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Justification of technologies of minimum (surface) tillage

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Abstract. With the modern development of agricultural production, the introduction of resource-saving technologies, technologies based on intelligent systems, there is a need to introduce a system of machines for the implementation of surface tillage technologies (mini-till, no-till). The main factor largely determining the choice of an agricultural machine, its working bodies, and processing technology are the agrophysical properties of the soil. The research was based on experiments to determine the hardness after various types of treatment of various soils with different granulometric composition. The research was carried out for one year (autumn 2021, spring 2022, autumn 2022), a total of 12 fields were examined, the sample was about 300 measurements. As a result, mathematical dependences were obtained for determining the change in the depth of processing at different soil hardness and the working speed of the machine-tractor unit when performing the technological operation cultivation to a depth of 10 cm. Theoretical studies on the effect of different soil hardness and working speed on the resistivity of the cultivator were carried out according to the formulas of Kirtbay Yu.K. (1982) and Iofinov S.A. (1985). When processing experimental data obtained in determining the resistivity on soils of different hardness and different operating speeds, using the Matlab program, more precise mathematical dependences were obtained that determine the dependence of resistivity on the operating speed on soils with different hardness. Calculations on the formation of optimal aggregates of tractors with toothed chain harrows, performed considering theoretical and experimental studies on the effect of soil hardness and operating speeds on processing depth and resistivity revealed that the optimal unit with a harrow with a working width of 12 m is the Belarus 2022 + BZC-12 unit, with a harrow width of 18 m and 24 m – in a unit with a tractor K-744R1.

1 Introduction

Minimal technologies for tillage in the production of agricultural products provide for the rejection of plowing, reducing operating costs, increasing labor productivity. As a result of the use of minimal tillage technologies ("mini-till"), it becomes possible to accumulate and use crop residues to accumulate organic matter in the soil, to preserve the soil structure, to

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preserve moisture in the surface layer of the soil. At the same time, the role and importance of the plant protection system is increasing.

Considering the use of wide-cut and combined agricultural machinery (AM), "mini-till" technologies contribute to reducing soil density.

At the same time, in the Middle Urals, for the main processing of perennial grasses, when preparing the soil for corn for silage, potatoe, and vegetables, it is recommended to use real tillage. According to the recommendations of agricultural scientists of the Middle Urals, the Kuban State Agrarian University, the All-Russian Research Institute of Agriculture and Soil Protection from Erosion, "the use of surface treatments is even desirable ...", "... zero and surface methods of basic tillage cannot be systems in crop rotations, but can be used as methods for individual crops within the boundaries of existing systems" [1, p. 9].

Researchers clearly define the need for the use of combined systems of basic tillage with a combination of "deep tillage with zero and surface methods", considering the frequency of their use: on sod-podzolic and forest soils for no more than 2 years consecutively (such soils in the Sverdlovsk region - 72.5%), on various types of chernozems for 3-4 years (in the Sverdlovsk region – 17.6%).

It is necessary to note the work of scientists in recent years on the study of issues related to tillage. The researchers considered the following questions:

- study of processing methods and their effect on the structural and aggregate composition of soils, on the agrophysical state, properties and indicators, on soil compaction [2, 3, 4, 5];
- study of cultivation methods and their impact on soil fertility, on soil hardness and moisture availability, on hardness and yield, on moisture accumulation, study of basic processing methods and their impact on agrochemical properties and indicators, the impact of resource-saving tillage technologies on the water regime [6, 7, 8];
- study of the methods of basic processing and their impact on the yield, productivity and quality of crops, on the littering of fields [9, 10];
- study of the effect of basic processing methods, fertilizer systems on the economic efficiency of crop cultivation, the effectiveness of various methods of basic tillage [11, 12].

In different regions of the Russian Federation there are different types of soils from sod-podzolic to chernozems. All of them have different agrophysical properties. In our study, we will first consider *density* and *hardness.*

Density is the mass of a unit volume expressed in kg/m^3 (g/cm^3). There is a concept of *equilibrium density* and *optimal density.* The equilibrium density of the soil is formed in natural conditions under the effect of natural factors. Optimal density is the density of the soil that provides the highest yield of agricultural crops. According to the ratio of equilibrium and optimal density, it is possible to decide on the type of basic tillage.

The optimal density for cereals is 1100-1300 kg/m^3; for potato – 1000-1200 kg/m^3; for vegetables – 1100-1500 kg/m^3; for perennial grasses – 1200-1300 kg/m^3. The equilibrium density of sod-podzolic soils is 1350-1600 kg/m^3, chernozems - 1000-1300 kg/m^3. Different methods of processing form different soil densities: surface (shallow beardless), disking – 1200 kg/m^3; chiseling (beardless loosening) - 1120 kg/m^3; moldboard plowing – 1090 kg/m^3.

