Energy assessment of intensive protective tillage

V V Shchirov, A Yu Nesmiyan and V I Khizhnyak

Azov-Black Sea Engineering Institute of the FSBEI HE «Don State Agrarian University»
21, Lenin st., Zernograd, Rostov region, 21347740, Russia

E-mail: nesmiyan.andrei@yandex.ru

Abstract. The study analyzes the traction resistance of chisel ploughs when working on light clayey chernozems, widespread in the arid southern part of Russia. This study allows concluding that in the theoretical description of the process of deep loosening of the soil, the influence of the square of the working speed of the machine-tractor unit could be neglected. The use of linear dependence not only provided an increase in the convergence of experimental and theoretical studies but also simplified the analysis of the results. So, for example, the use of a linear trim based on the results of experimental studies made it possible to derive the average values of the empirical coefficients for classic arrow-shaped plows: \( f_p = 0.4 \); \( k_p = 15.15 \text{kN/m} \) and \( \varepsilon_p = 6.15 \text{kN s/m}^2 \), and for plows with a pair-block arrangement of working bodies: \( f_p = 0.4 \); \( k_p = 21.45 \text{kN/m} \) and \( \varepsilon_p = 1.61 \text{kN s/m}^2 \). The study found that the use of a pair-block arrangement of working bodies on subsoiler ploughs, in comparison with their arrow-shaped arrangement, helps to reduce the resistivity during chiselling by about 14%. At the same time, the share of energy consumption for useful soil deformation increases to values of more than 80%, while for classic subsoiler ploughs this figure is about 50%.

1. Introduction
The level of efficiency of crop production technologies essentially depends on the qualitative and quantitative composition of the equipment used [1 – 3]. At the same time, for a long time, technologies based on the use of moldboard ploughs remained the most widespread. Embedding the plant mass in the soil allows, with a relatively low level of pesticide use, to ensure effective control of weeds, pests and pathogens. However, at the same time, it was noted long ago [4] that the use of the classical system of tillage, getting rid of stubble and more mass lead to the intensification of manifestations of both water and wind erosion, which mechanically destroys the most fertile part of the soil. Also, the removal of plant residues from the surface of the field leads to a gradual decrease in the level of humus in the soil, even though it has long been established: a decrease in the content of this substance in the soil by 0.1% reduces its ability to water retention by 0.5-0.6%, porosity by 1%, increases the bulk density by 0.01-0.02 kg/dm³ [5, 6]. Additional soil compaction is facilitated by the impact of agricultural machinery [7, 8].

The desire to solve these problems, combined with attempts to reduce the labour and energy intensity of crop production processes, has led to the increasingly widespread use of zero technologies, based on the principled rejection of any soil treatment (except for opening furrows during seeding). The presence of plant residues on the surface of the field reduces the likelihood of water and wind erosion, reduces the loss of soil moisture by evaporation and the degree of soil freezing in the cold season, and promotes the accumulation of organic matter.

However, no-till technologies are characterized by rather serious disadvantages:
- a sharp horizontal stratification of the soil in terms of density, moisture supply and nutrient content;
- decrease in soil porosity;
increasing contamination of fields and the number and toxicity of fungi;
- inability to apply the primary doses of mineral fertilizers;
- severe working conditions of seeding units and other disadvantages.

The adherents of applying zero technologies assume that all these disadvantages with the active use of pesticides are compensated by their advantages, primarily associated with the presence of plant residues on the surface of the field. At the same time, it has long been established that most of the listed shortcomings can be eliminated through the use of moldboard-free tillage systems. Moreover, both domestic and foreign designers have developed and introduced into production a diverse and multi-level complex of tools for moldboard-free tillage [3, 9 – 13].

Currently, one of the most promising groups of moldless tools is considered to be subsoiler ploughs or chisel ploughs. Nevertheless, there are certain disadvantages for deep moldboard-free loosening of the soil, of which the most obvious is the high-energy intensity of this process. So, for example, the analysis of the test protocols of tillage implements showed that when chiselling to a depth of 35 – 40 cm, the specific fuel consumption is about 10% higher than when processing the soil with moldboard ploughs to a depth of 22 – 25 cm, and 2 to 4 times exceeds this figure for disc implements and steam cultivators [3]. Thus, reducing energy consumption for deep loosening of the soil is an important task, the solution of which can be most efficiently achieved based on a reliable energy assessment of this process. In this regard, the goal of the presented study is to improve the methods for assessing the components of the traction resistance of chisel ploughs of various layout schemes.

