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DIFFERENTIATION OF THE COMPOSITION OF COMBINED SOIL-TILLAGE MACHINES DEPENDING ON THE CONDITIONS OF USE

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ABSTRACT

The authors propose an approach to complete a task that is important for agricultural production, while ensuring a specified quality index of soil cultivation with minimal energy and labor costs and maximum reduction of negative environmental impact on soil and the surrounding environment. This is done using combined machines with an optimal set of working bodies. Achieving this goal involves differentiating the composition of combined soil-tillage machines depending on their operating conditions based on a methodology that can be based on an algorithm for determining the overall quality index, mathematical models of the functioning of individual working bodies, and appropriate original software.

Introduction

The long-term use of traditional soil cultivation technologies leads to deterioration of their agrotechnical and physical-mechanical properties, reducing fertility (Abo Al-Kheer et al., 2011; Azizi et al., 2020; Vasylkovska et al., 2016). Therefore, analysis of trends in the development of various agricultural directions indicates that in most cases, preference should be given to soil protection technologies aimed at preventing wind and water erosion, preserving and increasing fertility, and protecting the environment. The basis of such technologies is no-till cultivation, which requires many various flat-cutting, chisel, disc and combined machines that, with their characteristic low energy consumption and high productivity, can ensure the necessary quality indicators of primary soil cultivation without spreading destructive processes in it (Abo Al-Kheer et al., 2010; Almaliki, 2018; Azimi-Nejadian et al., 2019; Celik et al., 2019; Chirende et al., 2019; Ebrahimi et al., 2018; Zeng et al., 2017; Zeng et al., 2020; Karaiev et al., 2021).

In this regard, a current issue today is not only the justification of the optimal parameters of individual working bodies (Abo Al-Kheer et al., 2011; Azizi et al., 2020; He et al., 2018; Leschenko, 2014), but also their types, quantities, and mutual arrangement during joint mechanical action within a machine capable of meeting the requirements for new energy-saving and environmentally safe no-till soil cultivation technologies (Leshchenko et al, 2014; Prem et al, 2016).

The effectiveness of various soil cultivation methods and the working bodies or machines for their implementation is their ability to create favorable soil conditions for increasing fertility and, consequently, for the germination of agricultural crops, which is highly dependent on the optimal aggregate composition, which any soil cultivation process should aim to form (Azizi et al., 2020; Prem et al., 2016). Usually, preference is given to combined machines that can perform a series of technological operations in one pass over the field, thereby reducing not only the overall energy and labor costs but also the negative impact on the soil and the surrounding environment.

Indexes of soil loosening are significantly influenced by their mechanical and technological properties, which reflect their mechanical composition. The soil cover is very diverse in mechanical composition and responds differently to cultivation by various working bodies. Under real conditions, at the stages of designing and manufacturing combined machines, this is not considered, and they are used with the same set of working bodies, at least in different soil-climatic zones. In some cases, on heavy soils, such tools do not ensure the necessary loosening indicators provided by agrotechnical requirements, necessitating repeated passes over the field by various machines and additional energy costs. In other cases, in light soils, excessive loosening occurs, destroying valuable agrotechnical aggregates, turning them dusty, and again increasing unjustified energy costs.

This article proposes an option to solve the presented problem by justifying the composition of combined soil-tillage tools depending on the soil-climatic conditions of their use in the initial stages of their design.

Materials and Methods

To achieve the set goal, it is necessary to complete a number of preliminary tasks:

- to develop an algorithm for predicting the overall soil loosening index by a combined machine, which may include various types of working bodies;
- to develop mathematical models for predicting the probabilistic indicators of soil loosening by individual working bodies of different types and structural features;

– to optimize the rational composition of combined machines for soils of different mechanical compositions, based on the developed software.

Combined machines may include not only different types of working bodies that ensure the final result of soil loosening, but also similar types that sequentially or alternately affect the soil. Tiered soil tillage machines are also known, where similar or different working bodies loosen the soil with different characteristics at different depths. In most cases, combined machines include main working bodies that ensure the maximum possible specified depth of cultivation and additional bodies whose task is to loosen the surface layers of the soil to a shallow depth (Jirigalantu et al., 2017; Lezhenkin et al., 2021). The functions of the main working bodies can be performed by plow bodies, chisel, flat cutting, and disc working bodies. Various types of rollers, harrows, etc. are used as additional working bodies (Van Capelle et al., 2012).

