Vol. 35, No. 02, pp. 498-516/Junio 2022

ISSN-E 1995-9516
Universidad Nacional de Ingeniería

http://revistas.uni.edu.ni/index.php/Nexo
https://doi.org/10.5377/nexo.v35i02.14626

The basics for choosing energy-efficient working tools of tillage machines

Los conceptos básicos para elegir herramientas de trabajo de bajo consumo de energía de máquinas de labranza

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(recibido/received: 15-febrero-2022; aceptado/accepted: 30-mayo-2022)

ABSTRACT

Improving the efficiency of technological tillage methods is primarily associated with developing existing tools and creating new types of working tools for tillage machines. Tillage efficiency improvement depends on the correct choice of the most energy-efficient working tools belonging to the same class of the technological process. This research aims to develop scientific baselines for choosing energy-efficient working tools of different structural designs based on the criteria of power consumption and quality of shallow tillage. The object of this research includes working tools for shallow and deep tillage. The research subject is the changes in the criteria chosen to evaluate the working tools' efficiency. We involved mathematical modeling based on laws of science observed during tillage, carried out experiments and analyses, and summarised the experimental findings. The scientific novelty of this research justifies the criteria for evaluating the efficiency and quality of working tools used for shallow and deep tillage. The research relies on graphical and empirical dependencies describing the trends in efficiency evaluation criteria for tillage working tools with various operation speed modes. We discovered that to evaluate the efficiency and choose the most energy-efficient tillage working tool, one should use a system of criteria: specific tractive resistance of the active frontal area, terra-dynamic resistance coefficient, and the primary tillage quality parameters. The probability of compliance of the mean values of calculated and experimental findings (0.51–0.87) confirms the adequacy of proposed mathematical models describing changes in specific tractive resistance per unit of active frontal area and terra-dynamic resistance coefficient of tillage working tools. According to the research, when a more energy-efficient tillage working tool is chosen, the working tools under comparison belong to the same class of working tools based on the technological process principle and functioning conditions. Discovered trends in the changes in the efficiency evaluation criteria and the choice of energy-efficient tillage working tools for shallow and deep tillage are represented by empirical dependencies applicable in specific ranges of motion speed under certain functioning conditions. Consequently, we emphasized that further studies should justify the upper and the lower borders of the tillage working tools and terra-dynamic resistance coefficient in accordance with the agrotechnical quality indicators of tillage.

Keywords: Tillage, Energy efficiency, Efficiency and quality evaluation criteria, Tillage working tools, Comparative energy evaluation

RESUMEN

La mejora de la eficiencia de los métodos tecnológicos de labranza se asocia principalmente con el desarrollo de herramientas de trabajo existentes y la creación de nuevos tipos de herramientas para máquinas de labranza. La mejora de la eficiencia de la labranza depende de la elección correcta de las herramientas de trabajo de mayor eficiencia energética pertenecientes a la misma clase del proceso tecnológico. Esta investigación tiene como objetivo desarrollar líneas de base científicas para elegir herramientas de trabajo de bajo consumo de energía de diferentes diseños estructurales basados en los criterios de consumo de energía y calidad de la labranza superficial. El objeto de esta investigación incluye herramientas de trabajo para la labranza superficial y profunda. El tema de investigación son los cambios en los criterios elegidos para evaluar la eficiencia de las herramientas de trabajo. Participamos en el modelado matemático basado en las leyes de la ciencia observadas durante la labranza; realizamos experimentos y análisis, y resumimos los hallazgos experimentales. La novedad científica de esta investigación justifica los criterios para evaluar la eficiencia y la calidad de las herramientas de trabajo utilizadas para la labranza superficial y profunda. La investigación se basa en dependencias gráficas y empíricas que describen las tendencias en los criterios de evaluación de la eficiencia de las herramientas de trabajo de labranza con varios modos de velocidad de operación. Descubrimos que para evaluar la eficiencia y elegir la herramienta de trabajo de labranza más eficiente energéticamente, se debe usar un sistema de criterios: resistencia a la tracción específica del área frontal activa, coeficiente de resistencia terradinámica y los parámetros de calidad de labranza primaria. La probabilidad de cumplimiento de los valores medios de los hallazgos calculados y experimentales (0.51–0.87) confirma la adecuación de los modelos matemáticos propuestos que describen los cambios en la resistencia a la tracción específica por unidad de área frontal activa y el coeficiente de resistencia terra-dinámica de las herramientas de trabajo de labranza. Según la investigación, cuando se elige una herramienta de trabajo de labranza de mayor eficiencia energética, las herramientas de trabajo comparadas pertenecen a la misma clase de herramientas de trabajo basadas en el principio del proceso tecnológico y las condiciones de funcionamiento. Las tendencias descubiertas en los cambios de los criterios de evaluación de la eficiencia y la elección de herramientas de trabajo de labranza energéticamente eficientes para labranza superficial y profunda están representadas por dependencias empíricas aplicables en rangos específicos de velocidad de movimiento bajo ciertas condiciones de funcionamiento. En consecuencia, se enfatizó que los estudios posteriores deben justificar los bordes superior e inferior de las herramientas de trabajo de labranza y el coeficiente de resistencia terradinámica de acuerdo con los indicadores de calidad agrotécnica de la labranza.

Palabras clave: labranza, eficiencia energética, criterios de evaluación de eficiencia y calidad, herramientas de trabajo de labranza, evaluación comparativa de energía.

1. INTRODUCTION

Tillage is one of the most energy-consuming processes in crop cultivation; it consumes 30%–45% of the total energy consumed in the process, while around 7%–8% is used for secondary tillage. Significant power consumption during tillage dictates a need to find new ways to reduce it and, thus, increase the energy efficiency of the entire process. Tillage technology improvement depends on the proper choice of the most energy-efficient working tools belonging to the same class by the technological process principle.

National and international researchers continue studies to improve the energy efficiency of tillage further. N. B. McLaughlin (McLaughlin, Drury, Reynolds & Xueming, 2008) determined energy consumption during tillage in their research. Draft, the hourly and specific fuel consumption of eight tillage implements used for different operations were measured. The scholars (McLaughlin et al., 2008) figured wide ranges of the tractor's draft, fuel consumption, and efficiency, indicating that one can achieve significant power savings when using energy-efficient tillage machines. We determined the tractor dimensions and working parameters of the implements.

