THEORETICAL RESEARCH AND DEVELOPMENT OF INDICATOR OF PERMISSIBLE SOIL COMPACTION BY RUNNING SYSTEMS OF MACHINE-TRACTOR AGGREGATES

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Abstract. To essentially reduce soil compaction under real operating conditions of agricultural machinery, it is undesirable to exceed its permissible values. A theoretical study and analysis of the range of the most common machine-tractor aggregates (MTA) made it possible to establish a relationship between their design parameters and the energy (or work) that is spent on moving them across the field in the process of growing various crops. On the basis of the conducted theoretical research a new indicator of the allowed soil compaction by the running systems of the machine-tractor aggregates was developed, which regulates their movement across the field without deteriorating the state of the soil environment. Within the same field area, with the same working width of the machine-tractor aggregate, the value of the indicator of the allowed soil compaction by its running system does not exceed the maximum allowed value (0.75 GJ·ha^{-1}) and is practically indifferent with respect to changes in the length of the field headland and its width. Under the condition of more than one pass of the machine-tractor aggregate across the field, the constructive width of capture should increase according to the derived analytical regularity.

Keywords: machine-tractor aggregate, soil, compaction, index, working width.

Introduction

One of the key problems of modern agriculture is preservation of agricultural soil fertility [1]. Many scientific works are devoted to efficient solution of this problem [2-8]. Of the currently known impacts that cause a drop in the soil fertility the most dangerous is technogenic impact, which is completely due to the agricultural activities of the users of the land resources.

In the direction of solving this problem it was found that, if not for a complete, then at least for a significant reduction in soil compaction under real conditions of operation of agricultural machinery, it is necessary to provide such a deformation-compacting load on the soil environment that will not exceed a certain allowable value [9]. In practice such restrictive conditions in Ukraine are specifically reflected in the standard DSTU 4521:2006 “Agricultural mobile equipment. Norms of action of running systems upon the soil” [10]. However, it should be noted that, despite the undeniable importance of this national standard, it has not become a more or less full-fledged deterrent-restrictive factor. A number of reasons for this state of affairs and suggestions for its improvement are outlined in [1]. Considering this, there is a need to develop such indicators for the assessment of the intensity of the impact of the running systems of the machine-tractor aggregate upon the soil, the implementation of which would be effective and efficient.

According to some scientists, for example, V.V. Medvedev, one of these indicators can be an energy indicator [11]. In his opinion, it is advisable to regulate the level of the total load upon the soil of agricultural machinery, expressed in ton-kilometres per 1 ha (t·km·ha^{-1}) and determined through the product of the mass of the machine-tractor aggregate (t) by the path (km) that it passes across the field throughout the year in the process of growing certain crops. At the same time, it is proposed that the value of this indicator at the level of 50-100 t·km·ha^{-1} per year should be considered as the one that characterises exactly the permissible impact of agricultural machinery upon the soil. In addition, despite the potential efficiency of the above-mentioned indicator of the intensity of the impact of the running systems of machine-tractor aggregate upon the soil, there is no specific algorithm for its practical implementation yet.

One of the reasons for this result is connected with the working (capture) width of the machine-tractor aggregate. The matter is that, on the one hand, an increase in this parameter leads to the desired decrease in the number of passes of the aggregates across the field, but, on the other, - to an undesirable increase in their operating mass. The last factor, as is known, univocally leads to an increase in the compaction effect of the machinery on the agrotechnical background. All this is the reason for the lack of relevant scientific information on the functional regularities of the relationship between the design parameters of the machine and the tractor aggregates, and the energy costs for their movement across the field in the process of growing crops.

The purpose of the research is to develop a new indicator for regulation of the magnitude of intensity of the impact of the running systems of machine-tractor aggregates upon the soil compaction at a level that would practically exclude deterioration of its condition.

Materials and methods

Analysis of the nomenclature of the most common machine-tractor aggregates was made in order to establish an interrelation between their design parameters and the energy (or work) that is spent on their movement across the field in the process of growing crops. Theoretical aspects of the research are based on the main provisions of the theory of operation of agricultural machinery, higher mathematics.

Let us first determine the main initial prerequisites for the solution of this issue. Let a corresponding machine-tractor aggregate, performing a particular technological operation on a field with a width B_f (m) and a length of the working run L_p (m), process a certain area S_f (ha) in a certain time:

$$S_f = \frac{B_f \cdot L_p}{10000} \tag{1}$$

This dependence (1) gives an approximate result since under real conditions the parameter (L_p) is less than the length of the field (L_g) by the width of two headlands. At the same time in the problem that we are considering the difference ($L_g - L_p$) can be neglected with sufficient accuracy for practice. However, expression (1) is the basis for considering it quite adequate. Taking this into account and taking into consideration the proposals set forth in [12], the intensity index W of permissible soil compaction under the impact of the running systems of the machine-tractor aggregates upon the soil can be presented as follows:

$$W = \frac{G_a \cdot g \cdot \Sigma S}{S_f} = \frac{G_a \cdot g \cdot \Sigma S}{B_f \cdot L_p} \cdot 10^4, \tag{2}$$

where G_a – mass of the machine-tractor aggregate, kg;
g – acceleration of gravity (9.81 m·s^{-2});
ΣS – total path, travelled by the aggregate across the field in the process of its processing.