Let's consider fragments of solving set tasks using the example of a combined machine that includes a significant number of not only types of working bodies, but also options for their mutual arrangement in the horizontal and vertical planes - with tiered main working bodies in the form of flat cut heavy cultivator tines, with a possible set of additional working bodies - conventional tooth harrows, harrows with flat teeth and a blunt angle of entry into the soil, ribbed, ring, slatted, and spiked rollers (Jirigalantu et al., 2017).

When working with combined tools, the generally accepted soil loosening index C – the percentage content in the total volume of processed soil of aggregates of specified sizes – can be considered as the sum of the values of these indicators provided by the sequentially acting individual working bodies in the tool composition.

The general soil loosening index C3 with a single-tier sequential arrangement of working bodies will be determined as:

$$C_3 = \sum_{i=1}^{n} C_i \tag{1}$$

where:

C_i – the quality index of soil cultivation by individual working bodies;

n – the number of working bodies involved in soil loosening.

It is proposed to determine the quality index of soil loosening by one working body, expressed as a percentage, as follows:

$$\mathrm{C}_1 = \mathrm{P}_1 \cdot 100\% \tag{2}$$

where:

P_1 – is the probability of the soil being crushed into aggregates with sizes not exceeding the specified values, after the passage of the working body.

Soil aggregates whose sizes exceed the allowed value must be crushed to the specified sizes by subsequent working bodies. The relative index of the content of such aggregates in the soil after processing by the first working body will be $1 - P_1$.

Thus, the quality index of the soil crushing by the second working body will be determined as:

$$\mathrm{C}_2 = (1 - \mathrm{P}_1) \cdot \mathrm{P}_2 \cdot 100\% \tag{3}$$

where:

P_1 i P_2 – are the probabilities that after the passage of the first and then the second working body, the soil aggregates of the specified size will be crushed to the sizes provided by agrotechnical requirements.

Similarly, the soil loosening index is determined for subsequent working bodies.

When working as part of a combined tool with tiered and simultaneously and independently acting working bodies at different depths (in our case, flat-cutting, provided that different soil layers are loosened at different depths but with the same geometric parameters, i.e., $h_1 = h_2 = h_3 \ldots$), the overall soil crushing index will be determined by the expression:

$$C^{п}_{3Яр} = P_{я} \cdot 100\% = \left[\frac{\sum_1^{п} P_{iя}}{п}\right] \cdot 100\% \quad (4)$$

where:

$P_{я}$ – the probability that after the passage of all tiered working bodies, the soil will be crushed into aggregates whose sizes do not exceed the specified agrotechnical requirements;

$P_{iя}$ – the probability that after the passage of the (i)-th tiered working body, the soil will be loosened into aggregates whose sizes do not exceed the specified agrotechnical requirements;

n – the total number of tiered working bodies.

Then the overall quality index of soil loosening by a combined machine, in which the first to contact the soil are tiered working bodies, and then other working bodies sequentially act on the already partially loosened soil, can be determined by the expression:

$$C^{п}_{з} = [P_{я} + (1 - P_{я}) \cdot P_1 + (1 - P_{я} - P_1)P_2 + \ldots + (1 - P_{я} - P_1 - \ldots - P_{n-2}) \cdot P_{n-1} + \\ +(1 - P_{я} - P_1 - \ldots - P_{n-2} - P_{n-1}) \cdot P_n] \cdot 100\% \quad (5)$$

It is obvious that to implement such an algorithm, it is necessary to have analytical dependencies of the probability index of soil loosening for all types of working bodies, taking into account their structural parameters, mechanical and technological properties of the soil environment, kinematic and technological features of the technological process (Jiang et al., X, 2020; Ranjbar et al., 2013; Renon et al., 2005).