However, in another study (Fanigliulo, Biocca & Pochi, 2016), the scholars performed a comparative energy evaluation and selection of efficient tillage implements for medium-deep primary tillage in silty-clay soil, widespread in Central Italy. During the field studies, we compared tillage implements by measuring their operating speed, traction force, fuel consumption, energy demands, and various parameters of tillage quality (cloudiness and roughness of the tilled soil, biomass coverage index, burying degree). A comparative evaluation of energy parameters and tillage quality indicators helped us select efficient tillage implements.

Another team of scholars (Usaborisut & Prasertkan, 2019) conducted experimental studies of a combined tillage implement consisting of a subsoiler and a rotary harrow to assess energy saving due to step reduction in soil preparation. The degree of soil loosening, specific energy requirements, and operation parameters were studied. We established that the rotor speed and energy consumption during deep soil loosening significantly affected specific energy requirements.

An analysis of the operation of tillage implements (reversible mouldboard plow, short disk harrow, universal cultivator, and subsoiler) was based on such criteria as fuel consumption, wheel slip, and performance of implements at different working depths. Such an analysis revealed their reasonable operating modes (Moitzi, Wagentristl & Refenner, 2014). According to the findings, the specific fuel consumption per unit of the tilled area grew linearly with an increase in the tillage depth for moldboard plows and disk harrows. This indicator changed disproportionately for the subsoiler (Moitzi et al., 2014).

In addition, the authors of another study (Kasisira & du Plessis, 2006) evaluated energy consumption during deep tillage in sandy clay loam soil in South Africa depending on the tillage depth. According to the results, the cross-section area of tillage tools per unit of tractive resistance grew linearly, increasing the distance between them.

Consequently, we identified tensile force, a cross-section of loosened soil, and specific soil resistance to study the functional properties of blade tiller working tools during the tillage of loamy soil after the wheat harvest (Pražan, Hůla, Kovaříček & Jakub, 2018). We discovered that the width of blade chisels did not significantly affect the values of specific resistance of the soil. We recorded an increase in soil resistance at the growing recess into the ground (Pražan et al., 2018).

The authors of the scientific research on a related topic (Akhalaya, Shogenov, Starovoytov & Zolotarev, 2020) developed a combined tillage tool in the form of a cultivator blade with a ripper placed on the frame of a cultivator with a para-plow. With the help of this device, one can perform several operations simultaneously: cut weeds, loosen the soil with a vertical cut, and perform para-plowing. By studying the various angles of the cutting edge of the ripper and the para-plow in relation to the horizontal surface and identifying their reasonable values, one can ensure fuel-saving and decrease the tractive resistance of the implement (Akhalaya et al., 2020).

Studying the effect of the geometry of the cutting edge of tillage tools on soil resistance, soil destruction, and soil movement below the depth of tillage (Fielke, 1996), we discovered that one can use a tillage tool with a sharp geometry of the cutting edge with a further transition to a blunt one, observing an increase of up to 80% of the pulling force of a tillage tool with similar general geometry, while the direction of the vertical force changed depending on the force that acted to pull the device into the soil, to the force that lifted it.

Another research (Babitsky, Sobolevsky & Kuklin, 2019) focuses on improving the shapes of the working tool surfaces of cultivators based on mechanical and bionic approaches. The authors proposed a new form of the stubble cultivator working tool (e.g., alogarithmic spiral with a variable angle of crumbling). The results show a 16.5% decrease in the traction resistance of the discussed working tool compared to the traction resistance of a standard one.

Other scholars (V. Myalo, O. Myalo, Demchuk & Mazyrov, 2019) identified the primary disadvantages of the operation of a cultivator with serial working tools in soils prone to wind erosion. Based on this study, the authors proposed a new design of the cultivator's working tool, conducted a comparative laboratory study of the cultivator blades, and justified a scheme of a new working tool to meet the main requirements of soil-protective, environmentally safe, and resource-saving agriculture.

Several studies examine the effect of strip tillage on traction force, fuel consumption, and CO_2 emissions (Lekavičienė, Šarauskis, Naujokienė & Buragienė, 2019). Some scholars explored the efficiency of deep soil loosening (Bădescu, Croitoru, Marin & Ivan, 2014), while others analyzed the methods of modeling the interaction of soil environments with soil tillage machines (Lysych, 2019) or assessed the effect of improved tillage machine on power consumption and various methods of tilling the soil (Vilde, Cesnieks & Rucins, 2006).

Another research (Gheorghe, Petru, Vlăduţoiu & Tutunaru, 2018) focuses on the methods of optimizing large assemblies of deep soil tillage machinery. The authors discussed the primary optimization issues and described the potential advantages of using the results of the best methods.

Some researchers (Dzhabborov, Dobrinov & Eviev, 2019; Dzhabborov, Maksimov, Semenova, 2017) studied the improvement of energy efficiency of tillage implements with various structural designs.

Finally, we should mention one more research (Berezhnov & Syrbakov, 2017), which evaluated tractive and energy indicators of the Case IH Stieger STX-435 tillage machine with PK-12.2 "Kuzbass-T" through dynamometer testing. During the test, the following parameters were measured: motion speed, tractive resistance of the agricultural machine, the slip of the drive wheels, and their statistical parameters. Reasonable operating parameters ensuring the efficiency of this machine were identified.

A brief overview of the papers published by different authors containing data regarding various types of working tools and machines provides controversial information regarding their energy efficiency and tillage conditions during studies. Sometimes this phenomenon is explained by the drawbacks of the existing experimental methods since experiments often involve various unaccounted external effects, making comparisons based on energy efficiency criteria rather inappropriate. The tillage working tools under comparison are supposed to have the same position in gangles, dimensions of shanks in the soil, and quality of surface tilling. Experimental studies lay the groundwork for the comparative evaluation of standard and newly designed working tools with improved quality.

According to these studies, the prerequisite for a scientifically justified choice of energy-efficient tillage working tools is obtaining fundamental mathematical models of the interaction between the tillage working tool and soil. Such models must provide a complete description of the physical processes active in the contact area. When considering standard tillage working tools and developing new ones, one should apply new criteria for a comparative assessment of their effectiveness. Such indicators can be used as a unified criteria system enabling a comprehensive multi-criteria evaluation of energy efficiency. Such a system of criteria has to ensure an objective comparative evaluation of the efficiency of tillage working tools and machines with similar functions. Meanwhile, working tools can differ from the structural point of view.