Hardness is the property of the soil to resist compression and wedging [13]. The soil hardness is the main criterion determining the traction resistance of the AM, expressed in kg/cm^2. According to the classification, soils can be from "loose" - less than 10 kg/cm^2 to "solid" - more than 100 kg/cm^2. The optimal hardness for grain crops is 5-25 kg/cm^2, for tiller crops – 5-15 kg/cm^2. Hardness over 25-30 kg/cm^2 is critical. The hardness is influenced by density, humidity, and the relationship between individual particles.

2 Materials and Methods

The research methods: experimental, computational and analytical, economic and statistical, comparative and system analysis, etc. The research was carried out from August 2021 to October 2022 in the fields of the educational and experimental farm of the Ural State Agrarian University, in the branch of the FSBSI URFANITS Ural Branch of the Russian Academy of Sciences, the Research Institute of Agriculture - Uralniiskhoz.

3 Results and Discussion

The hardness is significantly influenced by the tillage method. The hardness after flat-cutting treatment is 3.6% lower than when plowing, but the lowest soil hardness after disk harrow treatment is 9.2% lower than plowing. The hardness, in turn, and the speed of the machine-tractor unit (MTU) affect the treatment depth. The results of experimental studies on the effect of hardness and speed of MTU movement, on the technological operation cultivation to a depth of up to 10 cm, on the treatment depth are shown in Figure 1.

The results of studies on the effect of the hardness and MTU speed on the processing depth are subject to the following mathematical dependencies:

- with soil hardness of 0.51 MPa $y = -0.238x + 11.9$;
- with soil hardness of 0.81 MPa $y = -0.384x + 13.2$;
- with soil hardness of 1.2 MPa $y = -0.482 x + 14.2$.

When calculating the composition of the machine-tractor unit, it is necessary to consider that solid soils have a higher resistivity, but a lower rolling resistance coefficient.

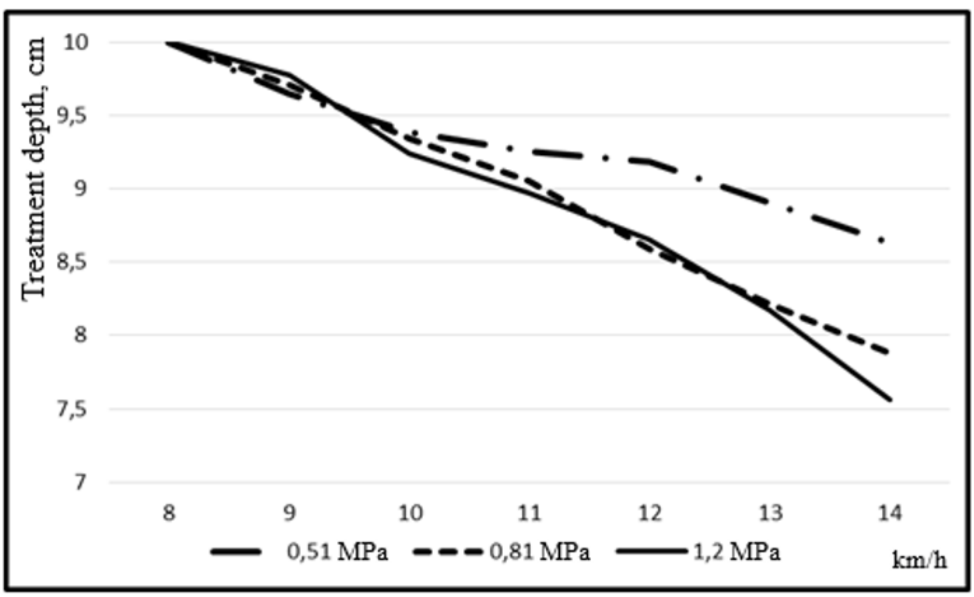

Fig. 1. The dependence of the treatment depth on the soil hardness and the working speed.

For a more accurate formation of the unit, at any technological operation, it is necessary to consider the increase in the resistivity of agricultural machines with an increase in the operating speed of the unit [14, 15]. Theoretical dependences of these values are proposed by Yu.K. Kirtbay (1) (for technological operation – plowing), which can be used for any technological operation for tillage, S.A. Iofinov (2).

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$$k_v = k_0\left[1 + \Delta k_c (V_d^c - V_o^c)\right] \quad (1)$$

$$k_v = k_0\left[1 + \frac{\Delta_c}{100}(V_d - V_0)\right] \quad (2)$$

where k_0 is the specific resistance of the soil at the speed of movement V_0; V_0 = 8 km/h; Δk_c - the increment of the traction resistance in fractions of the initial resistance k_0 (kN/m) per 1 km/h increase in the movement speed (for agricultural machines surface treatment Δk_c= 0.005); V_d – the actual movement speed; c - degree indicator (for modern machines c = 1.5; Δ_c – coefficient characterizing the increment of traction resistance as a percentage (for surface treatment Δ_c = 3-4%).

Over the past decades, the designs of the working bodies of agricultural machines have changed significantly, therefore, it is more rational and correct to use the value V_0 = 8 km/h (operating speeds at nominal specific traction resistance) for calculations.