Thus, as a result of the theoretical study (using elements of queuing theory), a mathematical model of the soil crushing by a flat-cutting cultivator tine index was developed, as a representative of the main working bodies. The mathematical apparatus for analyzing this process is quite cumbersome, so the final form of the model is as follows:

$$C_{П} = \left\{1 - exp\left[\frac{-8{,}37 \cdot a_0^3 \cdot \varepsilon^2 \cdot \nu^2 \cdot h_0}{l_0^2 \cdot V_c \cdot sin^2\,\psi} \cdot \left(1 - e^{-\delta\varepsilon t_{в}}\right)^{-2}\right]\right\} \cdot 100\% \quad (6)$$

where:

8.37 – a coefficient obtained experimentally;

a_0 – the permissible size of soil aggregates, cm

ε – the proportionality coefficient considering the plastic properties of the soil;

ν – the plastic deformation coefficient;

h_0 – the depth of cultivation by the flat-cutting working body, cm
l_0 – the initial elastic deformation, cm
φ_2 – the internal friction angle of the soil, degrees;
ψ – the soil slice angle, degrees;
δ – the kinetic absorption coefficient, $1 \cdot s^{-1}$
$t_в$ – the soil slice separation time.

The graphical interpretation of the mathematical model (Fig. 1) clearly demonstrates the nature of the dependence of the soil loosening quality index on a number of influential factors.

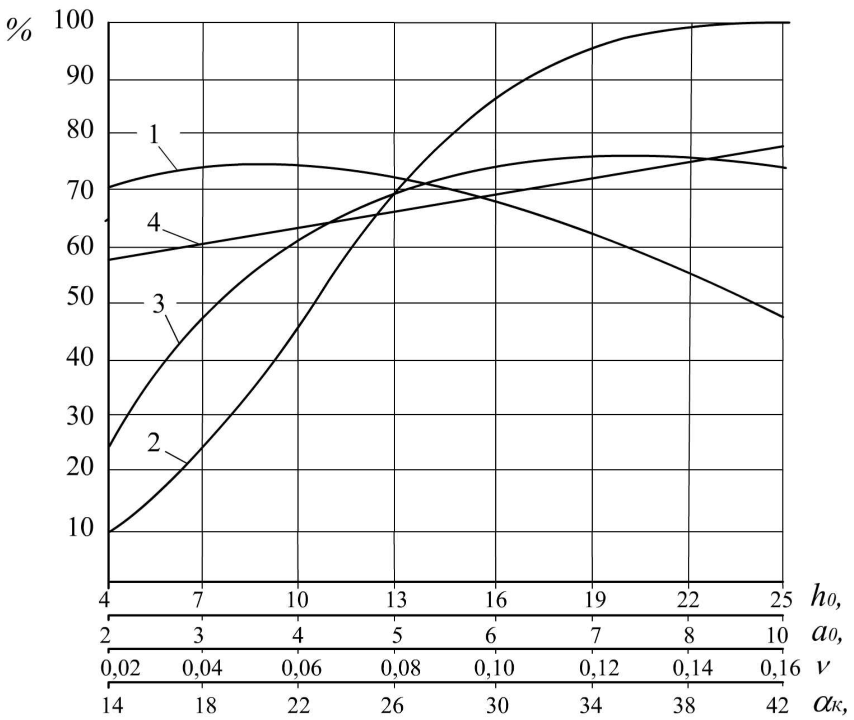


Figure 1. Dependencies of the quality index of cultivation on soil properties, working body parameters, and cultivation modes:

The presented graphical dependencies of the quality index on soil properties, parameters, and cultivation modes are calculated using formula (6) for $\varepsilon = 0.9$ the angles of external and internal friction of the soil at degrees $\varphi_1 = 28$ and $\varphi_2 = 38$ degrees under the following conditions and limitations:

$C_1 = f(h_0)$ – calculated at $\alpha_k = 34$ degrees, $\nu = 0.0812$, $a_0 = 5$ cm
$C_2 = f(a_0)$ – calculated at $\alpha_k = 34$ degrees, $\nu = 0.0812$, $h_0 = 13$ cm

$C_3 = f(\nu)$ – calculated at $\alpha_k = 34$ degrees, $a_0 = 5$ cm,$h_0 = 13$ cm

$C_4 = f(\alpha_к)$ – calculated at $a_0 = 5$ cm, $\nu = 0.0812$, $h_0 = 13$ cm, for heavy clay, with a density of $\rho = 1.5$ g·cm^{-3} and a change in absolute soil moisture from 1 to 27%. (α_k – the angle of crushing of the flat-cutting working body - a value that is included in the expression for determining ψ).

