produced by the engine at these clusters indicate that these states were directly attributed to tillage. Hence, these clusters were treated as a whole. In the case of field 3 the location of the clusters was clearly different. The time share of tillage was the greatest during cultivation of field 1 (tab. 3) and amounted to 75.2% of the total cultivation time of this field. In filed 2 and 3 this parameter was smaller by approx. 1.1 and 1.6 respectively. When cultivating fields of smaller areas, the relative time of tillage was reduced in favor of the time related to the reduction of the aggregate speed at the start and end of the runs (also forced by coupling and decoupling of the roller), making u-turns and plow maneuvering when plowing the end of the fields.

This resulted in a reduction of the average speed of the tractor during cultivation of individual fields, and consequently, the reduction of the hourly efficiency of tillage in small fields. During the tillage of field 1, 2 and 3 the values of these parameters were 2.11, 2.19 and 1.97 $m \cdot s^{-1}$ and 2.35, 2.23 and 1.64 $ha \cdot h^{-1}$ respectively. It is noteworthy that the average speed of the tractor compared to the relatively even speed of the plow during tillage in individual fields (tab. 1) was lower by approx. 17, 15 and 25% respectively. The hourly efficiency of tillage compared to the highest efficiency obtained in filed 1 (of the area of 26.00 ha), was by approx. 5% smaller for field 2 (12.74 ha) and 30% smaller for field 3 (3.22 ha).

Figure 3 presents the distribution of fuel consumption occurring during cultivation of the discussed field. It shows the obtained values of fuel consumption per 1 ha of field (all stages of the tillage process - engine load states included), fuel consumption during tillage, and fuel consumption during accompanying activities.

The fuel consumption directly related to tillage in fields 1, 2 and 3 was similar and amounted to 12.8, 12.6 and 11.5 $dm^3 \cdot ha^{-1}$ respectively. This confirms similar soil and operating conditions in all the investigated fields during tillage, which was vital for completing the objective of the investigations.

The increase in the total fuel consumption and the fuel consumption for the accompanying activities is significant as the area of the cultivated field decreases (Fig. 3). Particularly great differences occur between indexes for fields 1 and 2 compared to field 3. In the case of field 3, characterized by a small area of 3.2 ha and a triangular shape, the total fuel consumption was approx. 22 and 20% greater compared with fields 1 and 2 respectively (fields 1 and 2 had regular shape and were of the area of 26.00 and 12.74 ha). For fields 1 and 2 the differences in the total fuel consumption were insignificant (Fig. 3), despite field 1 being almost twice as large as field 2.

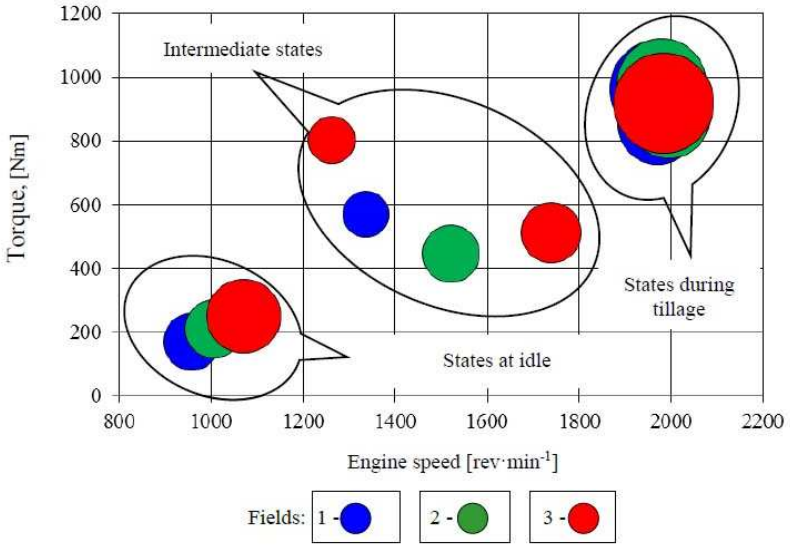

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Fig. 2. Clusters of engine operating states when operating on individual fields

Rys. 2. Zestawienie skupień stanów pracy silnika ciągnika przy orce poszczególnych pól