2. MATERIALS AND METHODS

This research involved methods of mathematical modeling based on the study of physical processes taking place during the interaction of soil with tillage working tools. The experimental findings were generalized and analyzed.

The study aims to choose efficiency evaluation criteria and develop a methodology for selecting the most efficient shallow tillage working tools of various structural designs.

The research object is tillage working tools (see Fig. 1, 2, 3, and 4) for shallow (see Fig. 6, 7) and deep tillage.

The research subject is trends in the changes in the criteria for evaluating the efficiency of tillage working tools.

Experimental findings were obtained during laboratory and fieldwork in the area of an experimental and production facility of the Institute for Engineering and Environmental Problems [IEEP].

We used a data measuring system (IIK-IEEP) consisting of a mounted unit with tensometric trolleys and a data measuring system IP 264 RosNIITiM to evaluate the energy parameters of tillage working tools at different speed and load modes.

In addition, we conducted comparative studies of a standard and dynamic tillage working tool in the following conditions:

- Field area, ha-10;
- Length of furrow (average), m: 100;
- Stone content per 1 m^2, pcs-0.005;
- Average stone size, mm-350;
- Type of soil -soddy medium-podzol soil, middle loamy soil (moraine loam);
- Relief, grad. -1–2;
- Average soil hardness in a layer up to 20 cm, MPa- 0.85 – 1.4;
- Soil moisture, % in a layer from 0 to 10 cm – 13.5; in a layer from 10 to 20 cm – 16.8.

Figure 1: Dynamic stiff shank tillage working tool with an energy-storage transmitter

Figure 2: Standard stiff shank tillage working tool

Figure 3: Dynamic, flexible shank tillage working tool

Figure 4: Standard flexible shank tillage working tool

The active frontal area of a standard tillage working tool (see Fig. 2 and Fig. 4) at a depth of 12 cm is $F^{*} = 137.96$ cm^2 or 0.013796 m^2. The same parameter for a dynamic tillage working tool at a depth of 12 cm at rest is $F^{*} = 193.05$ cm^2 or 0.019305 m^2. The F^{*} value of the dynamic working tool, depending on the speed and load modes, varies in the following range: $F^{*} = 174.0 - 193.05$ cm^2.

We performed a comparative energy evaluation of the working tools for shallow tillage (see Fig. 1–4) with the help of the IIK-IEEP data measuring system and tractor MTZ-920 (see Fig. 5).

Figure 5: Experimental studies of working tools for shallow tillage using the IIK-IEEP data measuring system

Experimental studies of the deep tillage process involved the use of subsoilers of the IEEP design mounted on the frame of a universal combined tillage machine UKPA-2,4 (see Fig. 6 and Fig. 7). We applied the following conditions:

- Field area, ha-5;
- Length of furrow (average), m- 400;
- Stand of grass, cm - 8–12;
- Stone content per 1 m^2, pcs - 0.005;
- Averagestonesize, mm- 350;
- Type of soil-soddy medium-podzol soil, middle loamy soil (moraine loam);
- Predecessors-fruit crop nursery (planting stock and rootstock) and bushes (currant and raspberry);
- Relief, grad. -1–2;
- Ridgeness of the field surface, cm-3–4;
- Relative air humidity, % -52–60;
- Soil density before subsoiler, (MPa):
- For layers of 0–10 cm – 0.73;
- 10–20 cm– 1.10;
- 20–30cm– 1.33;
- 30–40cm– 2.07.

Figure 6: Two-row configuration of the working tools for deep tillage (tools positioned at 90°, left-side view)

Figure 7: Single-row configuration of the working tools for deep tillage (tools positioned at 81^0, right-side view)

The results obtained during the experiments were processed using the methodology described in the study (Valge & Jabborov, 2015).

During the processing of the experimental findings, we identified a standard statistical error of the sample mean of energy parameters and quality indicators of tillage with different working tools using the following formula (Valge & Jabborov, 2015):

$$S_m = {}^{\sigma_m}/_{\sqrt{n}}, \tag{1}$$

where σ_m – the root mean square of a parameter/indicator; n – sample size.

The standard statistical error S_m of the sample mean of tractive force in the case of dynamic tillage working tools varied within the range of 0.096 – 0.0269 kN.

The standard error of the sample mean S_m of the motion speed of the dynamic tillage working tool varied within the range of 0.012–0.032 m/s.

The standard error of the sample mean S_m of the tillage quality indicators varied within the range of 2.3%–3.5% by the soil loosening degree; 0.38–0.472 cm by the soil tillage depth; and 0.35–0.42 cm by the width of the furrow left by the shank of the deep tillage working tool.

3. RESULTS AND DISCUSSION

Depending on the objectives of the studies aimed at optimizing the parameters and operating modes of the equipment and evaluating the efficiency of technological crop cultivation processes, the optimization criteria can be partial, integral (or generalized), local, and global (Dzhabborov & Dobrinov, 2010).

The chosen optimization criteria include energy, technical-economic, and environmental indicators, the quality of technological processes, reliability, and labor safety.

The analysis of the system of optimality criteria (applied during the choice of tillage working tools and machines) that are the most significant from the point of view of ensuring energy efficiency in parallel with the high quality of the technological operation of tillage shows that the most important are quality indicators, as well as the specific traction resistance per unit of the active total frontal area of the working body and the coefficient of dynamic resistance.

Let us consider the indicators mentioned above in more detail; we chose them as the critical criteria for choosing efficient tillage working tools.

Specific tractive resistance R_{ud}^{ro} per unit of the active total frontal area of the tillage working tool was calculated according to the following formula:

$$R_{ud}^{ro} = \frac{R_a}{F^*}, \tag{2}$$

where R_a – tractive resistance of a tillage working tool, kN (N); F^* – active frontal area of a tillage working tool, m^2 (cm^2); the active frontal area $F^*$of tillage, the working tool depends on its structural parameters.