The results of experimental studies processed in the Matlab program are presented in Figures 2, 3, 4.

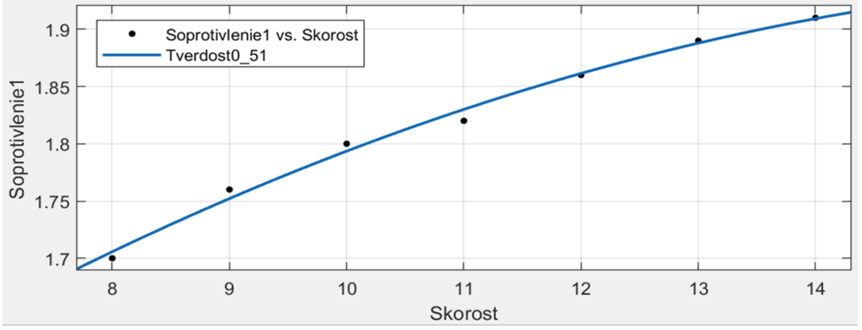

Fig. 2. The dependence of the specific traction resistance on the operating speed at soil hardness of 0.51 MPa.

The effect of the operating speed on the specific traction resistance at a hardness of 0.51 MPa is subject to the following mathematical dependence:

$$y = -0.0025x^2 + 0.08893x + 1.154. \quad (3)$$

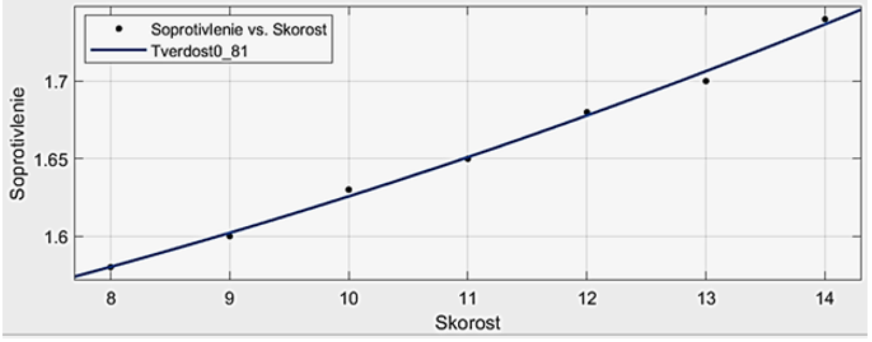

Fig. 3. The dependence of the specific traction resistance on the operating speed at soil hardness of 0.81 MPa.

At hardness of 0.81 MPa, it obeys the following mathematical dependence:

$$y = 0.0008333x^2 + 0.007738x + 1,465. \quad (4)$$

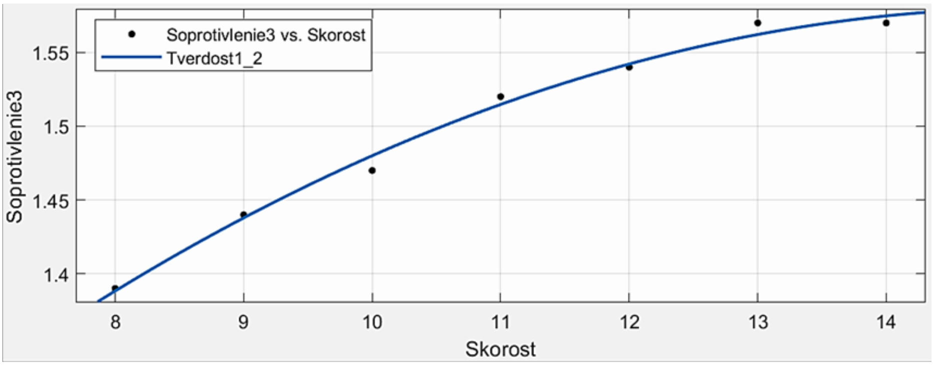

Fig. 4. The dependence of the specific traction resistance on the operating speed at soil hardness of 1.2 MPa.

At hardness of 1.2 MPa, it obeys the following mathematical dependence:

$$y = -0.00369x^2 + 0.1123x + 0.7264. \quad (5)$$

For surface treatment, as providing the lowest soil hardness, a variety of AM can be used. The following types can be attributed to the system of machines for minimum tillage:

- for basic processing, after harvesting – combined cultivators (combined tillage tools), mulching cultivators; discators. If necessary, chisel plows can be used.
- for early spring harrowing (closing of moisture) – coupling of tooth harrows, tooth chain harrows;
- for sowing grain crops – sowing complexes, seeders;
- for crop treatment – wide-cut self-propelled sprayers.

Domestic and foreign manufacturers of agricultural machinery offer a wide selection of these agricultural machines, we will present their brief characteristics in Table 1.