Table 3. Indexes characterizing the clusters obtained from the measurement data

Tab. 3. Wskaźniki charakteryzujące skupienia uzyskane z danych pomiarowych

Field	Cluster	Engine speed, rpm	Torque, Nm	Operating time share, %	Power, kW
1	1a	1973.26	962.47	45.27	198.88
	1b	1970.21	853.14	29.89	176.02
	1c	1335.58	570.27	9.94	79.76
	1d	956.95	170.63	14.86	17.10
2	2a	1979.76	978.19	37.89	202.80
	2b	1995.25	874.69	30.87	182.76
	2c	1520.83	446.06	15.62	71.04
	2d	1004.86	209.70	15.62	22.07
3	3a	1983.73	919.36	46.78	190.98
	3b	1738.75	513.06	16.94	93.42
	3c	1262.08	802.49	10.46	106.06
	3d	1071.12	250.92	25.81	28.15

Source: own work / Źródło: opracowanie własne

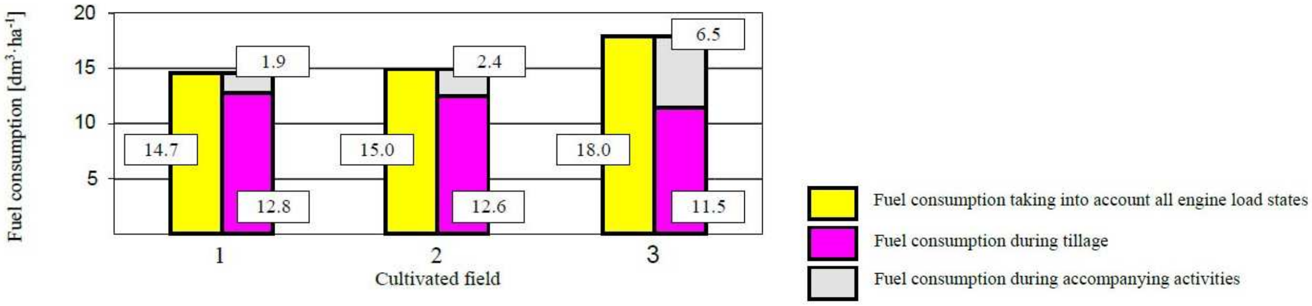

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Fig. 3. Fuel consumption by the engine of a tractor during tillage of fields of different areas referred to the cultivation area taking into account all engine load states during tillage and accompanying activities

Rys. 3. Zużycie paliwa przez silnik ciągnika rolniczego podczas orki pól o różnej powierzchni odniesione do areału uprawy przy uwzględnieniu wszystkich stanów obciążenia silnika, przy bezpośrednim wykonywaniu orki i przy czynnościach towarzyszących orce

The increase in the fuel consumption related to tillage accompanying activities is significant with the decreasing field area (Fig. 3). In field 2 this consumption was 1.3, and in field 3, 3.4 times greater compared to the fuel consumption in field 1. This is related to the increase in the relative operating time of the tractor at idle and under transient states as the area of the cultivated fields decreased (Fig. 2, tab. 3). When cultivating fields 1, 2 and 3 the relative engine operating time was 24.8, 31.2 and 53.2% of the total tractor operating time.

4. Conclusions

The presented results of the investigations confirm the generally assumed fuel consumption and hourly efficiency-related regularities occurring during works performed in fields of varied areas. However, the quantitative relations between the above quantities and the area of the cultivated fields are still unknown. The presented results are an attempt to answer such a formulated research problem.

It has been observed that during tillage, irrespective of the area of the cultivated fields, two fundamental engine operating states are dominant – tillage and idle. In fields 1, 2 and 3, of the area of 26.00, 12.74 and 3.22 ha respectively, the time share of the engine state at tillage compared to the total operating time was 75.2, 68.8 and 46.8%.

The efficiency of tillage during the cultivation of fields 1, 2 and 3 obtained by a 7-furrow reversible plow coupled with John Deere 8330 (230 kW) was 2.35, 2.23 and 1.64 $ha \cdot h^{-1}$ respectively. The efficiency in field 2 (12.74 ha) was 5%, and field 3 (3.22 ha) 30% lower than the greatest efficiency obtained in the largest field (field 1, 26.00 ha).

The total fuel consumption during tillage, i.e. fuel used for tillage and accompanying activities (e.g. u-turns) increased as the area of the fields decreased. During tillage of fields 1, 2 and 3 this fuel consumption was 14.7, 15.0 and 18.0 $dm^3 \cdot ha^{-1}$ respectively. The proportions in the fuel consumption changed as well. For smaller fields the share of the fuel consumption for accompanying activities in the total fuel consumption grew significantly and for fields 1,2 and 3 amounted to 1.9, 2.4 and 6.5 $dm^3 \cdot ha^{-1}$ respectively, which constitutes approx. 13, 16 and 36% of the total fuel consumption.

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