This indicator is an expression of a complete comparative evaluation of the efficiency of tillage machines with different working tools and the level of perfection and energy efficiency of such working tools. This value can show the energy efficiency of the working tool or the machine as a whole. The minimum allowable value of R_{ud}^{ro} will correlate with the minimum tractive resistance of the working tool and the machine, power requirements, specific fuel consumption, and energy reduction for the technological process.

The terra-dynamic resistance coefficient K_t of a tillage working tool can be illustrated by the following formula:

$$K_t = \frac{2R_a}{\mathrm{T}_p \cdot V_r^2 \cdot F^*}, \tag{3}$$

where T_p – soil hardness, kg/cm^2; V_r – motion speed of a tillage working tool, m/s; $\text{T}_p \cdot V_r^2$ – dynamic pressure (or pressure speed)-the value of kinetic energy having the pressure dimension.

Coefficient K_t, which takes into account the air shape of the working tools, depends on the shape, quality of the tool surface, and soil hardness (density).

Based on formula (2), we can determine the tractive resistance of a tillage working tool R_a using the following equation:

$$R_a = 0.5 \cdot K_t \cdot \text{T}_p \cdot V_r^2 \cdot F^* \tag{4}$$

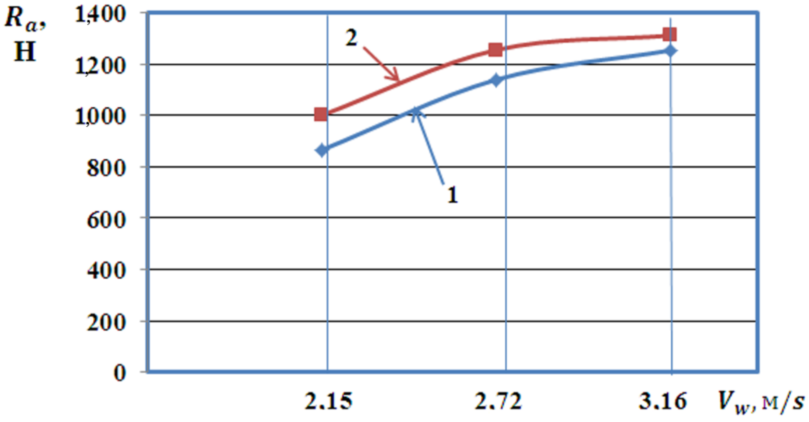
Terra-dynamic resistance coefficient K_t is the main parameter describing the terra-dynamic efficiency of the working tools of the tillage machines.

Tillage quality indicators. According to the Rules of Mechanised Works, depending on the technological process of tillage, one should evaluate the quality of tillage implements by such agrotechnical indicators (criteria) as tillage depth, the degree of loosening (or crumbling), smoothness of the field surface after tillage, ridgeness of the field, the degree of killing and burying of weeds.

Methodology for identifying the indicators of tillage quality evaluation was taken from GOST 33687-2015 Machines and Tools for Surface Treatment of Soil. Test Methods (Standartinform, 2015) and GOST 33736-2016 Agricultural Machinery. Machines for Deep tillage. Test Methods (Standartinform, 2016).

The examples below show changes in the above criteria for efficient working tools for shallow and deep tillage.

Fig. 8 shows graphical and empirical dependencies of the tractive resistance of a standard working tool and a dynamic working tool with an energy-storage transmitter on the speed of their motion.



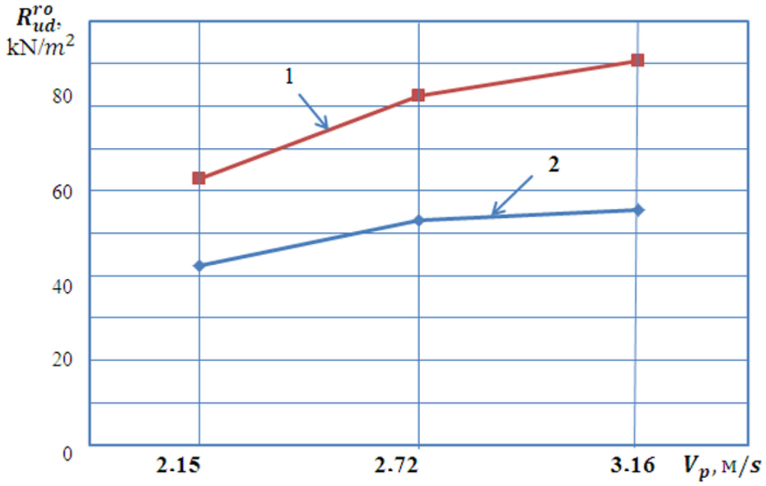
$$1 - R_a = -217.6797V_w^2 + 1539.0473V_w - 1436.7275$$
$$2 - R_a = -315.1894V_w^2 + 1980.5865V_w - 1800.2979$$

Figure 8. Dependencies of the tractive resistance of tillage working tools: 1– standard tool; 2 – a dynamic tool with an energy-storage transmitter (with the fixed tillage depth of h=12 cm)

With an increase in the motion speed of the standard and the dynamic tillage working tools, their tractive resistance grew as well. With the motion speed range of 2.15 to 3.16 m/s, the tractive resistance of the standard tillage working tool changed from 866.0 to 1253.0 N (see Fig. 8, curve 1). With the same speed range, the tractive resistance of the dynamic tillage working tool with an energy-storage transmitter rose from 1001.0 to 1311.0 N (see Fig. 8, curve 2). One should note that such a substantial difference in the tractive resistance values is due to differences in the active frontal area of the working tools: $F^* = 137.96$ cm^2 for the standard one and $F^* = 193.05$ cm^2 for the dynamic tool with an energy-storage transmitter (with the tillage depth of 12 cm).

Empirical dependencies (1) and (2) shown in Fig. 8 are valid for the motion speed change range of $V_w = 2.15 - 3.16$ m/s, with the average tillage depth of 12.0 cm.

Graphical and empirical dependencies of specific resistance per unit of the active frontal area of the tillage working tools on their motion speed are shown in Fig. 9.



