Experimental determination of field microrelief ridgeness after secondary tillage with Stepnyak 7.4 cultivator

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Abstract. Four wheels are installed on the frame in the front part, the rear part of the frame is supported by two rows of rollers to ensure stable operation of the Stepnyak-7.4 cultivator in depth and maintain the required ridgeness of the soil field. The speed of movement of the unit, the depth and the running uniformity of working tools, and the traction resistance of the machine depend on the ridgeness and microrelief of the field. A priori ranking of factors of the cultivator’s operation revealed that the most significant factors in studying the ridgeness of the cultivated soil are the speed of movement of the unit $V_u$, the diameter of the rolling basket drum $D_{rb}$ and the setting angle of the scraper $\gamma$. The variation levels of natural factors are established and values of coded values of factors are calculated. An orthogonal central composite design was used to design the experiments. Based on the results of experimental data processing, a mathematical model of field ridgeness variation after processing depending on the varied factors is obtained, and rational ranges of operational parameters are determined. The studies revealed that the minimum ridgeness of the field soil is achieved with a rolling basket diameter of 0.40-0.45 m and an inclination angle of the scraper bend of 75-80 degrees with a unit speed ranging from 2.8 to 3.2 m/s.

1. Introduction

Soil treatment is the main method of regulating soil regimes and maintaining its good phytosanitary condition. To grow plants and microflora, the soil shall have an aggregate structure thus creating favorable conditions for water, air, nutrient and thermal modes. The main task of soil treatment is to create favorable conditions for uniform distribution and germination of seeds with minimum losses of soil moisture. These conditions are ensured by high stability of the running depth of a working tool, the required structure of the topsoil, the absence of ridgeness and the removal of moist soil to the daylight surface, and, at the same time, the tillage unit shall operate at high speeds thus increasing the productivity by 30-40%. The microrelief of the field section is critical among the technological indicators of tillage equipment. It determines the speed of the unit, depth and uniformity of the working tools, quality of soil cultivation, traction resistance, uniformity and depth of seeding-down. Testing of the equipment takes into account the microrelief with small relative fluctuations of the soil surface within 0.05...0.15 m.

Combined tillage units with rollers of various designs are currently used to ensure the required ridgeness of the field [1–3].
Microrelief contributes to uneven development and formation of crop yields, therefore, agrotechnical assessment of microrelief of a field section is quite relevant after the tillage unit treatment, which characterizes its high-quality technological capabilities in typical zonal conditions under optimal and permissible limit operating modes [4].

The quality analysis of soil treatment with domestic tillage machines shows that in the conditions of risky agriculture in Western Siberia they are quite comparable with imported ones in terms of ensuring the quality indicators of the treated surface, such as field uniformity, cloddiness, ridgeness, soil pulverization, weed removal, and in terms of the quality-price ratio they are more affordable for agricultural producers [5, 6]. Despite this it is necessary to further improve the soil system, simplify the design and reduce the variability of the ridgeness treatment depth [7, 8].

One of the actively used combined tillage units is Stepnyak-7.4 (Fig. 1) by Omsk Experimental Plant. Stepnyak-7.4 is designed for continuous secondary and underwinter tillage, killing of weeds with the maximum preservation of stubble field and other residues treated with flat-cut and beardless plowing for spring, vegetable and arable crops. The sowing width of the studied combined tillage unit was 7.4 m. It is aggregated with tractors of the drawbar category 50 kN. The cultivator represents a wide-coverage pull-type machine with a hinged-sectional frame and a three-row arrangement of working tools [4].

![Stepnyak-7.4 combined tillage unit](image1)

**Figure 1.** Stepnyak-7.4 combined tillage unit

Next to duckfoot teeth there are sections with two rows of rollers: travelling and rolling. They pulverize the clods of soil and smoothen the field surface after treatment with duckfoot teeth [6].

The scheme of the rolling basket is shown in Figure 2.

![Scheme of the rolling basket](image2)

**Figure 2.** Scheme of the rolling basket:
1 – disk; 2 – strip-scraper; $D_r$ – roller diameter; $L_s$ – scraper height; $\gamma$ – setting angle of a scraper in circumferential direction; $\beta$ – setting angle of a scraper in longitudinal direction
The tilling depth is ensured by gage wheels. In existing designs they are placed at a considerable distance from the working tools, which does not allow for high stability of their movement. Four wheels are installed on the frame in the front part, the rear part of the frame is supported by two rows of rollers to ensure stable operation of the Stepnyak-7.4 cultivator in depth and maintain the required ridgeness of the soil field.