Table 1. Brief description of the AM for minimum treatment**.**

AM name	*Mark*	*Cut width range, m*	*Weight per 1 m of the cut width, kg/m*	*Tractor power range, kW*
Combined cultivators	Smaragd	2,6-10	226-284	58,8-205,9
	KKP	2,0-12	337-808	58,8-268,5
	KNK	4,0-6,0	442-555	90,4-187
	KOS	2,1-6,0	343-380	53,3-169,2
	Cenius	3,0-4,0	311-350	91,9-117,7
Discators	BDM	2,8-9,0	894-929	103-353
Stubble heavy cultivators	KST	4,2-9,0	437-914	140-313
	KR	2,1-9,0	430-450	80,9-290
	KSU	4,8-14	150-447	95,6-239
	KPD "Vityaz"	4,0-14	312-532	62,5-217
Chisel plows	PCh	2,1-8,0	300-729	99,3-393
	John Deer 2410	9,1-18,5	461-558	169-309
Harrows	Single cart BGZ	10-18	175-238	58,8-165
	Double cart BGZ	12-27	221-322	103-309
	Tooth chain harrows	12-24	237-327	80,9-121
Sowing complexes	Feat Agro	7,2-12,5	1111-1160	202-320
	Agra Tor	6,6-16	969-1197	101-332
	PK "Kuzbass"	6,1-12,2	1025-1410	140-277
	John Deer	8,7-18,8	582-1091	180-313

For use in minimum tillage systems, "new", in our opinion, agricultural machines are of particular interest that are little used in agriculture in Russia – tooth chain harrows. These agricultural machines are developed and manufactured in LLP "NPC Agroengineering" (city of Qostanay, Rep. of Kazakhstan) [16]. With the help of tooth chain harrows (according to the developer-manufacturer), it is possible to perform early spring harrowing (closing of moisture), with sufficient precipitation in the region, it is possible to perform a technological operation to level the winter tillage, can be used both on stubble and on plowed "furrow" field. The working body is an "anchor" chain with teeth (from 2 to 4, Fig. 5), with a working tooth length of 70 mm, rotating in bearing units. The chain pitch, depending on the width of the grip, is 96 mm or 102 mm.

The experience of using tooth chain harrows is available in the branch of the Federal State Budgetary Scientific Institution "Ural Federal Agrarian Research Center of the Ural Branch of the Russian Academy of Sciences" - Ural Research Institute of Agriculture (URFANITS UrB RAS - Uralniiskhoz). In this institution, a chain-tooth harrow with a grip width of 6 meters, with 4 teeth on a link, 180 mm long, was operated.

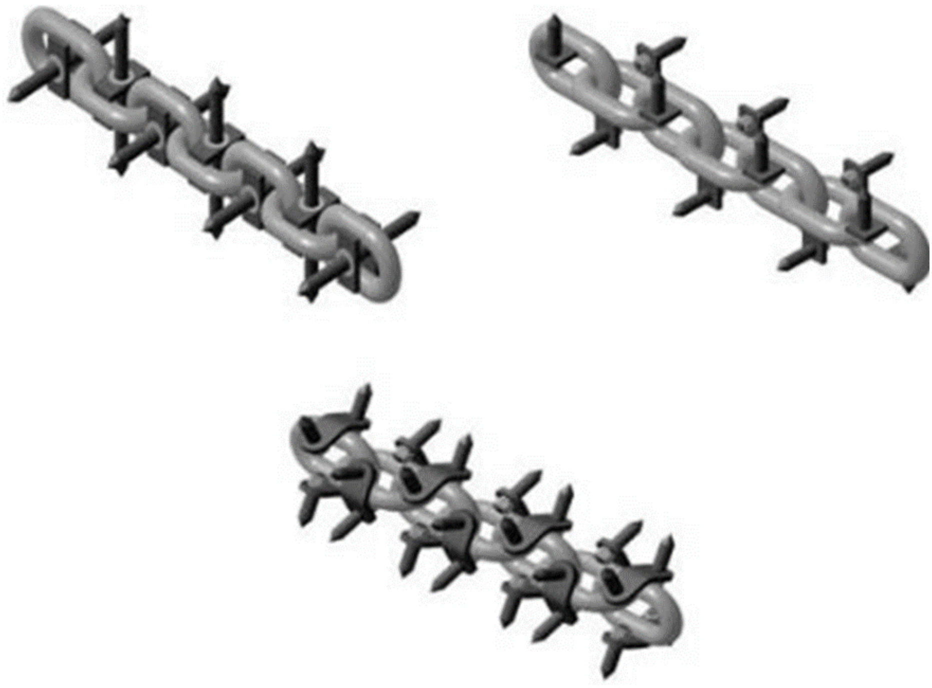

Fig. 5. The working organ of the tooth chain harrow.

In this study, we will make calculations on the formation of the optimal composition of the unit with tooth chain harrows of various gripping widths – 12 m; 18 m; 24 m.