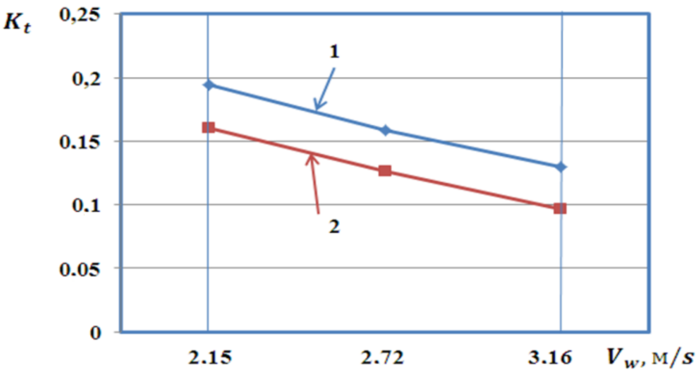
$$1 \text{ - } R_{ud}^{ro} = -15.64656V_w^2 + 110.86544V_w - 103.25444$$

$$2 \text{ - } R_{ud}^{ro} = -13.39713V_{w_p}^{2\ 2} + 84.13876V_{w_p} - 76.73010$$

Figure 9: Dependencies of specific resistance per unit of the active frontal area of the tillage working tools: 1 – standard tool; 2 – dynamic tool with an energy-storage transmitter (with the fixed tillage depth of h=12 cm)

As one can see from Fig. 9, with the range of the motion speed of the standard tillage working tool from 2.15 to 3.16 m/s, specific resistance per unit of its active frontal area changes within the range of 62.78…90.84 kN/m^2. With the above-mentioned speed range, specific resistance per unit of active frontal area in the case of the dynamic tillage working tool with an energy storage transmitter increased from 42.24 to 55.37 kN/m^2. The available data confirm that the R_{ud}^{ro} values of the dynamic tillage working tool with an energy storage transmitter decreased by 32.7%…39.0% compared to the standard working tool with the above-mentioned motion speed range, suggesting that the dynamic tillage working tool is more energy-efficient than the standard one. Empirical dependencies (1) and (2) shown in Fig. 9 are valid for the motion speed of $V_w = 2.15 - 3.16$ m/s.

Fig. 10 shows graphical and empirical dependencies of the terra-dynamic resistance coefficient of tillage working tools on the speed of their motion.



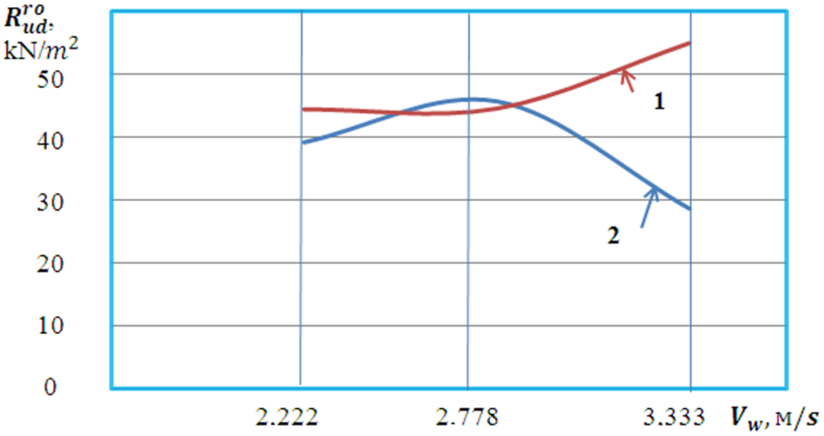
$$1 - K_t = -0.0045V_w^2 - 0.397V_w + 0.2999$$
$$2 - K_t = -0.0062V_w^2 - 0.0295V_w + 0.2520$$

Figure 10: Dependencies of the terra-dynamic resistance coefficient of tillage working tools: 1 – standard; 2 – dynamic on an energy storage transmitter (with fixed tillage depth ofh=12 cm)

The analysis (see Fig. 10) of the trends in the changes of the terra-dynamic resistance coefficient on the speed motion of the standard tillage working tool and the dynamic tool with an energy storage transmitter showed that the increase of the speed rate brings the K_t values down. When the working speed of motion amounts to $V_w = 2.15 - 3.16$ m/s, the K_t coefficient falls in the range of $K_t = 0.194 - 0.13$ in the case of the standard tillage working tool and $K_t = 0.16 - 0.097$ in the case of the dynamic one with an energy storage transmitter, suggesting that the dynamic tillage working tool with an energy storage transmitter is better than the standard one.

Empirical dependencies (1) and (2) shown in Fig. 10 are valid for the motion speed change range of $V_W = 2.15 - 3.16$ m/s.

By generalizing the empirical findings, we managed to identify dependencies of specific tractive resistance per unit of the active frontal square of the flexible shank tillage working tools (see Fig. 11).



$$1 - R_{ud}^{ro} = 16.7323V_w^2 - 83.4312V_w + 147.2434$$
$$2 - R_{ud}^{ro} = -38.2986V_w^2 + 203.2142V_w - 223.2279$$

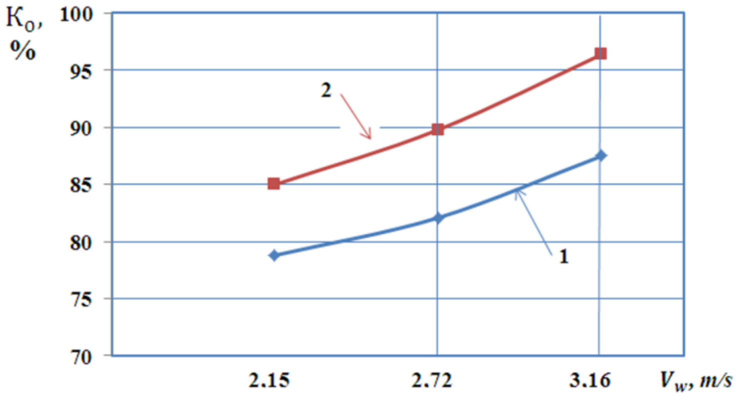
Figure 11: Dependencies of specific resistance R_{ud}^{ro} per unit of the active frontal area of (1) a standard and (2) a dynamic tillage working tool with a flexible shank on the speed V_w of its motion (tillage depth of 12 cm)

Changes in specific resistance R_{ud}^{ro} per unit of the active frontal area of the standard and dynamic flexible shan, the tillage working tools reveal other dependencies (see Fig. 11). With an increase in the speed of motion of a standard flexible shank tillage working tool from 2.222 to 3.333 m/s, the R_{ud}^{ro} value grows continuously from 44.471 to 55.045 kN/m^2. With an increase in the motion speed of a dynamic, flexible shank tillage working tool from 2.222 to 2.778 m/s, the R_{ud}^{ro} value increases from 39.22 to 45.74 kN/m^2, and then as the speed goes up from 2.778 to 3.333 m/s, the R_{ud}^{ro} value diminishes from 45.74 to 28.63 kN/m^2.