The mathematical model of field ridgeness variation after processing with Stepnyak-7.4 is obtained. Reasonable ranges from operational parameters \( D_{rb} \), \( \gamma \) and unit speed are determined.

It was found that the use of the field experiment and processing of its results may be used in production conditions to determine the speed of the unit, select the diameter of the rolling basket and set the angle of a scraper.

The purpose of the study is to search for rational operating modes and parameters of the rolling basket of Stepnyak cultivator, which affect the ridgeness of the field surface.

2. Materials and Methods

The field studies were carried out in accordance with the requirements of STO AIST 4.6-2003 and STO AIST 4.2-2004, GOST 33687-2015.

The field studies were carried out in the field area ensuring the implementation of the entire complex provided for in the research program. The required number of experiments was determined from the condition of obtaining an error not exceeding 5% with a confidence probability of 80%.

The equipment was adjusted and balanced:

- • cultivator working tools – according to the recommendations of the operating manual;
- • measuring tools and equipment – according to GOST 8.002-86.

The soil is leached medium chernozem, in terms of mechanical composition – medium loamy, soil moisture at the running depth – 15%. Besides, physical and mechanical properties of soil before treatment and size-distribution before and after treatment were determined. The equipment shown in Figure 3 was used to evaluate the solid phase of the soil (dispersed aggregate composition, physical-mechanical, physical properties [9–11].

![Figure 3](image)

**Figure 3.** Equipment to determine physical and mechanical properties of soils: a – Revyakin soil hardness tester; b – exicator; c – set of sieves; d – moisture tester

Soil hardness was determined by method [12] using Revyakin soil hardness tester (Figure 3a). The device to determine the soil moisture is shown in Figure 3d.

Humidity measurements were performed to a depth of up to 20 cm in five-fold repetition. The thermogram data were recorded in the observation log and processed on a personal computer according to the standard procedure [12].

A priori ranking of factors of the cultivator’s operation revealed that the most significant factors in studying the ridgeness of the cultivated soil are the speed of movement of the unit \( V_a \), the diameter of the rolling basket drum \( D_{rb} \) and the setting angle of the scraper \( \gamma \).

The field surface ridgeness and microrelief were determined using a cross-bar rack. When determining the profile before the test machine passed through the field, two pins with height-adjustable groves were placed on the registration plot, on which a rail with divisions was placed on
level in a horizontal position. The transverse profile of the field surface (perpendicular to the movement) and longitudinal (in the direction of movement) were determined after the cultivator passed through the field. The distance to the soil surface was measured from the upper side of the coordinate rack every 10 cm with an error of ±1.0 cm. The transverse profile was determined for the entire width of the machine grip, the longitudinal profile was determined on a 5 m long section. Based on the results of the measurements, the transverse and longitudinal profiles of the section were drawn [13].

The field area on which the tests were carried out consisted of two parts – measuring and acceleration sections. The acceleration section was 25 m long, and the measuring section was 200 m. The required speed of the unit was set on the acceleration section. Three tillage rates were used during the experiment – 9, 11 and 13 km/h. The tractor speed was measured by a stop-watch timer upon passing the control points of the 30 m section [13, 14].

3. Results and Discussion
The experiments were carried out using an orthogonal central composite design. Before the experimental plan was designed the factors were encoded according to the formula:

\[ X_i = \frac{x_i - \bar{x}_i}{\Delta x_i} \]  

where \( X_i \) – encoded factor value;
\( x_i \) – natural factor value;
\( \bar{x}_i \) – average (zero) value of \( i \) natural factor;
\( \Delta x_i \) – semi-difference of the maximum and minimum values of \( i \) natural factor.

The variation levels of coded and natural factors are shown in Table 1.

| Table 1. Levels of factor variation |
|-------------------------------------|
| Factor / value | Running speed, m/s | Drum diameter, m | Scraper setting angle, deg. |
|----------------|-------------------|------------------|-----------------------------|
| Coded (non-dimensional) | \( X_1 \) | \( X_2 \) | \( X_3 \) |
| -1 | 0 | +1 | -1 | 0 | +1 |
| Natural | \( V_a \), m/s | \( D_{rb} \), m | \( \gamma \), deg. |
| 2.50 | 3.05 | 3.61 | 0.30 | 0.40 | 0.50 |
| 30 | 60 | 90 |

The experimental plan matrix is shown in Table 2.