Initial data for calculations: traction characteristics of tractors on various gears; specific traction resistance – 0.9 kN/m; rolling resistance coefficient – 0.12 (for treated stubble, tilled arable land); operating speeds from 9 km/h to 16 km/h (studies when creating harrows were carried out at operating speeds up to 19 km/h), the traction force reserve is 7.5%.

Traction resistances of aggregates.

BZC-12. $R_A = R_M + R_f = 13.7$ kN.

$R_M = kB_p = 0{,}9 \times 11{,}6 = 10.4$ kN.

$R_f = fm_e = 0{,}12 \times 27{,}8 = 3.34$ kN.

BZC-18. $R_A = R_M + R_f = 24$ kN.

$R_M = kB_p = 0{,}9 \times 18 = 16.2$ kN.

$R_f = fm_e = 0{,}12 \times 64{,}7 = 7.76$ kN.

BZC-24. $R_A = R_M + R_f = 30{,}8$ kN.

$R_M = kB_p = 0{,}9 \times 24 = 21.6$ kN.

$R_f = fm_e = 0{,}12 \times 77 = 9.24$ kN.

We will present calculations for the unit consisting of Belarus 1025 + BZC-12.

The technological operation can be performed on the transmission III1 – 8.7 km/h, with a tractive effort of 15.1 kN.

Hourly productivity is determined by the formula:

$$W_H = eB_pV_p = e\xi_B\xi_V\tau B_aV_T \tag{6}$$

where e is a coefficient that considers the units of measurement of the unit speed. $e = 0.1$; B_p – the working width of the unit grip, m; $B_P = \xi B_a$, where ξ_B - the coefficient of the grip width use considers the difference between the working width of the grip from the constructive one: $\xi_B = \frac{B_p}{B_a}$. During surface treatment

$\xi_B = 0.95\text{-}0.96$; V_P is the operating speed of the unit, km/h; $V_P = \xi_V V_T$, where ξ_V is the speed utilization factor: $\xi_V = \frac{V_P}{V_T}$. $\xi_V = 0.77$ for tractors cl. 1,4-2 ts; τ - the coefficient of shift time use: $\tau = \frac{T_w}{T_{SH}}$, where T_w is the time of clean (useful) work, hour; T_{SH} is the total shift duration, hour. With good work organization and normal operating conditions, $\tau = 0.7\text{-}0.8$.

Calculation of fuel consumption.

$$g_{HA} = \frac{G_{T.W} + G_{T.P} + G_{T.CR} + G_{T.HD}}{W_H} \tag{7}$$

where $G_{T.W}$, $G_{T.P}$, $G_{T.CR}$, $G_{T.HD}$ – average hourly fuel consumption during the shift, kg/h when performing basic (clean) work, during idling on turns, crossings and engine idling (during stops of the unit with the engine running). The average hourly fuel consumption is taken according to reference data or calculated using the specific fuel consumption per 1 ef.hp and the degree of engine loading.

$W_H = 0{,}1 \times 0{,}955 \times 0{,}77 \times 0{,}75 \times 12 \times 8{,}7 = 5{,}76$ ha/h

$g_{HA} = \frac{14{,}9 \times 0{,}75 + 8{,}9 \times 0{,}25}{5{,}76} = \frac{11{,}2 + 2{,}22}{5{,}76} = 2.33$ kg/ha

The results of calculations for the BZC-12 with tractors Belarus 1221, Belarus 1523, Belarus 2022 are presented in Figure 6.

It can be seen from the presented calculations that the most optimal variant of the unit for carrying out the technological operation is the unit consisting of Belarus 2022 + BZC-12. The performance of this unit is almost 2 times higher than that of the Belarus 1025 + BZC-12 unit, the specific fuel consumption is 1.3% higher. It is impractical to use a more powerful tractor for the BZC-12.

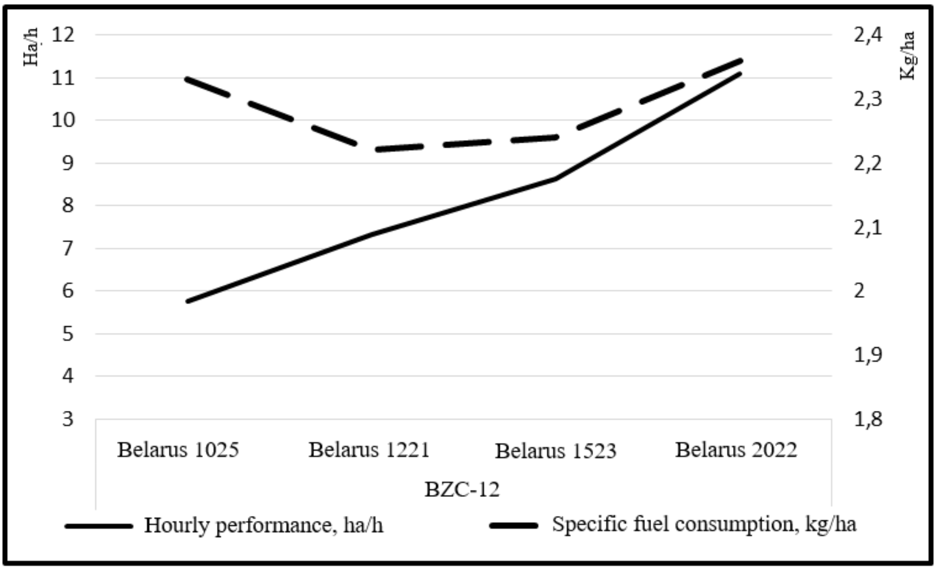

Fig. 6. Hourly productivity, specific fuel consumption of units consisting of: BZC-12 harrow with tractors Belarus.