2. Materials and methods
The need for the development and development of methods for assessing energy consumption during the primary tillage became aggravated in the late 19th – early 20th centuries due to the need to optimize the loading of agricultural tractors, which are becoming more and more widespread in production. Initially, the energy assessment of soil cultivation processes was carried out using experimentally determined indicators of specific resistance (N/m²). However, at the same time, many scientists noted that this method is too general and does not allow predicting the effect of specific parameters of tillage tools and their operating modes on energy consumption during soil cultivation. When considering the process of moldboard tillage, the founder of agricultural mechanics, Professor V.P. Goryachkin substantiated the use of a trinomial, which takes into account not only energy consumption for resistance to soil destruction but also other elements of energy consumption. Today, the formula proposed by him is considered a classic one. It is used, among other things, for an energy assessment of the process of soil chiselling (taking into account the correction of the empirical coefficients included in it). However, taking into account the development of the design of tillage tools, the diversity and variability of the physical and mechanical properties of soils, the increase in the working speeds of machine-tractor units, the dependences obtained by previous researchers, considered canonical, may not give an adequate result concerning specific production conditions.

This study is devoted to assessing the influence of the layout schemes of chisel ploughs on the energy consumption of the process of deep loosening of the soil. The assessment was carried out based on a comparative analysis of the test reports of subsoiler ploughs of a classic swept configuration (Figure 1) [11] and ploughed with a pair-block arrangement of working bodies (Figure 2) [12, 13].
In both cases, the data used in the comparative analysis were obtained on the example of the processing of low-humus light clayey chernozems, widespread in the southern steppe zones of the Russian Federation and the countries of eastern Europe [11 – 14]. This hypothetically allows assuming the uniformity of the main physical and mechanical properties of soils in the options under consideration, first of all, according to the most characteristic indicator affecting the traction resistance of the chisel tool – soil hardness (the difference in the average values was no more than 4%).

3. The study of base of data
Data processing of the test reports for chisel ploughs made it possible to form a database for further analysis (Table 1). In this case, the specific traction resistance per one meter of the width of the tool capture was taken as a universal output factor. This process made it possible to compare the performance indicators of implements aggregated with tractors of various traction classes. The total value of the traction resistance force was determined by strain gauging.

When forming the data in Table 1, the data of the preliminary study were taken into account. This study showed that when chisel ploughs are working, about 8% of the traction resistance is created by the roller, which accounts for almost a quarter (and in some structures more) the mass of the implement. In the presented study, only the mass and resistance of the plough itself were taken into account.

The initial analysis of the data in Table 1, carried out on the example of ploughs of a classical arrow-shaped layout, made it possible to conclude that in a theoretical description of the process of deep
loosening of the soil, the effect of the square of the working speed of the machine-tractor unit can be neglected. In this case, the value of the specific resistance of the chisel plough with sufficiently high accuracy (93 – 99%) can be described by the expression

\[ R_{sr} = f_p \cdot g \cdot M/V_t + k_p \cdot h + e_p \cdot h \cdot V_{tm} \]  

(1)

where \( f_p \), \( k_p \) and \( e_p \) are coefficients determined empirically.

**Table 1.** Database for the analysis of traction resistance of chisel ploughs of various layout schemes [11-13]

| Plough brand | \( h \), m | M, kg | Indicator | Experience |
|--------------|-----------|-------|----------|------------|
| PRB-4A       | 0.395     | 1480  | \( V_{tm} \), m/s | 1.86 1.94 2.08 |
| PRB-3        | 0.399     | 1105  | \( V_{tm} \), m/s | 1.78 1.86 2.03 |
| Chisel ploughs with a classic swept design of working bodies | | | | |
| PChM-4       | 0.434     | 1890  | \( V_{tm} \), m/s | 2.11 2.28 2.64 |
| PChP-0.7 KM  | 0.393     | 3255  | \( V_{tm} \), m/s | 1.50 1.83 2.17 |
| GChN-4.5B    | 0.449     | 2120  | \( V_{tm} \), m/s | 1.89 1.97 2.17 |
| PRB-3        | 0.399     | 1105  | \( V_{tm} \), m/s | 1.78 2.14 2.47 |
| GChN-4.5B    | 0.449     | 2120  | \( V_{tm} \), m/s | 1.89 1.97 2.17 |
| Chisel ploughs with a pair-block arrangement of working bodies | | | | |
| RVN-2        | 0.418     | 390   | \( V_{tm} \), m/s | 1.67 2.11 2.25 |
| RVN-3        | 0.441     | 930   | \( V_{MTA} \), m/s | 1.72 2.08 2.25 |