The experiments were carried out in three-fold repetition. To eliminate the accuracy error, the experimental procedure was randomized. The speed in accordance with the given plan was set at the acceleration section.

The results of multifactorial experiment were processed according to the methods of planning and mathematical statistics using special computer programs [15, 16].
Table 2. Field experiment matrix

| Type of points within factor space | X₀ | X₁ | X₂ | X₃ | X₁X₂ | X₁X₃ | X₂X₃ | X₁X₂X₃ | X₁² | X₂² | X₃² |
|---------------------------------|----|----|----|----|------|------|------|--------|------|------|------|
| CFE points ±1                   | 1  | 1  | -1 | -1 | -1   | 1    | 1    | -1     | 0.27 | 0.27 | 0.27 |
|                                 | 2  | 1  | 1  | -1 | -1   | -1   | 1    | 1      | 0.27 | 0.27 | 0.27 |
|                                 | 3  | 1  | -1 | 1  | -1   | 1    | -1   | 1      | 0.27 | 0.27 | 0.27 |
|                                 | 4  | 1  | 1  | 1   | -1   | 1    | -1   | -1     | 0.27 | 0.27 | 0.27 |
|                                 | 5  | 1  | -1 | 1   | 1    | -1   | -1   | 1      | 0.27 | 0.27 | 0.27 |
|                                 | 6  | 1  | 1  | -1 | 1    | -1   | 1    | -1     | 0.27 | 0.27 | 0.27 |
|                                 | 7  | 1  | -1 | 1   | 1    | -1   | 1    | -1     | 0.27 | 0.27 | 0.27 |
|                                 | 8  | 1  | 1  | 1   | 1    | 1    | 1    | 1      | 0.27 | 0.27 | 0.27 |
|                                 | 9  | 1  | -1.21 | 0 | 0   | 0   | 0   | 0       | 0.27 | 0.27 | 0.27 |
|                                 | 10 | 1  | 1.21 | 0 | 0   | 0   | 0   | 0       | 0.75 | -    | -    |
|                                 | 11 | 1  | 0   | -1.21 | 0 | 0   | 0   | 0       | -    | 0.75 | -    |
|                                 | 12 | 1  | 0   | 1.21 | 0 | 0   | 0   | 0       | -    | -    | 0.73 |
|                                 | 13 | 1  | 0   | 0   | -   | 0   | 0   | 0       | -    | -    | 0.73 |
|                                 | 14 | 1  | 0   | 0   | 1.21 | 0 | 0   | 0       | 0.73 | 0.73 | 0.73 |
|                                 | 15 | 1  | 0   | 0   | 0   | 0   | 0   | 0       | 0.73 | 0.73 | 0.73 |

The second order polynomial was chosen as the mathematical model of the response function [17]:

\[ y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n-1} \sum_{j>i}^{n} X_i X_j + \sum_{i=1}^{n} b_{ii} X_i^2 \]

where \( b_0, b_i, b_{ii} \) – polynomial coefficients; \( X_i, X_j \) – values of factors in coded form.

For a three-factor experiment, the regression equation is as follows:

\[ y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{123} X_1 X_2 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 \]  (2)

The homogeneity of variance of obtained results at each point of the experiment plan was checked by the Cochran’s Q Test [17].

The error of replicate experiments of one series was evaluated according to Student’s test [17].

The results of the experiment were processed according to the procedure described in the works [17].

The adequacy of the mathematical model was tested according to the Fisher’s criterion [17].

The mathematical model adequately describes the real process if the following condition is met:

\[ F_{\text{cal}} < F_{\text{tab}} \]  (3)
where $F_{\text{cal}}$, $F_{\text{tab}}$ – calculated and tabulated value of the Fisher’s criterion, respectively.

Optimization of basic parameters and mode of combined tillage unit.
After all experiments were completed, the results were recorded in Tables 3 for further analysis.