Calculations for the unit consisting of a tooth chain harrow BZC-18.

Versatile 2375 + BZC-18. The technological operation can be performed on the transmission II4 – 14.1 km/h, with a tractive effort of 27.4 kN.

$W_H = 0{,}1\times0{,}955\times0{,}83\times0{,}75\times18\times14{,}1 = 15.1$ ha/h

$g_{HA} = \frac{44{,}05\times0{,}75+25{,}6\times0{,}25}{15{,}1} = \frac{33+6{,}4}{15{,}1} = 2.61$ kg/ha

The calculation results for BZC-18 for tractors Belarus 3522, K-700A, Versatile 320, K-744P1 are shown in Figure 7.

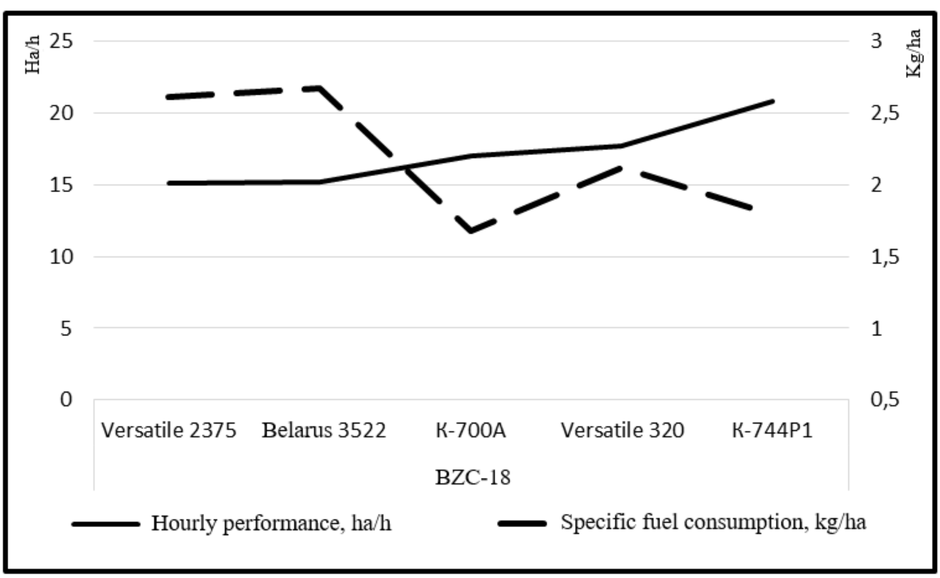

Fig. 7. Hourly performance, specific fuel consumption of units in the composition with the BZC-18 harrow.

From the calculations presented, it can be seen that the most optimal variant of the unit for carrying out the technological operation is the unit consisting of K-744R1 + BZC-18. The performance of this unit is 37.7% higher than that of the Versatile 2375 + BZC-18, and the specific fuel consumption is 31.4% lower.

Calculations for the unit consisting of a tooth chain harrow BZC-24.

K-744R1 + BZC-24. The technological operation can be performed on the transmission IV1 – 15.9 km/h, with a pulling force of 33.4 kN.

$W_H = 0{,}1\times0{,}955\times0{,}83\times0{,}75\times24\times15{,}9 = 22{,}7$ ha/h

$g_{\text{HA}} = \frac{41{,}5\times0{,}75+24{,}5\times0{,}25}{22{,}7} = \frac{31{,}1+6{,}12}{22{,}7} = 1{,}64$ kg/ha

The results of calculations for K-744P2, Versatile 395, Versatile 570 at an operating speed of 19 km/h (during experimental studies, the units consisting of BZC-18 and BZC-24 were tested at an operating speed of 19 km/h) are presented in Figure 8.