The developed mathematical model allows not only to calculate the predicted value of the soil loosening index C, but also to establish rational values of individual structural and technological parameters, such as the depth of cultivation by one working body h_0 (curve 1 has a pronounced extremum at a value close to 8…10 cm), or the value of the crushing angle α_k, which can be optimal for ensuring the specified value of the loosening index, taking into account other influential factors.

Justifying the composition of a combined soil-tillage tool to ensure rational performance indexes in different soil-climatic zones is possible if information is available on the soil loosening indexes not only by the main working bodies but also by additional ones, the types of which are listed above, without which it is impossible to ensure the specified homogeneous, fine-aggregate composition throughout the cultivation depth, necessary for favorable conditions for moisture and nutrient accumulation (Azimi-Nejadian, 2019; Celik et al., 2020).

The development of mathematical models for the functioning processes of other working bodies involves considering the features and nature of their impact on the soil environment and, undoubtedly, their structural parameters. Thus, among the additional working bodies, for which information on the possible method of justifying the composition of the soil-tillage machine is provided, harrows with flat teeth and a blunt angle of entry into the soil are considered. The contact field of these harrows with the soil represents parallel strips – the so-called teeth tracks 1 (Fig. 2).

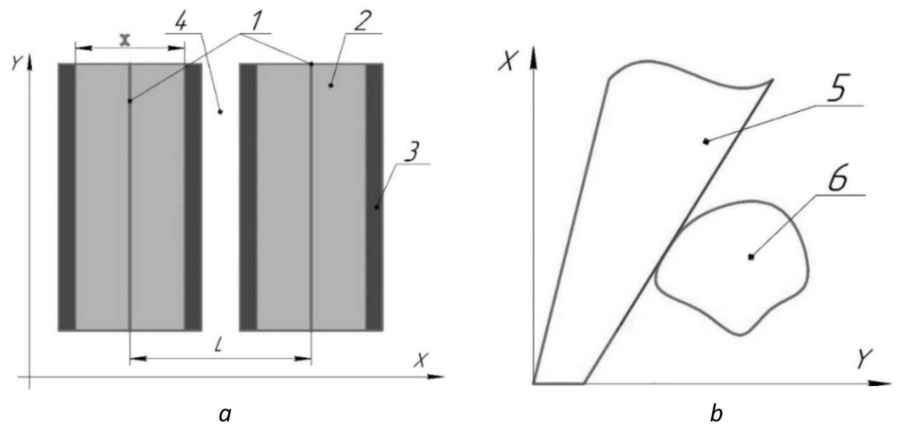


Figure 2. Zones of influence of harrow teeth on the soil during operation: a – horizontal plane; b – vertical plane; (L) – distance between teeth in the direction of machine movement; 1 – traces of adjacent harrow teeth; 2 – strips in the zone where soil loosening occurs under the influence of harrow teeth; 3 – zones where the influence of the working bodies is insufficient for soil loosening; 4 – zone where the teeth do not affect soil aggregates at all; 5 – tooth; 6 – soil aggregate (clod).

It can be assumed that the probability P of soil loosening to the specified value can be determined by the formula:

$$P = \frac{2}{L} \cdot x \qquad (7)$$

where $x$is determined from the equation:

$$\mathrm{x} = \sqrt{\frac{m}{k_T}\frac{v}{Rv}} F(x) - 1 + \frac{\pi R(3\cdot 10^3 + 4fRg\rho_0)\left(1-(2\cdot 10^5\sigma - 1)/30\right)}{3\{1-[(F(x)\,ctg\,\beta_0)^{-2}-1]^{-0.5}f\}k_T v} = 0 \qquad (8)$$

and

$$F(x) = 0.5\, sin^2\, \beta_0\{[1/(1-(x/R)^2) - cos^2\, \beta_0]^{-0.5} + [1/[1-(x/(1-\nu)/R)^2] - cos^2\, \beta_0]^{-0.5}\}$$

$$k_T = 2{,}08\frac{\sigma R}{\nu}$$

in which $\nu = \nu(\sigma)$.