With the motion speed change of $V_w = 2.22 - 3.33$ m/s for a standard and a dynamic, flexible shank working tool, the R_{ud}^{ro} value falls within the same range of $44.60 - 45.74$ kN/m^2. This aspect suggests that the effect of the adaptive property of the dynamic, flexible shank working tool shows up at the increased working speed of 2.8 m/s and higher.

Empirical dependencies (1) and (2) shown in Fig. 11 are valid for the motion speed change range of $V_w = 2.22 - 3.33$ m/s.

Let us consider changes in tillage quality using a standard and a dynamic working tool with an energy storage transmitter. Fig. 12 gives an example of graphical and empirical dependencies of the degree of soil loosening by working tools with the speed of motion varying from 2.15 to 3.16 m/s.



$$\boldsymbol{1}\text{ -К}_o = \boldsymbol{6.4191V_w^2 - 25.4714V_w + 103.8913}$$
$$\boldsymbol{2}\text{ - К}_o = \boldsymbol{6.5138V_w^2 - 23.3012V_w + 104.9875}$$

Figure 12: Dependencies of the degree of soil loosening (crumbling) on the speed of motion of the working tools: 1 – standard; 2 – dynamic with an energy storage transmitter (with fixed tillage depth ofh=12)

Experiments proved that an increase in the speed of motion of the working tools leads to a rise in the degree of soil loosening.

With the range of working speeds of 2.15…3.16 m/s, the degree of soil loosening rose from 78.8% to 87.5% for the standard working tool and from 85.0% to 96.4% for the dynamic one.

The trends in the changes in the degree of loosening using the standard and the dynamic working tool (1) and (2), shown in Fig. 12, are valid for the motion speed change range of $V_w = 2.22 - 3.33$ m/s.

The findings regarding the degree of soil loosening highlight the advantage of using a working tool with dynamic properties over a standard one.

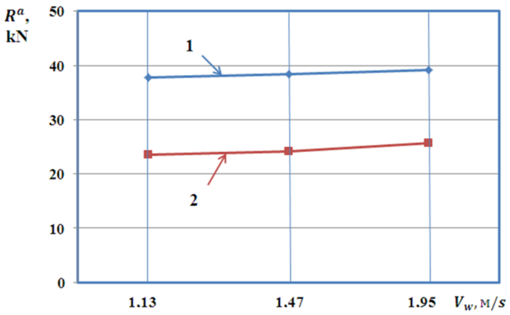
Fig. 13 and Fig.14 show the state of soil after tillage with the working tools under study.

Figure 13: State of soil after tillage with a standard working tool

Figure. 14: State of soil after tillage with a dynamic working tool

Now, let us consider how the chosen criteria of efficiency evaluation (specific tractive resistance R_{ud}^{ro} per unit of active total frontal area, terra-dynamic resistance coefficient K_t of the tillage working tool, and tillage quality indicators) change when using a tillage aggregate for deep tillage.

Fig. 15 shows graphical and empirical dependencies of the tractive resistance of the tillage machine UKPA-2,4 for deep tillage on the speed of its motion at different positioning angles of the shank.



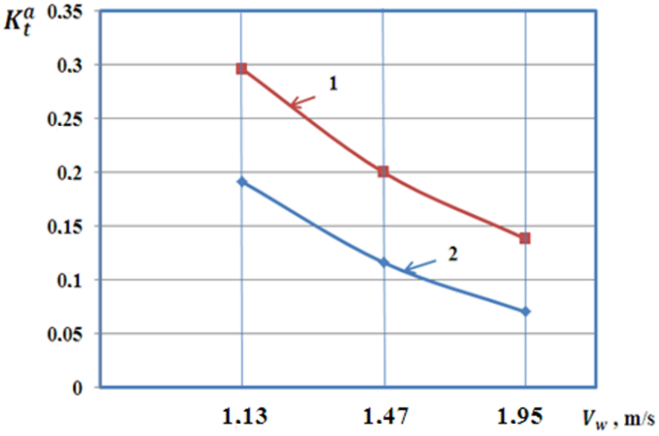
$$1\text{ - } R^a = -0.3945V_w^2 + 2.8494V_w + 35.0940$$
$$2\text{ - } R^a = 1.6529V_w^2 - 2.4446V_w + 24.1318$$

Figure 15: Dependencies of the tractive resistance of the machine UKPA-2,4 for deep tillage on the speed of its motion: 1– the shank of the working tool positioned at 90°, crumbling angle of 30°; 2-shank of the working tool positioned at 81°, crumbling angle of 21°

An increase in the working speed of motion of UKPA-2,4 leads to an increase in the tractive resistance of the tool. With the positioning angle of the working tool of 90° and the speed range of 1.13 to 1.95 m/s, the tractive resistance of the standard tool for deep tillage changed from 37.80 to 39.15 kN (see Fig. 15, curve 1). With the same speed range and the positioning angle of the subsoiler of 81°, its tractive resistance rose from 23.48 to 25.65 kN (see Fig. 15, curve 2).

Experimental data show that a change in the angle of the working tool leads to a substantial change in tractive resistance. A 9° decrease of the positioning angle and a 9° decrease of the crumbling angle of the chisel with the motion speed change range of 1.13–1.95 m/s, reduce tractive resistance by 34.5%–37.9 %. Empirical dependencies 1 and 2 (see Fig.15) are true for the motion speed change range of $V_w = 1.13 - 1.95$ m/s.