**Table 3. Results of the planning matrix (optimization criterion – soil ridgeness, %)**

| No. of experiment | Factor | Response |
|-------------------|--------|----------|
|                   | $X_1$ | $X_2$ | $X_3$ | $Y_1$ | $Y_2$ | $Y_3$ | $Y_{av}$ |
| 1                 | -1    | -1    | -1    | 2.8   | 2.7   | 2.9   | 2.8 |
| 2                 | 1     | -1    | -1    | 5.1   | 5.0   | 4.6   | 4.9 |
| 3                 | -1    | 1     | -1    | 2.0   | 2.3   | 2.0   | 2.1 |
| 4                 | +1    | 1     | -1    | 4.7   | 4.2   | 4.9   | 4.6 |
| 5                 | -1    | -1    | 1     | 1.8   | 1.7   | 1.6   | 1.7 |
| 6                 | 1     | -1    | 1     | 4.5   | 4.4   | 4     | 4.3 |
| 7                 | -1    | 1     | 1     | 1.1   | 1.0   | 1.2   | 1.1 |
| 8                 | +1    | 1     | 1     | 3.4   | 3.5   | 3.9   | 3.6 |
| 9                 | -1.215| 0     | 0     | 0.6   | 0.8   | 0.7   | 0.7 |
| 10                | 1.215 | 0     | 0     | 3.5   | 3.4   | 3.6   | 3.5 |
| 11                | 0     | -1.215| 0     | 1.8   | 1.9   | 2.3   | 2.0 |
| 12                | 0     | 1.215 | 0     | 0.9   | 1     | 1.1   | 1 |
| 13                | 0     | 0     | -1.215| 3.0   | 3.3   | 3.3   | 3.2 |
| 14                | 0     | 0     | 1.215 | 2.0   | 2.0   | 1.7   | 1.9 |
| 15                | 0     | 0     | 0     | 0.9   | 0.8   | 1.0   | 0.9 |

The calculated value of the Cochran’s Q Test – $G_{\text{cal}}=0.2564$.
The tabulated value of the Cochran’s Q Test at $k_1=3$ and $k_2=11$ at $\gamma=0.05$ equals $G_{\text{tab}}=0.3346$. Since the calculated value of the Cochran’s Q Test is less than the tabulated one, the hypothesis of the homogeneity of replicate experiments at the significance level of $\gamma=0.05$ is accepted.

To assess the significance of each coefficient, the following condition was checked:

$$|b| > \Delta b,$$

where $b$ – value of the regression coefficient to modulo; $\Delta b$ – value of the confidence interval.
If condition (4) is met, then the coefficient is considered statistically significant.

The field experimental study on soil surface uniformity made it possible to obtain the mathematical models:
- in coded form:

$$Y_{fp} = 2.011 + 1.2346X_1 - 0.3341X_2 - 0.4625X_3 + 0.34X_1X_2 + 0.0024X_1X_3 - 0.001X_2X_3 +$$
$$0.8204X_1^2 + 0.3631X_2^2 + 0.5798X_3^2 \quad (5)$$

- in natural form:

$$\Gamma fp = 63.1952 - 438256V_A - 17.244D_{nk} - 0.0609\gamma + 1.2143V_A D_{nk} + 0.00008V_A \gamma -$$
$$0.00029D_{rb}\gamma + 8.5384V_A^2 + 13.1842D_{rb}^2 + 0.000374\gamma^2 \quad (6)$$

- optimization criterion – surface uniformity (SU).
To move from a model in coded form to a model in natural values of factors, the formula (1) of moving from natural to coded values was used, which made it possible to obtain the following equations:

\[
X_1 = \frac{V_A - \bar{V}_A}{\Delta V_A} \tag{7}
\]

\[
X_2 = \frac{D_{rb} - \bar{D}_{rb}}{\Delta D_{rb}} \tag{8}
\]

\[
X_3 = \frac{\Delta \theta}{\Delta \alpha} \tag{9}
\]

The adequacy of the obtained models was tested according to the Fisher’s criterion:

\[
F_{c_{al}} = \frac{S_{A_{c}}^2}{S^2(y)} \tag{10}
\]

where \(S_{A_{c}}^2\) – adequacy variance;
\(S^2(y)\) – error mean square.

The adequacy variance was determined by the formula [26]:

\[
S_{A_{c}}^2 = \frac{\Gamma}{N-\lambda} \sum_{u=1}^{n} (\bar{y}_{u} - \bar{y}_{u})^2 \tag{11}
\]

where \(\Gamma\) – number of replicate experiments;
\(N\) – number of independent experiments;
\(\lambda\) – number of significant coefficients of equation (5);
\(\bar{y}_{u}\) – average value of response function in \(u\) experiment;
\(\hat{y}_{u}\) – value of response function in \(u\) experiment obtained during the calculation according to formula (5).