The following designations are adopted in Table 1: \( h \) – adjustment value of the depth of soil loosening, m; \( M \) is the mass of the subsoiler plough without taking into account the mass of the roller, kg; \( V_{tm} \) – working speed of the machine-tractor unit, m/s; \( R_{sr} \) – specific resistance of the subsoiler plough, kN/m.

The use of dependence (1) of the linear form not only provides an increase in the degree of convergence of experimental and theoretical studies (Figure 3a) but also simplifies the analysis of the results obtained, aimed at determining the empirical coefficients. For example, the generalization of the particular dependencies shown in Figure 3 an allowed obtaining the expression

\[ R_a = 2.46 \cdot V_{tm} + 7.74 \]  

(2)

This expression establishes the relationship between the values of the average specific traction resistance of subsoiler ploughs with a classic swept-type arrangement of working bodies on their working speed.
Figure 3. Dependencies of the influence of the speed of machine-reactor units on the specific traction resistance of subsoiler ploughs

Joint analysis of dependencies (1) and (2), with the adopted value $f_p = 0.4$, allows for light clay chernozems to establish the value of the other two empirical coefficients of equation (1): $k_{ch} = 15.15 \text{kN/m}$ and $e_{ch} = 6.15 \text{kN} \cdot \text{s/m}^2$.

It should be noted that dependence (1) is incomplete since it does not take into account the current technological state of the soil at the time of loosening, namely, such characteristics as moisture ($W, \%$) and hardness ($p, \text{MPa}$). A separate study showed that there is a significant correlation between the average values of these factors in a soil layer up to 50 cm deep, which, for example, for a light clayey low humus chernozem in a simplified form can be described by the dependence

$$R = -0.13W + 5.54$$

(3).

The presence of a stable relationship between these two factors allowed operating only one of them in the study, in our case – soil hardness, as a factor that most obviously affects the energy intensity of the process of its deep loosening.

Further analysis made it possible to reveal a direct correlation between soil hardness and its resistivity during deep loosening. However, the collected statistical material was not enough to confirm the reliability of this correlation. The resulting dependence, although it reflected the logical relationship between the hardness and resistance of the soil to loosening, however, was characterized by a slight degree of adequacy. The error rate when using it was over 80%. Moreover, an attempt to include this dependence in expression (1) led to a decrease in the reliability of the results obtained, an increase in the difference between theoretical and experimental data. This fact made it possible to dwell on formula (1) as the final expression for determining the specific traction resistance of subsoiler ploughs.

Joint analysis of equation (1) and expression (4) obtained by approximating experimental data for ploughs with a pair-block arrangement of working bodies, when

$$R_{sp} = 0.52 V_{tm} + 10.23$$

(4),

allows determining the value of the empirical coefficients included in equation (1) for the corresponding type of plows-subsoilers: $f_p = 0.4$; $k_{ch} = 21.45 \text{kN/m}$ and $e_{ch} = 1.61 \text{kN} \cdot \text{s/m}^2$. 

Further analysis was carried out by comparing the averaged calculated values of the elements of expression (1) for the investigated types of subsoiler ploughs, of which the most characteristic are presented in Table 2.

