Methods and means of digital measurement of soil parameters and conditions of functioning of tillage machines for deep loosening of soil

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Abstract. Due to of the widespread application of intensive technologies using energy-saturated machine-tractor units, the formation of over-compacted layers occurs in arable horizon, the presence of which significantly worsens the conditions for the growth and development of cultivated crops, and also violates the ecological balance of agrolandscapes. To eliminate soil compaction, a subsoiler tillage is used, for the successful implementation of which it is required to ensure the setting of rippers below the depth of the dense layers. At the same time, deep loosening requires significant energy expenditures, and therefore the task of finding a rational adjustment value of the depth of deep loosening, at which fuel costs are minimized while ensuring the required quality of soil cultivation, arises. To accomplish the tasks with using of digital measuring systems, the soil state was monitored to a depth of 60 cm. Using of the original methodology for determining the depth of an over-compacted layer, it was possible to obtain a random process of its position and calculate estimates of statistical characteristics. The setting of rippers based on calculations of the statistical characteristics of the random process of the depth of the overcompacted layer according to the results of monitoring the soil condition allows us to ensure the required quality of soil cultivation and minimize energy costs for its implementation.

1. Introduction

Under conditions of increased intensification of agricultural technologies, the main factor worsening the ecology of agricultural landscapes is soil over-compaction resulting from the anthropogenic impact on it of energy-saturated machine-tractor and harvesting-transport units [1-3]. This leads to a significant deterioration in the state of the root layer of plants, which negatively affects the course of production processes, reduces the efficiency of the use of water resources, and causes water and wind erosion of the soil [4, 5]. Of particular note is the formation of over-compacted soil layers, in the form of the so-called “plow pan”, formed during the work of plows that perform plowing at the same depth. Studies have established [6–8] that when the soil density exceeds a critical value of 1.6 g/cm³, the growth and development of the root system of most plants is very difficult or impossible.

The elimination of the effects of the marked anthropogenic impacts is carried out using tools for deep tillage (deep-rippers), which require significant energy costs [9, 10]. It is possible significantly reduce these costs by fine-adjustment the rippers to a depth of tillage that ensures the destruction of soil compaction. Such adjustment of the tools requires a sufficiently high accuracy when determining the position of over-compacted soil layers in the root-inhabited layer. This can be done by using digital systems to determine the parameters of the soil conditions when fulfil mapping the fields using...
the Top Soil Mapper measuring complex [11], which allows monitoring the soil state by a non-contact method (Figure 1).

2. Methods and materials

As known, agricultural crops have varying degrees of penetration of the root system, while most of them are quite sensitive to soil compaction.

When assessing the mechanical resistance of the soil to the development of the root system of plants, an indicator in the form of cone index was used. It is an analog of its density, having a high degree of mutual correlation [12]. Using the soil cone index can significantly increase the efficiency of obtaining estimates of the soil condition.

To select and justify the settings of the subsoiler, an information model was built a technological model of its functioning. The block diagram of this model is shown in Figure 2. At the input of the model, random processes of the surface profile of the field \( Z_f(l) \) and the depth of the over-compacted layer \( h(l) \) obtained by using digital measuring systems used in precision farming operate.

The output processes of this model are random processes in the form of the depth of working of the loosening tines \( a(l) \) and fuel consumption \( g(l) \), which characterizes the energy consumption. As a tuning action, this model considers the installation value of the depth of the Ha ripper, which is selected for each section of the field in accordance with an electronic map with soil compaction zones horizontally plotted on it (Figure 3). To assess the compliance of the parameters obtained during monitoring with real soil conditions, the soil cone index resistance was measured using a special Penetrologger instrument, which records the soil resistance when deepening the cone-shaped deformer to a depth up to 60 cm.

![Figure 1. Soil monitoring with Top Soil Mapper](image)

![Figure 2. Scheme of the model of the technological process of functioning of the subsoiler](image)
To ensure a high degree of reliability of the results of studies obtained during field experiments, estimates of the random process of the soil cone index were determined at 300 points along the head length $L = 60$ m with a step $\Delta l = 0.2$ m in the visible range. Horizons are in depth every 1 cm. According to the obtained implementation of the random process, $R_i(l)$ were calculated to assess the statistical characteristics of soil cone index, as well as changes in the depth of the position of the over-compacted soil layer $h(l)$.

**Figure 3.** Field map indicating the depth of over-compacted soil layers

To search for the position of the over-compacted layer $h(l)$ in depth, we used the principle [13], a graphical interpretation of which is shown in Figure 4. The tangent to the graph of changes in soil hardness $r'(h)$ are the first derivatives of $R(h)$ at depth $h$. The derivative $R'(h_1)$ at a depth $h_1$ less than the depth $h_0$ of the position of the reconsolidated layer has a positive value, i.e. $R'(h) > 0$, because $r$ increases with increasing $h$. For $h = h_0$, the cone index takes its maximum value, and its derivative is zero $R'(h) = 0$. For $h > h_0$, the cone index of the soil decreases, and its derivative takes a negative value i.e. $R'(h) < 0$. Thus, the position of the over-compacted layer in depth is determined at the moment when the first derivative of the soil cone index $R'(h)$ is zero, changing its sign from positive to negative.

**Figure 4.** Graphical interpretation of the algorithm for finding the depth of the over-compacted layer
The model of the object under study makes it possible to implement the possibility of tillage for deep soil loosening with minimal energy consumption for the destruction of the over-compacted layer based on the accurate determination of its position.

3. Results and discussing

Based on the theoretical studies and full-scale experiments, for the first time it was possible to obtain estimates of the random process $h(l)$ of the location along the depth of the over-compacted layer [14]. An analysis of the process $h(l)$ showed that it obeys the normal distribution law. Figure 5 shows a segment of the implementation of this process. Estimates of the statistical characteristics of this process are as follows: mathematical expectation $m_h$ - 34.0 cm; standard deviation $\sigma_h$ - 4.24 cm; coefficient of variation $V_h$ - 12.5%.

Therefore, when providing adjustment of a subsoiler for current soil conditions, it is necessary to set the tuning value of the depth of tillage equal to the value $a = m_h + 3\sigma_h$. This ensures guaranteed destruction of the over-compacted soil layer and a reduction in energy consumption, estimated by fuel consumption, up to 15%.

The obtaining of electronic maps indicating the depth of re-compacted soil layers can be used to automatically control the operation of deep soil loosening in precision farming. For this purpose, tillage implements should be equipped with a hydraulic depth control system with an electric or hydraulic drive.

The obtained patterns can be used in the development of the algorithm of the device for automated monitoring and control of the operation of deep-rippers. In addition, the presented data can be used to calculate the minimum control length, which determines the current position of the over-compacted layers of the soil horizon for operational adjustment of the adjustment value of the soil depth of the automated implement.

4. Conclusion

As a result of the use of means of digitalization of the parameters soil conditions during subsoiler operating, a method was developed for finding the location of the plow pan. This method is based on the processing of a random process of the placement depth of the over-compacted soil layer along the length of the field and estimates of its statistical characteristics. The data obtained are used to select rational settings for subsoilers that ensure the fulfillment of the required indicators of the quality of tillage while minimizing energy consumption.
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