The error mean square was determined by the formula:

\[
S^2(y) = \frac{1}{N} \sum_{t=1}^{n} s_t^2 \tag{12}
\]

The tabulated value of the Fisher’s criterion was determined at coefficients \(k_1=3\) (number of factors); and \(k_2=N-n-1=15-3-1=11\), where \(n\) is the number of factors. The adequacy of the model is confirmed: \(F_{c_{al}}=1.644\), and the tabulated value \(F_{tab}=3.59\) at the significance level \(\gamma=0.05\).

To estimate the extreme values of factors, partial derivatives according to \(X_i\) were taken and equated to zero. As a result, the following extreme values of factors were obtained:

\[X_1^* = -0.7523 = 2.57 \text{ m/s}; X_2^* = 0.46 = 0.454 \text{ m}; X_3^* = 0.5798 = 78.03 \text{ degrees}.\]

With these values, the ridgeness of soil surface uniformity makes 1.5...2 cm.

To assess the effect of individual factors \(X_i\) on the ridgeness of the soil surface, the equation (5) was solved at the given factor values, and the remaining factors were taken at zero level. Thus, for factor \(X_i\), the following equation was obtained:

\[Y_{deg} = 2.011 + 1.2346X_1 + 0.8204X_1^2 \tag{13}\]

Figure 4 shows the dependence of the field surface ridgeness on the machine speed, rolling basket diameter and scraper setting angle.
Figure 4. a) dependence of surface ridgeness on machine speed; b) dependence of surface ridgeness on rolling basket diameter; c) dependence of surface ridgeness on scraper setting angle

The analysis of the curve in Figure 4a allows determining the rational speed of the machine-tractor aggregate based on the required minimum field ridgeness. The recommended speed $V_a$ is in the range of 2.61 to 2.73 m/s (speed interval indicated in the graph). The rational value – 2.64 m/s.

The dependence analysis in Figure 4b reflects the effect on the uniformity of the field surface after machining and allows determining the rational diameter of the rolling basket. The recommended diameter $D_{rb}$ ranges from 0.42 to 0.46 m (rational value – 0.454 m). The size range of the roller is highlighted in the graph.

The dependence of surface uniformity on the scraper setting angle is shown in Figure 4c. The analysis of the graph shows that the rational scraper setting angle based on the required ridgeness of the treated field is in the range from 70 to 80 degrees. The rational value – 78 degrees.

The curves in the graphs show that the diameter of the rolling basket and the scraper setting angle have the greatest influence on the optimization criterion.

The dependence of the soil surface ridgeness on the machine speed and the diameter of the rolling basket is shown in Figure 5.
The analysis of the graph illustrating the combined effect of the machine speed and the diameter of the rolling basket shows that the area corresponding to the minimum field ridgeness (1-2 cm) is limited by the speed range from 2.8 to 3.2 m/s and the diameter of the rolling basket from 0.35 to 0.45 m.

The dependence of the ridgeness of the soil surface on the machine speed and the scraper setting angle is shown in Figure 6.

The analysis of the graph in Figure 6 illustrating the combined effect of the machine speed and the diameter of the rolling basket shows that the area corresponding to the minimum field ridgeness (1-2 cm) is limited by the speed range from 2.8 to 3.2 m/s and the scraper setting angle from 75 to 80 degrees.

The dependence of the soil surface ridgeness on the diameter of the rolling basket and the scraper setting angle is shown in Figure 7.

The analysis of the graph in Figure 7 shows that the area corresponding to the maximum uniformity of the field is limited by the range of changes in the diameter of the rolling basket from 0.40 to 0.45 m and the scraper setting angle from 75 to 80 degrees. The diameter of the rolling basket amounting to...
0.43 m and the scraper setting angle amounting to 78 degrees may be recommended as the rational parameters.

4. Conclusion
The analysis of the field experiment and the processing of its results made it possible to obtain a mathematical model of changing the uniformity of the field surface after treatment with Stepnyak-7.4 cultivator. The calculations according to the mathematical model allowed determining the rational ranges of their operational parameters $D_b$, $\gamma$ and the machine speed. The minimum soil ridgeness of 1-2 cm is achieved with the diameter of the rolling basket from 0.40 to 0.45 m and the scraper setting angle of 75-80 degrees at the machine speed in the range from 2.6 to 2.78 m/s.

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