Table 2. Average calculated values of elements of expression (1) for deep-ripper ploughs with arrow-shaped and pair-block layouts of working bodies

| Indicators | \( x_{sk} \) | \( x_{pbk} \) | \( \frac{100(x_{pbk}-x_{sk})}{x_{sk}} \) \( \% \) | \( \frac{100x_{sk}}{R_{sr,sk}} \) \( \% \) | \( \frac{100x_{pbk}}{R_{sr,pbk}} \) \( \% \) |
|------------|---------------|--------------|---------------------------------|---------------------------------|---------------------------------|
| \( M, \text{kg} \) | 428.2         | 258.8        | -39.6                           | -                               | -                               |
| \( h, \text{m} \) | 0.41          | 0.43         | 4.9                             | -                               | -                               |
| \( V_{tm,cp}, \text{m/s} \) | 2.0           | 2.1          | 5.0                             | -                               | -                               |
| \( f_p \) | 0.4           | 0.4          | 0                               | -                               | -                               |
| \( k_{chr}, \text{kN/m} \) | 15.15         | 21.45        | 41.6                            | -                               | -                               |
| \( \varepsilon_{chr, \text{kN/s/m}^2} \) | 6.15          | 1.61         | -73.8                           | -                               | -                               |
| \( R_{sr,1}, \text{kN/m} \) | 1680          | 1016         | -39.5                           | 13                              | 9                               |
| \( R_{sr,2}, \text{kN/m} \) | 6212          | 9213         | 48.3                            | 48                              | 83                              |
| \( R_{sr,3}, \text{kN/m} \) | 5043          | 864          | -82.7                           | 39                              | 8                               |
| \( R_{sr}, \text{kN/m} \) | 12935         | 11093        | -14.2                           | 100                             | 100                             |

In Table 2, the following designations were adopted: \( x_{sk} \) – the value of the indicator for a plough with an arrow-shaped arrangement of working bodies; \( x_{pbk} \) – the value of the indicator for a plough with a pair-block arrangement of working bodies; \( R_{sr,i} \) – the corresponding component of the trim (1), kN/m.

It should be noted that the data in Table 2 were obtained with a relatively small number of investigated tools, especially tools with a pair-block layout of working bodies. Improving the quality of the results achieved requires further study of the presented research and production issue. Nevertheless, analysis of the data in Table 2 allows drawing several preliminary conclusions.

The arrangement of the working bodies on the subsoiler plough frame not only affects the indicators of its traction resistance but also significantly determines the ratio of its main components.

Tools with a pair-block arrangement of working bodies on subsoiler ploughs, in comparison with the arrow-shaped arrangement of working bodies, helps to reduce the resistivity during chiselling by about 14%.

The use of tools from tools with a pair-block arrangement of working bodies allows reducing the proportion of harmful resistance (the first component of the trim (1)) with the deep loosening of the soil by almost 40%. First of all, this is due to a proportional decrease in the specific mass of the tool, since tools with a pair-block arrangement of working bodies, while maintaining the working width of the tool, provides a significant reduction in the transverse size of its frame structure.

The use of tools with a pair-block arrangement of working bodies on subsoiler ploughs leads to a more than 80% decrease in the speed resistance of the soil (which does not have a beneficial effect on soil deformation) to processing. At the same time, the useful component of the trim (1) increases by almost 1.5 times.

In total, the use of tools with a pair-block arrangement of working bodies leads to an increase in the efficiency of useful soil deformation up to values of more than 80%. In comparison, for subsoiler ploughs with a swept-type arrangement of working bodies, this figure is about 50%.

4. Conclusion

The theoretical assessment of the resistance of the soil during its deep loosening is a demanded element of agricultural science, both for reducing the energy consumption for performing this operation and for justifying the rational loading of tractors used with ploughs. Today, for the energy assessment of the soil chiselling process, the trine of Professor V.P. Goryachkin, taking into account the correction of the empirical coefficients included in it. However, the analysis of the test reports for chisel ploughs with a classic arrow-
shaped arrangement of working bodies made it possible to conclude that in a theoretical description of the process of deep loosening of the soil, the effect of the square of the working speed of the machine-tractor unit can be neglected. The attempt to take into account in the trim used the effect of soil hardness on its specific resistance to loosening had to be abandoned, due to the high degree of variability (instability) of the experimental data obtained. The use of linear dependence not only provided an increase in the convergence of experimental and theoretical studies but also simplified the analysis of the results. So, for example, the use of a linear trim based on the results of experimental studies made it possible to derive the average values of the empirical coefficients for classic arrow-shaped plows: \( f_n = 0.4; \ k_n = 15.15 \text{ kN/m} \) and \( e_n = 6.15 \text{ kN/s/m}^2 \), and for plows with a pair-block arrangement of working bodies: \( f_n = 0.4; \ k_n = 21.45 \text{ kN/m} \) and \( e_n = 1.61 \text{ kN/s/m}^2 \). It should be noted that the results were obtained with a relatively small number of tools studied, especially tools with a pair-block arrangement of working bodies. Nevertheless, their analysis allows making a preliminary assessment of the influence of the arrangement of working bodies on the rationality of energy consumption during deep loosening of the soil. So, for example, by analyzing the equations obtained, it was found that the use of a pair-block arrangement of working bodies on subsoiler ploughs, in comparison with their arrow-shaped arrangement, helps to reduce the resistivity during chiseling by about 14%. At the same time, the share of energy consumption for useful soil deformation increases to values of more than 80%, while for classic subsoiler ploughs this figure is about 50%.