Graphical dependencies of the terra-dynamic resistance coefficient of the deep tillage tool on its motion speed and its change trends are shown in Fig. 16.



$$1\text{ - } K_t^a = 0.32008V_w^2 - 1.16979V_w + 1.19587$$
$$2\text{ - } K_t^a = 0.15347V_w^2 - 0.62049V_w + 0.69659$$

Figure 16: Dependencies of the terra-dynamic resistance coefficient of the UKPA-2,4 deep tillage machine: 1 – the shank of the working tool positioned at 90°, crumbling angle of 30°; 2 – the post of the working tool positioned at 81°, crumbling angle of 21°

As shown in Fig. 16, with the positioning of the working tool at 90˚ and the speed change range of 1.13 to 1.95 m/s, coefficient K_t^a decreases from 0.2964 to 0.1383. With the positioning of the working tool at 81˚, K_t^a goes down from 0.1914 to 0.0702.

A decrease in the positioning angle of the working tools improves their streamline characteristics, which eventually reduces the tractive resistance of the deep tillage implement.

Trends in the changes of the K_t^a coefficient (see Fig. 16) are valid for the motion speed change range from 1.13 to 1.95 m/s.

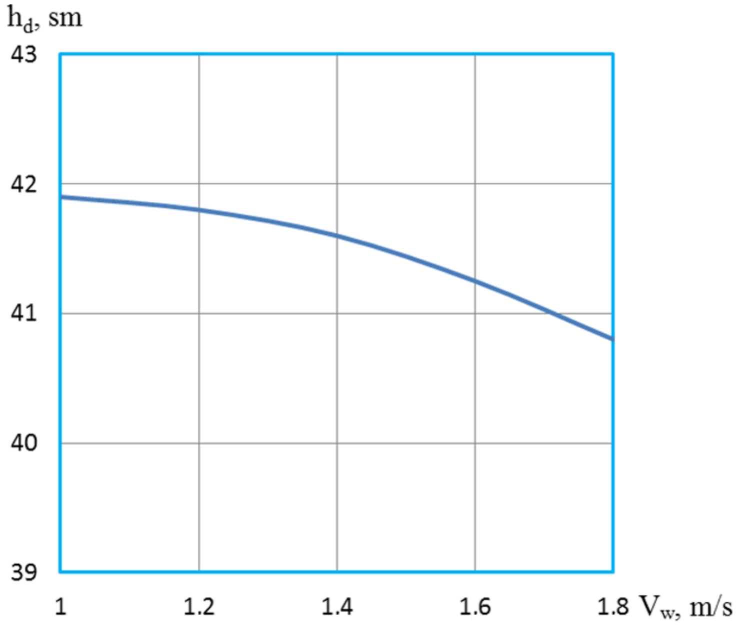
The operating quality of the deep tillage implement was evaluated based on two indicators: the tillage depth and the width of the furrow in the trace left by the shank of the working tool.

In both cases, with the fixed positioning angles of 90˚ and 81˚ and the crumbling angles of 30˚ and 21˚, respectively, the quality indicators of the implement did not show any substantial differences.

Data analysis shows that the established values of the agrotechnical indicators fell within the range of agrotechnical requirements imposed on the technological process of deep chiseling and deep tillage.

A detailed analysis of the above experimental findings shows that the identified values of the agrotechnical indicators fall within the range of agrotechnical requirements applied to the deep tillage process.

Fig. 17 illustrates the graphical dependency of the tillage depth on the motion speed of the deep tillage implement



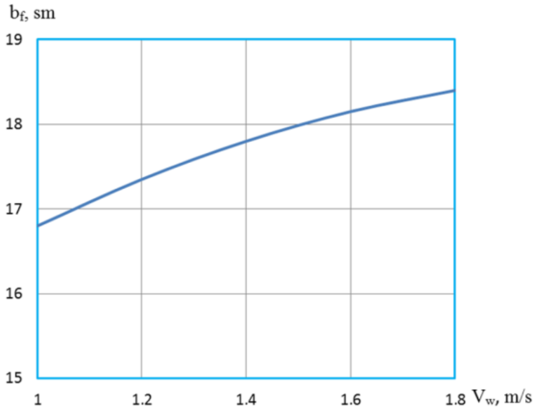
$$\boldsymbol{h_d = -1.1294V_w^2 + 1.6376V_w + 41.4908}$$

Figure 17: Dependency of the mean value of the soil tillage depth h_d on the motion speed V_w of the UKPA-2,4 deep tillage machine (single-row configuration).

With the established speed modes of the UKPA-2,4 machine, the mean value of the soil tillage depth decreased from 41.89 to 41.20 cm, that is, by 1.60 %, which testifies to its stability.

The empirical dependency of the soil tillage depth (see Fig. 17) is true for the speed change range of $V_w = 1.14 - 1.61$ m/s.

Graphical and empirical dependencies of the mean value of the width of the furrow in the trace left by the shank of MTA MTZ-920+UKPA-2,4 with its motion speed can be found in Fig. 18.



$$\boldsymbol{b_f = -3.3534V_w^2 + 12.2005V_w + 7.2495}$$

Figure 18: Dependency of the mean width b_f of the furrow in the trace left by the shank on the motion speed V_w of the deep tillage machine UKPA-2,4 (single-row configuration, average tillage depth $h_d =$ 41.89 cm

Experiments showed that an increase in the speed of motion of the tillage machine MTZ-920+UKPA-2,4 leads to an increase in the width of the furrow left by the shank. When the motion speed increased from 1.14 to 1.61 m/s, the mean b_f width of the furrow rose from 16.8 to 18.2 cm (i.e., by 8.3%). The obtained values of the width of the furrow fall within the range of the agrotechnical requirements since the value has to be $b_f \leq 20$ cm.

The identified changes in the furrow width in the trace left by the shank of the subsoiler's working tool on the speed of motion of MTZ-920+UKPA-2,4 are true for $V_w = 1.14 - 1.61$ m/s.
Fig. 19 shows the state of soil before and after deep tillage.

Figure 19: The state of soil before (on the right) and after (on the left) deep tillage using the tillage machine MTZ-920+UKPA-2,4

The analysis and generalization of the experimental findings indicate that the lower the value of specific tractive resistance R_{ud}^{ro} per unit of active total frontal area and the terra-dynamic resistance coefficient K_t of a tillage working tool, the lower the traction resistance and, at the same time, the energy consumption during tillage decreases.

The theoretical and experimental studies performed proved that the terra-dynamic resistance coefficient coefficients of a tillage working tool K_t and machine K_t^a require further study. The upper and the lower borders of their variation, given the compliance with the requirements of the technological process quality, must be established.