In fact, the product $G_a \cdot g \cdot \Sigma S$ in expression (2) represents the work (N·m) or energy (J) that the machine-tractor aggregate spends on its movement. Taking this into account, the dimension of the proposed new indicator of the intensity of the impact of the running systems of the machine-tractor aggregate upon the soil is N·m·ha^{-1} or J·ha^{-1}. In further analysis we will focus on the last version of the W dimension. Based on our analysis of about 500 compositions of the machine-tractor aggregates for various technological purposes, it was found that with a determination coefficient R2 = 0.98, the weight force of one or another machine-tractor aggregate $G_a \cdot g$ may be approximated by a function the argument of which is the width of the aggregate:

$$G_a \cdot g = A \cdot \ln(B_p) + C, \tag{3}$$

where A = 80000 and C = 43000 – approximation coefficients.

Let ΣS, the path passed by the aggregate through the field in the course of its processing, be the sum of two components:

$$\Sigma S = \Sigma S_p + \Sigma S_{xx}, \tag{4}$$

where ΣS_p, ΣS_{xx} – path, travelled by the aggregate during the movement on the working runs and headlands, respectively.

When making turns $n = B_f/B_p$ on the field, the expression for calculating the first of these paths is as follows:

$$\Sigma S_p = L_p \cdot \frac{B_f}{B_p}. \tag{5}$$

The value of the second path can be determined by the following expression:

$$\Sigma S_{xx} = L_{xx} \cdot (n-1), \tag{6}$$

where L_{xx} – length of one turn of the machine-tractor aggregate.

The operation practice of modern machine-tractor aggregates shows that the vast majority of them carry out the “shuttle” mode of movement. In such a case:

$$L_{xx} = k_1 \cdot \pi \cdot R_a, \tag{7}$$

where k_1 – coefficient showing the degree of difference between the value of the parameter L_{xx} and the length of the semicircle;
R_a – turning radius of the machine-tractor aggregate, m.

The last parameter can be defined in the following way:

$$R_a = \frac{k_2 \cdot B_p}{2}, \tag{8}$$

where k_2 – coefficient representing the degree of difference between the values of the turning radius of the machine-tractor aggregate and half the width of its capture.

Taking into account the above expression (6), in the final version it will have the following form:

$$\Sigma S_{xx} = \frac{k_1 \cdot k_2 \cdot \pi}{2} \cdot (B_f - B_p). \tag{9}$$

If now the obtained dependences (3), (5) and (9) are substituted into (2) and the corresponding transformations are made, then, as a result, we will obtain the final expression for determination

$$W = [A \cdot \ln(B_p) + C] \cdot \left[\frac{1}{B_p} + \frac{k_1 \cdot k_2 \cdot \pi}{2} \cdot \left(\frac{B_f - B_p}{B_f \cdot L_p}\right)\right] \cdot 10^4 < W_{\max}. \tag{10}$$

In expression (10), the first square bracket presents the weight force of the machine-tractor aggregate in newtons (N). The dimension of the second square bracket is m^{-1}. Factor 10^4, as follows from formula (1), has the dimension $m^2 \cdot ha^{-1}$. Ultimately, the dimension of the indicator W is $N \cdot m \cdot ha^{-1}$ or the specific energy $J \cdot ha^{-1}$.

The indicator $W_{\max}$ in equation (10) represents the limit of the acceptable value of the indicator W. In addition to work [12], neither compromise, nor alternative considerations, regarding the nature and values of $W_{\max}$, have been found in the literature. Only source [5] indicates, as noted above, that the allowed value of the indicator W (i.e.$W_{\max}$) should be within 50-100 $t \cdot km \cdot ha^{-1}$ or 0.5-1.0 $GJ \cdot ha^{-1}$. However, the resulting theoretical expression is valid and can be used for any other (regulated) values of this indicator.

In a general case, equation (10) can be analysed precisely within these limits of the change in the indicator $W_{\max}$. It is obvious that in each particular production situation this should be done. But in this case, to understand the regularities of the process, expressed by equation (10), it is quite convenient and sufficient to use the average value of the indicator, $W_{\max}$, i.e. 0.75 $GJ \cdot ha^{-1}$.

Results and discussion

As the experience of practical operation of the modern machine-tractor aggregates shows, for the vast majority of them the values of coefficients k_1 and k_2, included in expression (10), differ little from number one. In the process of theoretical research of dependence (10), the width of capture of the machine-tractor aggregate was considered within the range of 4-24 m. The minimum field area was taken at the level of 40 ha, and the maximum one – as 100 ha.

The analysis of the calculation results shows the following. For a field with an area of 100 ha an increase in the length of its run from 600 to 1400 m (i.e., more than twice) leads to the desired (although insignificant) decrease in the indicator of the allowed soil compaction by the running systems of the machine and tractor aggregates (Table 1).