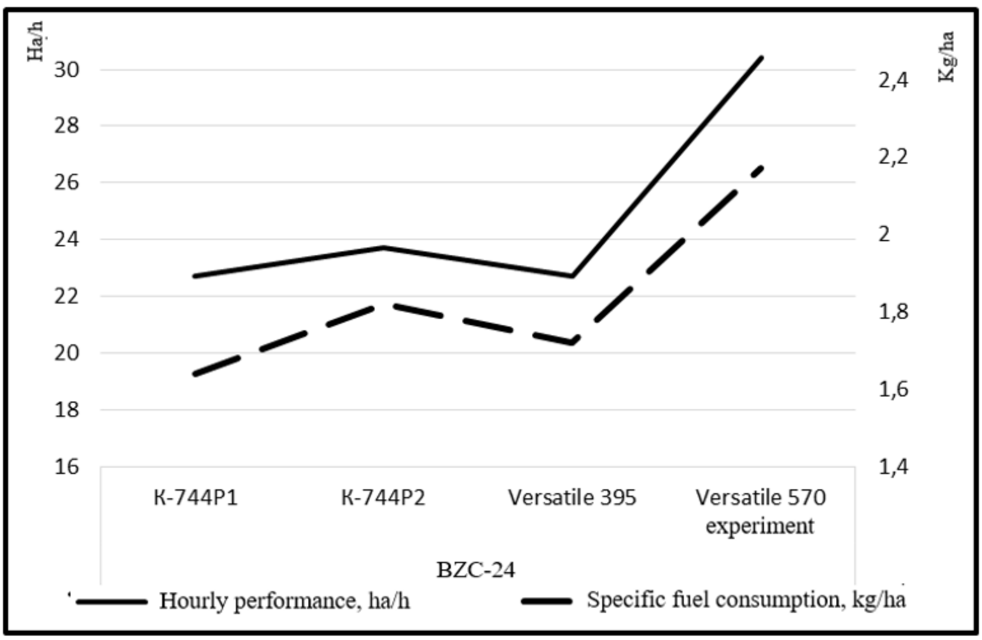

Fig. 8. Hourly productivity, specific fuel consumption of units in the composition with the harrow BZC-24

From the calculations presented, it can be seen that the most optimal variant of the unit for carrying out a technological operation is an aggregate consisting of K-744R1 + BZC-24 (without using the unit at an operating speed of 19 km/h). The performance of this unit is 4.2% lower than the unit composed of K-744R2 + BZC-24, but the specific fuel consumption is 9.9% lower, with the unit composed of Versatile 395 + BZC-24 has the same performance, the specific fuel consumption is 4.6% lower.

The authors also have studies on the formation of machine-tractor units in the implementation of resource-saving technologies in agricultural production [17, 18].

To compare and determine the economic efficiency of using tooth chain harrows, let's compare their technical and economic indicators with traditional harrowing units based on the tractors presented above: Belarus 2022, K-744R1 (Fig. 9).

The unit is part of Belarus 2022 + BGZ-12×2. Initial data: the resistivity of medium-tooth harrows is 0.55 kN/m, the operating weight without harrows is 2290 kg.

Traction resistance of BGZ-12×2.

$R_A = R_M + R_f = 15,9$ kN.

$R_M = kB_P = 0,55 \times 2 \times 12 = 13,2$ kN.

$R_f = fm_e = 0,12 \times 22,5 = 2,7$ kN.

The technological operation can be performed on the transmission II6 – 13.3 km/h, with a traction force of 18.8 kN.

$W_H = 0,1 \times 0,955 \times 0,81 \times 0,75 \times 12 \times 13,3 = 9,26$ ha/h

$g_{HA} = \frac{30,35 \times 0,75 + 13,75 \times 0,25}{9,26} = \frac{22,8 + 3,44}{9,26} = 2,83$ kg/ha.

The unit is composed of K-744R1 + BGZ-18×2. Initial data: operating weight without harrows – 4410 kg.

Traction resistance of BGZ-18×2.

$R_A = R_M + R_f = 25$ kN.

$R_M = kB_P = 0,55 \times 2 \times 18 = 19,8$ kN.

$R_f = fm_e = 0,12 \times 43,2 = 5,18$ kN.

The technological operation can be performed on the transmission IV1 – 15.9 km/h, with a pulling force of 33.4 kN. The coefficient of traction force utilization is 74.8%.

$W_H = 0,1 \times 0,955 \times 0,83 \times 0,75 \times 18 \times 15,9 = 17$ ha/h

$g_{HA} = \frac{38,8 \times 0,75 + 22,9 \times 0,25}{17} = \frac{29,1 + 5,72}{17} = 2,05$ kg/ha.

The unit is composed of K-744R1 + BGZ-24×2. Initial data: operating weight without harrows – 5614 kg.

Traction resistance of BGZ-24×2.

$R_A = R_M + R_f = 33$ kN.

$R_M = kB_P = 0,55 \times 2 \times 24 = 26,4$ kN.

$R_f = fm_e = 0,12 \times 55 = 6,6$ kN.

The technological operation can be performed on the transmission III4 – 13.8 km/h, with a traction force of 38.3 kN.

$W_H = 0,1 \times 0,955 \times 0,83 \times 0,75 \times 24 \times 13,8 = 19,7$ ha/h

$g_{HA} = \frac{41,5 \times 0,75 + 24,5 \times 0,25}{19,7} = \frac{31,1 + 6,12}{19,7} = 1,89$ kg/ha.