The values of σ and ν have a high level of correlation, and the relationship between them is defined.

The graphical representation of the presented dependency clearly demonstrates the level of influence of various factors on the effectiveness of the harrow's work in additionally loosening the surface soil aggregates (Fig. 3).

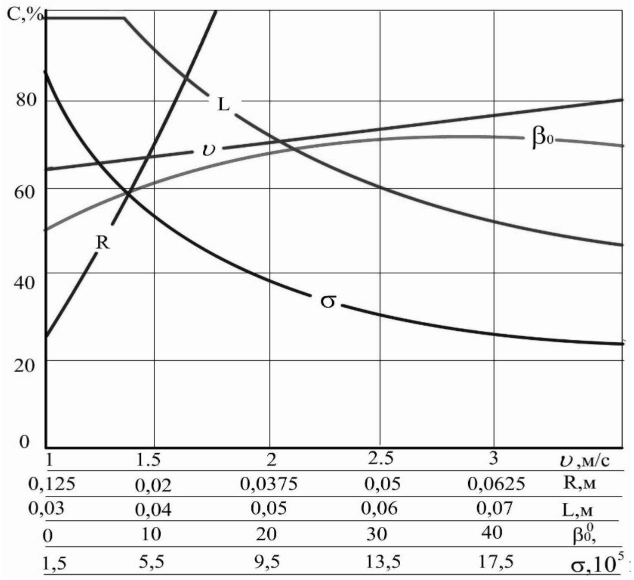


Figure 3. Graphical representation of the dependence of the quality index of soil cultivation C by a harrow with flat inclined teeth on:

σ	–	ultimate resistance of individual soil aggregates to destruction by compression;
R	–	average radius of the soil fraction;
L	–	distance between the traces of the harrow teeth in the direction of movement;
υ	–	working speed of the unit;
β_0	–	angle of inclination of the harrow teeth relative to the vertical position (dependencies of P on υ, R, L, σ obtained at $\beta_0 = 40$ degrees).

In this case, the most acceptable and effective way to improve the quality of the technological process performed by a harrow with inclined teeth may be to reduce the distance L between the traces of the teeth in the direction of the harrow's movement and to consider the optimal value of the angle β_0 of the teeth inclination relative to the vertical position. Similar to the considered ones, corresponding mathematical models of interaction with the soil environment are developed for other types of working bodies.

Results and Discussion

For the convenience of calculating the overall quality index of soil loosening by combined soil-tillage machines, differentiating their composition concerning the soil-climatic conditions of use, and justifying the rational structural parameters of individual working bodies that may be part of the machine, a special program based on Mathcad has been developed for implementation using a personal computer. The calculation algorithm involves using fixed, previously justified values of the working bodies' depth of operation at different tiers and considers the change in soil properties, represented by the relative index of linear plastic deformations ν, along the depth of cultivation.

The final calculation result is presented as a matrix, which is intended to place information about the value of the quality indicator *C* in three variants of tiered arrangement of flat-cutting working bodies and the available number of options for the possible use of additional working bodies of different types (Vasylkovska et al., 2016; Leshchenko et al., 2014). The rational set of working bodies is the one that provides the minimum value of the quality indicator, among those greater than the specified or provided by the agrotechnical requirements.

For experimental verification in the fields of farms in the Central Ukraine, the work of experimental deep rippers (Fig. 4 and 5) was evaluated in real field conditions. The results of the study of the experimental sample of the combined deep ripper with tiered arrangement of the main working bodies are presented in Table 1.

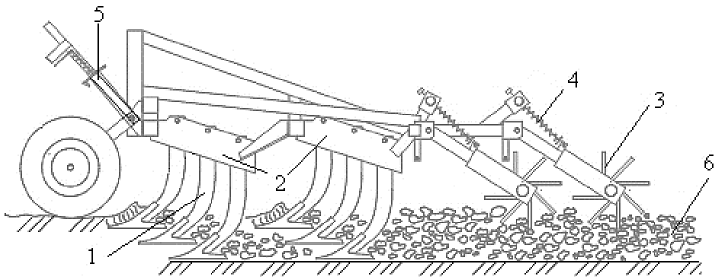


Figure 4. Technological scheme of the experimental deep ripper: 1 – heavy cultivator tines; 2 – beams; 3 – spiked rollers; 4 – pressure rods; 5 – mechanism for adjusting the depth of the working bodies; 6 – soil

Figure 5. Experimental sample of the deep ripper in operation.