4. CONCLUSION

The findings described above showed that when a more energy-efficient tillage working tool is chosen, the working tools under comparison belong to the same class of working tools by their technological principle and functioning conditions.

We also established that for efficiency evaluation and the choice of the most energy-efficient tillage working tools, one should use a system of criteria including specific tractive resistance per unit of active frontal area, terra-dynamic resistance coefficient, and tillage quality indicators.

The mathematical models ((1), (2)) describe such target functions as specific tractive resistance per unit of active frontal area and terra-dynamic resistance coefficient; they can be presented in the form of the primary criteria for evaluating the energy efficiency of tillage working tools.

The identified trends in the changes of the efficiency evaluation criteria and the choice of energy-efficient tillage working tools for shallow and deep tillage, in the form of empirical dependencies, are valid for particular ranges of the motion speed change and certain functioning conditions.

To sum up, one should note a need for further research on the given problem in order to substantiate the upper and the lower borders of the terra-dynamic resistance coefficient of a tillage working tool in compliance with the indicators of the agrotechnical tillage quality.

Acknowledgments

This study was supported by the Russian-Finnish project “Environmentally Friendly Smart Organic Agriculture [EFSOA] of the South-East Finland-Russia Cross Border Cooperation Programme 2014–2020.”

REFERENCES

Akhalaya, B., Shogenov, Yu., Starovoytov, S., & Zolotarev, A. S. (2020). Combined tillage implement. Vestnik BSAU, 2020(2), 706-773.

Babitsky, L. F., Sobolevsky, I. V., & Kuklin, V. A. (2019). Theoretical background for the bionic substantiation of parameters of the stubble cultivator working bodies. Agrarnayanauka Evro-Severo-Vostoka. Agricultural Science Euro-NorthEast, 20(2), 183-191.

Bădescu, M., Croitoru, St., Marin, E., & Ivan, Gh. (2014). Current status in the construction of equipment for deep chiseling of the soil worldwide. Annals of the University of Craiova-Agriculture, Montanology, Cadastre Series, XLIV, 12-24.

Berezhnov, N. N., & Syrbakov, A. P. (2017). Evaluation of traction and energy indicators of a tillage and planting tractor machine using the method of dynamometer testing. AgroEkoInfo, 2(28), 17.

Dzhabborov, N. I., & Dobrinov, A. V. (2010). Classification of efficiency criteria and their use in optimising performance characteristics of towing machine-tractor aggregates. Saint Petersburg, Russia: Institute of Agroengineering and Environmental Problems of Agricultural Production.

Dzhabborov, N. I., Dobrinov, A. V., & Eviev, V. A. (2019). Evaluation of the energy parameters and agrotechnical indicators of aggregate for deep subsurface tillage. Journal of Physics: Conference Series, 1210, 012036.

Dzhabborov, N. I., Maksimov, D. A., & Semenova, G. A. (2017). Evaluation of traction and dynamic indicators of tillage machines. Tekhnologii i Tekhnicheskie Sredstva Mekhanizirovannogo Proizvodstva Produktsii Rastenievodstva i Zhivotnovodstva, 93, 53-64.

Fanigliulo, R., Biocca, M., & Pochi, D. (2016). Effects of six primary tillage implements on energy inputs and residue cover in Central Italy. Journal of Agricultural Engineering, 47(3), 177-180.

Fielke, J. M. (1996). Interactions of the cutting edge of tillage implements with soil. Journal of Agricultural Engineering Research, 63(1), 61-71.

Gheorghe, G., Petru C., Vlăduţoiu, L., & Tutunaru, L. F. (2018). Deep soil tillage tools optimization study. Proceedings from: The 15th International Congress of Automotive and Transport Engineering. Cluj-Napoca, Romania: Technical University of Cluj-Napoca.

Kasisira, L. L., & du Plessis, H. L. M. (2006). Energy optimization for subsoilers in tandem in a sandy clay loam soil. Soil and Tillage Research, 86(2), 185-198.

Lekavičienė, K., Šarauskis, E., Naujokienė, V., & Buragienė, S. (2019). The effect of the strip tillage machine parameters on the traction force, diesel consumption and CO2 emissions. Soil & Tillage Research, 192(2019), 95-102.

Lysych, M. N. (2019). Review of numerical methods for modeling the interaction of soil environments with the tools of soil tillage machines. Journal of Physics: Conference Series, 1399, 044014.

McLaughlin, N. B., Drury, C. F., Reynolds, W. D., & Xueming, Y. (2008). Energy inputs for conservation and conventional primary tillage implements in a clay loam soil. Transactions of the ASABE, 51(4), 1153-1163.

Moitzi, G., Wagentristl, H., Refenner, K. (2014). Effects of working depth and wheel slip on fuel consumption of selected tillage implements. AgricEngInt: CIGR Journal, 16(1), 182-190.

Myalo, V. V, Myalo, O. V., Demchuk, E. V., & Mazyrov, V. V. (2019). Basic parameters substantiation of the cultivator working body for the continuous tillage in the system of ecologically safe resource-saving agriculture. IOP Conf. Series: Earth and Environmental Science, 224, 012023.

Pražan, R., Hůla, J., Kovaříček, P., & Jakub, Č. (2018). Functional properties of blade tiller working tools. Res Agr Eng, 64, 63-69.

Standartinform (2015) Machines and tools for surface treatment of soil. Test methods, GOST 33687-2015 (July 1, 2017). Moscow, Russia.

Standartinform. (2016). Agricultural machinery. Machines for deep tillage. Test methods, GOST 33736-2016 (January 1, 2018). Moscow, Russia.

Usaborisut P, Prasertkan K (2019) Specific energy requirements and soil pulverization of a combined tillage implement. Heliyon 5(11):e02757.

Valge, A. M., & Jabborov, N. I. (2015). Fundamentals of statistical processing of experimental data in the conduct of researches on mechanization of agricultural production with examples on statgraphics and excel. Saint Petersburg, Russia: Elista.

Vilde, A., Cesnieks, S., & Rucins, A. (2006). Energetical, economical and ecological aspects of soil tillage minimization. Environment Technology Resources Proceedings of the International Scientific and Practical Conference, 1(294). doi:10.17770/etr2003vol1.2023.