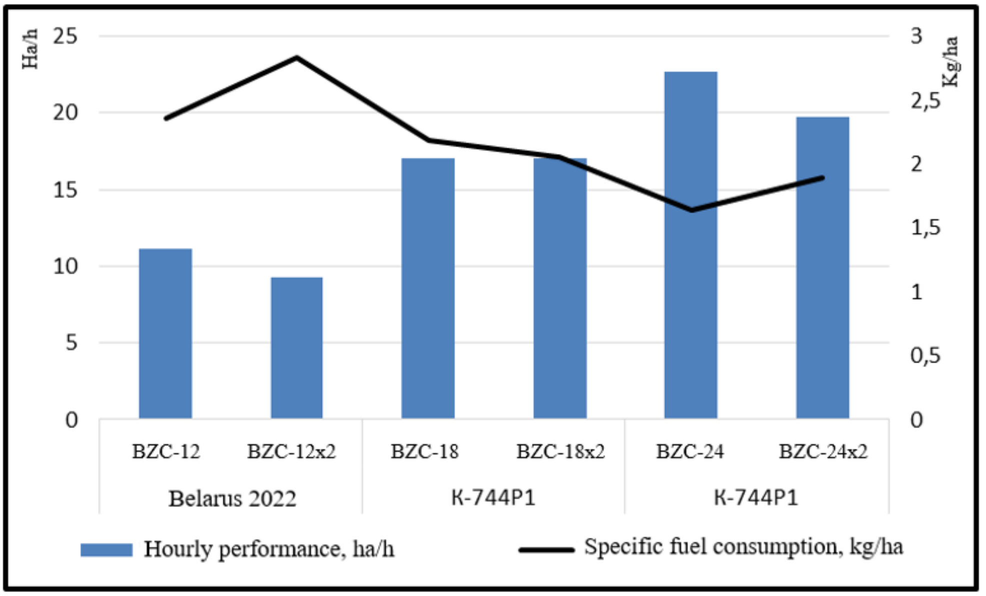

Fig. 9. Technical and economic indicators of the use of aggregates with tooth chain harrows, with traditional harrowing aggregates.

From the information obtained during the analysis and presented in Figure 9, the following can be seen: when using the unit as part of Belarus 2022 + BZC-12, the hourly performance is 19.9% higher, the specific fuel consumption is 16.6% lower than that of the unit as part of Belarus 2022 + BGZ-12×2; the units as part of tractor K-744P1 with harrows with a working width of 18 m - the hourly performance is the same, and the specific fuel consumption in the unit with BGZ-18×2 is 6.4% lower, due to the fact that the tractor's traction force is used by 74.8%; when using the unit as part of K-744P1 + BZC-24, the hourly performance is 15.2% higher, the specific fuel consumption is 13.2% lower than that of the unit consisting of K-744R1 + BGZ-24×2.

4 Conclusion

The use of "mini-till" technologies, in addition to reducing labor and financial costs, reduces the soil hardness, which favorably affects the optimal formation of machine and tractor units. In turn, the hardness is significantly influenced by density, humidity, and other factors. To comply with agrotechnical requirements, when performing technological operations for tillage, during sowing, it is necessary to consider the effect of soil hardness and working speed on the treatment depth. These factors must be considered when forming the MTU. As a result of experimental studies, it was revealed that an increase in the vertical component of the tractor's traction force will have an effect on reducing the treatment depth, with an increase in the working speed, an increase in the soil resistance force. Thus, during the technological operation, cultivation to a depth of 10 cm, with a hardness of 0.51 MPa, the processing depth will decrease by 13.7% or up to 8.63 cm when the working speed changes from 8 km/h to 14 km/h; at a hardness of 0.81 MPa – by 21.2%, up to 7.88 cm; at a hardness of 1.2 MPa – by 24.4%, up to 7.56 cm.

During experimental studies on the effect of working speed on the specific traction resistance at different soil hardness, the following was revealed: despite the deepening of the working bodies with an increase in working speed, the specific traction resistance, at a hardness of 0.51 MPa, with an increase in speed from 8 km/h to 14 km/h - increased by 12.3% or up to 1.91 kN/m; at a hardness of 0.81 MPa increased by 10.1%, from 1.58 kN/m to 1.74 kN/m (lower resistivity as a result of greater deepening of the working body with increased working speed, with increased hardness); at a hardness of 1.2 MPa increased by 12.9%, from 1.39 kN/m to 1.57 kN/m.

When using tooth chain harrows in minimal tillage systems, it must be considered that the agrotechnically permissible humidity for tillage, for all types of soils – from 13% to 22%, humidity for high-quality treatment, with a minimum resistivity - 15-17%.

When forming aggregates with a tooth chain harrow BZC-12, the best option is an aggregate consisting of a tractor Belarus 2022, with BZC-18 and BZC-24 - with a tractor K-744R1. In a comparative analysis of aggregates with tooth chain harrows, with traditional harrowing aggregates, it was revealed that the technical and economic indicators of the former exceed the indicators of traditional harrowing aggregates.

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