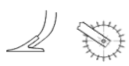
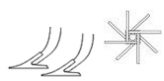
Table 1.
Results of the study of the experimental sample of the combined deep ripper with a tiered arrangement of the main working bodies

Indicators, units of measurement	Index values						
Field background, predecessors	Peas		Sugar beets			Fallow	Wheat
Soil type by mechanical composition	medium clay	medium loam	medium loam	medium clay	heavy clay	medium loam	light clay
Soil moisture, %	7.7	14.6	23.9	23.7	15.0	22.4	25.2
Soil hardness, MPa	5.04	2.1	1.33	3.83	5.16	0.48	2.47
Composition of the combined machine	Three tiers of tines +	Three tiers of tines +	Two tiers of tines + spiked	Two tiers of tines + harrow	Two tiers of tines + spiked	One tier of tines + harrow	One tier of tines + harrow

	spiked roller	disc roller	roller + combs	with flat teeth	roller with crossbars	with flat teeth	with flat teeth
Cultivation depth, cm	29	26	21	22	19	10.3	17.4
Soil loosening layer, %: (aggregates size from 0 to 50mm) experimental values	57.4	84.5	90.9	85.1	79.1	89.2	84.3*
Predicted by the developed methodology	51.9	84.48	85.2	81.8	81.6	87.05	78.9
Deviation between indicators, %	+5.9	-0.3	+6.3	+3.9	-3.1	+2.5	-4.1

For better perception, the recommendations can be presented in the form of a table with a graphical representation of the sets of working bodies that are optimal for achieving the set tasks when working on soils of different mechanical compositions (Table 2).

Table 2.
Approximate, calculated set of working bodies in the composition of a tiered combined soil-tillage tool, adapted for working on specified soil types.

Depth (h), cm	Soil type by mechanical composition			
	heavy clay	medium clay	heavy loam	medium loam
	Soil crushing indicator value C=80%			
9				
18				
27				

Conclusions

The experimental studies of soil-tillage tools with the sets of working bodies presented in Table 1 showed a high correlation between the quality indicators of soil loosening obtained experimentally and by calculation, which, in turn, confirms the viability of the proposed methodology for justifying the composition of combined soil-tillage machines.

The proposed approach, at first glance, seems quite labor-intensive. However, using the developed software, it can be implemented for the operational justification of the composition of combined machines with different types of working bodies (moldboard, no-till, disc, tiered, etc.). This is possible, provided that a broad base of mathematical models of the functioning of working bodies suitable for performing the specified technological operations is available, and updated.

A positive characteristic of the proposed methodology is that the database with information on the work of new working bodies can be updated without changing the overall algorithm of the software within one type of machine.

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ZRÓŻNICOWANIE SKŁADU AGREGATÓW UPRAWOWYCH W ZALEŻNOŚCI OD WARUNKÓW UŻYTKOWANIA

Streszczenie. Zaproponowano podejście do rozwiązania zadania ważnego z punktu widzenia produkcji rolnej, przy jednoczesnym zapewnieniu określonego wskaźnika jakości uprawy gleby, minimalnych kosztach energii i pracy oraz maksymalnym zmniejszeniu negatywnego wpływu na glebę i otaczające środowisko. Podejście zakłada zastosowanie agregatu uprawowego z optymalnym układem zespołów roboczych. Osiągnięcie tego celu wymaga zróżnicowania układu zespołów roboczych agregatów uprawowych w zależności od warunków ich pracy. Określa się je z wykorzystaniem metodologii, która może bazować na algorytmie w celu określenia ogólnego wskaźnika jakości oraz opracowania modeli matematycznych funkcjonowania poszczególnych organów roboczych, a także z wykorzystaniem autorskiej aplikacji.

Słowa kluczowe: różnicowanie, metodologia, agregaty uprawowe, zespoły robocze, modele matematyczne, spulchnianie gleby