In addition, this decrease is the greater, the greater is the width of capture of the aggregate. For example, if at $B_p =$ 4, an increase in the length of the field headland from 600 to 1400 m leads to an increase in the value of the estimated indicator W by 1.3%, then at $B_p = 24$, this increase reaches 5.9%.

Table 1

Impact of the working width of capture of a machine-tractor aggregate upon the value of the coefficient *W* at various values of the length of the run with an area of the field 100 ha

Operating width of MTA, m	**Value of indicator *W*,** GJ·ha^{-1}		
	Length of the run, m		
	600	1000	1400
4	0.391	0.387	0.386
8	0.270	0.265	0.264
12	0.211	0.205	0.204
16	0.176	0.170	0.168
20	0.152	0.146	0.144

Approximately a similar situation appears when changing the width of the field B_f. As a result, evaluating the significance of the obtained calculation results, it can be stated that within the same field area (S_f) with the same width of capture of the machine-tractor aggregate (B_f), the value of the indicator (W) of the allowed soil compaction by its running system does not exceed the maximum allowed (W_{max}), and it is practically indifferent to the change in the length of the headland of the field (L_p) and its width (B_f). Note that the above results of the theoretical research are valid for a single pass of one or another machine-tractor aggregate across the field. In fact, there may be more such passes. Considering this, we have the following result. In a case of double movement of the machine-tractor aggregate across the field in the process of growing crops, condition (10) may be met when the width of the aggregate is at least 5 m (Curve 2, Fig. 1).

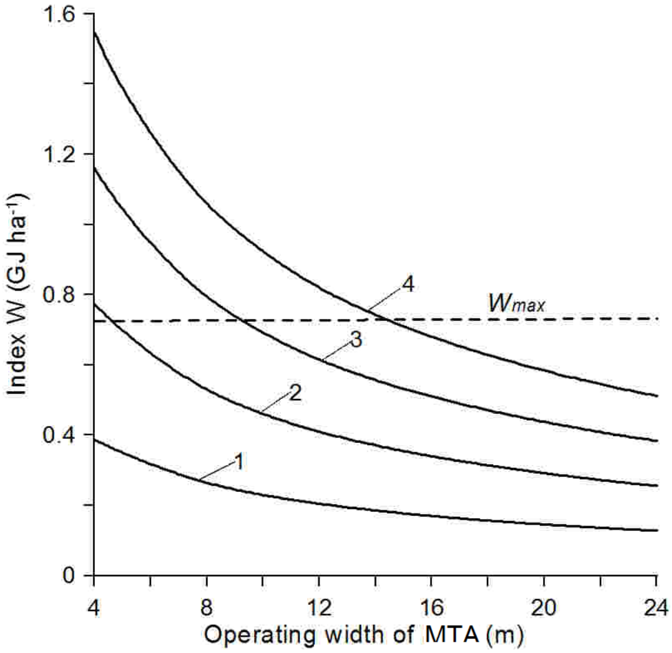

Fig. 1. **Influence of the working width (width of capture) of the machine-tractor aggregate upon the index W with a various number of the field treatments per year:** 1, 2, 3, 4 – respectively, the number of passes (treatments) per year

If growing of one or another agricultural crop involves three-fold passing of the machine-tractor aggregate across the field, then the working width of capture must be more than 9 m (Curve 3, Fig. 1). In case of a four-fold passing of the machine-tractor aggregates across the field, which is quite realistic for practice, the working width (capture) of the machine-tractor aggregate must be at least 14 m (Curve 4, Fig. 1). For non-fulfilment of this condition, which in the real conditions of managing most agroformations can be quite problematic, the cultivated soil environment can suffer such damage, the levelling of which is associated with a significant investment of time and money. As we can see, the derived theoretical dependence (10) is of significant scientific and practical importance and may be used in the process of developing technologies and technological maps for growing crops at the stage of choosing the composition of machine and tractor aggregates. First of all, this concerns the constructive width of capture of their technological parts.

Conclusions

1. On the basis of the conducted theoretical research a new indicator of the allowed soil compaction by the running systems of the machine-tractor aggregates was developed, which regulates their movement across the field without deteriorating the state of the soil environment.
2. Within the same field area, with the same working width of the machine-tractor aggregate, the value of the indicator of the allowed soil compaction by its running system does not exceed the maximum allowed value (0.75 $GJ \cdot ha^{-1}$) and is practically indifferent with respect to changes in the length of the field headland and its width. Under the condition of more than one pass of the machine-tractor aggregate across the field, the constructive width of capture should increase according to the derived analytical regularity (10).

Author contributions

Conceptualization, V.B. and V.N.; methodology, S.I. and V.N.; validation, A.A. and V.B; formal analysis, V.B., I.H., A.A. and S.I.; investigation, V.B., S.I., V.N..; data curation, A.A. and V.B.; writing – original draft preparation, V.B.; writing - review and editing, S.I. and V.N.; visualization, V.N.; project administration, V.B.; funding acquisition, S.I. and A.A. All authors have read and agreed to the published version of the manuscript.

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