References
[1] Shevtsov V, Lavrov A, Izmailov A and Lobachevskii Y 2015 Formation of quantitative and age structure of tractor park in the conditions of limitation of resources of agricultural production SAE Technical Papers vol. 2015-September, pp 1-4
[2] Mudarisov S G, Gabitov I I, Rakhimov R S, Lobachevskiy Y A, Mazitov N K, Rakhimov Z S, Rakhimov I R, Galimov A L, Yamaletdinov M M and Mukhametdinov A M 2019 Reasoning of modular-type tillage and seeding machines construction diagram and parameters Journal of the Balkan Tribological Association 25(3) 695-707
[3] Nesmiyan A Y, Chernovolov V A, Semenihin A M, Zabrodin V P and Nikitchenko S L 2018 Crop production efficiencies Research on Crops 19 (3) 560-567.
[4] Edward H. Faulkner 1943 Plowman’s Folly (the University of Oklahoma Press Publishing Division of the University)
[5] Bondarenko A M, Kachanova L S, Lipkovich E I, Seregin A A and Gleichikova N A 2017 Organizational and economic mechanism of fertilizer application technology management as a basis for region’s progressive development Journal of Environmental Management and Tourism 8 (5) 1096-1104
[6] Bondarenko A M, Kachanova L S and Lipkovich E I 2018 Control of technological processes of organic fertilizers application as a tool to ensure food safety Journal of Environmental Management and Tourism 9 (1(25)) 5-11
[7] Mudarisov S, Gainullin I, Gubitov I, Hasanov E and Farhutdinov I 2020 Soil compaction management: reduce soil compaction using a chain-track tractor Journal of Terramechanics 89 1-12.
[8] Lipkovich E I, Nesmiyan A Y, Nikitchenko S L, Schedrivo V V and Kormiltsev Y G 2020 Agricultural tractors of the fifth generation Scientia Iranica 27(2) 745-756. DOI: 10.24200/sci.2018.50339.1643.
[9] Mudarisov S G, Gubitov I I, Lobachevsky Y P, Mazitov N K, Rakhimov R S, Khamaletdinov R R, Rakhimov I R, Farkhutdinov I M, Mukhamedtadinov A M and Gareev R T 2019 Modeling the technological process of tillage Soil & Tillage Research 190 70-77
[10] Ovchinnikov A S, Mezheva A S, Fomin S D, Pleskachev Y N, Borisenko I B, Vorontsova E S, Zvolinskij V P, Tyutyuma N V and Novikov A E 2017 Energy and agrotechnical indicators in the testing of machine-tractor units with subsoiler ARPN Journal of Engineering and Applied Sciences 12(24) 7150-7160
[11] The database of the test results of agricultural equipment, available at: http://sistemamis.ru/protocols. The date of circulation: 11.10.2018.

[12] Zhidkov G A, Kalyuzhny A V, Belyi I F, Bobryashov A P, Khlystov E I and Shchirov V V 2014 Protocol No. 11-42-14 (1010042) of December 16, 2014, acceptance tests of the plow-ripper RVN-3 (Zernograd)

[13] Zhidkov G A, Kalyuzhny A V, Belyi I F, Bobryashov A P, Khlystov E I and Shchirov V V 2015 Protocol No. 11-15-15 (4010072) of November 9, 2015, acceptance tests of the RVN-2 moisture-saving cultivator (Zernograd)

[14] Kireev I M, Koval Z M and Zimin F A 2014 Devices for determining the relief and micro-relief of a field plot Measurement Techniques 57(8) 879-883